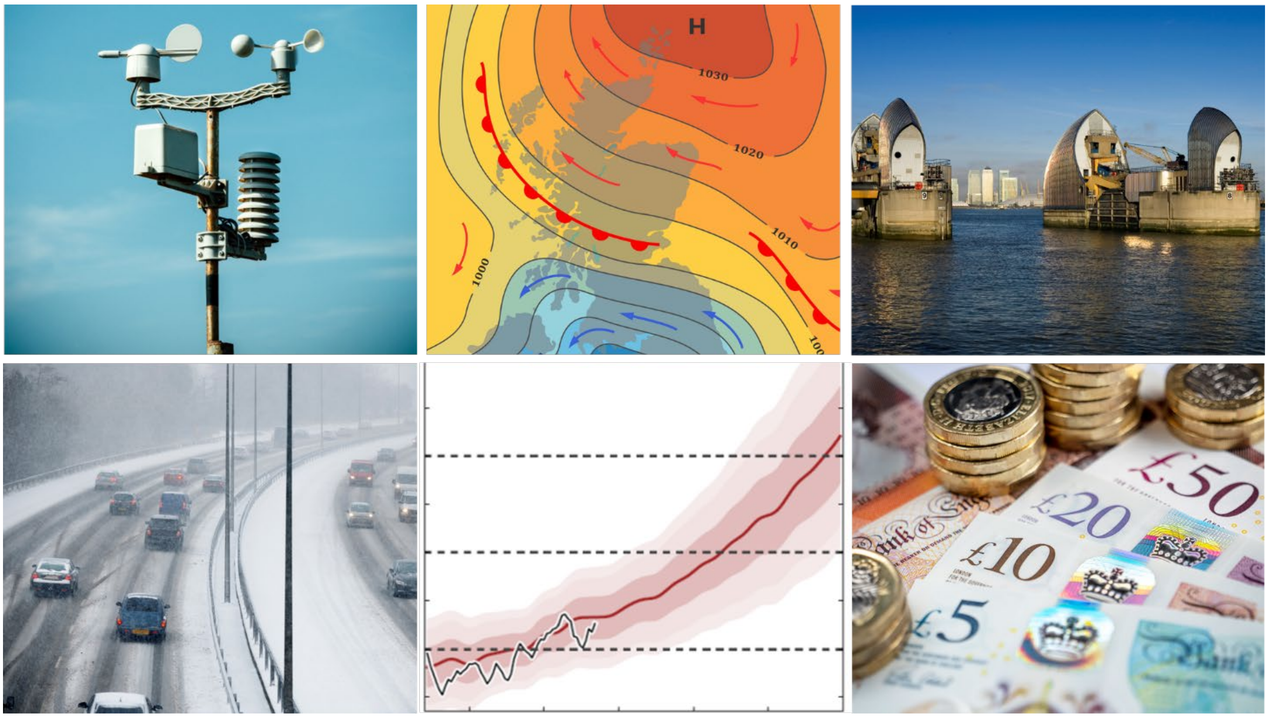
Valuing and Monitoring Climate Services



Final Report

on the Work and Case Studies on Valuing and Monitoring Climate Services

Paul Watkiss and Alistair Hunt

as part of the project

‘Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services’

Summary of the Project

This report presents the overall work undertaken on monitoring and valuing climate services as part of the contract *Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services*.

The aim of the work was to:

- Propose a methodology and set of guidance for valuing climate services, as well as a suggested method and guidance for analysing value for money (as part of monitoring) (Deliverable 2).
- Apply the methods and guidance in a set of case studies and provide lessons from testing the methodology (Deliverable 4).

The overall findings of the work and case studies is outlined in this document. A separate guidance document and academic paper has also been produced as part of the study.

Valuation of adaptation services

Investing in climate services leads to improved information, for example, from new or enhanced seasonal forecasts. In turn this information provides economic benefits to users, as it leads to positive outcomes from improved decisions. However, for these economic benefits to be realised, there needs to be an effective flow of information along the climate service value chain, from the production of information through to its uptake and use in a decision.

There are existing approaches for valuing traditional weather and climate information (W&CI) services, i.e., for weather or seasonal forecasts. These involve a series of steps: identifying potential benefits; developing a value chain; choosing a method; and then analysing the economic value of the service relative to a baseline. These valuation approaches are also potentially applicable to climate services, including adaptation services. However, adaptation involves different types of information, timescales and decisions, and so there may be adjustments needed to transfer methods to the adaptation context. This study has developed guidance for climate service valuation, which includes adaptation services.

Definition of climate services

There are numerous definitions of climate services, and these include different temporal periods and a varied range of information types[1]. For this report, we focus on climate services that support end-users with decisions, as it these applications that can potentially generate economic or social value. This is a narrower definition of climate services than the CR20-2 study on standards is using.

We also differentiate climate services in terms of information timescales. The climate services literature, and the overall CR20-2 study, consider climate services as a single set of services, that include climate variability and climate change, noting this excludes weather information (short-term, hourly, daily or weekly forecasts).

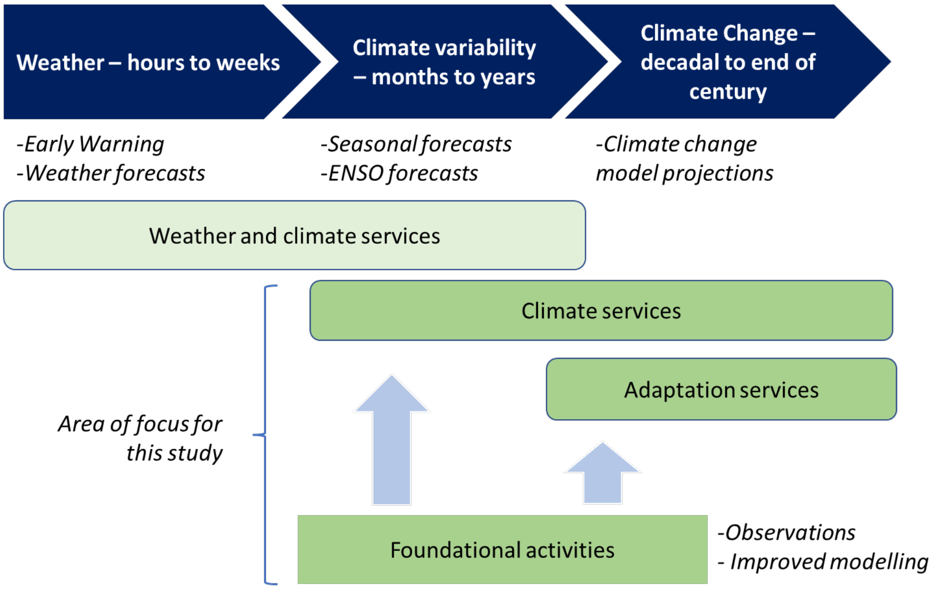
However, for this valuation guidance, we separate climate services into two distinct periods and associated decision types.

[1] The Global Framework for Climate Services reports that Climate Services ‘provide climate information to help individuals and organizations make climate smart decisions’…with ’customized products such as projections, trends, economic analysis and services for different user communities’, with the aim to ‘equip decision makers in climate-sensitive sectors with better information to help society adapt to climate variability and change’. https://gfcs.wmo.int/what-are-climate-services

- Information and services for months to years ahead (seasonal forecasting, inter-annual variability). These are associated primarily with services that address climate variability.
- Information including climate projections for future decades or centuries ahead. These are associated with climate change adaptation decisions (and sometimes called adaptation services).

This separation is needed for valuation, because the two time periods involve different methodological issues. Indeed, a key focus of this work has been to examine whether traditional methods for valuing W&CI services (e.g., weather forecasts, seasonal forecasts, and early warning, see WMO, 2015) can be transferred to the climate change and adaptation context.

The study has also considered the economic benefits of improved observations and historic information, in their role in improving climate services. The overall focus of this study, in terms of the different timescales of information and decisions of relevance from weather and climate services, is shown in the figure below.



Time scales of information and decisions, including the study focus areas.

Methodology

The study has developed a general method for climate services, drawing on the existing literature in this area. This includes the following steps:

1. List the potential economic benefits that the climate service may provide.
2. Develop the value chain for the service.
3. Review and decide on the potential methods for assessing economic benefits.
4. Build a baseline scenario (or counter-factual) without the new climate service.
5. Assess the benefits with the climate service in place.
6. Assess the costs of the project developing the climate service.
7. Compare benefits against service costs.
8. Undertake sensitivity and bias analysis, then review how benefits could be enhanced.

A separate guidance summary has also been produced from this study (separate report) which sets out these methodological steps and provides examples from the case studies.

Case studies

The project has tested this method in four case studies, which reflect different types of climate services in the figure above. The case studies are:

- Seasonal forecasting, looking at the potential economic benefits of the Met Office winter seasonal forecast for the transport sector.
- Improved observations for weather and climate services, looking at the potential benefits for the wine sector in the UK from improved frost forecasting arising from improved observations, including for current weather services and also future adaptation (climate services).
- Reactive adaptation, looking at the use of climate information to support adaptation decisions for the heat health alert scheme, including a possible extension of the scheme geographically.
- Proactive adaptation, looking at the use of climate projections and the Environment Agency climate allowances in infrastructure decisions, including the consideration of uncertainty.

These are presented in the table below. It is stressed that the four case studies were 'light-touch' studies rather than detailed assessments, but they provide a good test of the general method, and also were able to look issues of transferability in applying methods from current W&CI services to the adaptation services context.

Case studies undertaken, with the user decision, climate information and valuation focus.

	Winter seasonal forecast for the transport sector	**Observational data and wine**	**Reactive adaptation and heat alert schemes**	**Proactive Adaptation climate allowances**
User Decision	Use of seasonal forecasts in winter planning for the transport sector	Action to protect vines from frost event damage that would reduce grape yields. New vineyard decisions.	Extension of an existing early warning (heat alert) to a new location (Scotland)	Use in flood management (national) and project design of drainage Use in design for a sea wall project
Climate information	Winter seasonal forecasts	Short-term forecasts of air temperature. Long-term agro-climatic suitability.	Current heatwave forecast. Extension of forecast to Scotland, including future climate model projections / fatalities	Future climate projections (UKCP18) over next 50 years for key design parameters and incorporation in climate allowances
Value with climate information use in decision	Avoided impacts in the transport sector (road, rail, air)	Value of the grape production saved. Potential support to investment decisions.	Value of heat wave forecast-HHWS (current) and value of new forecast-HHWS in Scotland.	Value of reduced impacts from climate change / enhanced performance Consideration of if-then with decision making under uncertainty

Method and Valuation Findings

The methodology development and its application in the case studies provide a number of insights.

The methodology and the eight steps were found to be directly applicable and work well for the analysis of the economic benefits of climate services for climate variability (e.g., seasonal forecasts). This was demonstrated in the winter seasonal forecasting case study. The use of the value chain approach in the method also allowed the economic benefits of improved observations to be assessed, from an analysis of the improved accuracy in weather or climate services that these observations lead to. This was demonstrated in the wine case study. While the case studies demonstrate the general suitability of the method, in practice, both studies were slightly limited by the available evidence, notably on the efficiency losses at each stage of the value chain, but also in finding sufficient real-world information on user uptake and actions. It would be possible to fill these gaps, but this would require more detailed studies and corresponding analysis.

Moving to climate services for adaptation, there has been little application of W&CI information valuation methods to adaptation services to date. Instead, most adaptation valuation studies have used a different approach, primarily based on impact assessment methods.

To explore this, the methodology was first applied to a case study of reactive adaptation. This is adaptation in response to an observed and experienced changes in the climate. This was explored in the case study on extending the current heat health alert scheme. In this case, climate information was used to consider a geographical extension to an existing weather service (the adaptation decision) to address rising climate risks that are already occurring. Such action leads to immediate economic benefits. The methodology was found to be applicable for the analysis of such reactive adaptation decisions, although some additional steps were useful to consider future climate projections as part of the analysis, and to help build the case for action. Indeed, the case study application found that the use of a value chain approach was a useful addition to adaptation assessment more generally, and these approaches could be used to improve studies on the economics of early adaptation.

Finally, the study applied the methodology to proactive adaptation. This is adaptation that involves anticipatory, planned decisions, which are based on climate model projections and subject to higher levels of uncertainty. While there are theoretical studies of such action, there are not many studies of the economic benefits of adaptation services in real-world proactive decisions (noting it is only practical applications that generate concrete economic benefits). This case study looked the application of climate allowances for infrastructure design decisions. It found that the traditional methods for the valuation of weather and climate information services (as above) to proactive adaptation involves additional challenges, especially around the accuracy of the information and in terms of actual outcomes. The case study compared two methodological approaches – a theoretical static approach (if-then) and decision making under uncertainty with consideration of possible real-world outcomes and regret – and estimated the benefits and costs of these. The case study found that the benefits of adaptation services vary depending on the decision support method that is used. This also means that some of the ‘value of information’ generated by adaptation services for proactive adaptation should be attributed to the decision support service step, and not just to the climate information provision.

Monitoring and Value for Money

A related issue for climate services is around the framework for monitoring and evaluation (M&E), and this links to the concepts of a Theory of Change and Logical Frameworks.

The process of programme or project development for climate services can use logic models (also known as logical frameworks or logframes) to encourage a structured approach. This involves a standardised set of steps (the causal pathway or results chains) of a logical framework, and the flow from input and activities, through to the subsequent outputs and outcomes, and finally, to the overall impact.

Any climate service project can be framed in terms of a logical framework. These logframes also form the foundation for monitoring and evaluation. A climate service can identify output and outcome-based indicators that can be used to monitor and evaluate the performance of the climate service, for example capturing the number of forecast products or the number of end-users trained in their use. The economic benefits from climate services can be included as an outcome or impact metric for such a logframe.

Finally, there are linkages between economic benefits, Monitoring and Evaluation, and Value for Money (VfM). VfM is not about securing lowest prices or costs, it is about delivering best overall value. This is framed in the UK through the 3Es: economy (spending less, reducing the costs of inputs), efficiency (inputs to outputs, i.e., spending well) and effectiveness (i.e., outputs to outcomes/impacts, i.e., spending wisely efficiency). These 3Es can be linked to a logical or results framework to help drive VfM in managing inputs, and maximising the level, quality and impact of outputs and outcomes.

Economic studies can help to develop an improved understanding and better articulation of a project's efficiency and especially its effectiveness, and they can provide quantitative information to help demonstrate and report on Value for Money (VfM).

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List of acronyms / Key glossary terms

3Es – Components of Value for Money: Economy, Efficiency and Effectiveness.

AR5 – Fifth Assessment Report (of the IPCC)

BCR - Benefit to Cost Ratio. A metric used in cost-benefit analysis that presents the total present value of benefits divided by the total present value of costs. Interventions that have a benefit to cost ratio of >1 have a positive net present value.

CBA – Cost Benefit Analysis. CBA is an economic decision support tools that measures all relevant costs and benefits to society (including non-market effects), in present value terms, and then estimates a net present value and/or a benefit-to-cost ratio.

DMUU – Decision Making Under Uncertainty. The use of decision support tools for adaptation which consider uncertainty, through principles such as robustness, flexibility, etc.

DRM – Disaster Risk Management.

DRR – Disaster Risk Reduction.

Ex ante – before, i.e. ex ante appraisal of a climate service before it is introduced.

Ex post – after, i.e. ex post evaluation of a climate service after it is introduced.

EIRR – Economic Internal Rate of Return.

EWS – Early warning system.

GBON - World Meteorological Organization's Global Basic Observing Network.

GCM – Global Circulation Model.

GHG – Greenhouse Gas (Emissions).

HMT – Her Majesty's Treasury.

IPCC - Intergovernmental Panel on Climate Change (IPCC) - the United Nations body for assessing the science related to climate change.

NMHS - National Meteorological and Hydrological Services.

NAO - National Audit Office.

NPV – Net Present Value.

NWP - Numerical Weather Prediction.

RCP – Representative Concentration Pathways.

SEB – Socio-Economic Benefits. A term sometimes used to describe economic benefits, i.e. the benefits of a policy, programme or project in terms of improved social welfare or wellbeing.

STPR - Social Time Preference Rate.

UKCP18 - UK Climate Projections 2018.

UK MO – UK Met Office.

W&CI – Weather and Climate Information.

WISER – Weather and Climate Information SERvices for Africa.

WMO - World Meteorological Organization.

VfM – Value for Money. UK Government frames Value for Money in three areas: Economy, Efficiency and Effectiveness), alongside a fourth component on equity.

VoI – Value of information.

Methodology for Valuing and Monitoring Climate Services to Manage Climate Variability


Deliverable 2 of the contract:

'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services'

Paul Watkiss, Federica Cimato, Alistair Hunt

June 2021.

Summary

This report presents the 'methodology for monitoring and valuing climate services', which is Deliverable 2 of the contract 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services'. The aim of the work is to propose a methodology and set of guidance for valuing climate services, as well as a suggested method and guidance for analysing value for money (as part of monitoring).

Definition and boundaries. A key issue for this deliverable is the definition of climate services and the boundaries for the study. There are numerous definitions of climate services, and these relate to a broad range of types of information. For valuation (the focus of this deliverable), climate services contribute economic or social value when users benefit from better decisions, as a result of the use of information (as compared to a counterfactual). This deliverable, therefore, narrows the boundaries of climate services to such applications. The overall CR20-2 study, which is considering standards, is using a much broader definition of climate services.

A further important way to separate climate services - especially for socio-economic benefit analysis - is using the timescale of the climate information provided. This can include:

1. Observed and historic information;
2. Forecasts over hours to weeks ahead (early warning, weather forecasts);
3. Forecasts for months to years ahead (seasonal forecasting, inter-annual variability); and
4. Projections for future decades, even centuries ahead (climate change).

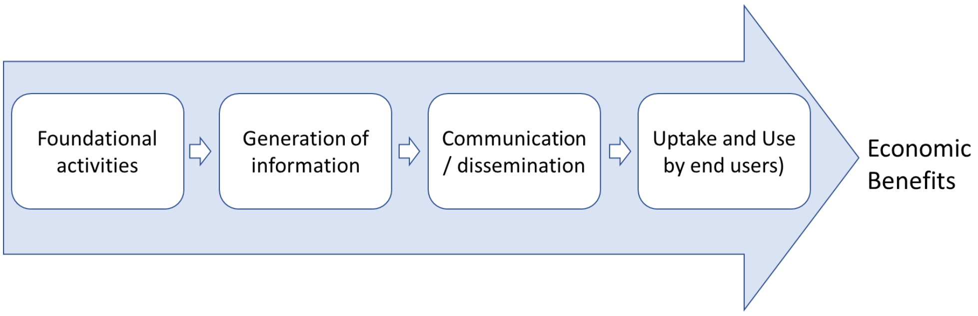
Following discussion with the Met Office, the current study excludes area 2), i.e. weather forecasting (short-term. The other three areas are covered as follows. The methodology initially focuses on area 3) Climate services that target climate variability for future months to years, as this represents the main application area, and a large amount of case study material. It then extends this method to consider area 1) observed and historic information and its role in improving climate services. These are often associated with more general (foundational) benefits, but can be assessed using broadly similarly concepts. Finally, the applicability of these methods is considered for area 4), services for (longer-term) climate change (adaptation services). These longer-term services are very different, because they involve different types of services and different decisions, as well as greater complexity around scenario and modelling uncertainty.

Valuing climate services (for variability i.e. months to years ahead). Investing in weather and climate information (W&CI) services leads to improved information, such as better forecasts, early warning, and seasonal forecasts. In turn, these provide benefits to users when they lead to avoided negative losses or positive outcomes as a result of the actions and decisions that users subsequently take. The benefits of such information is termed the Value of Information (VoI).

The existing research on the value of W&CI services has found that these generally lead to high economic benefits, including economic, social, and environmental benefits, with positive benefit to cost ratios. The quantification and valuation of these economic benefits, sometimes called socio-economic benefits (SEB), of climate services can be useful in highlighting and communicating project impact, and the benefits of investments. There are two strands of literature in this area. The first sets out the overall societal benefits of climate services and has been used to estimate benefits of National Meteorological Services at national scales. A brief review of some of the key studies has been undertaken for this study. The second is centred on the economic costs and benefits of

individual climate services, such as a new seasonal forecast. The focus of this study, and the guidance, is on valuation of individual services.

However, for the economic benefits of W&CI services to fully materialise, there is a need to invest along the value chain, from foundational activities including science and observations, forecasting capacity and accuracy, effective communication to users, and the uptake and use of this information by end-users. Importantly, there is a fall-off at each stage of the value chain, which reduces the overall benefits, as compared to the theoretical potential. This is shown in the figure below, which shows a simplified value chain. For example, if a climate service reaches a low level of end-users, then the *actual* overall economic benefits will be lower than the *potential* benefits. Similarly, if most people receive the information, but they do not use it effectively, the benefits of each action taken will be proportionally lower. A key part of the valuation is to develop **value chain analysis**. As well as helping in the estimation of benefits, such analysis can also be used during design (*ex ante*) and evaluation (*ex post*) to refine the services, hence improving the level of benefits further.



A key element of valuation relates to the choice of the methodology to assess benefits. In the literature, there are a number of distinct but complementary methods for identifying the impacts and benefits, as well as a range of metrics for estimating the economic value of climate information. The different approaches used in the literature have been reviewed and can be broken down into *ex ante* methods, which assess the potential benefits, and *ex post* methods, which draw on the results during or after implementation. The methods include:

- To model the potential benefits from the use of information, e.g. using crop models to look at the potential benefits of seasonal forecasts, or hydrological and disaster risk models;
- To use game-based approaches to deriving potential benefits, i.e., using experimental economics to provide users with an opportunity to simulate the use of climate services;
- To directly survey users to explore benefits through their willingness to pay for climate services (e.g. contingent evaluation methods);
- To survey users to explore potential benefits, including household surveys or participatory processes;
- To conduct econometric analysis (regression) to assess the role of climate services in affecting economic or other outcomes;
- To conduct *ex post* impact assessment to measure the application of climate services compared to a control group (e.g. test plots in agriculture);
- To use benefit transfer methods that take estimates developed in one context and apply these in another context.

All of these have relative strengths and weaknesses, which are discussed in this report. Importantly, they differ in terms of the capacity, expertise, time, and resources required, which are likely to be key factors in the choice of method, and are important elements in the subsequent guidance.

Review of climate services for climate variability. This study has undertaken a literature review to look at the valuation applications of seasonal forecasting and inter-annual variability forecasting (such as the El Niño – Southern Oscillation (ENSO) cycle). This provides key information on the methods that have been used, as well as the levels of benefits that can arise.

Application of the method to Area 1) Observed and historic information

It is possible to use a similar approach as above, i.e. with benefits analysis and a value chain assessment, to look at the improvement of observations in improving forecast accuracy and in delivering economic benefits. There are studies that have undertaken such analysis, looking for example at the economic benefits of improved surface observations. However, such analysis requires information on the existing role of current services and a baseline of economic costs (before the improved information), as well as an estimation of the improvement in forecast accuracy, which is challenging. It also requires an analysis of the benefits of current level of weather and climate services. Many projects will not have this information to hand and it requires additional analysis. In most cases, analysis is likely to be in the form of 'what-if' analysis, rather than any of the more detailed approaches set out above.

It is theoretically possible, though more difficult, to apply the same approaches to historic information and estimate economic benefits. In this case, there has to be an analysis of how historic data improves forecast accuracy, or some other component of foundational activities. There are no studies, that we are aware of, that have tried to estimate such benefits in economic terms. There are also potential economic benefits generated from improved historic information that is used in downstream analysis, e.g. a better and longer historical record of observed return periods for heavy rainfall or floods, which can be used for the analysis of flood estimates, and thus can improve the design of infrastructure. However, estimating these benefits is difficult, because it requires a baseline analysis, an estimation of the level of improvement the historic information provides, and then a subsequent analysis of the improvement along the value chain and through to users.

Application of the method to Area 4) Projections for future decades, even centuries ahead (climate change and adaptation services).

The overall study (on standards) is also including future orientated climate services, often termed adaptation services. The methods for valuation of W&CI services benefits described above, have not to our knowledge been applied to this area. However, the potential for such application has been reviewed in this study.

The study has first reviewed which types of adaptation might be relevant. Adaptation can be planned or autonomous, and reactive or pro-active. Any focus on the valuation of adaptation services needs to be on planned adaptation, as by definition, pure autonomous adaptation does not use information. Reactive adaptation is a response to the experienced change in the climate, i.e. it is a short-term response, and information on these changes could be useful for immediate decisions (and is closer to the weather and climate services considered above). Pro-active adaptation is longer-term, and generally uses climate change projections. This is very different in nature to weather and climate services, because it involves different types of services and decisions, as well as greater complexity due to the long-term time frames involved due to uncertainty. This means there are complex issues around how climate information is used for pro-active adaptation. There is also a focus in the adaptation domain of looking for no- and low regret adaptation, i.e. actions which are good to do irrespective of future climate change. These typically target current weather and climate variability, and are thus similar in nature to the weather and climate service applications.

The study has then looked at the definition of adaptation services. There are some definitions in the literature which describe climate services for adaptation as being all public and private services supporting adaptation to climate change. However, this is extremely general, and the focus here is on climate information for adaptation, in order to focus down on economic benefits. This study has reviewed some of the literature on adaptation services. Importantly, this shows that the landscape for adaptation services is different to weather and climate services, and there is a question of whether the value added is produced from the climate information (climate model projections) or from the subsequent product/knowledge development and decision support. We believe much of the value added is likely to be in the latter, not least because of the high uncertainty, and thus effective adaptation services need to consider decision making under uncertainty (DMUU) downstream of the climate information. This is compounded because there has been a mismatch between climate information projections (focused on mid to late century) and the time-scale of most adaptation decisions, which are for the next few decades. Furthermore, there are particular challenges with the economic analysis of adaptation, because benefits often arise in future periods, and thus as standard practice in economic appraisal, these are discounted to provide present values. As a result, there is lots of potential for economic mal-adaptation, i.e. to design adaptation where the costs exceed the benefits (in present value terms).

Taking account of the issues above, we identify three types of climate information - adaptation service categories.

- Information on the changes that have occurred or are starting to happen (trends) in the climate for reactive adaptation.
- Information to inform early low and no-regret adaptation.
- Information for pro-active adaptation. This requires climate change model projections.

The first two have a relatively strong overlap with weather and climate service information, and could follow similar benefits and value chain analysis, although there are important differences. The third (longer-term information and pro-active adaptation) is very different and alternative approaches are needed, because of methodological challenges, and because much of the value of information (valued added) is added downstream (from the climate information). The potential for benefit analysis for the first two applications (reactive and no-regret adaptation) will be developed by using case studies in the Main Stage of the project (case studies). The Main Stage will also consider the application of the same concepts to a longer-term example (adaptation services), to provide a clearer example of the challenges involved and look at the potential for methods.

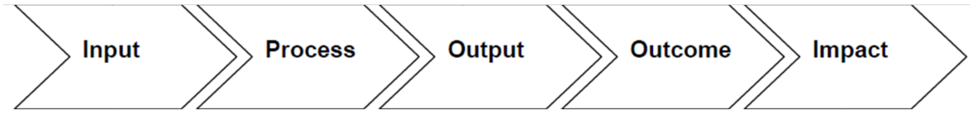
Guidance for climate variability. The study has developed guidance for the valuation of the economic benefits of climate services for climate variability. This aligns with, but builds on, the existing methods in the literature and in existing guidance. A series of steps are recommended:

- List the potential economic benefits that the climate service may provide.
- Develop the value chain for the service.
- Review and decide on the potential methods for assessing economic benefits.
- Build a baseline scenario (or counter-factual) without the new climate service.
- Assess the benefits with the climate service in place.
- Assess the costs of the project.
- Compare benefits against costs.
- Undertake sensitivity and bias analysis, then review how benefits could be enhanced.

The guidance also includes a checklist for good practice during the concept and proposal stages of climate service development.

Alongside this, the paper has outlined the suitability and selection of various methods, by considering two key issues: the type of weather and climate information service and thus the applicability of different methods; and the capacity, level of expertise, and the time and resources available.

Monitoring and Evaluation / Value for Money. The final part of this Deliverable relates to monitoring and evaluation, and in particular the linkages to Value for Money (VfM). The process of policy, programme, and project development – and subsequently monitoring and evaluation - often uses logic models (also known as logical frameworks or logframes) to encourage a structured approach. There is a standardised set of steps (the causal pathways or results chains) in a logical framework, which flow from the inputs and activities (also known sometimes as processes), to the subsequent outputs and outcomes, and finally, to the overall impact. This is shown below. Any climate service project can be framed in terms of a logical framework. Mostly importantly, the economic benefits of climate services can be considered as an outcome or impact metric. This provides an opportunity to link to monitoring.



Alongside this, there is an established concept of VfM in UK government programming of the 3Es:

- Economy: minimising the cost of resources used or required (inputs) – spending less;
- Efficiency: the relationship between the output from goods or services and the resources to produce them – spending well; and
- Effectiveness: the relationship between the intended and actual results of public spending (outcomes) – spending wisely.

These elements map to the logical framework and can be used to help ensure VfM. The document sets out these linkages and provides examples of VfM indicators that can be included in climate services projects, by i) setting out the 3 'E's rationale to frame the VfM approach; ii) minimising costs with the use of cost benchmarking, and iii) maximising benefits through economic benefit analysis.

1. Introduction

This report presents the draft version of the 'methodology for monitoring and valuing climate services', which is Deliverable 2 of the contract 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services'. This work is being undertaken by a consortium of JBA Consulting (lead), in association with ClimateSense, Paul Watkiss Associates (PWA), Professor Rob Wilby, and Becky Venton, on behalf of the Met Office. This Deliverable is led by PWA.

The Deliverable proposes a methodology for valuing climate services, as well as a suggested method and guidance for analysing value for money (as part of monitoring). The method and guidance will be tested in the subsequent task on case studies (see Deliverable 4).

Defining Climate Services and the Study Boundaries

A key issue for this study is on the definition of climate services, and the boundaries for this study and Deliverable. There is a wide use of this term in the literature.

The Global Framework for Climate Services[2] uses the definition '*Climate services provide climate information to help individuals and organizations make climate smart decisions*'. It also sets out that '*The data and information collected is transformed into customized products such as projections, trends, economic analysis and services for different user communities*', thus '*Climate services equip decision makers in climate-sensitive sectors with better information to help society adapt to climate variability and change*'.

However, there are a number of other definitions in the literature, for example:

Vaughan and Dessai (2014) define climate services as follows: '*Climate services involve the generation, provision, and contextualization of information and knowledge derived from climate research for decision making at all levels of society*'. They also state that '*climate services provide timely, tailored information and knowledge to decision makers (generally in the form of tools, products, websites, or bulletins)*' and '*that they can use to reduce climate-related losses and enhance benefits, including the protection of lives, livelihoods, and property*'.

Hansen et al (2019) suggest that: '*Climate services involve the production, translation, transfer, and use of climate knowledge and information in relevant decision-making, policy and planning*.'

The European Commission roadmap for climate services (2015) uses the term very broadly as '*the transformation of climate-related data — together with other relevant information — into customised products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counselling on best practices, development and evaluation of solutions and any other service in relation to climate that may be of use for the society at large. As such, these services include data, information and knowledge that support adaptation, mitigation and disaster risk management (DRM)'.*

A key issue – and difference in definitions – is on the temporal classification of the climate information provided. This is shown in the figure below (from Hansen et al., 2019). Some definitions of climate services (e.g. Vaughan and Dessai, 2014) are more focused on information from climate variability, i.e., the centre of the figure and exclude weather (capturing this as weather forecasts, or weather services). At the same time, there are some definitions that separate out information

[2] https://gfcs.wmo.int/what-are-climate-services

related to future climate change information i.e. the right of the figure, sometimes termed adaptation services. For example, Cavelier et al. (2017) state that climate services for adaptation '*are defined as all public and private services supporting adaptation to climate change*'.

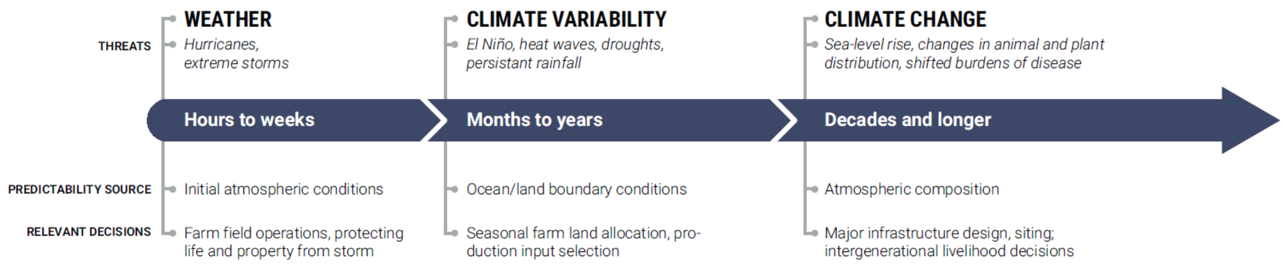


Figure 1 Time scales of atmospheric variation, information, and climate-sensitive decisions. Source Hansen et al. (2019).

For the overall study, CR20-2 study, which is considering standards, these temporal aspects do not matter so much. However, for valuation these differences are critical, because they rely on different approaches and involve different issues. Therefore, for this study (and Deliverable) we use different boundaries for analysis.

The potential different types of information for the valuation study can include:

- Observed and historic climate information;
- Forecasts of weather from hours to days to weeks ahead (nowcasting, short-range weather forecasts, medium term weather forecast [e.g. 3 to 10 days]), including early warning systems such as flood or storm forecasts;
- Forecasts of months to years ahead, focused on climate variability, notably seasonal forecasting (and sub-seasonal forecasting), which typically provides forward looking quarterly forecasts. It also includes seasonal early warning, e.g. for slow onset events such as drought forecasts, as well as inter-annual variability forecasts, such as with El Niño – Southern Oscillation (ENSO) cycle and El Niño and La Niña events.
- Projections for future decades focused on climate change (adaptation services).

Following clarification from the Met Office, the standards component of the study (CR20-2) is including observed and historic climate information. This information can have economic benefits by leading to a general improvement in meteorological services. It is also including adaptation services, while noting these are very different. The Met Office also clarified that the current study (CR20-2) is excluding weather forecasting (short-term).

There are a wide range of different types of climate services, as identified in the literature (Vaughan and Dessai, 2014; Visscher et al., 2020; Cavelier et al., 2017; Hansen et al., 2019 and many more).

For valuation, which is the focus of this deliverable, we take a different approach. As highlighted by Hansen et al (2019) '*climate services do not contribute economic or social value unless users benefit from better decisions as a result of the information*'.

Therefore, the valuation analysis focuses on services where users benefit from better decisions as a result of (climate) information. We narrow the focus of our study, and this deliverable and the guidance, to such applications. We highlight that this focus is narrower than the wider CR20-2 study, which is considering standards for climate services.

Finally, there are very large differences – for valuation – between the three focus areas of the study, i.e., between climate services which help address climate variability, information from observations and historic data, and climate change services to inform (longer-term) adaptation. This is because of the different type of information provided, the different types of decisions that are influenced (short/medium term vs more long-term), the type of users, and the level of uncertainty (which is much higher in the case of long-term climate change).

The document starts with a focus on climate services for managing climate variability. These climate services involve the provision of climate information in a way that assists decision making by individuals or organizations. They may include seasonal outlooks, drought forecasts, agroclimatic bulletins, and so on (Vaughan and Dessai, 2014). As such, they convey information on departures from average conditions, including low-probability events. These are focused on sub-seasonal-to-interannual climate forecasts. The most common services are seasonal forecasts, which are typically quarterly (3 month) future outlooks, and also longer-term forecasts, for example for the Asian monsoon and the El Niño – Southern Oscillation (ENSO) cycle.

It then considers the potential to apply these same approaches to observed and historic information. Finally, it considers the issues involved in extending these methods to consider future long-term projections and adaptation services.

Structure of the Deliverable

This deliverable is set out as follows.

The Deliverable starts with a description of the concepts of the valuation of climate services for climate variability, and then outlines possible methods.

It next summarises a review of the literature for previous examples of valuation of climate services for climate variability (the full review is in an appendix).

This information is then used to produce guidance steps for undertaking economic analysis.

The guidance is then considered in terms of the applicability for Area 1) Observed and historic information, and then Area 4) Projections for future decades, even centuries ahead (climate change and adaptation services).

Finally, the document discusses the issues of linking valuation to monitoring and evaluation and value for money frameworks.

2. Valuation of Climate Services

Introduction

Weather and climate information services (W&CI), such as weather forecasts, early warning and seasonal forecasts, generate information. These services are often considered to be non-technical in nature and people do not often consider their benefits in quantitative terms.

However, W&CI services can provide economic benefits for users because the information can be used to generate positive outcomes from the actions and decisions that users take (WMO, 2015). This is known as the Value of Information (VoI)[3]. As examples:

- Early warning systems can significantly reduce the damages and losses – and reduce loss of life and injuries – caused by extreme weather and disasters;
- Seasonal forecasts can help improve agricultural production (higher yields) or reduce losses from extreme events.

It is possible to quantify the economic benefits of weather and climate information (W&CS) services. Such studies generally look at the activities and outcomes from the use of enhanced weather and climate services, then compare these to a baseline or counterfactual without such additional information: the difference between the two is the incremental benefit directly attributable to enhanced services.

In the literature, many studies focus on private benefits (to users) resulting from the use of information. The estimation of private benefits of W&CI services is important to make the case for the use of these, i.e., to incentivise those who receive the information to act upon it.

However, it is also possible to estimate the economic benefits of information. Economic analysis, as used by Governments, is based on the principles of welfare economics, and aims to assess the ability of a policy, programme or project to improve social welfare or wellbeing (HMT, 2020). Economic analysis is therefore carried out from the perspective of society and includes the economic valuation of non-market effects, such as environmental, cultural, social and health benefits. Because of the consideration of these non-market aspects, these are sometimes referred to as socio-economic benefits (SEB), though it is stressed that this is unnecessary, as the term economic benefit (as defined in the economic literature) includes these.

The estimation of the economic benefits of W&CI services allows policy makers to understand the benefits of these services overall, i.e. to society.

The analysis of economic benefits is the focus of this Deliverable, and this approach is routinely used in UK government economic appraisal (HMT, 2020). It includes all significant benefits that affect the welfare and wellbeing of the population, not just market benefits.

A useful starting point is to categorise private and social benefits. There are some areas where climate services provide an obvious financial benefit to individuals, which can be captured by market prices (e.g., increased agriculture yields or profits). Alongside this, there are many benefits which are

[3] Keisler et al. (2014) define the value of information (VoI) as the increase in expected value that arises from making the best choice with the benefit of a piece of information compared to the best choice without the benefit of that same information. Hansen et al. (2011) define VoI as the expected improvement in economic outcome of management that incorporates the new information.

more difficult to monetize, but which can be considered by a broader economic analysis. In summary, benefits include:

- **Tangible benefits**. These include direct effects (reduced loss of an asset, reduced damage to buildings and infrastructure, increased crop yield and revenues). These may also include indirect benefits (reduced traffic disruption affecting business supply, or reduced effects on the wider economy).

- **Intangible (non-market) benefits.** These include reduced loss of life and injuries or avoided environmental damage. There can also be indirect intangible benefits, e.g. reduced impacts on dependants.

These are shown in the matrix below. Importantly, each cell in the matrix requires a different analytical approach. Direct tangible effects can usually be valued using market prices, but the intangibles involve non-market effects, and require use of different methods to estimate economic values, such as revealed or stated preferences studies (see later). The indirect benefits may also require different approaches, as they may not be derived from primary surveys, but require modelling analysis, for example.

Table 1 Matrix of example benefits from W&CI services.

	Tangible (market)	Intangible (non-market)
Direct	Enhanced electricity generation system management from enhanced weather information Reduced damage to buildings, infrastructure, or crops from early warning Enhanced agricultural yields or avoided losses from seasonal forecasts	Reduced loss of life or injury or reduction in damage / loss of ecological goods and services from early warning.
Indirect	Reduced loss of industrial production, or traffic disruption affecting business supply, or effects on wider economy, from early warning of major disasters	Reduced impact post disaster on vulnerability.

There are two sets of literature in this area. The first lays out the overall national benefits of climate services, and has been used in relation to National Meteorological Services. The second – which is the focus of this study – is on costs and benefits of individual climate services. More details on both are presented in the next chapter.

Analysis of individual climate services can assess the economic benefits of a service, then compare costs to benefits though a cost-benefit analysis. This assesses the services or a project in terms of the benefits versus the costs (from a societal perspective), expressed as the Net Present Value (NPV), the Benefit to Cost Ratio (BCR)[4], or the Economic Internal Rate of Return (IRR)[5]. When compared to the costs of investment, climate services are found to produce a high benefit to cost ratio (i.e., they have large economic benefits, with benefits that far outweigh costs).

[4] Total discounted benefits minus total discounted costs. This is sometimes presented as a benefit to cost ratios (NPV benefits divided by NPV costs). In economic analysis, this estimates the economic NPV (ENPV) and economic IRR (EIRR) while for financial analysis, the financial NPV (FNPV) and financial IRR (FIRR).
[5] The rate at which the NPV is zero, which can be compared with the discount rate to assess if a project generates a sufficient return on investment to be viable.

It is stressed that in economic appraisal, timing matters. Costs and benefits in such assessments are estimated in 'real' base year prices, which means the effects of inflation are removed. Subsequently costs and benefits that arise in different future time periods are adjusted to provide equivalent values using some form of discount scheme. Many governments and organisations use a 'social time preference rate' (STPR), reflecting the fact generally people (and society) prefer to receive goods and services now rather than later. The use of these discount schemes estimates values in equivalent present value terms.

Analysis of previous W&CI services shows these services can generate large economic benefits. For example, Clements et al. (2013) identified 139 studies of the benefits of climate services (both weather forecasts and seasonal forecasts), providing a breakdown by sector and region. Around half of these were in the agriculture sector. The ECONADAPT (2017) project extended this review and focused on those studies of climate services that provide benefit to cost ratio (BCR). They identified around 40 such studies, where benefits have been quantified and valued, and compared to costs. This showed benefit to cost ratios in the range of 2:1 up to 36:1. There has been a particular focus on the costs and benefits of early warning systems (EWS) (e.g., Shreve and Kelman, 2015). The Global Commission on Adaptation (GCA, 2019) reported that EWS, while being a climate service outside the scope of this project, have very high benefit to cost ratios, with an average benefit to cost ratio of 9:1 (i.e., for every £1 invested, £9 of societal benefits are generated).

More generally, there are several reasons why it is beneficial to consider economic benefits (WISER, 2017):

- The analysis can help to develop an improved understanding (and better articulation) of a project and help to make more informed, evidence-based choices, i.e., to improve the design.
- The focus on benefits can help in maximising the impact (the benefit) of weather and climate information services, ensuring that appropriate interventions along the value chain are included.
- The information from an economic benefits study can be used to highlight the success of the project, and how it is delivering tangible benefits. This is extremely useful in promoting the project as well as for justifying current and future investment in these services.
- They can provide quantitative information on effectiveness and help demonstrate and report on Value for Money (VfM), in line with the Government VfM framework (NAO[6]). This is discussed in more detail in the monitoring section.

Climate Service Value Chains

In order for the economic benefits of W&CI services to be realised, there needs to be a flow of information from the producer to the user and, further, an effective uptake and use of this information in a decision. It is the use of this information that leads to better outcomes than would otherwise be the case. In this respect, it is important that potential users of climate services have the resources to act effectively on the information they receive (i.e., they have access to financial resources, or the ability to change behaviour or respond to risks) and/or are incentivised to act. This is determined by the type of information provided and its accessibility (including users' understanding of the information), and its perceived reliability (forecast skill). All these aspects are

[6] https://www.nao.org.uk/successful-commissioning/general-principles/value-for-money/assessing-value-for-money/

relevant and form what is called a W&CI services value chain. This maps the sequence of actions that generate the overall economic benefit. A number of examples are shown below (Figure 4).

Steps in a value chain include the information provision itself, and the infrastructure and foundational activities, including science, that generate it. This affects the forecasting capacity and accuracy. The value chain also includes the communication to users, and thus the reach (the number of beneficiaries or users). However, it also needs to take account of the uptake, understanding, and effective use of this information by end-users in order to generate value.

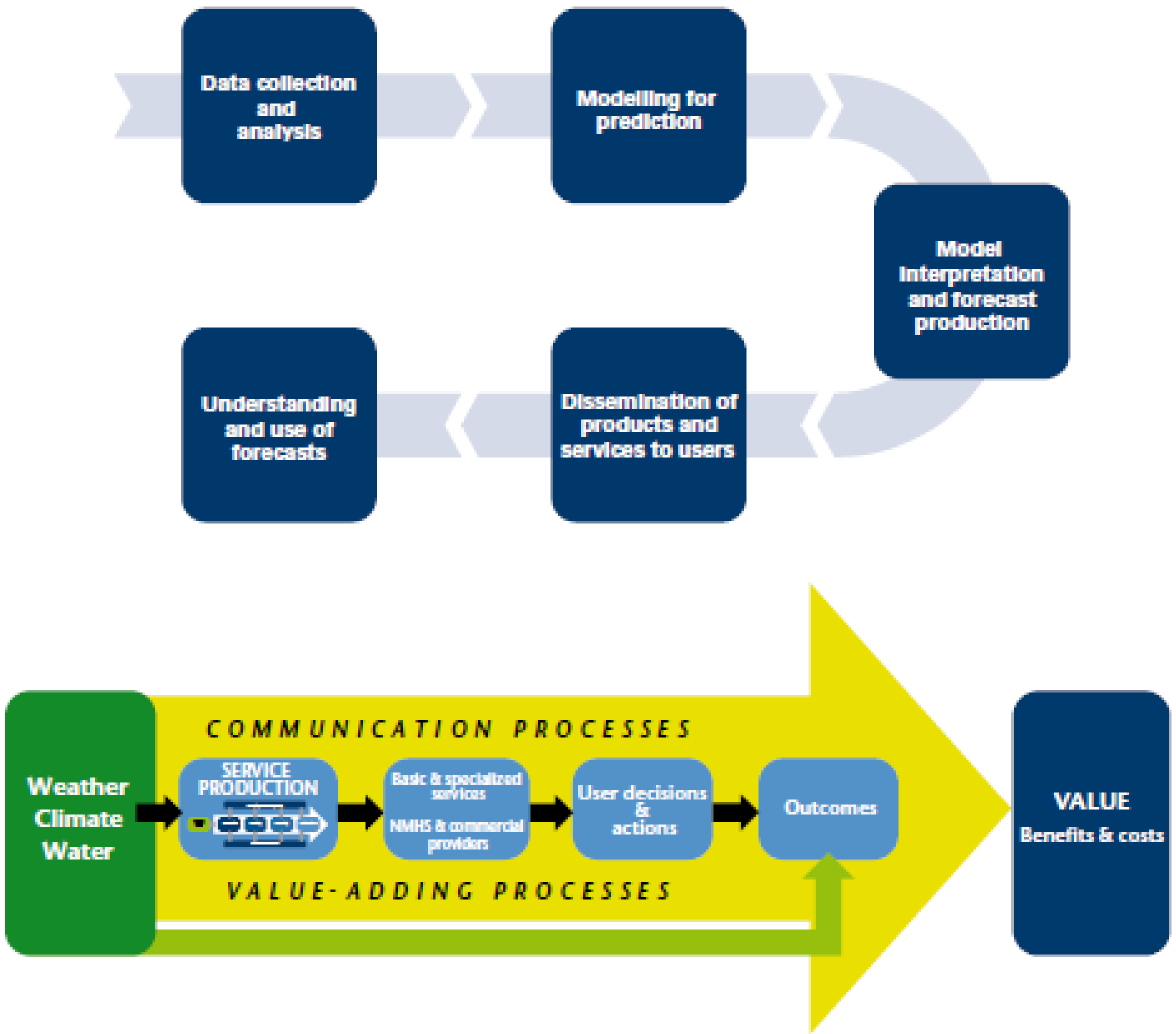


Figure 2 Weather and climate services value chains. Source: Top WMO (2014), Bottom WMO (2015).

A critical point is that <u>economic benefits are generated at the very end of the value chain</u> (on the right-hand side in the lower part of Figure 3). This is important because there are often large efficiency losses (or decay) along a W&CI value chain (Perrels., et al 2013; Nurmi et al., 2013), which lead to much lower actual benefits than potential (maximum) benefits. For example, if a service has a low level of reach (e.g., due to poor communication) then the economic benefits will be low, as there is a smaller number of users. Similarly, if a large number of users who receive the information do not act on it (or do not act effectively), the level of benefits achieved will be lower than the potential benefits. Therefore, in order to provide a realistic estimation of benefits of W&CI services, a value chain needs to be constructed that considers such efficiency losses. Previous analysis has identified the key steps in the chain where efficiency losses can occur as (Perrels, 2013):

- Forecast accuracy;
- Tailoring of information to user groups;
- Access to information;
- Comprehension of information by users;
- Ability to respond;
- Effectiveness of response; and
- Redistribution (leaks) of initial benefit.

Similarly, Nurmi et al. (2013) list to what extent:

- Forecasts are accurate;
- Forecasts contain appropriate data for end-users;
- Decision-makers have timely access to the forecasts;
- Decision-makers adequately understand the forecasts;
- Decision-makers can use forecasts to effectively adapt their behaviour;
- Recommended actions actually help to avoid damage due to unfavourable climate outcomes; and
- Benefits from adapted actions or decisions are transferred to other economic agents.

It is also highlighted that, when assessing the benefits of individual climate services, understanding where these efficiency losses occur along the value chain can be very useful for improving the services themselves and therefore generate greater value. Indeed, the overall level of economic benefits is usually determined by the weakest link in the value chain.

Evidence suggests that to maximise economic benefits it is important to invest along the whole value chain, not just in information generation itself, and further, to tailor products to users' needs. There will also be benefits from targeting the weakest links (or pinch-points) in the value chain, as these may generate the largest benefits (and have highest VfM).

Economic Benefit Quantification Methods

Climate services can yield a wide range of benefits, which can be estimated through different methods. To select an appropriate method, it is useful to identify the climate-induced impacts (of present climate variability and extremes) that the service is seeking to address, and then the benefits that climate services could deliver. A number of methods exist (e.g., IIED, 2014; WMO, 2015; WISER, 2017; Vaughan et al., 2019).

Methods can broadly be distinguished between those that assess *potential* benefits of climate services, and those that look at *actual* benefits after implementation. The former are typically based on *ex ante analysis* (before the service is introduced) whilst the latter on *ex post analysis* (after the service). The more common methodological approaches are as follows:

- ***Ex ante models.*** This approach typically uses decision-theory based models, sometimes combined with other models (e.g. bioeconomic models), to estimate the potential benefits from the use of information i.e., climate service benefits. This approach is widely used for estimating the value of climate services in the agriculture sector. In this case, crop models (biophysical) or bioeconomic models are used (sometimes with utility-maximisation models) to assess the potential benefits of receiving and using better information (or different types of information). Such assessments can be applied to seasonal forecasts, to assess improved decisions. Benefits can be calculated through a range of metrics (e.g., enhanced yields, enhanced profits, water savings) and at different scales (e.g. crop, farm, national). In some cases, assumptions are made about the relative risk-aversion of decision-makers. Studies using models have the advantage of providing detailed technical analysis and quantitative results. However, benefits are only estimated, not observed, and rely critically on a high number of assumptions. Further, *ex ante* models can only consider the 'expected' benefits whereas there may be 'unforeseen benefits' as a result of a service. These include forecast accuracy, the uptake of information, and the cost-loss analysis in the chain. The ability of models to accurately reflect individuals' decision-making in the real world is also questionable. In many cases, these studies assume that management decisions are based on 'perfect' knowledge of climate data or the forecast available at the time, and often assume 'perfect' forecast accuracy. There are some examples of the use of agent-based modelling, which have the advantage of characterising different types of actors and their responses, but these are complex and time consuming to develop and apply.

- ***Integrated economic models***. These include models such as input-output, trade, partial or computable general equilibrium models, which can be used to estimate the VoI from climate services on a macro-economic level. For example, these have been used in the agriculture sector to look at the potential wider economic effects of W&CI on agricultural prices.

- ***Cost-loss models***. Benefits can also be estimated using hydrological and disaster risk models (also known as cost loss models, etc.) that use historical events as their basis. This is particularly relevant for EWS, to assess losses associated with previous disasters or events of defined return periods (i.e., probabilistic events) and then estimate how an EWS could avoid or reduce these. Benefits can be estimated for short-term EWS, e.g. for storms, but also longer-term, e.g. for meteorological, hydrological or agricultural drought. Cost-loss models have the advantage of incorporating some observed (*ex post*) data on losses but are still built on many assumptions. There are also examples where *ex post* data have been used to look at the failure of forecasts (i.e., where a seasonal forecast has missed a major extreme weather event). Note that in cases where the benefits of EWS are assessed, the benefits are estimated in terms of avoided losses: these include the avoided costs of damage, but also the reduction in fatalities and injuries. The latter can be monetised using non-market valuation techniques. A simpler form of this approach is to use analogues of previous events to scope out the potential benefits. For example, looking at the costs of previous large-scale floods or droughts (ideally matched in terms of their return period, i.e., a 1 in 50 year event). This can include looking at information on damages recorded (e.g. in national or international databases on events, such as the EM-DAT or DesInventar databases) or looking at humanitarian spending post event.

- ***Game-based approaches***. Game-based approaches to deriving potential benefits apply experimental economics to provide users with an opportunity to simulate how they might implement climate services, then use this information to assess likely outcomes and benefits. These can be potentially useful but are challenging and time consuming to set up.

- ***Ex ante surveys***. Another *ex ante* approach is to directly survey users to explore potential benefits through their willingness to pay for climate services. This can use measures of revealed preference, i.e. recorded observations of how people change their behaviour, including their decision-making, in instances where new climate information has been introduced. An alternative (or a further complementary validation) is for stated preference methods. These apply interviews with identified user communities to determine their willingness to pay for climate services directly, i.e. to derive their benefit (to these users). However, particularly for sectors such as agriculture, users often cannot assess, or typically underestimate, the value of services.

It is also possible to look at the effects of climate services *ex post*, i.e. after implementation, following the implementation of climate services to assess the benefits. This can be done using different approaches.

- ***Ex post surveys***. One *ex post* approach is to directly survey users to explore actual (or perceived) benefits from using climate services. A variety of methods can be used to collect and analyse evidence. This might be household surveys that quantitatively and/or qualitatively sample individuals to assess opinions and experiences. Methods may range from one-to-one interviews through to participatory processes such as focus groups to structure evidence gathering through group activities. Data collected through *ex post* surveys can be used to build (*ex post*) cost-benefit analysis to estimate the cost-effectiveness of the services.
- ***Statistical and econometric analysis***. It is possible to use statistics to look at the effects from using climate information, then apply econometrics analysis to deal with the issue of attribution, i.e. to isolate the role of climate services from other elements in determining benefits. Such studies have the advantage of using direct observations to determine how (statistically) the use of climate services have led to certain outcomes or benefits (e.g. increased yields, increased income, etc). Econometric models can "control" for other variables by isolating the climate service effect from other effects in shaping the outcome(s). As these studies look at the outcomes directly, they avoid the need to consider steps in the value chain. However, econometric models are complex to build, and can be time consuming to undertake, requiring real data to be collected on a number of economic variables. Further, it is often difficult to fully separate out (attribute) the role of climate information from other factors.
- ***Impact assessments***. These are typically undertaken to assess the effectiveness of an intervention (treatment, project, or program) by measuring its impact on a group (the treatment group) relative to others who have not received the treatment (the control group). Alternatively, information of the same group can be gathered before and after the intervention (before-after analysis). There are examples in the VoI literature of impact assessment studies that estimated the benefits to people who received and used climate information versus those who did not (see next chapter). For some applications, notably agriculture, it is possible to use test plots to do this. Studies that use this method look at specific plots of land throughout the season, and compare them to control plots, to measure the benefits of the climate services. However, although this method has the advantage of providing information on observed (actual) benefits, unless supported by more rigorous analysis (including econometric analysis), it may not resolve the issue of attribution. Importantly, impact assessment studies need to be well designed in advance to avoid methodological biases such as a poor selection of the control group, or low reliability of the self-reported information (in before-after analysis), or too short period for assessing impacts.
- ***Value (Benefit) transfer***. Finally, it is possible to use benefit transfer methods that take estimates developed in one context and apply these in another context, as a substitute for

undertaking primary studies. This could, for example, take the results of the typical benefits from seasonal forecasts, and apply these to a new study on a user basis. However, value chains tend to be quite context and location specific, and thus this approach can struggle to take account of the specific value chain context (both of the source study and the application), and the effectiveness of communication, reach, use, uptake, etc.

All of the above methods could, in theory, be used to estimate the benefits of climate services for climate variability. Examples are provided in the Appendix, but in practice, most of the studies use modelling and surveys (see Vaughn et al., 2019). However, it is also possible to apply combinations of methods. Indeed, recent review papers (Soares et al., 2019) recommend this type of combined approach. For example, a study may combine survey-based information on farmers' use of climate services with estimates from other studies (benefit transfer) to estimate the likely economic benefits. Or a study may develop a model, and then improve its accuracy through information from test plots. Soares et al. (2019) recommend a greater focus on *ex post*, qualitative, and participatory approaches.

It should be noted that all *ex ante* methods only generate estimates of *possible* benefits of the climate service, not the *actual* outcomes. This means such methods have to identify and estimate efficiency losses along the value chain, recognising that it is challenging to conduct real-world value chain analysis. Many of the *ex ante* studies reviewed are perhaps too optimistic about the assumptions they make, e.g. with greater reach or higher effectiveness, leading to higher benefits compared to *ex post* assessments of operational (existing) services. This was confirmed by a meta-analysis conducted by Parton et al. (2019) on the VoI for agriculture in Australia.

Ex post assessments address this limitation, by evaluating *actual* benefits of climate services, but they suffer from different issues. These include data collection, the reliability of measurement over the time-periods over which the VoI is assessed, and the attribution of benefits. This is made more difficult by the high levels of inter-annual variability associated with climate services for seasonal to annual forecasts. Most of the events these services aim to address are probabilistic in nature i.e., they vary between years and even over decadal time periods. This makes it hard to attribute outcomes, because any positive outcomes identified over a project lifetime may, in part, be due to climate variability. To illustrate, a service may be found through surveys or econometric analysis to deliver enhanced yields or revenues, relative to a baseline period. However, because of high rainfall variability, it is difficult to know whether the benefits in a given period, relative to the baseline, are a function of the variability (i.e. more favourable weather conditions) or the actions taken. This either requires very long and frequent evaluation periods, or it requires additional attribution or econometric analysis to isolate confounding effects and the climate variability, which is complex to do and rarely undertaken.

Finally, it is stressed that all of these approaches involve different capacity, time and resources. This may limit their applicability, depending on resources available, or require different expertise depending on the selected method. The risk preferences of the decision makers and potential users – particularly for *ex ante* assessments – also have an influence on the choice of method to estimate the potential benefits of climate services (including whether information is used to maximise gains or minimise losses). The time, resources, and expertise available are, therefore, key considerations when selecting the economic method. More information on the choice of the method is given in Chapter 4.

Economic analysis

The results of the benefits studies above are included in an economic analysis, which typically used to assess the economic benefits of the W&CI services over time and in total, and to compare these benefits to the costs of the service.

As highlighted earlier, economic appraisal or evaluation is based on the principles of welfare economics and is undertaken from the perspective of society (HMT, 2020). This analysis usually undertakes cost-benefit analysis. This assesses a W&CI service by estimating the economic benefits it produces over time, and compares these to the costs (from capital, operating and maintenance costs over time) from a societal perspective.

In economic appraisal, costs and benefits are assessed in terms of present values through the use of discount rates (HMT, 2020) to allow analysis on a consistent basis[7]. The results of an economic appraisal are expressed as the Net Present Value (NPV)[8], the benefit to cost ratio (BCR)[9], or the Economic Internal Rate of Return (EIRR)[10].

It is highlighted that economic appraisal differs from a financial appraisal (or analysis). A financial appraisal considers the incremental revenues and costs generated by an investment or project, and the ability of the project to generate cash flows, recover the financial costs, and generate profits. It is therefore carried out from the perspective of an investor, not the perspective of society[11].

There is existing guidance on undertaking economic cost-benefit analysis in WMO (2015). This will be applied for the case studies in the next phase of the study to provide some examples.

[7] Costs and benefits in appraisal are estimated in 'real' base year prices, which means the effects of inflation are removed. Subsequently, costs and benefits that arise in different future periods are adjusted to provide equivalent values using some form of discount scheme. Many governments and organisations use a 'social time preference rate' (STPR), reflecting the fact generally people (and society) prefer to receive goods and services now rather than later, though some schemes use alternatives, such as the social opportunity cost of capital.

[8] The Net Present Value (NPV) is the sum of future values (in real prices) that have been discounted to bring them to today's value (HMT, 2019) and is estimated as the total present value (discounted) benefits divided by total present value of costs.

[9] Total present value of benefits divided by total present value of costs.

[10] The rate at which the NPV is zero, which can be compared with the discount rate to assess if a project generates a sufficient return on investment to be viable.

[11] A financial analysis only uses market prices – it excludes environmental or social benefits. The financial attractiveness of a project is usually expressed in terms of an Internal rate of return (IRR), the annual return that makes the net present value equal to zero, or a payback period. This generally takes a short-term perspective, and uses (higher) discount rates which reflect a required rate of return or the opportunity cost of capital, noting commercial or private investors typically expect much higher returns than public investments.

3. Review of Benefit Studies of Climate Services for Managing Climate Variability

The current study has undertaken a detailed review of previous studies that value climate services for managing climate variability. This is presented in Appendix 1. This Chapter summarises the findings of this review.

Review Outline

This has looked at three sets of literature:

- Synthesis papers that consider multiple studies;
- Individual climate services studies;
- National studies of climate services (to the economy) and the potential value of the market for climate services.

Findings

There are a number of review papers (Meza et al., 2008; Clements et al., 2013; Vaughan et al., 2019; Soares et al., 2018: Parton et al., 2019) which look at valuation studies. Alongside this, there is a reasonable literature of individual studies (approximately 50 studies). These capture the value of seasonal forecasts and annual forecasts to different actors (individuals, firms) and at various scales (micro and macro).

The general findings are positive, i.e., these climate services have positive economic benefits. However, the review and evidence suggest that benefit estimates are very context specific. They also vary depending on the method used – hence should be interpreted with care.

Most of the estimates for these seasonal and annual forecasts are derived by using *ex ante* analysis, and particularly models, rather than *ex post* evaluation. However, the scope of individual studies is often limited (e.g., one crop, type of decision, or country). The models used, particularly in *ex ante* analysis, are based on a number of assumptions, that if relaxed could change results. For example, decision-makers' risk aversion, price of inputs, and timing of decisions all matter. Importantly, not all studies consider the costs of information to decision-makers, which, however, would also impact the VoI. Overall, generalisations and cross-comparability between studies are problematic. As highlighted in the previous chapter, these *ex ante* studies have limitations, and many studies assume decision-makers have 'perfect' knowledge and make optimal decisions (e.g., Soares et al. 2018), although this is rarely the case (at scale). These studies may, therefore, overestimate benefits.

There is much less adoption of other methods, such as contingent valuation, and only one econometric study was found. This may be because these tend to require more resources and time to undertake, especially to do well, e.g. contingent valuation studies need to account for strategic behaviour, protest answers, response bias, etc.

There are some benefit transfer studies. These offer a quick approach, but doing benefit transfer properly requires careful site and context considerations to be accurate (across the value chain), as well as the transfer of unit values themselves.

There are some interesting findings when moving to the aggregate scale. When larger systems are considered, this can reveal different findings, such as on the VoI to non-adopters (see Rubas et al.

2008), and asymmetric impacts with winners and losers (e.g. consumers vs producers) (see Chen and McCarl, 2000).

Finally, several studies, especially in the agriculture sector, show the importance of factors other than seasonal forecasts in affecting decision-making, most notably prices, access to credit, and interest rates, among many others, notably land use decisions and water availability. These determine the capacity of decision-makers to act upon information, and the type of actions they can take.

Together these provide a useful set of reference material for the CR20-2 study. They can be used to provide methodological examples of particular approaches, as well as providing benchmark values for comparison with new analysis. They will be particularly useful for the case studies.

4. Observed and Historic Information

Observed and historic climate information can also have economic benefits by leading to a general improvement in meteorological services (WMO, 2015). However, the analysis of these benefits is different to the climate services considered in previous sections, because it is not always associated with a defined service, and thus a specific set of users and benefits. This section reviews some applications of economic benefit analysis to observed and historic climate information, and then uses this to provide additional guidance for valuation.

Valuation studies and approaches for observed information

Observations are foundational activities in weather and climate services, and combine with modelling and forecasting, to allow delivery of services. This is shown in the WMO (2015) guidance on valuation of meteorological and hydrological services.

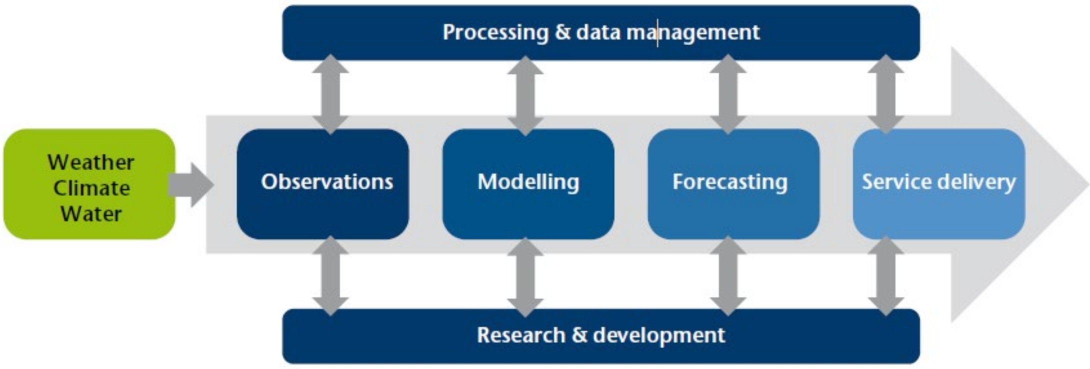


Figure 3 *Components of the service production and delivery system of NMHSs. WMO, 2015.*

It is therefore possible to look at the benefits of observations, in terms of improving forecasting (accuracy or timeliness) and thus in improved services and in turn, higher economic benefits. There have been a number of studies that have estimated the benefits of general improvements in observational data, as an input to climate services.

Hallegatte (2012) estimated the economic benefits of hydro-meteorological information and EWS. These were estimated to be large for developing countries The benefits were driven by the early warning benefits, in terms of reduced asset losses, reduced human losses, and additional economic productivity. Hallegatte et al (2017) updated this analysis to look at wider well-being, with associated higher benefits.

Kull et al (2016) looked at the economic benefits of strengthening national hydrometeorological services through cascading forecasting (across global, regional, and national centres). This looked at the influence of global forecasting products in improving forecast accuracy, and transferred the values from Hallegatte, thus was also driven by EWS benefits. The analysis assumed that the provision of the full suite of global forecasting products would increase forecasting quality in low-income countries by 15 to 35 percent. The increase in forecasting quality subsequently leads to increased benefits of weather and climate forecasting. However, the study does identify that these benefits can only be realized by concurrently investing in Regional Specialist Meteorological Centers (RSMC), National Meteorological and Hydrological Services (NMHS) and national risk management actors’ capacities to leverage this increased access to global numerical weather prediction (NWP).

Kull et al. (2021) assessed the benefits of surface-based meteorological observation data, and the role in improving NWP, and in turn, the improvements in accuracy and lead-time. The analysis estimated how improvements in the coverage and exchange of surface-based observations – as part of the World Meteorological Organization's Global Basic Observing Network (GBON) - would improve global NWP and forecasting quality, in data sparse regions, but also over the rest of the globe. As well as the benefits from early warning from Kull et al. (2016), the analysis also assesses economic benefits in other sectors, e.g. in agriculture, water, energy, transportation and construction. As an example, current weather-related losses are estimated for agriculture (production losses due to variability), and then an assumption made about the current impact of reducing these losses with climate services, to generate a baseline. The analysis then looks at the potential improvement from better observations, i.e. the impact of the observations on the skill of NWP output. Ideally these are derived from experiments (Observing System Experiments (OSEs)), with and without the improvements, to assess the improvement in accuracy. They can also be produced using Forecast-Sensitivity-to-Observation-Impact (FSOI), which calculates the increase in forecast accuracy attributable to each observation assimilated. The latter method is used in the paper. It assesses the contribution of surface-based components, and identified the improvement from increasing surface observations, and in turn, the improvement in forecast accuracy (estimated at 4%, and thus when applied to the baseline, benefits of US$5.2 billion per year). This was then applied to the current estimates of the value of W&CI services. While all regions of the world would benefit from these improvements, regions with limited surface-based observation networks would benefit the most, particularly Africa, South America and Asia

The studies discussed above rely on some considerable assumptions. These include the baseline assumptions on economic losses and the current benefits of W&CI services, and then the estimation of the improved level of accuracy from the added observations. They also assume that this accuracy is translated into improved forecasts that are used to improve decisions, i.e. that the improvements in foundational activities do indeed pass along the value chain (without any efficiency losses).

Some studies have also highlighted (e.g. Kull et al., 2016) that if forecast accuracy does increase, and users can perceive this, this could increase uptake and use, although this is likely to require high levels of improvement.

It is therefore possible to use a similar approach as for climate variability in the previous section, i.e. with benefits analysis and a value chain assessment, in order to identify the improvement of observations in improving forecast accuracy and thus delivering economic benefits. However, this requires information on the existing baseline of economic costs, as well as estimation of the improvement in forecast accuracy, which are challenging. Many projects will not have this information to hand and it requires additional analysis. In most cases, analysis is likely to be in the form of 'what-if' analysis, rather than the more detailed approaches set out above.

In conclusion, it is relatively more difficult to produce robust estimates of the economic benefits of observations, but it is possible to make some indicative estimates. The more well-defined the contribution of observations to a specific weather and climate service value chain, the easier this is likely to be.

Valuation studies and approaches for historic information

It is theoretically possible, though more difficult, to apply the same approaches and estimate economic benefits for historic information.

In this case, there has to be an analysis of how historic data can improve forecast accuracy, or some other component of the foundational activities.

There are some examples where historic data has been digitised, leading to improved forecast accuracy, although there are no studies that we are aware of that have subsequently estimated the economic benefits of these improvements. Nonetheless this could be possible, if the improvement can be quantified, and provided there is a baseline of existing economic costs (or benefits), and also the current contribution of weather and climate services in reducing these.

There might also be some potential benefits generated from improved historic information for downstream analysis, e.g. a better and longer historical record of observed return periods (frequency of events of different intensity) could be useful in estimating risks, and in turn, in improving the design of infrastructure, because it would allow more accurate analysis of design criteria (i.e. to a 1 in 100 year return period, for example). An example could the Flood Estimation Handbook that uses a large quantity of observed rainfall data for use in deriving estimates of the 100-year flood and the 100-year rainfall at any location. The improved estimates of floods would, in turn, lead to a more optimal design of infrastructure, reducing costs and/or reducing the downside risks of major extremes. However, estimating the benefits of these benefits would be much quite challenging to assess, because it requires a counterfactual (i.e. of how accurate the historic records are before), the level of improvement in the historical records, and how the improvement actually translated into benefits, which would then need to be quantified and valued. This might be possible with a 'what-if' analysis, to consider the indicative level of possible benefits, but a more detailed analysis would be quite complex.

5. Climate Change and Adaptation Services

The standards component of the study (CR20-2) includes future orientated climate services, often termed adaptation services.

The methods used for valuation of W&CI services– described in previous chapters – has not, to our knowledge, been applied to this area.

This section defines the general area of adaptation and adaptation services. It then reviews the existing approach to the economic analysis of adaptation. Finally, it considers the potential for using the methods outlined in previous sections (i.e. for climate variability) for valuing adaptation services.

Adaptation and Adaptation Services

The starting point is to define adaptation and look at the areas where adaptation services are relevant. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC, 2014) defines adaptation as the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects. Further, it differentiates between incremental adaptation (adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale) and transformational adaptation (adaptation that changes the fundamental attributes of a system in response to climate and its effects). A more useful breakdown is perhaps shown below (Burton, 2008). This shows the types of adaptation.

ADAPTATION			
Based on	**Type of adaptation**		
Intent *In relation to climatic stimulus*	Autonomous *(e.g. unmanaged natural systems)*		Planned *(e.g. public agencies)*
Action	Reactive *(post)* *(From observed modification)*	Concurrent *(during)*	Anticipatory *(ante)* *(Prior modification)*
Temporal scope	Short term *Adjustments, instantaneous, autonomous*		Long Term *Adaptation, cumulative, policy*

Figure 4 *Adaptation Typology. From Burton (2008) modified from Smit et al, 1999.*

Autonomous adaptation is a response to experienced climate and its effects, without planning explicitly or consciously focusing on addressing climate change (also called spontaneous adaptation). Note that many definitions of autonomous adaptation (e.g. from earlier IPCC reports) included all private sector adaptation, but applying the term autonomous to such action is incorrect, as the private sector can undertake planned adaptation.

Pure autonomous adaptation i.e. that happens automatically, does not use information, and therefore it is not relevant here. The focus of adaptation services therefore needs to be on planned adaptation where W&CI is used.

Reactive adaptation is a response to the experienced change in the climate rather than a pro-active planned approach, i.e. it is a short-term response. Climate information on these changes could be useful for immediate decisions, i.e. for such reactive adaptation, and this is likely to be closer in nature to the use of W&CI – and therefore, the valuation methods – set out in previous sections could be used. As an example, this might include farmers taking action in light of changing conditions, or a household taking action in response to being flooded. Note that as noted above, sometimes these actions are called autonomous, but clearly they involve a specific decision and thus there is opportunity for use of W&CI.

No and low regret adaptation. There is a focus in the adaptation domain of looking for no- and low regret adaptation. No-regret adaptation is defined as options that 'generate net social and/or economic benefits irrespective of whether or not anthropogenic climate change occurs' (IPCC, 2014). A variation of no-regret options are win-win options, which have positive co-benefits, such as wider social, environmental or ancillary benefits. These are differentiated from low-regret options, which may have relatively low costs or high benefits, or may be no-regret options that have opportunity or transaction costs in practice. These no- and low regret options typically target current weather extremes or climate variability, and are therefore quite similar in nature to the W&CI services listed in previous chapters. Indeed, W&CI are often on the list of low or no-regret options in their own right.

Pro-active planned adaptation is longer-term, and generally uses climate change projections. This is very different in nature to short-term W&CI services described in previous sections. These involve different types of information (future climate projections, not forecasts), and primarily involve different types of decisions, for example, making new infrastructure 'climate-proof' to future conditions, or developing a new adaptation project in response to anticipated future change. They involve much more complexity due to the long-time frames involved, but also because of scenario and modelling uncertainty. This means that there is the potential for mal-adaptive decisions, i.e. it is more difficult to use climate information, and thus some potential to make decisions that are costly or not needed.

The next issue is to consider the definitions of adaptation services, and how they map to different types of adaptation identified above. Climate services for adaptation have been defined as all public and private services supporting adaptation to climate change (Visscher et al., 2020 citing Hewitt et al., 2012), but this definition is very general, and needs to be more focused for benefits analysis here.

Visscher et al. (2020) outline four climate services, (See Figure 6), which do cover the types of services that might be involved in climate information for adaptation.

Table 2 Typology of climate services. Source Visscher et al., 2020.

	Generic	Customised
Focused	**Maps & Apps** • General climate services • For all users • Made freely or cheaply available	**Expert Analysis** • Mono- or multidisciplinary climate services • Tailored to specific decision-making situations • Offered commercially
Integrated	**Sharing Practices** • Mutual climate- and climate policy services • Among knowledgeable peers • Made freely or cheaply available	**Climate-inclusive Consulting** • Interdisciplinary management, engineering, or policy services including climate data • Tailored to specific decision-making situations • Offered commercially

Visscher et al. provide examples of these for climate change and tourism in Europe:

- Maps & Apps, climate data and projections are provided on a national, regional, or local level to groups of civil servants, policy-makers, managers, entrepreneurs and citizens, which they can consider when making decisions on infrastructure, investment portfolios, policy measures, etc
    - An example is generic information on climate change impacts on tourism (e.g., changes in snow conditions, tourism demand) such as the IMPACT2C Atlas, showing the impacts of +2 °C global warming on the tourism sector, or CLIMAMAP, a project funded by the Austrian climate and energy fund, provides fact sheets of climate change impacts for each Austrian province, using several climate indices.
- Expert Analysis, services are provided by specialized, commercial consultancy firms and market-oriented branches of meteorological and research institutes, which interpret climate models to deliver tailored analyses regarding projections, climate policy, and mitigation arrangements. Users get the benefits by better risk assessments, design decisions, policy measures, etc., specific for the decision.
    - An example of tailored snow simulations, adding value to investment decisions of an individual ski resort. Compared to generic study results, these tailored services can provide higher spatial resolution and take local measurement data and individual snowmaking capacities into account. Information could be the change in average season length, the change in the probability of ski operation during Christmas holidays, etc
- Climate-inclusive Consulting, commercial, interdisciplinary consultancies, create and deliver climate services by taking climate data and projections into account when advising decision makers on a broad range of subjects, such as infrastructure, investments or corporate strategy. Value for users is created by more robust designs and more prudent and effective decisions, customized to the customer's decision-making situation.
    - An example could include the assessment of a ski area's importance for the regional economy, the assessment of the area's risks towards climate change, the analysis of opportunities and challenges, and an economic feasibility study of the different investment options. The analysis would be based on tailored snow simulations (i.e., Expert Analysis), accounting for the ski area's specific snowmaking capacities and extension plans. Using data on current skier days and sales, changes in ski season length

can be translated into monetary terms and incorporated into the economic feasibility study of the investment options

- Sharing Practices, users of climate services are also the producers of climate services. The identification of best practices and the sharing of experiences among knowledgeable peers – for instance local governments within a certain region, or companies within a certain branch. The exchange of services within these communities is facilitated by databases, platforms and events, which are partly sponsored by public bodies, and partly offered by commercial platform providers. These services relate to actual decisions and policy measures, which are integrated in more encompassing contexts of use
    - An example is sharing practice among ski resort operators in another field: neighbouring ski resorts jointly commissioned a market research study, including individual consulting for each ski resort. This could be an example for the use of climate services as well, e.g., joint acquisition of tailored snow simulations for a specific tourism region, and a starting point for sharing experiences on how to deal with decreasing snowfall.

However, we consider that these may be naive in terms of use of climate projection information for decisions, and on the benefits to users, primarily as there is no consideration of uncertainty, nor the complex issues of actual (real) world decision making, including the costs and benefits of action.

An alternative structure for adaptation services is presented by Cavelier et al. (2017), who consider the market uptake of climate services for adaptation in France and present the following figure.

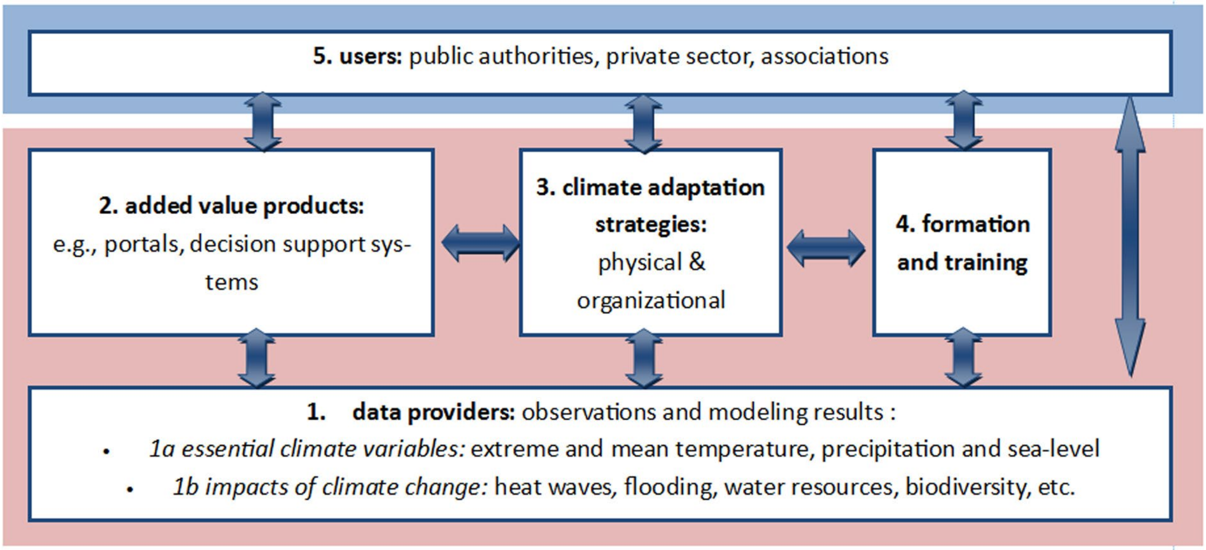


Figure 5 *Climate services providers and users and their interactions. Source Cavelier et al. (2017)*

In their analysis, data providers deliver the fundamental observations and modelling results that allow the evaluation of past, present, and future climate change. They then identify three categories of categories:

(1) organisations designing added value products such as portals and tools providing impact assessment results;
(2) design of adaptation strategies and support for decision making on adaptation;
(3) education and professional training, building capacity to adapt to climate change.

Importantly, this shows that the landscape for adaptation services is different to W&CI services, and involves different actors (i.e. added value products that are not climate information producers, as well as data providers). There is a question as to whether the value added is produced from the climate information (climate model projections) or from the subsequent product/knowledge development and decision support. We believe much of the value added is likely to be in the latter.

Further, they identify different services:

- Climate observations, models and knowledge;
- Impact studies, portals and advanced products;
- Adaptation studies.

The authors undertook case studies to provide information on opportunities and challenges. These are relevant for the consideration of benefit analysis here.

Table 3 *Summary of opportunities and constraints in the ecosystem of climate services Source Cavelier et al. (2017)*

Opportunities	Constraints
Strong scientific basis in support to the potential development of climate services	Difficulty in integrating the available climate information in the existing practices and workflows
Economic benefits are recognized by the private sector, mainly in the domain of saving costs	Different timeframes for climate impacts and for planning investment and return on investment cycles
Observed benefits of integrating climate change requirements in call for tenders and the regulations	Difficulties in translating climate change impacts in economic terms within both organizations and individuals
The challenge is increasingly being recognized important by businesses, citizens and governments (Paris agreement)	Difficulties in understanding current climate information and their uncertainties

The paper also highlights that uncertainties in climate projections are a major barrier to the uptake of climate services (adaptation services).

Hansen et al (2019) identifies that climate information plays a foundational role for adaptation. However, they also highlight the challenges around timing. While most climate model projections are for mid to late century, few, if any, adaptation decisions have planning horizons that extend to this period, and indeed, most have little use for climate outlooks beyond 20-30 years into the future. They conclude that that this has had the consequence of generating interest in and expending resources on downscaled climate projections in support of planning and decision-making that cannot readily deal with such information needs.

They highlight that for the 10-30 year timescales, which are most relevant for real-world adaptation planning, natural decadal variability dominates, and climate model projections of this time frame have substantial limitations as climate models tend to poorly represent natural variability and climate and weather extremes. They also identify that there are challenges in translating of historical data, forecasts and other types of climate information into more decision-relevant information. Further climate information is just one of many factors in decision-making.

Hansen et al. (2019) also report that climate change projections for mid-century are easily misused. They suggest that uncertainty is downplayed, often at the same time that higher-resolution, downscaled projections are provided. While the uncertainty of forecasts at a seasonal lead time can be described and calibrated in probabilistic terms by comparing the predictions with the observed data, this is not possible for climate change projections. Furthermore, they note that the presentation of climate change projections rarely makes explicit the limitations of this information and their consequences for decision-making. This re-enforces the earlier point that there is the potential for maladaptation with the use of this information.

The presentation of climate change projections rarely makes explicit the limitations of this information and their consequences for decision-making.

Benefits of Adaptation Services

Following from the review above, we identify three types of climate information - adaptation service areas:

- Information on the changes already happening in the climate (or early trends) for reactive adaptation;
- Information for low and no-regret adaptation;
- Information for pro-active adaptation.

The first two have a relatively strong overlap with W&CI service information, and could follow similar benefit and value chain analysis, although there are important distinctions

The third (longer-term information and pro-active adaptation) is very different. This requires General Circulation Models (GCMs)and projections, or downscaled regional models or statistically downscaled projections. This involves challenges around uncertainty and economic appraisal (discounting). As a consequence, alternative approaches are needed, because of these methodological challenges, and because the valuation of information (valued added) is added downstream.

Existing guidance on the economic analysis of adaptation (see ECONADAPT, 2017) highlights that the analysis of adaptation costs and benefits is complicated because of the challenges involved in estimating future benefits of adaptation. This is compounded by two major issues, i) uncertainty and ii) economic appraisal and discounting.

For the first of these, there is widespread recognition that uncertainty makes adaptation challenging. It is still not clear whether the world is on track to achieve the mitigation levesl needed to meet the Paris goals (of limiting temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit to 1.5°C). Greenhouse gas emissions (GHG) are still actually increasing globally (IEA, 2021) and the latest analysis (UNEP, 2020) indicates that the world is still heading for a temperature rise in excess of 3°C this century. This scenario and emission pathway uncertainty is usually considered by consideration of alternative future pathways, for example, sampling the Representative Concentration Pathways, RCPs. The second issue is that different climate models do not all give the same results for the climate for a given RCP scenario or the same global warming level. This can be considered by using different models in an ensemble, or as in UKCP18, with the derivation of a conditional probability range. This leads to an extremely large range of possible outcomes, and for some parameters (e.g. rainfall), it can even lead to a change in the sign, i.e. moving from an increase to a decrease in the projected change.

Clearly, the impacts and economic costs of climate change vary with this uncertainty. Accordingly the economic benefits of adaptation will vary with them as well. This has led to a shift in the literature from a predict-and-optimise framing for climate impacts and adapation, to the consideration of decision making under uncertainty (DMUU). This involves an adaptation service (DMUU) downstream of the climate information. It is also highlighted that several information inputs are needed for adaptation – it is not just the information on climate. There is also a need for information on adaptive capacity and vulnerability, as well as hazards. There is a also need for socio-economic information when considering future effects.

The second of these is related to economic appraisal, because in such analysis, the timing of costs and benefits matters. This reflects the principle that, generally, people (and society) prefer to receive goods and services now rather than later. This time preference is captured by discounting – a technique used to compare costs and benefits that occur in different periods. This applies discount rates to convert future costs or benefits to present values. As a consequence, lower weight is given to benefits that arise in the future. This is particularly important when these benefits arise from actions that involve costs in the present or short-term. These issues are compounded by uncertainty.

As a result, there is lots of potential for economic mal-adaptation, i.e. to design adaptation where the costs exceed the benefits (in present value terms). This involves more detailed economic analysis, to select options that have net benefits in present value terms, and also address the challenges of uncertainty.

It is also highlighted that there is a very large set of adaptation problems and activities, and a very large number of use-cases and users, i.e. the potential for adaptation services is very large. However, each of these applications is likely to favour a particular method for quantitative analysis, including undertaking economic analysis of benefits, and it would be extremely challenging to provide benefits guidance that could be useful for all these different uses.

The next steps of the project will focus on case studies to explore valuation of these areas. The potential for benefit analysis for the first two adaptation applications (reactive and no-regret adaptation) will be developed by using case studies in the next phase of the project. This phase will also consider the application of the same concepts to a longer-term example (adaptation services), to provide a clearer example of the challenges involved and look at the potential for application.

6. Methodological steps in Valuation Analysis for Managing Climate Variability and Observations

Several steps are typically taken in the analysis of the economic benefits of W&CI services (WMO, 2015: WISER, 2017), and these can be applied to services for managing climate variability, and for observations. These eight methodological steps are as follows:

1) **List the potential economic benefits of the W&CI service**. This includes the specification of the users, and the benefits that are expected/intended to be generated by the new information, including tangible and non-tangible, direct and indirect benefits.

2) **Consider the value chain for the service.** This maps out the steps in the value chain, i.e. from information provision to the users, with analysis of the key steps and assumptions for delivering benefits.

3) **Review and decide on the potential methods for assessing economic benefits.** This assesses how best to measure the benefits of the service and will vary depending on whether the preference is for an analysis *ex ante* (before introduction) or *ex post* (after introduction). Such preference should also take account of available resources and local context. The method selected could be one or a combination of methods (e.g. surveys of users with modelling analysis or benefit transfer).

4) **Construct a baseline.** Consider a scenario without the new (or improved) climate service. Ideally, this should take place at the start of the initiative, programme or project. To the extent possible, this should quantify the potential social, economic and environmental impacts of climate-induced events across sectors and actors (e.g. households, private and public sector) before the service is introduced (i.e. what is the problem). It should also consider the characteristics of existing (if any) weather and climate services, in terms of accuracy, uptake and use of current weather and climate information (i.e. for each part of the value chain), as a basis for evaluating benefits of the new/enhanced system.

5) **Assess the benefits with the (new or improved) climate service in place.** This should include analysis of all potential (*ex ante*) or actual (*ex post*) benefits, ideally in monetary terms, directly resulting from project activities. It should ensure that any efficiency losses along the value chain are considered.

6) **Assess the costs of the project.** This should include the investment in new or additional meteorological stations, system operation, and information provision (capturing equipment and resource/labour costs), as well as the delivery and maintenance of the services. It should also take account of the additional costs along the value chain, such as for communication. One step that is often omitted is the costs of the uptake and use of the information by users, as this will sometimes involve direct costs (e.g. taking action to prepare for a storm or a drought) but can also include wider costs (e.g. the opportunity costs of action or the lost time from acting on a decision).

7) **Compare benefits against costs**. This should look to assess the net economic benefit of the climate service. This analysis will typically undertake standard economic appraisal techniques, and thus look at the present value of costs and benefits.

8) **Undertake sensitivity and bias analysis, review how benefits could be enhanced**. Ideally a study should consider biases and uncertainties, potential omissions, and undertake sensitivity analyses

for key variables, testing how this affects the BCR. Depending on whether the analysis is *ex ante* or *ex post*, this can also be used to explore how benefits could be increased (in design, or as part of an evaluation, for revision).

Undertaking Economic Benefit studies

The previous section set out methods that can be used for economic benefit analysis. In many cases, it may not be a lot of additional work to include these components in the programme or project and such analysis can be designed to build on existing activities. For example, if a project is already doing survey work, then this could be extended to capture economic benefits. Similarly, the information needed for an economic benefits assessment – such as how people understand and use information – will be of relevance for the project overall, and there is potential to extend existing activities to consider these if included at the design stage. However, it can involve much more work to estimate economic benefits after a project has started, especially for projects that have not thought through benefits estimation issues, and are not undertaking routine analysis of beneficiaries, nor effectively monitoring and evaluating success.

The following sections set out some of the elements to consider for economic benefit assessment at different stages when developing a climate services programme or project.

Proposal stage

It is important to include the analysis of economic benefits when developing a project, i.e. at concept or proposal writing stage. This should set out the intended high-level benefits of the climate service. These should be reflected in the theory of change and/or logframes (these are described in more detail in the later monitoring and evaluation section). The key activities are to:

- **List (identify) the potential economic benefits** of the climate service, including how these benefits will be delivered down the value chain. It is also important to note the relevant actors (e.g. the public and private service providers and users) along the chain.
    - A useful way to start the analysis is to look at the current impacts of current climate variability and extremes. This might include the consideration of current risks, i.e. how sectors or end-users are affected. This can then be followed by listing the potential benefits that the climate service will have in reducing these impacts.
    - The consideration of benefits (and where relevant impacts) should include all categories of effects, i.e., tangible benefits such as avoided losses to property or agricultural benefits, as well as intangible or non-market effects such as avoided fatalities and injuries.
- **Review and decide on the potential methods for assessing economic benefits in the project**, taking account of the available resources for the economic benefits analysis, and how adequately these methods can be applied in the local context. These methods should ensure steps to quantify and potentially value both market and non-market sectors. It could include modelling (sectoral or integrated), survey and data analysis (including statistical or econometrics) or qualitative methods (see Chapter 2).
- **Consider the information on benefits (and costs) in the proposal**. The information from the steps above, particularly the identification of potential benefits, should be outlined, including

how these will be measured (*ex ante* or *ex post*) in the project. This information (on benefits) can also help to outline the benefits of the proposal more generally, and to help build the theory of change and the logframe.

- **Cost the activities and include the tasks in the proposal**. As the project moves to the full proposal stage, activities to deliver the economic benefits analysis should be included in the main programme of work. The various steps (activities) should be included in the proposal work tasks and costed in the budget. The valuation activities and results should also be integrated into the knowledge management and Monitoring and Evaluation (M&E) frameworks, including potential indicators. The activities to be included should reflect the steps outlined in the previous section.

Getting started

The following list of questions can be used in developing benefits analysis.

What are the potential benefits of your programme to users? For instance, are they likely to result in improved crop production or reduced losses from improved early warning? It is useful to identify the existing impact that you are trying to address, the list of beneficiaries, and the anticipated benefits.

What baseline assessment is used in your project proposal? It is useful to collate information on baseline conditions, e.g., on current conditions, or how large the potential current impacts of extreme events are. This could include gathering information on the current costs of disasters (of relevance for early warning) or information on current production in the agriculture sector you are targeting. Once you have a better idea of the method, this can be used to draw up a formal step for deriving this baseline.

What are the steps in the value chain, i.e., in the successful delivery of climate information through to end-users? It is useful to map how your climate service will flow along the chain to end users, and to identify what barriers and additional steps are needed to maximise uptake and use. It is also useful to consider the ability of users to respond and effectively use information. It may be worth including user forums or surveys to explore these issues in your project and use this to help the design.

What type of climate service are you providing and which methods might be applicable? There are a range of methods that can be used (see Chapter 3).

How does an economic benefit study feed into the M&E and/or VfM analysis? The results from a economic benefit analysis, when combined with the project cost information, generate the information for the effectiveness and cost-effectiveness components of a VfM analysis. Further work can be undertaken to show how the costs and benefits of the project compare to other alternative choices. It can also be used during project implementation to assess and report on the effectiveness component of VfM.

How can you use economic benefit information to summarise and disseminate the benefits of your project? It is worth thinking about how to use the results of an economic benefit study. This could include the production of relevant policy briefs and news items, that would enhance the impact of you project. It is worth including these activities in your proposal.

Suitability and Selection of Methods

As highlighted in a chapter 2, there are a number of different methods that can be used for valuation of weather and climate services. The choice of method depends on two critical issues:

- The type of weather and climate information service and the applicability of methods.
- The capacity, level of expertise, and the time and resources available for benefits analysis.

These issues are mapped for various weather and climate information services below, and for the observations and information for climate variability (the focus of the study), this includes example references.

Table 4 *Assessment of Potentially Methods for Valuation of W&CI Services (mapped for different types of services*

Time period	**Description of Method**	**Resource & Expertise Needs**	**Examples**
Observations **(could also apply to historic)**	Simple benefit transfer or 'what-if' analysis.	Low. Costs of review and analysis of indicative values. Low expertise required.	Hallegatte 2012; Kull et al 2016
	Modelling of benefits, e.g. Observing System Experiments (OSEs), applied to 'what-if' analysis, or combined additional modelling of benefits.	Medium to high. Cost of OSE and analysis. High level of expertise involved.	Kull et al 2021
Weather forecasts	Surveys of willingness to pay (*ex ante*) for new or improved services	Medium to high. Cost of survey and analysis. High level of expertise involved.	
	Revealed preferences studies.	Medium to high. Cost of studies and analysis. High level of expertise involved	
	Survey/questionnaire of likely beneficiaries of improved weather services (*ex post*), e.g. survey of farmer/farmer representatives, freight and household transport representatives, etc.	Medium. Cost of undertaking survey and processing/interpreting results modest, but can be included in baseline and end-line survey alongside analysis of outcome. Low -medium expertise required.	
	Physical modelling of weather benefit or impact.	Medium to high. Time spent on developing model and data analysis of results. High expertise required.	
	Benefits transfer, e.g. transfer from previous studies for equivalent improvements in weather services elsewhere, with adjustments for context.	Low cost. Review previous studies and interpretation to allow transfer to current context. Low expertise required.	
Early warning systems	Survey/questionnaire of likely beneficiaries (ex ante or *ex post* see above).	Medium cost and low-medium expertise required (see above).	
	Physical modelling, using simulations or historical analogues of events to calibrate impact costs (cost loss/ avoided losses).	Medium to high. Time spent on developing model and data analysis of results.	

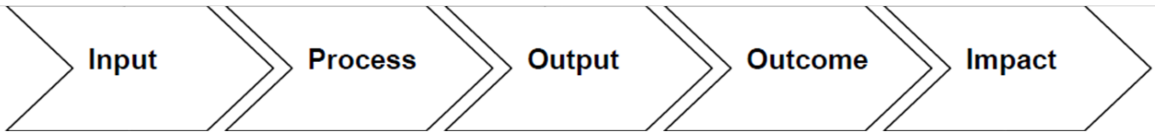
Managing variability (Seasonal forecasts)	Surveys of willingness to pay (*ex ante*) for new or improved services	Medium to high. Cost of survey and analysis. High level of expertise involved.	Amegnaglo et al. 2017; Zongo et al. 201
	Revealed preferences studies, e.g. averting behaviour	Medium to high. Cost of studies and analysis. High level of expertise involved	No studies found
	Survey/questionnaire of likely beneficiaries of improved weather services (*ex post*), e.g. survey of farmer/farmer representatives, freight and household transport representatives, etc.	Medium. Cost of undertaking survey and processing/interpreting results modest, but can be included in baseline and end-line survey alongside analysis of outcome. Low -medium expertise required.	Rahman et al. 2014; NCAER, 2020
	Bio-physical modelling of impacts resulting from seasonal variations (*ex ante*), e.g. simulations of effects on agricultural yields as a result of alternative seasonal conditions, and resulting changes in farmer income/revenue.	Medium to high. Time spent on developing model and data analysis of results. High expertise required.	Roudier et al, 2012 : An-Vo et al. 2019
	Economic modelling (*ex ante*)– suitable for larger scale change, e.g. computable general equilibrium modelling.	Medium to high. Time spent on developing model and data analysis of results. High expertise required.	Rodrigues et al. 2016
	Impact assessments, e.g. agricultural test plots to allow measurement of benefits.	Medium to high. Development and analysis of test plots and data and analysis of results. Medium – high expertise required.	Ouedraogo et al. 2018 and Rodrigues et al. 2016l Tarchiani et al. 2018
	Econometric analysis (*ex post*), e.g. quantification of income benefits of improved weather forecasting on basis of regression analysis of data.	Medium to high. Time spent on developing econometric analysis and data analysis of results. High expertise required.	Barrett et al., 2020

It is difficult to be prescriptive on the choice of methods. Existing guidance (e.g. WMO, 2015; Suckall and Bruno Soares, 2020 for ARRCC) is not prescriptive on the 'best' or most applicable methods. Studies that have higher resource needs and difficulty may require external expertise: these may produce more robust results, but this is not necessarily the case, and they all have strengths and weaknesses (see detailed earlier in chapter 2 on the discussion on the approach, and in the literature review findings in the Appendix, as well as in WMO, 2015, Table 6.2; and in Suckall and Bruno Soares, 2020).

7. Monitoring and Evaluation / Value for Money

The final part of this document concerns monitoring and evaluation (M&E), and the linkages to Value for Money (VfM), for climate services. M&E allows an analysis of the performance of a project. It can be used to measure outputs, outcomes, and impacts in order to assess whether the anticipated benefits have been realised. HMT (2020) and the Treasury Magenta Book (HMT, 2015) provide guidance on the evaluation stage of the policy process. This process of policy, programme, and project development – and subsequently monitoring and evaluation – often uses a Theory of Change (ToC) and logic models (also known as logical frameworks or logframes). These allow a structured approach.

A ToC sets out the problem and identifies the causal linkages and potential pathways that move through to achieving a desired impact (i.e. a clear hypothesis on how change is going to happen). These are used in policy and programme development. A logical framework applies at the programme or project level, showing how project activities will lead to the desired outputs, outcome and impacts. As set out in the Magenta book, developing a logic model enables the processes, outcomes, and impacts of an intervention to be identified and articulated, in a way that ensures they link to the anticipated results (UK Government Guidance, 2019). They also set out the assumptions that are associated with this pathway (and the delivery of impacts), at each stage, along with the preconditions for this to happen. There is a standardised set of steps (the causal pathways or results chains) in a logical framework, which follow from the inputs and activities (also known sometimes as processes), to the subsequent outputs and outcomes, and finally, to the overall impact. This is shown below.



Term	Definition	Example
Inputs	Public sector resources required to achieve the policy objectives.	Resources used to deliver the policy.
Activities	What is delivered on behalf of the public sector to the recipient.	Provision of seminars, training events, consultations etc.
Outputs	What the recipient does with the resources, advice/ training received, or intervention relevant to them.	The number of completed training courses.
Intermediate outcomes	The intermediate outcomes of the policy produced by the recipient.	Jobs created, turnover, reduced costs or training opportunities provided.
Impacts	Wider economic and social outcomes.	The change in personal incomes and, ultimately, wellbeing.

Table 5 *Logic Model. Source: Magenta Book, 2015.*

Note that activities are sometimes called processes, and intermediate outcomes are often just called outcomes.

A key determinant of the success of a ToC and logframe is the outcome, i.e. the goal that should be achieved. The term 'outcome' in this case relates to real-life economic, social and/or environmental improvements. There is also supplementary guidance on setting outcomes, to ensure that they are SMART (Specific, Measurable, Achievable, Realistic and Timebound) (NAO, 2019).

Any climate service project can be framed in terms of a logical framework. This assesses the inputs, activities, outputs, outcomes and impact. Mostly importantly, the economic benefits of climate services can be considered as an outcome or impact metric and can be measured as such. This also provides an opportunity to link to monitoring.

An example of a ToC and a Logframe for seasonal forecasting is shown below.

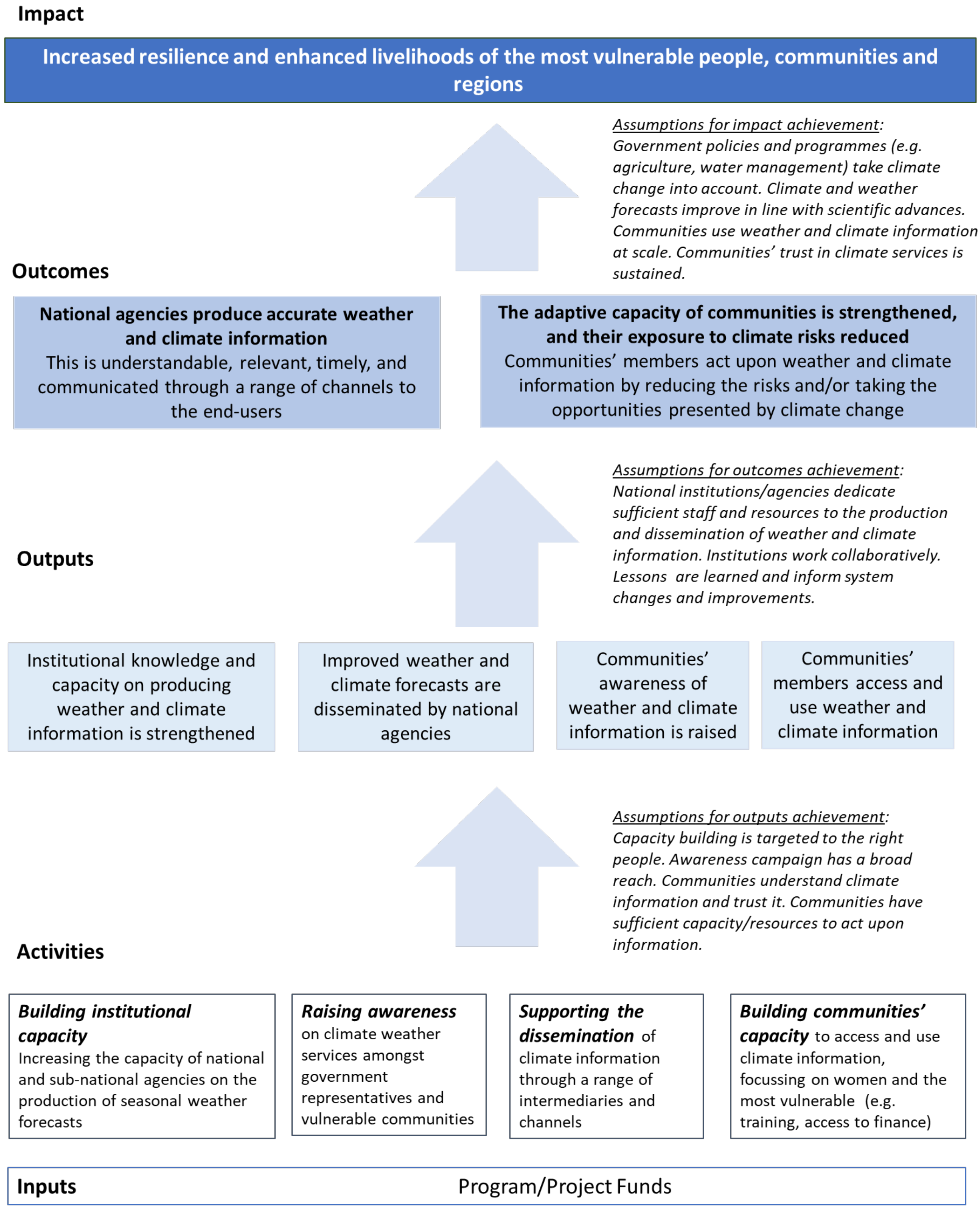


Figure 6 General Theory of Change for seasonal forecasts. Source: Authors.

Table 6 *General Logframe for seasonal forecasts. Source: Authors.*

Impact	**Indicator**	**Comment**
Increased resilience and enhanced livelihoods of the most vulnerable people, communities, and regions	Changes in GDP/reduction in poverty incidence thanks to weather services [Note: very hard to measure, and requiring sophisticated modelling]	Compared to baseline
	Number of people accessing climate information as a % of total population	Absolute number and compared to baseline
	Number of people using climate information as a % of total population	Absolute number and compared to baseline
Outcomes		
National agencies produce accurate weather and climate information (understandable, relevant, timely, and through a range of channels)	Number of bulletins containing improved information on weather and climate impacts, tailored to audience (e.g., farmers, fishermen etc)	Absolute number and compared to baseline
The adaptive capacity of communities is strengthened, and their exposure to climate risks reduced	Number of improved bulletins accessed	Absolute number and compared to baseline
	Number of recipients using information/acting upon it	Absolute number and compared to baseline
	% increase in benefits such as income/yields as a result of using weather and climate services	Absolute number and compared to baseline
Outputs		
Institutional knowledge and capacity for producing weather and climate information are strengthened	Number of governments representatives/meteorological agencies staff trained	
Improved weather and climate forecasts are disseminated by national agencies	Number of weather bulletins disseminated	Absolute number and compared to baseline
	Number of channels used to disseminate improved weather and climate information	Absolute number and compared to baseline
	Number of intermediaries trained	These could be radio broadcasters, or community intermediaries (extension services)
Communities' awareness of weather and climate information is raised	Number of people reached by information/awareness campaign, disaggregated by gender	[if information campaign is conducted]
Communities' members access and use weather and climate information	Number of people with enhanced capacity to use/act upon weather and climate information, disaggregated by gender	Number of people receiving training, access to finance, agriculture inputs etc.

Alongside this, there is a well-established concept of **value for money** (VfM)in UK government programming. Good value for money (NAO, 2019) involves the optimal use of resources to achieve the intended outcomes. 'Optimal' means 'the most desirable possible given expressed or implied restrictions or constraints'. VfM is not about achieving the lowest initial price. UK Government frames VfM as areas that are clearly linked to the theory of change: Economy (inputs), Efficiency (inputs to outputs) and Effectiveness (outputs to outcomes and impacts) (NAO, 2019). These are sometimes complemented with a fourth area on Equity.

- *Economy (spending less):* This refers to ensuring lowest cost procurement of goods and services. This focuses on making sure that input unit costs are benchmarked against market norms and thus that value is maximised through strong procurement processes.
- *Efficiency (spending well):* This refers to ensuring that the choice of goods and services to be procured results in the envisaged outputs. It aims to ensure that the quality and quantity of inputs are appropriate to achieve the envisaged outputs and that inputs are managed in an efficient way. The input to output ratios are the key consideration.
- *Effectiveness (spending wisely):* This refers to the selection of those outputs most likely to result in the desired outcomes (and impacts). It considers whether a programme can demonstrate that the chosen outputs are the most effective way to achieve these outcomes, and how these outcomes can be measured.
- *Equity:* The extent to which services are available to and reach all people that they are intended to – spending fairly. Some people may receive differing levels of service for reasons other than differences in their levels of need.

These can be linked to a logframe as below.

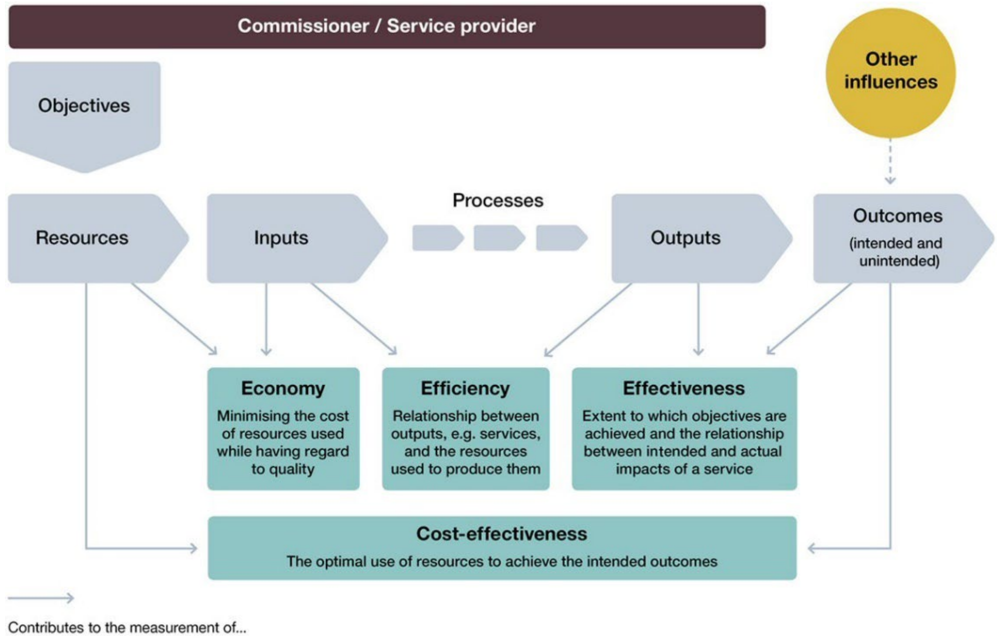


Figure 7 Value for Money in a Logical Framework Source. NAO, 2019.

In the context of climate services, activities can involve:

1. **Setting out the 3 Es rationale** to frame the overall VfM approach;
2. **Minimising costs** through the use of cost benchmarking;
3. **Maximising benefits** through the use of economic benefit analysis to inform design or to evaluate benefits.

The final element is captured in the preceding chapters. Some additional information on the first two are given below.

Setting out the 3Es

Examples for the setting out the 3Es for climate services are given below.

Table 7 *Examples of the 3Es for weather and climate services. Source WISER, 2017.*

	3Es issues	Focus areas
Economy	Ensuring lowest cost procurement of goods and services. Cost-benchmarking involves exploring the unit costs for a given input, output, or outcome	• Unit costs associated with the intervention (e.g. £/meteorological station, day rates,) and how these benchmark against similar interventions or against other market price data; • Programme management or contractor costs as a % of overall budget and how these benchmark against other programmes.
Efficiency	Ensuring the necessary training, analysis capability and communication/ dissemination to ensure benefits reach potential users, i.e., to deliver the outputs. There is also an efficiency aspect in the choice of areas to focus on, i.e., uneven benefits across sectors, noting this will be driven by local risk context	• Key output indicators that will drive costs (and therefore determine VfM) for the type of intervention (e.g. number of meteorological stations installed and operational, number and extent of climate services developed); • The potential barriers to these outputs being delivered (e.g. integration of technology, capacity of staff to interpret met data and produce forecasts), and how these are being addressed (e.g. smart procurement, training); • How commercial, management and M&E will support effective delivery and cost control.
Effectiveness	Choosing the balance of investment between equipment, capacity, institutional strengthening, dissemination, user uptake and training, etc. to result in the desired outcomes (and impacts). It is also likely to focus on the areas that are most likely to deliver cost-effective benefits, noting this should include non-market benefits (e.g. valuation of life) and equity consideration (the most vulnerable).	• Justify the focus on a given (sub-)sector represents the most sensible use of funds (medium term agriculture forecasting vs. short term EWS); • Examples of the relevant log-frame outcome indicators for this type of intervention. (e.g. # farmers changing agricultural practices based on medium range forecasts, # pre-emptive response actions based on EWS) • Justify the balance, type and volume of no regret activities/outputs represent the most effective route to achieving these outcomes. Identify other routes to achieve the same goals (e.g. hard flood protection infrastructure). • Compare specific results with similar type interventions elsewhere (as demonstrated by the earlier evidence list). Identify any non-market benefits and equity considerations that have not been included in the CBA that might make the case more attractive.

It is highlighted that the analysis of economic benefits, i.e. the value of climate services, has particular relevance to the efficiency and effectiveness components of VFM.

Minimising costs through cost benchmarking

The second element is focused on minimising costs, using cost benchmarking.

***Table 8**: Overview of Cost benchmarking approach. Source: WISER, 2017.*

Economy			
Main input cost drivers	**Cost per input (unit cost) (£)**	**Benchmark comparator**	**Procurement process**
Input 1 e.g. staff Input 2 e.g. capital equipment Input 3 e.g. Travel costs Input 4 Management cost	Day rate £ per station £ per flight % of budget	Other project rates Market cost % other projects	How are procurement processes being managed to ensure that costs are minimised?
Efficiency			
Main outputs	**Cost per output (£)**	**Benchmark comparator**	**Management process**
Output 1 e.g. Training course Output 2 e.g. Forecast model Output 3 e.g. Stakeholder process Output 4, e.g. seasonal forecast product	£/course delivered £/model developed £/workshop £/ per seasonal forecast product developed	Comparable data from existing programmes and initiatives where appropriate	How are management processes structured to ensure that outputs can be delivered (e.g. addressing potential barriers to uptake) and that costs are appropriately apportioned to outputs?
Effectiveness			
Main outcomes	**Cost per outcome (£)**	**Benchmark comparator**	**Measurement process**
Outcome 1 e.g. # resilient beneficiaries Outcome 2 e.g. # avoided loss of life Outcome 3 e.g. # avoided infra. Damage Outcome 4 e.g. # trained forecasters Outcome 5 e.g. # increased yield	£/beneficiary reached £/avoided DALY £/avoided £impact £/forecaster trained £/tonne of yield improvement	Other programmes	How are outcomes to be measured during programme implementation, and how will cost per outcome will be reported during project implementation?

Overall, projects should therefore be able to demonstrate high VFM by:

- Providing assurance (during design) that projects understand their costs and benefits, and ensure that resources are prioritised to where they have the greatest impact;
- Offer a more detailed insight into the economic returns of W&CIS programmes, creating a stronger justification for investment in this area (during implementation);
- Generate evidence (*ex post*) on the most effective approaches to programme implementation, supporting transfer of this knowledge to other programmes.

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Methodology for Valuing and Monitoring Climate Services to Manage Climate Variability

Case Study: Economic Valuation of Winter Seasonal Weather Forecast Data for the Transport Sector

Deliverable 4 of the contract:

‘Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services’

Alistair Hunt and Paul Watkiss

Summary

This report presents the first case study for the project 'methodology for monitoring and valuing climate services', which is Deliverable 4 of the contract 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services'. This case study provides a worked example of the methodology and guidance for valuing climate services, focusing on an example of seasonal forecasting. The methodology we adopt has the following steps that are used to provide a structure for the study:

1. List the potential societal benefits that the climate service may provide.
2. Develop the value chain for the service.
3. Review and decide on the potential methods for assessing economic benefits.
4. Build a baseline scenario (or counter-factual) without the new climate service.
5. Assess the benefits with the climate service in place.
6. Assess the costs of the project developing the climate service.
7. Compare benefits against service costs.
8. Undertake sensitivity and bias analysis, then review how benefits could be enhanced.

This case study focuses on the Met Office seasonal prediction of winter weather and its use in the transport sector - for air, road and rail operators. Particular emphasis is given to the North Atlantic Oscillation (NAO) index, and associated likelihood of a colder than average, or wetter and windier, winter. The case study uses, as a key input, the analysis of Palin et al. (2016) which identifies a range of impacts associated with these winter weather modes. We then make a quantitative estimate of the potential benefits that are associated with use of the (unpublished) Met Office winter weather forecast service. These are presented below. The impact costs associated with the three characterisations of prevailing winter weather in a given year are presented in three columns labelled Wet/Windy, Average and Cold/Calm, along with the corresponding NAO Index score. The final column in the right of the table shows the deviation of impact costs from the expected average costs in a cold winter – the type of winter associated with the highest costs. These cost deviations therefore indicate the size of benefits that could result from knowledge that a given winter will be cold rather than average. It should be noted that these benefits are an upper bound as to what could be realised; imperfect knowledge will ensure that not all possible benefits are made. The estimates presented are based on the perceived value [benefit] of the service for a small number of specific users/ use cases rather than covering all possible impacts/ benefits but nonetheless give a good first indication of the benefits delivered. very partial Whilst the Met Office were unable to supply us with quantitative estimates of the costs of service provision, our expectation – based on informal communications with the Met Office, is that these costs will be less than the benefits, i.e. a benefit-cost test is likely to be passed[12]. Nevertheless, we are currently unable to complete step 7.

It should also be noted that the benefits we identify are those that may be realised if the Met Office seasonal forecast information is acted upon by the individual organisations in their preparations for Winter weather hazards. Thus, whilst the costs of preparedness are borne following the availability of the seasonal forecast information, the benefits of the forecast are felt both immediately – since the organisation benefits from reputational, cost-saving, and other advantages of preparedness – and at the time(s) during the Winter when adverse effects of specific weather events are able to be averted as a result of the seasonal preparations.

[12] Note that impact costs – those costs associated with weather conditions – are different from service costs incurred in the establishment and operation of the winter weather forecast service.

Key assumptions adopted in our analysis include the following. Based on our judgement we rank them in importance in determining uncertainty in the quantitative estimates, from highest importance to lowest importance:

- The efficiency loss of GloSea5-based forecasts of the NAO index being imperfectly related to the observed NAO index of 38%;
- 75% of relevant end-users use the weather forecast information;
- End-users are 75% effective in their use of the forecast information.
- Maximum potential gross benefits of having a seasonal winter weather forecast arise from a perfect flow of information along the value chain, as well as perfect uptake and use, and perfect effectiveness of end-user decisions;
- Available time-series data on NAO index and transport performance impacts are sufficiently long to generate statistically valid relationships;
- Causation between patterns of winter weather and specific impacts on transport performance;
- Validity of transfer of unit values related to transport impacts from original study to current study;

Whilst these assumptions are required in order to generate quantitative measures of the benefits of improved seasonal weather forecasts they do highlight that there is considerable uncertainty involved in the estimation process. It should be clear, however, that the lack of data observations means that defining upper and lower bounds on that uncertainty, using e.g. confidence intervals, is not currently feasible. Our own judgement is that estimates may be +/- 50%; future research should look to challenge this judgement.

We highlight the relative merits of alternative methodological approaches that can be used to derive quantitative estimates of seasonal weather patterns on the transport sector. Our case study demonstrates that the underlying impact assessment uses relatively sophisticated statistical analysis in it's treatment of observed (as opposed to survey) data and that – combined with value transfer of economic values - the resulting impact cost estimates may consequently be espected to have substantial robustness. However, lack of time plus limited data availability constrain the extent to which we can test this conclusion.

Table A. Table A. Summary of Weather Impact Costs (£ million, 2020 price year)

	NAO Index Winter Type	>0.8 Warm/Wet/Windy	>-0.8<0.8 Average	<-0.8 Cold/Dry/Calm	Average Costs	Cost Deviation in cold winter
BA Flights	Total Delay Costs per year - average	6.4	11.7	25.7	12.15	13.6
BA Flights	Cost of De-Icing – average	0	1.3	5.9	1.5	4.4
Road	Total Accident-Related Costs	179.5	193.81	186.8	189.1	- 2.2
Road	Road Salt Costs	4.9	7.5	7.4	7	0.3
Rail	Total Incident costs	1.3	1.4	5.9	1.8	4.1
Total		192.2	215.8	231.7	211.5	20.2

Introduction

Investing in weather and climate information (W&CI) services leads to improved information, such as enhanced early warning or seasonal forecasts. In turn, this information provides economic benefits to users (individuals/organisations[13]), to the extent that it leads to positive societal outcomes from the actions and decisions that users subsequently take. Such an economic benefit is therefore known as the value of information.

This report presents the a case study for the project 'methodology for monitoring and valuing climate services', which is Deliverable 4 of the contract 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services'. This work is being undertaken by a consortium of JBA Consulting (lead), in association with ClimateSense, Paul Watkiss Associates (PWA), Professor Rob Wilby, and Becky Venton, for the Met Office as client. This Deliverable is led by PWA.

The project has developed a methodology and draft set of guidance for valuing climate services, as well as a suggested method and guidance for analysing value for money (as part of monitoring). The methodology we adopt has the following steps that are used to provide a structure for the study:

1. List the potential societal benefits that the climate service may provide.
2. Develop the value chain for the service.
3. Review and decide on the potential methods for assessing economic benefits.
4. Build a baseline scenario (or counter-factual) without the new climate service.
5. Assess the benefits with the climate service in place.
6. Assess the costs of the project developing the climate service.
7. Compare benefits against service costs.
8. Undertake sensitivity and bias analysis, then review how benefits could be enhanced.

These are being tested through a series of case studies (Deliverable 4). This is the first of these case studies and is focused on seasonal forecasting in the UK. The three case studies in this project are light touch studies, with around 1 person month of time each for analysis. Therefore, the study has focused on the key areas where information on the services and their potential benefits are already available from Palin et al. (2016).

Winter Seasonal Forecasts: Case Study

This first case study is focused on the economic benefits of seasonal forecasts – in particular, GloSea 5 produced by the Met Office. This is an area where there is a substantial amount of pre-existing literature, with examples of valuation of such forecasts, as reported in reviews by Meza et al. (2008), Clements et al. (2013), and Soares et al (2019). These are documented in the annex to the main report. To date, the majority of these applications focus on the agriculture sector.

By contrast, this t case study is undertaken on the Met Office seasonal forecast service for winter weather for the transport sector (Palin et al., 2016). This service draws on seasonal predictions developed and run by the Met Office Global Seasonal forecasting system, GloSea, version 5 of the system (GloSea5) system (MacLachalan et al. 2015; Scaife et al. 2014). GloSea is an ensemble prediction system built around the high-resolution version of the Met Office climate prediction system: HadGEM3 family atmosphere-ocean coupled climate system. GloSea5/6 has two components:

[13] In this report we use "organisations" as being representative of all parties that value weather information.

the forecast itself and an associated set of hindcasts, also called historical re-forecasts, used for calibration purposes and for skill assessment.

The case study focuses on an existing use of this seasonal prediction system to predict the winter North Atlantic Oscillation (NAO), and a climate service that the Met Office produces for winter weather seasonal predictions for the transport sector in the UK. This service rests on the use of GloSea5/6 for predicting the winter North Atlantic Oscillation (NAO) which relates to variations in the large-scale surface pressure gradient in the North Atlantic region. The NAO is defined by MO (2021) as below:

In the average state of the atmosphere, the North Atlantic surface pressure is relatively high in the subtropics at latitudes 20°N to 40°N ('the Azores High'), and lower further North at latitudes 50°N to 70°N (the 'Icelandic Low'). The North-South pressure difference determines the strength of the westerly winds across the Atlantic and is known as the North Atlantic Oscillation (NAO).

The NAO is also associated with variations in temperature and rainfall across both Europe and North America. A positive NAO index is generally associated with warmer, wetter, stormier conditions whilst a negative NAO index is typically associated with calmer, drier, and colder conditions.

These conditions are associated with seasonal and longer-term variability of the NAO, which is predictable from November for the coming winter (Scaife et al. 2014). Hence, with outlooks of the NAOS, it is possible to forecast higher/average/lower winter storminess, near-surface temperature, and wind speed, all of which are likely to have high value for planning and preparing for extreme winter conditions. More specifically, better knowledge of likely winter weather patterns ahead of time – derived from more accurate and better understood forecasts - can inform decisions amongst relevant organisations about the level of preparation for a range of forms of disruption, including in the transport sector for road, rail and air.

The Met Office issues seasonal forecasts of the winter NAO for a number of major transport users, as part of existing services. This is the key climate service of focus in this case study. There has been some pre-existing work on this, which provides essential inputs to the case study. Palin et al. (2016) report on the improvements in predictability of the winter NAO at seasonal time scales, using GloSea5. They also provide relationships between the observed and forecast NAO and a variety of UK winter impacts on transport in the road, rail, and aviation sectors. These include consideration of the following forms of winter travel disruption:

- Delays in flights;
- Aeroplane de-icing provision;
- Road accidents and associated delays;
- Road salt provision;
- Rail incidents.

The aim of this case study is to look at the economic benefits of this seasonal prediction service and consider the value that they can afford recipients of the climate service. We therefore utilise the data that relate NAO index values with weather impacts on transport in order to quantify these impacts in economic terms. The exercise therefore simply serves as an illustration of the type of analysis that could be undertaken to estimate the value of such a service over a much wider variety of sectors.

Application of the method

Study methodology

An earlier report as part of this study develops guidance for the valuation of the economic benefits of climate services for climate variability. This aligns with, and builds on, the existing methods in the literature and in existing guidance (e.g., WMO, 2015; WISER, 2021). The methodology involves the following steps:

1. List the potential economic benefits that the climate service may provide.
2. Develop the value chain for the service.
3. Review and select potential methods for assessing economic benefits.
4. Build a baseline scenario (or counter-factual) without the new climate service.
5. Assess the benefits with the climate service in place.
6. Assess the costs of the project developing the climate service.
7. Compare benefits against service costs.
8. Undertake sensitivity and bias analysis, then review how benefits could be enhanced.

These steps have been applied to this case study.

Step 1: List the potential societal benefits that the climate service may provide.

The first task is to catalogue the potential benefits of the new or enhanced W&CI service. The starting point for this is to list the possible end-users or beneficiaries, with the benefits of the W&CI service to each of these groups. This should capture all benefits, including both market benefits (e.g., financial benefits to users) and non-market benefits (e.g., health and environmental benefits) in relation to human welfare. It should also include indirect benefits that may arise, such as the potential benefits for other organisations or beneficiaries who might gain from the new or improved information, as well as indirect benefits that might arise from spill-overs to other activities, sectors or the wider economy, including employers who avoid potential productivity losses resulting from employee absences. For this case study, the following end-users and benefits are identified. Note that the analysis is limited to the impacts on the transport operators identified in Palin et al. (2016). It is therefore illustrative of a range of applications that encompass a much wider array of operators and their suppliers and customers.

Table 9 Examples of end-users and expected benefits to end-users from a new or enhanced W&CI service.

End-user	**Expected benefits**
Transport operators	
Heathrow airport and airlines	Reduced flight delays
	Better planning for de-icing operations
Train operators	Reduced service delays
	Reduced rail accidents and incidents
Highways agency and local authorities	Reduced accidents (costs of response)
	Better planning for use of salt
Passengers	
	Reduced travel time losses
	Reduction in risk of accidents, reduced damage

	Reduction in risk of accidents, avoided fatalities and injuries
Freight transport operators	
	Reduced disruption and travel time delays
Wider economy	
Upstream suppliers & other dependent businesses	Local and other economic effects such as planning stock inventories

Whilst the impacts considered here are those that result from short-term, specific, weather events, the quantification of the benefits in this case study is undertaken at a 3-month period of aggregation. Thus, in principle it is possible to use this data to inform decisions made by organisations regarding their resource planning for this seasonal period – as characterised in Table 2. It should therefore be emphasised that the increased likelihood of the operational benefits listed in Table 1 being realised is contingent on the individual end-users acting on the seasonal information in the ways identified in Table 2. The immediate benefits of the planning actions listed in Table 2 then consist of those that result from institutional resilience, and may include reputational standing as well as the more tangible advantages of e.g. purchasing operational materials such as road salt and de-icing liquid in advance and in bulk, thereby facilitating potential cost-savings[14][15]. The subsequent, indirect, benefits realised in the operational activities that reduce the adverse impacts of specific weather events can therefore be seen as proxy measures of the immediate benefits from better seasonal planning.

Table 2. Use of Seasonal Weather Forecasts for Transport Operators

Sector	Beneficiary	Expected Usage
Air transport	Airport operator	Review and update contingency plans including resource supply chains for de-icing, snow clearance etc
	Airline	Review and update contingency plans including crew rosters and passenger management
Road transport	Local authority	Review gritting service requirements; Review road salt stocking and ordering requirements;
	Highways Agency	Review maintenance scheduling
	Gritting service	Review resourcing requirements
	Road hauliers	Review resourcing requirements
Rail transport	Network rail	Review contingency plans and resource levels Review track maintenance scheduling
	Train operators	Review contingency plans and resource levels
	Rail freight hauliers	Review contingency plans and resource levels

Each benefit. identified as accruing to the different users is listed separately in Table 2, reflecting the fact that each is likely to require specific, differentiated, data.

The next task in Step 1 is to identify which benefits to focus on in the analysis. This depends on the objectives of the analysis, as well as the information, time and resources available.

[14] An indication of the types of financial savings that might be made is provided by the price difference when bulk buying is undertaken. For example, brown rock salt is approximately 25% cheaper when bought in bulk.
[15]https://www.peacocksalt.com/winter/?gclid=Cj0KCQjwxIOXBhCrARIsAL1QFCZ32fI2GbnNoGo0Qc5ovVjiazqQqTF1BsyyP8zRVvPcGKj1kmvCugUaAmzGEALw_wcB

The analysis focuses on the costs of weather disruption affecting transport organisations, and climate services that provide them with improved information for winter prediction. In the baseline case, transport organisations are assumed to prepare for the possibility of weather disruption on the basis of their, or others', prior experience. The level of baseline preparation will depend on:

a) There being actions to take that would reduce their exposure to weather-related risk for specific weather hazards;
b) There being sufficient financial and other resources to undertake actions;
c) The size and importance of the weather-related risks to the organisation's performance;
d) The level of risk aversion that the organisation holds in relation to the weather risk.

It should be noted that benefits may result under two conditions when:

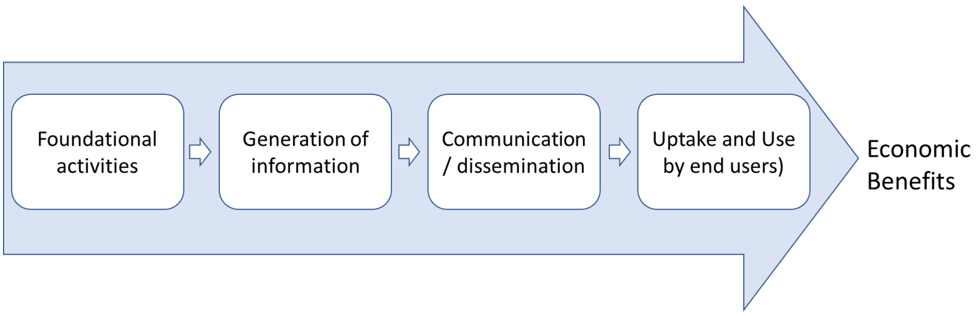
a) The level of preparation effectively counteracts a damaging and costly seasonal weather event(s), and;
b) The level of preparation is less given a higher likelihood of absent or less damaging seasonal weather events.

The transport organisation will therefore make decisions about the expenditure (in time and/or money) on actions to mitigate and adapt to weather risks on the basis of whether those costs will be outweighed by the benefits (performance or welfare improvements) of being better prepared, subject to budget constraints.

New information regarding the likelihood of alternative weather patterns occurring will be invested in and used as long as it is perceived that its' cost is less than the benefits resulting from being able to make better decisions about the amount and timing of preparatory actions.

Step 2: Develop the Value Chain

The next step in the method is to develop a value chain for the service. This should list the successive steps in the new or enhanced service, that go from the generation of information through to uptake by end-users, as shown below. Note that in practice, there will likely be a feedback-loop so that lessons learned can improve future socio-economic benefits or devise ways of managing risks from false alarms



Relevant steps and considerations - from early activities through to end-use - may include the following (Perrels, 2013):

- Foundational activities, such as provision of new infrastructure or modelling;
- Generation of information;
- Accuracy of information;
- Timeliness of information;
- Communication and dissemination of information;

- Access to information amongst target end-user groups;
- Understanding of information;
- Trust in the information;
- Ability of users to respond to the information;
- Level of use/uptake by end-users;
- Effectiveness of response of users – both positively and negatively;
- Redistribution of benefit.

For this case study, a simple value chain has been produced. This centres on the following steps.

- Foundational activities for seasonal prediction of the NAO;
- Generation of the prediction;
- Accuracy of the prediction;
- Communication of the prediction to end-users (targeted);
- Use of the information;
- Effectiveness of actions.

These value chain steps are described in further detail in our companion report: Methodology for monitoring and valuing climate services' in Deliverable 2 of the contract 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services'. In this case study context it is clear from the discussion in Step 1 that the weather service user will be looking to achieve the ultimate objective of reducing transport passenger/user disruption by better targeting the provision of its' own services (e.g. de-icing services for British Airways, road salting for local authorities) so that its service costs are reduced.

Step 3: Selection of method(s)

The next step is to select the method(s) for the analysis of benefits of improved weather forecasting systems. Several methods have been used for use in Socio-Economic Benefit (SEB) studies of weather and climate information services. These are outlined in the box below. They are described in detail in the report: Methodology for Valuing and Monitoring Climate Variability: Deliverable 2 of the contract 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services'. It should be highlighted that these methods are closely related to each other and may have inter-dependencies. For example, models based on parameterising the observed relationships between changes in climatic/weather variables and direct impacts include Cost-Loss models and Impact Assessment models and make use of Statistical and Econometric analytical methods to quantify these parameters. In turn, the value of such (avoided) impacts is gauged by observed associated costs (cost-loss models) or by surveying those stakeholder groups that have been, or are likely to be, affected by the identified impacts.

Ex ante models

Decision-theory based models that can be applied to estimate potential benefits, for example, using a crop model to assess the possible increases in yield from improved seasonal forecasts. Ex ante models use established relationships between key variables, e.g. precipitation and crop yield, in conjunction with decision models to predict how new information such as on the likelihood of occurrence of anomalous rainfall events will affect the decisions of economic agents and subsequently affect yields.

Integrated economic models

Models that can quantify aggregate effects of changes in one sector or market on others, and include cross-economy, or cross-sectoral, linkages that use, for example, input-output matrices, trade models, and partial or computable general equilibrium economic models.

Cost-loss models

Models used to quantify the effects of extreme weather events and the effectiveness of averting measures such as Early Warning Systems (EWS). These include probability loss curves based on historical event information (e.g. the relationship between flood events of different magnitudes and the economic losses associates with these) that can be extended to look at non-monetary effects e.g. fatalities.

Ex ante surveys

This approach uses survey-based elicitation of individuals' preferences, to assess their willingness to pay (WTP) for potential new services e.g. sailors' WTP to have an enhanced 3-day shipping forecast.

Ex post surveys

These directly survey users to explore actual (or perceived) benefits from climate services following their experience of utilising a given short- or long-term service.

Statistical and econometric analysis

These use statistical analysis (*ex post*) to assess impact/outcomes from the introduction of W&CI services, controlling for other variables to attribute benefits. For example, such analysis may quantify the relationship between winter flood events and the number and/or value of insurance claims. Alternatively, such analysis can quantify the preferences of individuals for a given service (e.g. a customised) weather app by recording their expenditure on the weather app. This latter technique is known as the *Revealed Preference method*.

Impact assessments

These undertake direct measurement of service impact on a group or area, before and after, or relative to a control, e.g. using agriculture field plots to identify differences in crop yields as a result of a change in management practices informed by the climate service, and are complementary to statistical and econometric analysis.

Value (Benefit) transfer

This method takes estimates of benefits developed in one context and applies them in another, rather than undertaking primary studies, adjusting for context where possible. Such a transfer process can be undertaken with findings from studies that use any of the benefit methods outlined in this box.

The selection of method depends on two issues:

- The type of W&CI service and the suitability of various methods to make estimates of benefits.
- The capacity, level of expertise, time and resources (including data) available for the SEB analysis.

For seasonal forecasts, the report: Methodology for Valuing and Monitoring Climate Variability: Deliverable 2 of the contract 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services' sets out the potential methods and the ways in which these two constraints relate to each is summarised in Table 3. An indicative ranking of the overall resource/expertise requirements – Low, Medium and/or High - is provided.

Table 3 Potential methods and applications for seasonal forecasting valuation

	Description of Method	**Resource & Expertise Needs. Limitations.**
Seasonal forecasts	Ex ante Surveys of willingness to pay for new or improved services. For example, a survey of airline operational managers at UK airports of their WTP for an enhanced seasonal forecast and attendant benefits.	High. Cost of survey and analysis. High level of expertise involved. Hypothetical survey context may lead to over-bidding WTP.
	Revealed preference studies, e.g. averting behaviour. For example, additional expenditures made to fly from less frost-prone airports.	Medium to high. Cost of studies and analysis. High level of expertise involved. Difficult to isolate weather-related effects from other influences on expenditure decisions.
	Ex post Survey/questionnaire of likely beneficiaries (ex post). For example, a survey of airline operational managers at UK airports of their WTP for an enhanced seasonal forecast and attendant benefits, following a cold winter.	Medium. Cost of survey and processing results but can be included in the baseline and end-line survey. Low -medium expertise required. May be difficult for survey respondents to isolate effects of weather-related events from other events that had similar effects.
	Ex ante Modelling of impacts from seasonal variations. For example, decision modelling of road salt investment with and without an enhanced seasonal forecasting.	Medium to high. Time spent on developing model and data analysis of results. High expertise required. Behavioural decision rules sensitive to modeller's assumptions.
	Integrated Economic modelling suitable for larger scale change, e.g. computable general equilibrium modelling. For example, regional input-output may quantify effects of closure of major roads due to snowfall.	High. Time spent on developing model and data analysis of results. High expertise required. Aggregated outputs/results may not be appropriate to local-scale analysis.
	Impact assessments, e.g. pilot studies to allow measurement of benefits. For example, time and accident benefits resulting from enabling action to reduce road snow & ice inform overall benefit assessment.	Medium to high. Development and analysis of pilot studies and results data. Medium – high expertise required. May depend on decision context arising and impact data being recorded and made available.
	Statistical and Econometric analysis (*ex post*), e.g. quantification of income benefits of improved weather forecasting on basis of regression analysis of data. For example, statistical analysis of the relationship between historical incidents of winter weather events and rail disruption inform quantification.	High. Time spent on developing econometric analysis and data analysis of results. High expertise required. Depends on decision context having arisen and impact data having been recorded and made available

	Value Transfer of results from a previous study to a new decision context. For example, use of travel time values estimated by DfT in surveys can be transferred to the rail delay context.	Low to Medium. As long as data is available from another application the main challenge is to transfer in an appropriate and defensible way, which requires some expertise. Transfer from original study context to current decision context introduces uncertainties that limit accuracy of resulting estimates.

We have used a combination of existing impact assessment-based modelling (from Palin et al. [2016]) and benefit transfer of appropriate economic unit values (i.e. transfer of values derived in previous studies but judged to be suitable for use in the current context)– use of the latter data reflecting limited time available. It is useful to highlight the importance of data availability in undertaking analyses of this sort. In undertaking Step 4, for instance, it is apparent that a number of the data-sets are specific to organisations that have no remit to publish all relevant data. This is particularly applicable to the data relating to impact quantification which was supplied directly to Met. Office staff from client- or collaborating organisations in a number of instances. Additionally, it is the case that the data time series is often not sufficiently long to gain statistical robustness in the impact analysis. It is therefore suggested that a future research or operational priority should be to encourage potential forecast users to establish protocols for collection of principal weather impact data-sets.

Step 4: Build a Baseline Scenario

In order to estimate the baseline cost (i.e. losses due to weather-related risks without additional mitigating or adapting action)) we need to measure the 'severity' of a winter season and relate this to observed/known costs. We can do this using the NAO index. This case study therefore estimates baseline impact costs (i.e., without a seasonal forecast service in place) through the following four tasks: necessary to derive quantitative estimates:

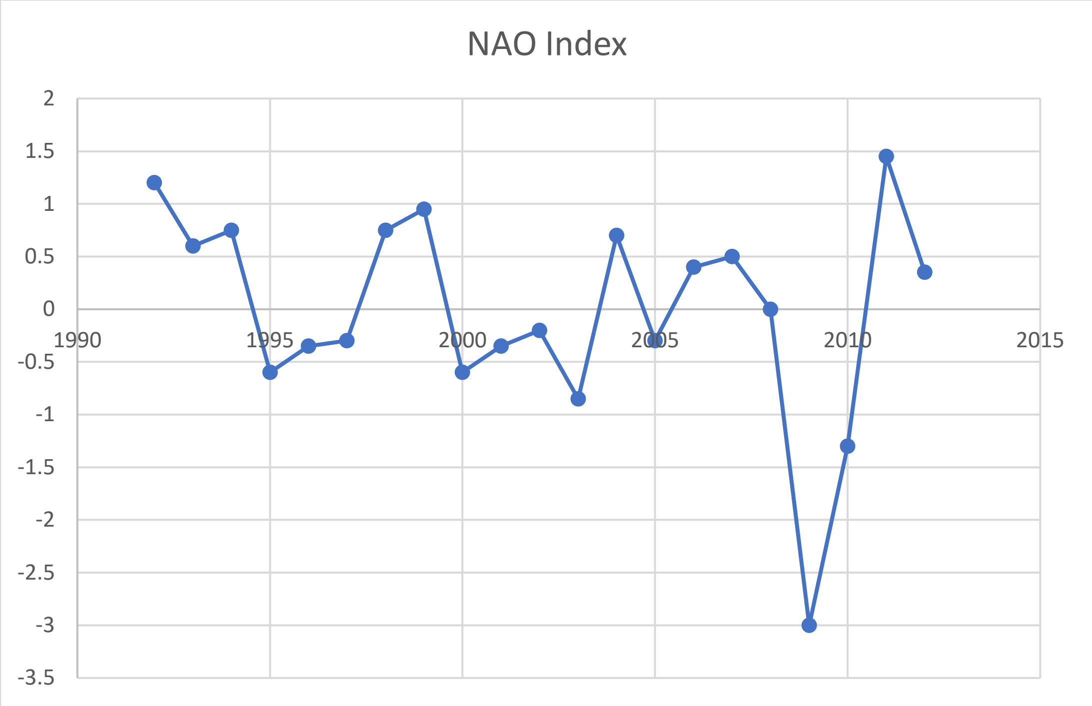
- Characterise the type of winter by the NAO index category (i.e., positive, average, negative);
- Establish the NAO index – cost relationship;
- Estimate the cost by type of winter and modes of transport.
- Calculate winter type frequency and cost of events.

Step 4.1: Characterise the type of winter[16] in terms of the NAO index level

The NAO index is quantified by the normalized difference in mean sea level pressure between Iceland and the Azores. The observed NAO index data for the period, 1992/1993 winter seasons to 2011/2012 winter seasons is presented in Figure 1 and is consistent with the time-series presented in Palin et al. (2016). A positive NAO index is linked with warmer, wetter, stormier conditions whilst a negative NAO index is linked with calmer, drier, and colder conditions. The 2009/10 and 2010/11 winters had significantly negative NAO index values, hence a high likelihood of colder weather, whereas 1992/3, 1999/2000 and 2011/2012 winters had relatively high positive NAO index values and therefore more likely to be warmer and wetter than average.

[16] Winter is understood here to be December, January and February – following Palin et al. (2016)

Figure 1 Winter NAO Index values observed over the time period, 1992 – 2011.



Source: Derived from Palin et al. (2016)

In our analysis we assume that winters can be characterised as warm/wet/windy or cold/dry/calm when values of the NAO index are >0.8 or <-0.8, respectively y. This characterisation is used to simulate the way in which we might expect a seasonal weather forecaster provider to communicate the principal features of a winter forecast. Thus, it is a simple way of translating the numerical NAO index value to the predominant expected seasonal weather conditions. The threshold values of >0.8 and <-0.8 used to characterise wet/warm/stormy and calm/cold winters, respectively, are based on their characterisation as ≈1:10 year events informed by a qualitative assessment of the associated impacts, in the absence of alternative guidance; the values could be adjusted to be higher or lower according to the preferences of the forecast provider and/or the user to specify a narrower and/or more extreme set of conditions.

Step 4.2: Establish the NAO index – cost relationship

The next task is to identify the costs associated with the types of seasonal weather characterised through use of the NAO index. We estimate weather impact costs on the basis of historical observations. Specifically, we utilise data on recorded NAO index values (see Figure 1) and combine these with the costs associated with impacts on transport reported for the corresponding winter periods. The transport impacts that we quantify were previously identified by Palin et al. (2016) from financial and economic welfare-based monetary data. The latter category is important since some of the impacts that are identified are likely to have effects on individuals' welfare but are not necessarily expressed in market prices. We therefore make estimates of the welfare costs rather than market price-based financial costs. These are summarised below in Table 4. Data sources are given in Step 4.3. Note that the financial costs are effectively the costs incurred by an organisation when trying to mitigate the welfare costs.

Table 4 Transport-related Impact Costs associated with Winter Weather

Transport impact	Welfare impact	Averting action & cost
Aviation		
Delays in flights	Increase Travel time costs * no. of passengers affected	De-icing resource cost
Number of flights de-iced	Reduction in travel time delay	
Road		
Attributed % of winter accidents	Increase Travel time costs * no. of individuals affected	Salt use resource cost
Road salt usage	Reduction in number of accidents	
Rail		
Number of incidents (trains delayed)	Increase Travel time costs * no. of individuals affected	De-icing resource cost

Step 4.3: Cost by type of winter and modes of transport

The cost components identified in Table 4 above are estimated for the three types of winter characterised by high NAO index, low NAO index, or central NAO values. These cost estimates are made by calculating the average impact costs for the individual winters mapped against the three types in Table 5. This is based on 19 years of data, as provided in Palin et al. (2016); as a consequence there are only a small number of observations available – two each – for the winter types characterised in the two extremes of the NAO index values. Consequently, the resulting average cost estimates are not statistically robust and should be treated as indicative. A statistically robust analysis would look to use a time series of > 30 years

Table 5 Observed NAO Index – Winter Mapping for winters 1992/92-2011/12

NAO Index value	Winters
>0.8	1992/93; 1999/2000; 2011/12
>-0.8<0.8	1993/4; 1994/5; 1995/6; 1996/7; 1997/8; 1998/9; 2000/1; 2001/2; 2002/3; 2004/5
<-0.8	2003/4; 2009/10; 2010/11

Source: Derived from Palin et al. (2016)

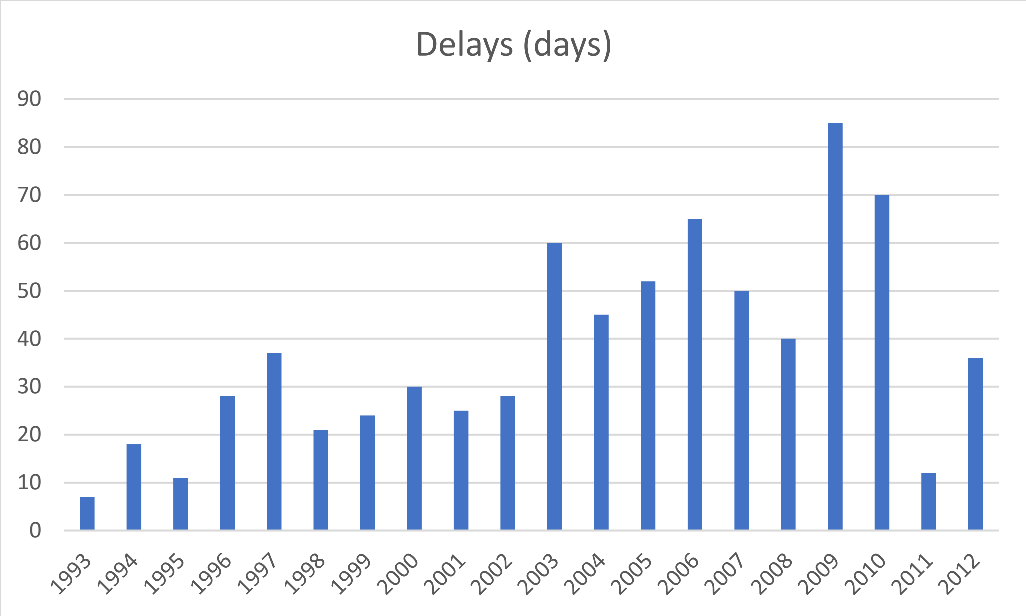
The study has then built up the baseline analysis by mode below.

Data – Air Transport

In the first instance, we are looking to estimate the cost of delayed flights associated with winter weather events. We utilise a value of £1.18/minute/passenger, derived from US data (Gayle and Yimga, 2018). A lower-bound value of £0.40/minute/passenger given in the DfT WebTag guidance for rail delay time can also be used for comparison. These two values are used to derive the high and low total cost estimates in Table 6. (By way of validation of these unit values it should be noted that the current rate of compensation to passengers for flights delayed for more than three hours equates to £1.22/minute/passenger).

Our analysis is further restricted to flight delays experienced by British Airways (BA) flights from London Heathrow Airport[17]. Flight time delay data for the same 20-year time period as in Palin et al. (2016), originally supplied to the authors by BA, is presented as the total number of days of delays suffered by the BA fleet at LHR each winter as a result of weather conditions (Figure 2). We convert these data from days to minutes, and from numbers of flights to passengers. Based on the seat capacity of the typical BA aircraft we assume that each flight has on average of 300 passengers[18]. The analysis is centred on British Airways as an example of a potential user of enhanced weather forecasting services. Scaling up these estimates to an airport scale or a regional or national scale would require delay data for all other airlines and airport locations.

Figure 2. Total number of weather-induced delays (days) to BA flights at LHR (1993-2012)



In order to generate total average costs for the three winter weather types, we find the average annual delays for the three NAO modes and corresponding winters presented in Table 5 above. We then multiply the average annual delay data by the passenger-minute values to produce the estimates of total costs. These results are presented below in Table 6.

Table 6 Winter Delays & Welfare Costs – by Winter Type: BA Flights at LHR (£m)

NAO Index Values	**<-0.8**	**>-0.8<0.8**	**>0.8**
Winter Characterisation	Cold, Dry,Calm	Average	Warm, Wet, Windy
Flight delay – minutes	0.1	0.05	0.03
Passenger delay – minutes	31	14	8
Total Delay Costs per year - high	**37**	**17**	**9**
Total Delay Costs per year - low	**15**	**7**	**4**

It is clear from Table 6 that the total annual costs are lower than average for the mild, wet and windy winter type (approximately 45%) and higher than average for the cold, calm winter type

[17] Owing to lack of quantitative data, other costs that may be associated with icy conditions (e.g. salting of access roads and car parks are not included in our analysis.
[18] https://www.britishairways.com/en-gb/information/about-ba/fleet-facts

(approximately 220%). The large quantity of delays in cold, dry, and calm winters reflect the fact that snow and ice present the most dangerous hazard to flight safety. A likely corollary of this fact is that more effort is expected to be needed in the form of de-icing aircraft as a result of cold conditions. Data on the number of BA planes needing to be de-iced each winter is derived from Palin et al. (2016) and presented in Figure 3. It suggests a significant, positive, relationship between the delay times reported in Figure 2 and the scale of de-icing required.

Figure 3. Number of BA Aircraft De-Iced at London Heathrow (1993-2012)

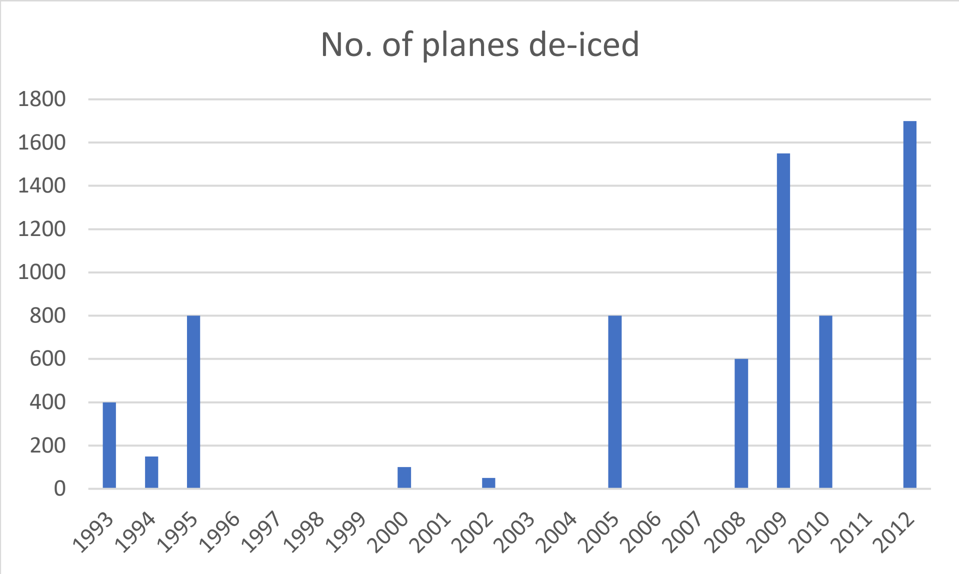


Table 7 presents the summary data for the numbers of planes de-iced, and associated costs, according to the three NAO modes. It shows that in the winters characterised as being mild, wet and/or windy in the 20-year period being considered, no planes needed de-icing. This compares with a mean of 171 planes per year in an Average winter NAO and mean of 783 planes per year in the cold, dry, calm winter NAO – the pattern conforming to our expectations. Anecdotally, the cost of de-icing a plane costs at least £5000, and up to £10,000. Adopting this unit cost, the costs are then found to range from zero to £7.8 million for the mild and cold winter types, (high de-icing cost) respectively.

Table 7: Number and cost of Planes De-Iced – by Winter Type: BA Flights at LHR (£m)

NAO Index Values	**<-0.8**	**>-0.8<0.8**	**>0.8**
Winter Characterisation	Cold, Dry, Calm	Average	Warm, Wet, Windy
Planes De-Iced	783	171	0
Cost of De-Icing – low (£/annum)	**4**	**1**	**0**
Cost of De-Icing – high (£/annum)	**8**	**2**	**0**

Data – Road

Data on the percentage of winter road accidents caused by either cold, dry and calm weather or warm, wet and windy weather is taken from Palin et al. (2016) for the 20-year period, 1993-2012. These data are presented in Figure 4 which highlights a pattern of variability that is most striking in the pattern for snowy winters. We then convert this into the actual number of weather-related accidents in each winter using accident data compiled by Department for Transport. This data-set also provides a breakdown of injuries – severe and slight, as well as fatal - that were associated with the accidents. These estimates of the number of injuries are then converted into economic costs by applying the unit values for different injury severities given in the Department for Transport WebTag guidance on economic appraisal. The relevant unit values are: Fatality – £2,028,837; Serious Injury - £226,558; Slight Injury - £17,428. Total annual costs are presented in Figure 5 which shows that the highest injury costs are associated with the cold/dry/calm winters, 1995-1996 and 2009-2010. Figure 6 presents illustrative costs associated with time delays associated with winter weather-related accidents. Based on the DfT database, these assume that, on average, an accident results in the delay of one thousand people for 10 minutes. Time delay unit values are taken from the DfT WebTag guidance. Whilst they are much lower in scale than injury costs they mirror the pattern of these costs over the time period.

Figure 4. Percentages of Winter Accidents associated with weather events (1992-2011)

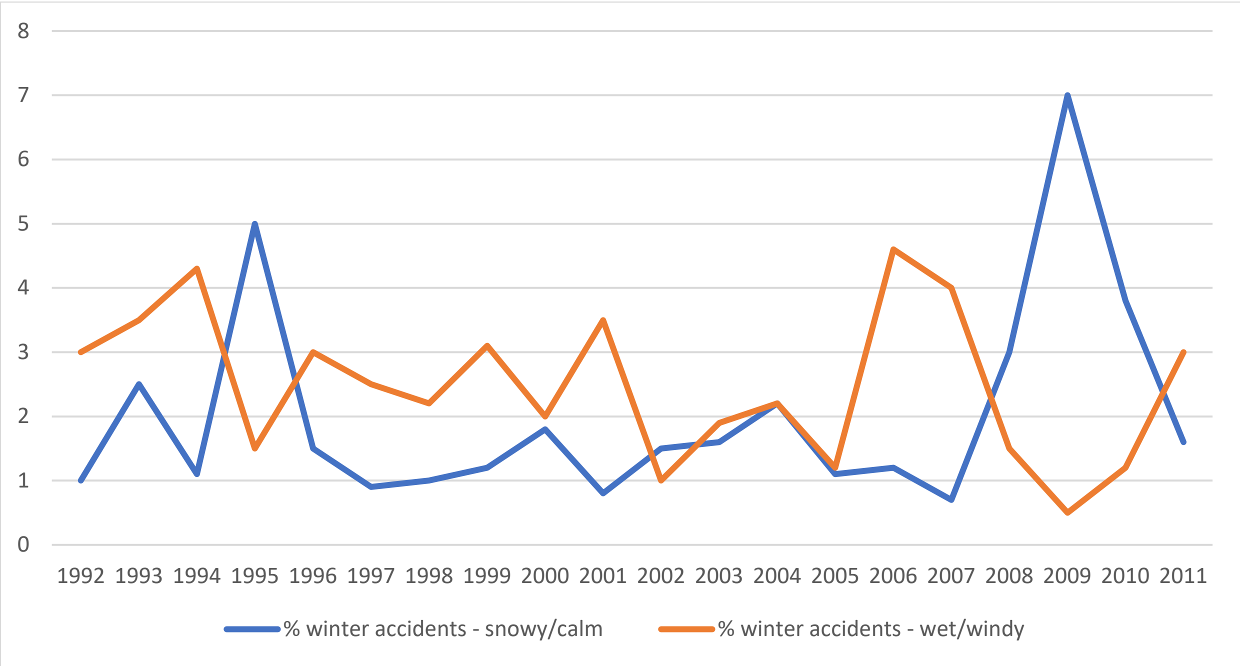


Figure 5. Costs associated with Winter Weather Event Types (£)

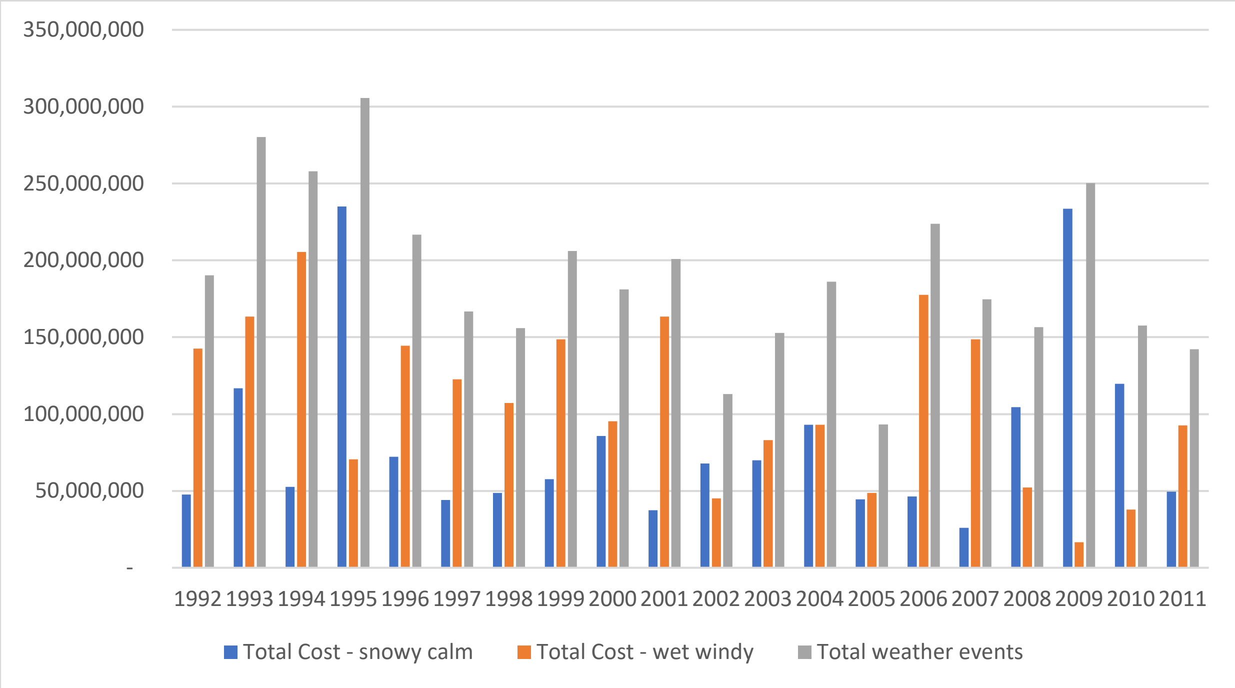
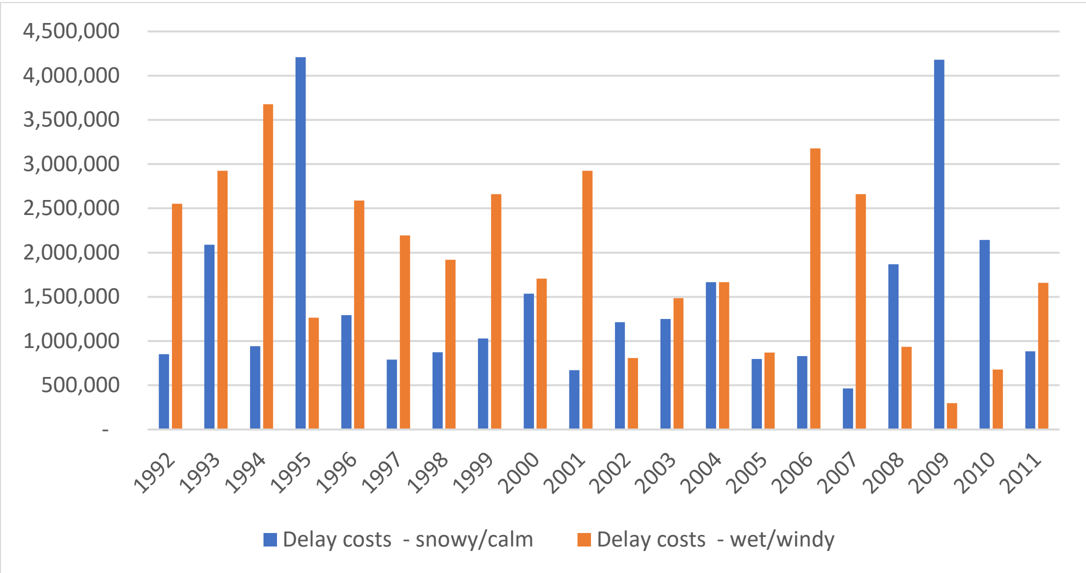


Figure 6. Time Delay Costs from Winter Weather Event Types (£)



Road-salt usage data across motorways and major trunk roads in England are derived from Palin et al. (2016) for the period, 2003-2012. We estimate the total costs by applying a value of £35/tonne – the central estimate given by the Local Government Association[19]. (Note that these costs do not include the operational costs of applying the salt to road surfaces since this data was not available). These total costs are presented in Figure 7, below. It shows that in the winter – 2009/2010 - where these costs are highest is when the observed NAO index is highest.

[19] https://www.local.gov.uk/your-winter-weather-questions-answered-0

Figure 7. Total Road Salt costs in England (2003-2011) (£)

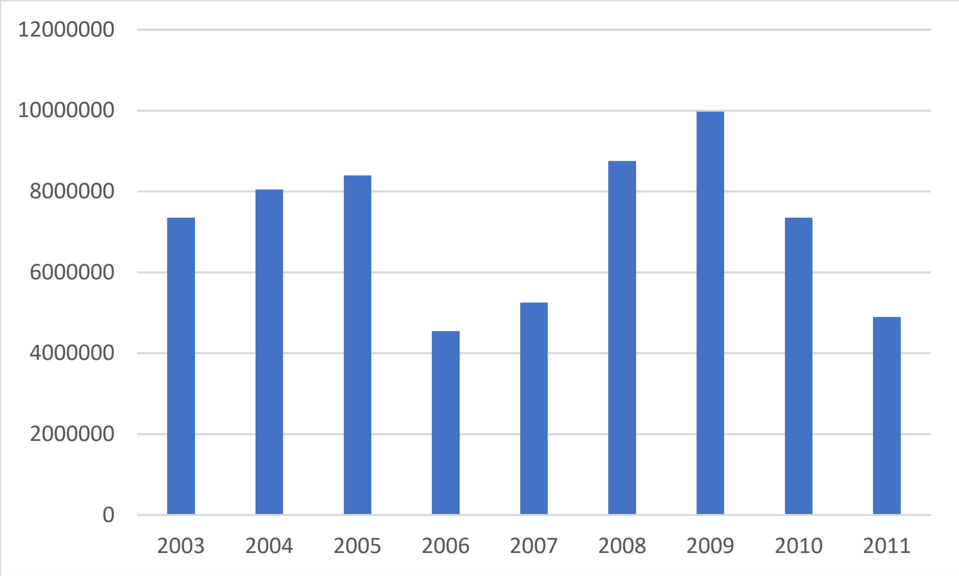


Table 8 presents a summary of the road accident and salting costs associated with the winter characterisations and NAO index values. As we would expect, costs resulting from road accidents in warm, wet and windy conditions are highest in winters characterised by a high NAO Index value whilst costs resulting from road accidents in cold, dry and calm conditions are highest in winters characterised by a low NAO Index value. Whilst the costs associated with salting roads are lower, on average, for winters characterised as warm, wet and windy, the costs associated with average and cold conditions are not discernibly different from each other; indeed, they are slightly higher for the average winter. This latter finding may be the consequence of having a more limited data time series than that for accidents – though it may also reflect other factors such as repeat salting after wet-cold-wet weather sequences, or changes in local authority budgets/rules for when/where salt is applied. This finding does serve to emphasise the data constraints that currently limit the robustness of our quantitative analysis.

Table 8 Accident and Salting Costs for alternative winter types (£m)

NAO Index Values	**<-0.8**	**>-0.8<0.8**	**>0.8**
Winter Characterisation	Cold, Dry, Calm	Average	Warm, Wet, Windy
Accidents in warm/wet/windy weather	46	117	128
Accidents in cold/dry/calm weather	141	77	52
Total Accident-Related Costs	**187**	**194**	**179**
Road Salt Costs	7	7	5
Overall Total	194	201	184

Data – Rail

In order to provide first order estimates of costs associated with rail incidents caused by winter weather events we use data from Palin et al. (2016). These data includes the number of winter rail incidents in Great Britain between 2004 and 2012, inclusive, judged to have resulted from weather-related hazards. Infrastructure-related incidents and train and rolling stock incidents are reported separately. These data were plotted against the observed NAO index data, presented in Figure 1.

We understand that the principal effect of rail incidents on human welfare relates to delays; people would prefer to arrive at a destination at the expected time rather than being delayed. In order to express these welfare effects in monetary terms we convert the numbers of incidents to time delay-equivalents. The following assumptions are therefore adopted, based on Network Rail data and other sources:

- All incident delay costs relate to passenger time as no data on freight costs were identified;
- Average delay per incident equals 15 minutes;
- Average number of people delayed per train equals 300;
- Unit values (£ per hour): Commuter (14); Work (40); Leisure (6) – taken from WebTag guidance;
- Proportion of journeys by purpose – from DfT Williams Rail Review 2019.

By combining these data with the rail incident data we are able to calculate the monetary value of rail passenger delays resulting from winter weather events in Great Britain. Annual aggregate values for the nine-year period are presented in Figure 8, whilst values are disaggregated according to the winter NAO mode in Table 9. The results show a spike in costs in the winters of 2009/10 and 2010/11. In fact, 2009/10 and 2010/11 are the only winters in the period which have an observed winter NAO index of less than -0.8, denoting a cold, dry and calm winter. Compared to the aggregate costs for winters characterised as average, warm, wet and stormy winters are found to have costs of about 90% whereas cold, dry and calm winters have costs of almost 400% of average.

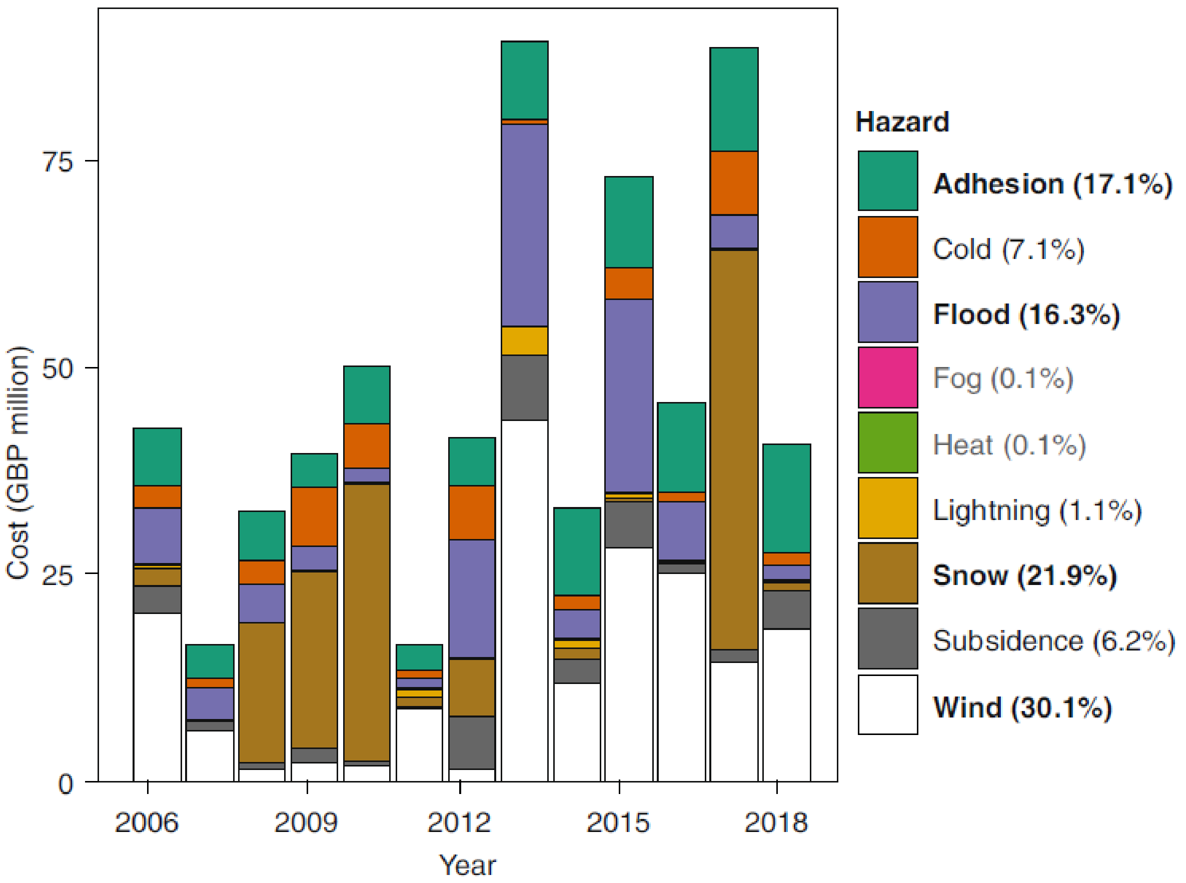
Figure 8. Welfare costs of winter weather-induced rail incidents: Great Britain (2004-2012)

Table 9 Rail incident Costs for Alternative Winter Types (£m): Great Britain (2004-2012)

NAO Index Values	<-0.8	>-0.8<0.8	>0.8
Winter Characterisation	Cold, Dry, Calm	Average	Warm, Wet, Windy
Infrastructure-related	5	1	1.3
Train & Rolling stock	1	0.1	0.04
Total Incident costs	**6**	**1.1**	**1.3**

There are also data on service costs delays by the Rail sector (as part of the schedule 8 costs), which break down costs by weather events, including the costs of service disruption (Network Rail, 2017). These attribute delays to a much wider range of different weather-related events than we consider – see Figure 9. However, the aggregate results appear to broadly corroborate the scale and pattern of our cost estimates. This also shows the peak in cold related disruption in 2009/2010, 2011/2012 and 2017/18, as well as the high costs from snow related disruption in these years.

Figure 9. Weather Hazard related costs to the UK Rail Network



Source: Hillier et al. (2020)

Step 4.4: Calculate winter type frequency and cost of events

The final task is to calculate the frequencies and associated probabilities of the three winter types characterised by the NAO index. For the period 1980-2012, these data are presented in Table 7, below. The record in Table 10 covers a longer period than available for the transport impact data utilised in the analysis above but is useful for deriving historic likelihoods since the larger sample increase statistical robustness. Based on the thresholds used herein about three-quarters of winters are characterised as average, whereas 15% are wet/windy, and just under 10% are cold/calm.

Table 10 Observed NAO Frequencies (1980-2012)

	Frequency	Prob. (%)
<-0.8	3	9
>-0.8<0.8	25	76
>0.8	5	15

Source: Derived from Palin et al. (2016)

These likelihoods are used to estimate baseline costs (without the seasonal forecast). These costs are the average annual costs over the historical period for which there are data.[20] These average costs – also known as expected costs (EC) - are calculated as the costs of a wet/windy winter multiplied by the probability of this winter type (pC_w) plus the costs of a cold/dry/calm winter multiplied by the probability of this winter type (pC_c) plus the costs of an average winter multiplied by the probability of this winter type (pC_a).

$EC = pC_w + pC_c + pC_a$

The expected costs for each of the impacts considered here are presented in the second-to-right column in Table 11. Given that the likelihood of the average winter type is 0.76, it is not surprising that the expected costs are similar to those for this winter type.

Table 11 Annual Costs for Winter Types (£m): Impact Summary

	NAO Index Winter Type	<-0.8 Cold, Dry, Calm	>-0.8<0.8 Average	>0.8 Warm, Wet, Windy	Expected Costs	Cost Deviation in cold winter
	Winter probs.	0.09	0.76	0.15		
BA Flights	Total Delay Costs per year - average	26	12	6	12	14
BA Flights	Cost of De-Icing – average	6	1	0	1	4
Road	Total Accident-Related Costs	187	194	179	189	- 2
Road	Road Salt Costs	7	7	4.9	7	0.3
Rail	Total Incident costs	6	1	1.3	2	4
Total Impact Costs		**232**	**215**	**192**	**211**	**20**

[20] Note that our method of estimating baseline costs assumes that time-series data exists and that organisations use the average of this time-series data rather than an alternative, potentially more accessible, benchmark such as the previous winter's costs.

Step 5: Assessment of Benefits of a Seasonal Forecast Service

The next step is to assess the economic benefits – the reduction in the costs quantified above, from the seasonal forecast. This needs to assess the potential flow of information along the value chain, and its use by end users in reducing the costs presented in Table 10[21]..

In the instance where the NAO index allows the type of winter weather to be forecast correctly in every year, the end-user using the forecast information is able to calibrate their response precisely. Thus, years in which impact costs are expected to deviate from average impact costs will be known with certainty. The size of this deviation is taken here to be the difference between the statistical average of impact costs over the time series and the winter type that has the highest impact costs for the impacts considered. These deviations can be identified from the summary data presented in the furthest right column of Table 12. For these impacts, it is generally the cold, calm winter type that has the highest associated costs; the exception to this is the case of road accident delay costs where those in the average winter are found to be highest. It should be noted that whilst the cold, calm winter is estimated to occur with a frequency of less than 1 in every 10 years, the reputational and other non-financial risks associated with these impacts may be more significant.

The impact cost deviations highlighted in the final column of Table 10 can be interpreted as the costs of not having a seasonal winter weather forecast; no extra averting measures to avoid these costs are taken. Equivalently, the cost deviation indicates the cost that may be associated with acting incorrectly relative to the actual type of prevailing weather.[22] Conversely, if the forecast NAO index exactly matches the observed NAO index then the cost deviations associated with delays can be interpreted as the potential gross benefits of having a seasonal winter weather forecast. However, this assumes the perfect flow of information along the value chain, as well as perfect uptake and use, and assumes effectiveness of end-user decisions.

However, there are large efficiency losses (or decay) along a W&CI value chain (Perrels., et al 2013;), which lead to much lower actual benefits than potential (theoretical maximum) benefits. For example, if a service has a low level of reach (e.g., due to communication not reaching end-users), then the economic benefits will be low, as there is a smaller number of users. Similarly, if a large number of users who receive the information do not act on it (or do not act effectively), the level of benefits achieved will be lower than the potential benefits. Therefore, in order to provide a realistic estimation of benefits of W&CI services, the efficiency losses along the value chain need to be assessed.

The <u>first efficiency loss</u> is associated with the accuracy of the forecast. Palin et al. (2016) explore the extent to which the GloSea5-based forecasts of the NAO index perform against the observed NAO index. Specifically, when the forecast NAO index data is regressed against the observed NAO index data the correlation coefficient (R^2) value is found to be 0.62. This value does not directly translate to the probability of the forecast being correct. However, in the absence of this data we use this value as an indication of the likely frequency of getting the NAO category right or wrong. Thus, in this case the forecast is found to be correct 62% of the time. Adopting the assumption that the resulting benefits of the forecast are proportional to the instances in which the forecast is correct, we estimate these benefits in Table 12.

[21] Note that the costs estimated are indicative and subject to the multiple constraints and caveats mentioned in the text.
[22] Note that alternative measures of the cost of acting incorrectly can be estimated by the differences between the total costs in the middle three columns in Table 11.

Table 12 Estimates of Benefits of the seasonal prediction, for perfect forecast, and adjusted for accuracy (£m).

	NAO Index Winter Type	Cost Deviation in cold/dry/calm winter	Correctly Forecast Benefits
	Winter probs.		
BA Flights	Delay Costs per year - average	14	8
BA Flights	Cost of De-Icing – average	4	3
Road	Accident-Related Costs	2	1
Road	Road Salt Costs	0.3	0.2
Rail	Incident costs	4	3
Total		20	15

There is a question of whether there are any costs associated with the incorrect forecasts, i.e. for the 38% of the time when the forecast is incorrect. This will further reduce the effectiveness of the benefits if users act for predicted winter regimes that do not subsequently happen. This is related to the phenomenon of risk aversion and attitudes to risk more generally. For example, there is some anecdotal evidence that end-users use the information they receive in slightly different ways, depending on the nature of the forecast, i.e. there is asymmetry to its use. This has been found through user interactions and cost-loss matrices. Some users appear to focus on minimising regrets (specifically minimising downside risk), so that if a prediction is colder than normal they will act. For example, they may buy additional road salt to ensure supply for a cold/dry/calm winter. However, if a warmer than average winter is predicted, they do not reduce road salt purchase, but buy enough for a normal winter.

The <u>second efficiency loss</u> results from the effectiveness of communication and reach of the seasonal forecast. In the study context, a tailored service is provided to transport operators. The forecast is presented in a way that offers direct usable information to relevant end-users, including impact forecasts and climate information. Therefore, as well as the general information on the NAO index and prediction, relevant information is included to help communicate the potential impact on end-users, and thus encourage uptake and action. The impact forecasts for particular UK transport impacts are created by combining information from the seasonal weather forecast for contingency planners and existing impact data. The forecasts therefore focus on anticipated winter transport impacts rather than meteorological conditions thereby presenting information about the chances of the winter impact being higher than typical. At the request of Met Office, the template that is used is not shown in this report. Note that our analysis here in this study builds on this impact-based approach, but extends to valuation, including societal values.

The communication method for the forecast also targets end-users directly. It is shared with key operators through a Department for Transport stakeholder group. Hence, there is a direct line of communication through to end-users, and additional context and information is presented through the group to maximise the understanding of the predictions.

There are no data available on how this tailored information, the direct stakeholder group, and the use of impact based seasonal prediction affects uptake and action, or about the level of efficiency loss that results from the prediction through to end-use. However, we consider that this more focused approach is likely to lead to a higher level of uptake and use than a typical meteorological based seasonal forecast. For illustrative purposes we assume a 75% efficiency for this step, i.e. 75% of relevant end-users use the information. Further work to establish the likely efficiency drop-off for this step would be useful and could be obtained through a survey of DfT stakeholders.

The efficiency loss for this step is combined with the 62% accuracy forecast above. In Table 13 it can then be seen that this lowers the benefits quite considerably, as compared to the perfect use of information, even for these two steps (the 62% accuracy combined with 75% use yields more than a 50% reduction).

Table 13 Estimates of Benefits of the prediction, adjusted for accuracy and uptake (£m).

	NAO Index Winter Type	Correctly Forecast Benefits	And adjusting for likely uptake and use (assumed 75%)
	Winter probs.		
BA Flights	Delay Costs per year – average	8	6
BA Flights	Cost of De-Icing – average	3	2
Road	Accident-Related Costs	1	1
Road	Road Salt Costs	0.2	0.1
Rail	Incident costs	3	2
Total		15	11

The <u>final efficiency steps</u> are to assess the effectiveness of the decisions taken, by end-users, i.e. do they use the information effectively, and how much does this reduce the impacts, noting that it is very unlikely that action will reduce all potential winter impacts to zero. For example, applying road salt will reduce winter related accidents, but it will not eliminate them.

There is no information on the effectiveness of the actions that users take. In the absence of further information, we assume for illustrative purposes that effectiveness is 75% and present the results in Table 14.

Table 14 Estimates of Benefits of the prediction, adjusted for accuracy, uptake and effectiveness (£m).

	NAO Index Winter Type	Adjusted for effectiveness
	Winter probs.	
BA Flights	Delay Costs per year - average	5
BA Flights	Cost of De-Icing – average	2
Road	Accident-Related Costs	1
Road	Road Salt Costs	0.1
Rail	Incident costs	1
Total		9

Step 6: Assess the costs of the project developing the climate service

Information on benefits can be combined with information on costs to answer the question of 'how do the costs of the service compare with the benefits of the service?'

From the perspective of the Met Office as provider of the seasonal weather forecasting service, decisions regarding investment into the service – and associated investments e.g. in super-computers - will be informed by the costs of provision. These costs include all activities associated with the set-up and running of the service. This includes recurrent/operating costs associated with staff salaries, modelling and forecasting, and maintenance, etc. These costs are complicated to estimate since the service also includes shared costs with other Met Office activities. Moreover, the seasonal prediction system is used for multiple sectors additional to transport and thus there is an issue of how to allocate the costs of the prediction to different sectors. Discussions were held with the Met Office about the service cost, i.e. the operating costs of the prediction and the delivery of the forecast. This was considered commercially confidential, and it was not possible for Met Office to share this information.

Step 7: Compare benefits against service costs

Step 6 reports that it was not possible to quantify costs for the service. Thus, Step 7 – required in an economic appraisal – is not possible to undertake in this instance. Given the potential scale of benefits above, however, even with efficiency losses we consider it likely that the service would pass a cost-benefit test, especially as prediction service costs would be shared between various sectors, and the marginal costs associated with the transport climate service would be modest.

It should also be noted that each user – in this case the various transport operators – will have fee costs associated with receipt of the forecast service and its use. It is assumed that – formally or informally – these costs are weighed against the perceived benefits of the service. Whilst we identify both financial and non-market benefits in the above, it may be that these transport operators focus on the financial benefits only. In the contexts above, however, it is likely that non-market benefits will be reflected indirectly in terms of reputation as transport delays are reduced.

Step 8: Undertake sensitivity and bias analysis, then review how benefits could be enhanced.

In the absence of service cost data there is no sense in undertaking a sensitivity analysis of cost-benefit analysis. However, it should be noted that were such a Cost-Benefit Analysis (CBA) to be possible we would explore how the uncertainties in the baseline assessment (Step 4) could be tested through the adoption of a range of benefit estimates. Whilst the uncertainty attached to the de-icing costs is explored in Step 4 through the adoption of low and high unit costs and used in the benefit assessment other cost categories exist to which uncertainty is also attached. These include assumptions surrounding specification of NAO-Winter type characterisation, and delay length and number of people affected by road incidents.

Decisions relating to the use of seasonal forecasts by organisations such as – in this case study - British Airways and the Local Government Association, will be dependent on making defensible projections of future impact costs, and the benefits that would result from the reduction of these impact costs. In the most basis analysis, the average potential benefits estimated in Step 5 can be extrapolated. These extrapolations would need to be augmented by data on projected numbers of users of transport modes. Relevant data may be found at: https://www.ukri.org/wp-content/uploads/2022/01/IUK-110122-UK-Transport-Vision-2050.pdf

Conclusions

This case study utilises an 8-step approach to the economic appraisal of a seasonal weather forecasting service – in this case the GloSea5 seasonal prediction system to predict the winter North Atlantic Oscillation (NAO). The case study application is focussed on weather impacts on the transport sector (air, road and rail) in the winter season (December – February). The quantification of impacts is informed primarily by the data reported in Palin et al. (2016). The baseline impacts are considered to be equivalent to the maximum benefits that could result. Clearly, however, some costs such as planning costs cannot be avoided. The benefit categories are summarised in Table 15. The baseline impact assessment expresses the quantified impacts using a monetary metric. It should be noted that the monetary measures attempt to capture the strength of preferences that people have regarding the (avoidance of these) impacts. They therefore include values for impacts that do not have purely financial costs but which peoples' broader welfare. In that respect the baseline impact costs represent social costs.

Table 15. Summary of Benefit categories

End-user	Expected benefits
Transport operators	
Heathrow airport and airlines	Reduced flight delays
	Better planning for de-icing operations
Train operators	Reduced service delays
	Reduced rail accidents and incidents
Highways agency and local authorities	Reduced accidents (costs of response)
	Better planning for use of salt
Passengers	
	Reduced travel time losses
	Reduction in risk of accidents, reduced damage
	Reduction in risk of accidents, avoided fatalities and injuries
Freight transport operators	
	Reduced disruption and travel time delays
Wider economy	
Upstream suppliers & other dependent businesses	Local and other economic effects such as planning stock inventories

Key assumptions adopted in our analysis include the following. Based on our judgement we rank them in importance in determining uncertainty in the quantitative estimates, from highest importance to lowest importance:

- The efficiency loss of GloSea5-based forecasts of the NAO index being imperfectly related to the observed NAO index of 38%;
- 75% of relevant end-users use the weather forecast information;
- End-users are 75% effective in their use of the forecast information.
- Maximum potential gross benefits of having a seasonal winter weather forecast arise from a perfect flow of information along the value chain, as well as perfect uptake and use, and perfect effectiveness of end-user decisions;

- Available time-series data on NAO index and transport performance impacts are sufficiently long to generate statistically valid relationships;
- Causation between patterns of winter weather and specific impacts on transport performance;
- Validity of transfer of unit values related to transport impacts from original study to current study;

Whilst these assumptions are required in order to generate quantitative measures of the benefits of improved seasonal weather forecasts they do highlight that there is considerable uncertainty involved in the estimation process. It should be clear, however, that the lack of data observations means that defining upper and lower bounds on that uncertainty, using e.g. confidence intervals, is not currently feasible. Our own judgement is that estimates may be +/- 50%; future research should look to challenge this judgement.

The sensitivity analysis, discussed in qualitative terms in Step 8, above, identifies that the robustness of the analysis is partly dependent on the quality of assumptions that are made. In the case of the characterisation of the types of winter using the NAO index, this case study has limited itself to the data provided in Palin et al. (2016). In a future exercise, the robustness of this characterisation should be tested by utilising a longer time series of NAO data. Future analysis would also look to develop quantitative estimates of the service costs in order to be able to undertake a complete cost-benefit analysis and so comment on the economic justification for the weather service. Such an analysis would incorporate a wider range of potential users (e.g. other airline operators additional to British Airways) and a wider range of impacts. Consequently, the benefits of the seasonal weather forecasting service is likely to be a multiple of the £7 million estimate presented here. Nevertheless, the existing analysis serves to demonstrate that there is currently significant potential for a range of organisations to make use of seasonal weather forecasts to better target resources and so realise cost-efficiencies in their operations.

This case study utilises data from the impact assessments undertaken across the transport sector by Palin et al. (2016) to quantify the impacts associated with a range of winter weather conditions. The costs of these impacts – in financial and economic terms – are then estimated using benefit transfer from pre-existing studies and databases. The limited data does not allow us to quantify the uncertainties associated with our cost estimates. However, by explicitly listing the assumptions entailed in the cost estimation process we allow the reader to derive a sense of the potential scale of the total uncertainty involved in the methodological application. Table 3 summarises the relative merits of alternative methodological approaches that can be used to derive quantitative estimates of seasonal weather patterns on the transport sector. Our case study highlights that the fact that the underlying impact assessment uses relatively sophisticated statistical analysis in it's treatment of observed (as opposed to survey) data and that the resulting impact cost estimates may consequently be espected to have substantial robustness.

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Methodology for Valuing and Monitoring Climate Services to Manage Climate Variability

Case Study: Wine Production in the UK: Role of Observed Meteorological Data for W&CI Services

Deliverable 4 of the contract:

'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services'

Alistair Hunt and Paul Watkiss

Summary

This report presents the second case study for the project 'methodology for monitoring and valuing climate services', which is Deliverable 4 of the contract 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services'.

This second case study focuses on the valuation of improved observations, enabling enhancements in weather and climate information (W&CI) services. The case study focuses on an example of improved observations for enhancing W&CI services for wine production in the UK for improving W&CI services including for climate change.

Valuation of observed and historic information

Investing in weather and climate information (W&CI) services leads to improved information, such as from enhanced early warning or seasonal forecasts. In turn, this information provides economic benefits to users, as it leads to positive outcomes from the improved decisions that users take. However, for these economic benefits to be realised, there needs to be an effective flow of information along the W&CI value chain, from the production of the forecast through to its uptake and use in a decision. The method for valuation follows that used in the overall study and includes the following steps.

- List the potential economic benefits that the climate service may provide.
- Develop the value chain for the service.
- Review and decide on the potential methods for assessing economic benefits.
- Build a baseline scenario (or counter-factual) without the new climate service.
- Assess the benefits with the climate service in place.
- Assess the costs of the project.
- Compare benefits against costs.

Observations and information, including historic observed data, are foundational activities for W&CI services, and underpin forecast generation. It is possible to value the benefits of improved observations through the enhancements in accuracy and/or timeliness of forecasts. This can be assessed by looking at the value chain for a W&CI service, before and after the introduction of improved observational data. In a similar way, it is also possible to identify the benefits of improved observations in improving climate model projections and thus the use of this information in adaptation decisions.

Case study

This case study explores the valuation of improved observations for a W&CI service for the UK wine industry, for improving current services but also the potential improvement for climate change projections and adaptation decisions. The study focuses on improved early warning information about spring frosts for vineyards, as these events can significantly damage production. It also looks at how improvements in this information can be relevant for planning for future climate change, through information on mean growing season temperatures (GST), as these influence the economic return when planning new vineyard locations. The case study analyses the potential benefits of improved accuracy of frost forecasts, underpinned by better observational information, and also extends this in the context of climate data for the likely expansion of vineyard area in the UK under warming trends from climate change. The benefits of this improved information are a lower level of frost related damage in existing vineyards (with more accurate forecasts allowing more targeted action to prevent frost damage), as well as reduced costs arising from inaccurate forecasts, and for future decisions,

the potential increase in wine production and profitability from increase in viticultural production under climate change.

The case study has also been extended to consider the potential role of observations in providing information for climate services, in this case for adaptation services. The analysis has first looked at the potential additional benefits from climate information in making future wine investments. This indicates the potential increase in hectares under wine production and the total annual average net returns over the period could equate to £49.5 million. In a case where the UK wine industry is using climate information to inform these new investments, this benefit could be attributed to climate information. In practice, however, there will be a considerable efficiency loss along the value chain for such decisions. Nonetheless, the analysis indicates that improvements in climate information for investors would be likely to generate large economic benefits, and relative to the costs of producing this information, would have high benefit to cost ratios.

The improvements in observations, as identified in the current W&CI service example, could also provide additional benefits in relation to these future investments, with economic benefits. There is a potential additional benefit from improved observations if these can help improve the accuracy of climate model projections or might contribute to more specific tailored information for viticulture investors. These would support the decisions that investor make, for example in location and grape choice, which could provide additional profits. However, it is difficult to attribute a % improvement due to the new observational information in this case. This is because it is not clear by how much improved frost observations might improve climate model projections, or how much it would improve investor confidence.

1. Introduction

1.1 Aims of the study

Investing in weather and climate information (W&CI) services leads to improved information, such as enhanced early warning or seasonal forecasts. In turn, this information provides economic benefits to users (individuals/organisations[23]), as it leads to positive outcomes from the actions and decisions that users subsequently take. These economic benefits are often known as the value of information.

These benefits may be assessed from the perspective of society and include the economic valuation of non-market effects, such as environmental, cultural, social and health benefits. Because of the consideration of these non-financial aspects, they are sometimes referred to as socio-economic benefits (SEBs), though this is unnecessary, as the term economic benefit (as defined in the economic literature) already includes such non-market aspects.

This report presents the second case study for the project 'methodology for monitoring and valuing climate services', which is Deliverable 4 of the contract 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services'. This work is being undertaken by a consortium of JBA Consulting (lead), in association with Climate Sense, Paul Watkiss Associates (PWA), Professor Rob Wilby, and Becky Venton, for the Met Office as client. This Deliverable is led by PWA.

The project has developed a methodology and draft set of guidance for valuing climate services. This method and guidance are being tested through a series of case studies (Deliverable 4), which are focused on different types of W&CI services. This is the second of three case studies and is focused on the valuation of improved observations (including historic observations) for climate services. It is focussed on the improvement of observational information for W&CI services for wine production in the UK. To help frame the case studies, the analysis considers three key questions.

1) What is the user decision? The case study looks at two user decisions. The first involves the owners / managers of vineyards, and the user decision relates to actions taken to reduce potential losses from spring frosts (and bud burst) as a result of improved frost forecasts. The second relates to potential investors in new vineyards, who are looking at siting decisions and using improved information to help locate suitable sites.

2) What climate information was used in making that decision? The information for spring frosts is associated with weather forecasts (hourly to weekly). The longer-term decisions relate to changes in spring forecasts as projected in climate models, on mean growing season temperatures and spring period frost days.

3) What is the value associated with the climate information used in that decision? The short-term weather forecasts provide economic benefits by reducing frost related damage, and thus wine production saved and profitability. The long-term decisions also have potential benefits from the improved profitability (and reduced losses) with viticulture expansion in new areas.

1.2. W&CI value chains and the role of climate projections and observations

In order for the economic benefits of W&CI services to be realised, there needs to be a flow of information from the producer to the user and, further, an effective uptake and use of this information in a decision. It is the use of this information that leads to better outcomes than would otherwise be

[23] In this report we use "organisations" as being representative of all parties that value weather information.

the case. To capture this, the economic analysis of W&CI service uses a value chain approach. As described in Deliverable 2 of the contract 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services' this value chain maps the sequence of actions that generate the economic benefit and value of W&CI services and considers the efficiency of the flow of information through to the end user. The steps in a value chain include foundational activities that encompass data collection, collation and processing, and the institutional and technical requirements, that all determine forecast accuracy, the communication of information to users (the reach of the service), and the uptake, understanding, and effective use of this information by end-users in order to generate value.

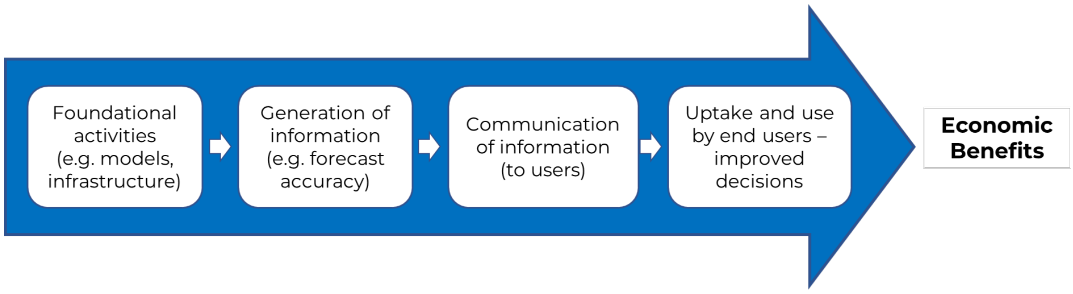


Figure 8. Simple W&CI service chains

Observations are part of the foundational activities in W&CI services (on the left-hand side of Figure *1*). Such information is combined with modelling and forecasting as part of W&CI services, as shown below (WMO, 2015).

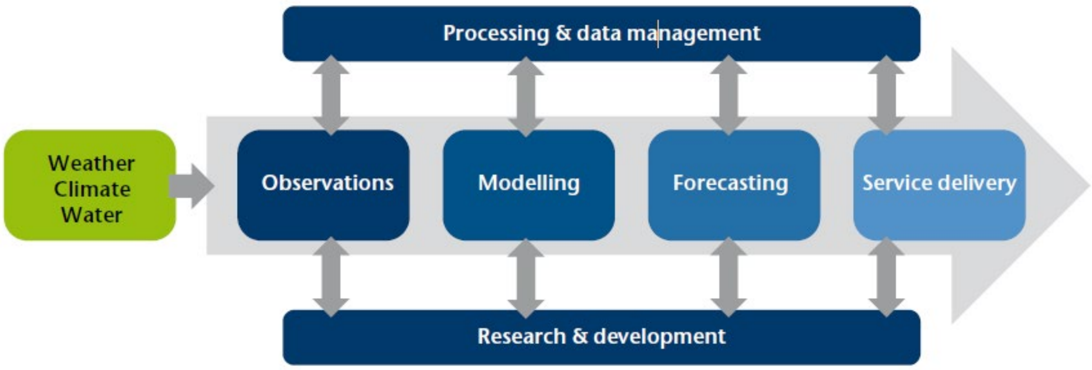


Figure 9 Components of the service production and delivery system of NMHSs. Source: WMO, 2015.

It is possible to assess the economic benefits of improved observations by looking at their role in improving forecasting, for example, from improved accuracy, and thus the cascade of this improved information along the value chain. In turn, this leads to economic benefits from the use of improved forecast by users.

There have been previous studies that have estimated the economic benefits of improvements in observational data, as an input to climate services. For example, Kull et al. (2021) assessed the benefits of surface-based meteorological observation data, and their role in improving global numerical weather prediction (NWP), from improvements in accuracy and lead-time. The analysis estimated how improvements in the coverage and exchange of surface-based observations, as part of WMO's Global Basic Observing Network (GBON), would improve global NWP and forecasting quality in data sparse regions, as well as over the rest of the world. The analysis estimated the potential improvement from better observations, i.e., the impact of the observations on the skill of NWP output and identified the improvement from increasing surface observations in forecast accuracy. This was then used to assess the financial benefits from improved accuracy in early warning and climate services in other sectors. Whilst a range of non-financial benefits were excluded from the analysis the authors identified potential additional global benefits that could be realized through improved forecasting and early warning of approximately US$32 billion per year.

While this demonstrates the feasibility of assessing the economic benefits of improved observations, the actual analysis of benefits, as improved forecasts, relies on many assumptions, most importantly, the improved level of accuracy that arises from the added observations. Ideally, estimates of improved skill are derived from experiments (Observing System Experiments (OSEs)), with and without the improvements, to assess the gains in accuracy, or from Forecast-Sensitivity-to-Observation-Impact (FSOI), which calculate the increase in forecast accuracy attributable to each observation assimilated.

The analysis also requires the analysis of the baseline economic benefits before the improved observations. This requires the economic valuation of a current W&CI service, including the value chain analysis. Such analysis can be estimated through different methods (WMO, 2015; WISER, 2017; Vaughan et al., 2019) that can broadly be distinguished between those that assess potential benefits of climate services (using *ex ante* analysis before the service is introduced), and those that look at actual benefits after implementation (*ex post* analysis after the service is introduced.

<u>Adaptation services.</u> The existing approaches for valuing W&CI services, i.e., for weather and seasonal forecasts, and the value chains above, are also potentially applicable to climate services associated with adaptation. The climate projections are centred on the left-hand side of Figure 1, with the use of climate models and the generations of projections. These can then be used in decisions, but involve different timescales and decision types, with much longer-term decisions and higher uncertainty (i.e., lower accuracy). This makes it more challenging to deliver the effective uptake and use of climate projection information.

In the context of new vineyards, the expansion of new cultivated area for wine (new planting) involves long life-times and considerable lock-in because it involves land-use change and high capital investment. The payback period on wine is longer than for many other agricultural crops because of the time for vines to establish themselves and produce crops that allow revenue to be generated. This means that decisions on new expansion areas in the short- and medium term need to consider the medium- and longer-term climate. **Figure 3** below identifies generic examples of decisions that have different lifetime lengths in the agricultural sector. In the case of investment into new vineyards, the minimum horizon is likely to be around 20 years – the average productive vine lifetime, and analogous to timber plantation. Our study therefore makes use of bioclimatic indicators based on climate projection data out to the year, 2040.

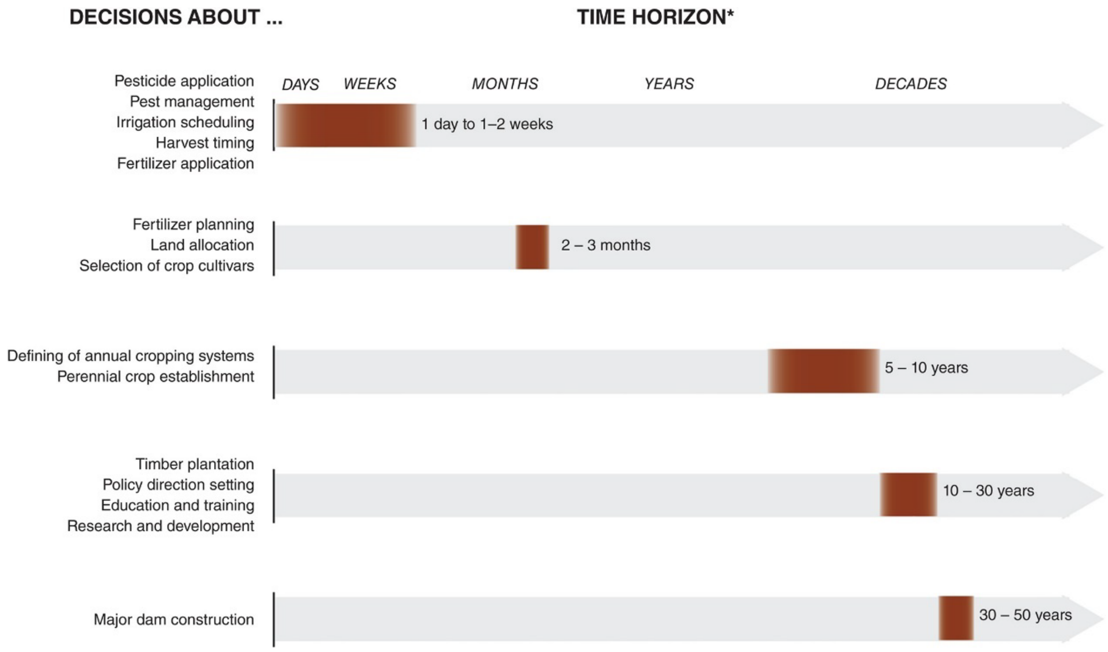


Figure 10. Time Horizons of decision-making in the Agricultural sector. (Source: Nissan et al. (2019))

2. The Case Study

This case study focuses on the valuation of improved observations, and the benefits in improving weather and climate information (W&CI) services for the wine sector. The case study focuses on W&CI services for frost in the wine sector of the UK, and the role for improved weather observations and climate projection data to increase the output and profitability of wine production (the economic benefits).

2.1. The UK Wine Sector

The UK wine sector is a **fast-growing sub-sector. Summary data for production over the period 1997 to 2021, presented in** Table 1**, highlights this growth trend in terms of hectarage under vine production, number of vineyards, and wine production by hector-litres and bottles. Over the last two decades, the amount of land under viticulture in the UK has grown significantly, and 2020 data indicates** a total area of 3,800 ha (Wine GB, 2021). The expansion in production has been considerable over the last decade, with hectarage growing by over 150% in the last 10 years and quadrupling since 2000 (Wine GB, 2020).

Currently, however, there are high levels of annual variability in wine production in the UK (as well as in quality), which are largely weather related (Nesbitt et al., 2016). This can also be seen in the statistics which shows a significant variation in total production (hl) and yield (hl/ha) between years.

Indicative information is available on costs of production per hectare and net returns per hectare in the UK. Standard annual costs for wine production are given as just below £10,000 per ha (Nix, 2015). However, it should be noted that harvesting costs are very yield dependent. Savills (2019) reports average net return per hectare of about £5,000 after 5 years from establishment. This is based on average yield and is very variable per year (ranging from above £15,000 to below £0).

Table 10 Summary of Trends in UK Vineyard Production

Year	Total Area (ha)	Total area in prod (ha)	Total white (hl)	Total red (hl)	Total (hl)	Yield (hl/ha)	No. of Vineyards	Av. Size of vineyard (ha)	Bottles (m)
1997	949	791	5,915	545	6,460	8.17	386	2.46	1
1998	901	842	10,160	1,042	11,202	13.3	382	2.36	1.5
1999	872	835	12,051	1,221	13,272	15.9	373	2.34	1.8
2000	857	822	12,749	1,466	14,215	17.29	363	2.36	1.9
2001	836	801	14,243	1,574	15,817	19.75	350	2.39	2.1
2002	812	789	8,035	1,350	9,385	11.89	333	2.44	1.25
2003	773	756	11,665	2,838	14,503	19.2	333	2.32	1.79
2004	761	722	16,140	2,931	19,071	26.41	339	2.24	2.5
2005	793	722	10,427	2,379	12,806	17.74	350	2.27	1.7
2006	923	747	20,184	5,083	25,267	33.85	362	2.55	3.37
2007	992	697	7,751	2,197	9,948	14.3	383	2.59	1.33
2008	1,106	785	7,833	2,254	10,087	12.8	416	2.66	1.34
2009	1,215	946	18,533	5,302	23,835	25.2	381	3.19	3.18
2010	1,324	1095	24,540	5,806	30,346	27.73	404	3.28	4.05
2011	1,384	1208	18,075	4,584	22,659	18.75	419	3.3	3.02
2012	1,438	1297	5,569	2,181	7,751	5.98	432	3.33	1.03
2013	1,884	1571	24,270	9,114	33,384	21.25	470	4	4.45
2014	1,840	1506	38,358	9,076	47,433	31.5	473		6.3
2015	1,956	1839	31,571	6,406	37,977	20.67	502		5.06
2016	2,077	1612			31,116	19.3			4.15
2017	2,245	1677	25,746	4,664	39,891	23.8			5.31
2018	2,889	2138	83,863	14,296	98,289	45.97			13.1
2019	3,500		67,865	10,731	78,606				10.48
2020	3,800						~800		7.1

Source: Adapted from Wine GB Data for 2020 from Wine GB (2021).

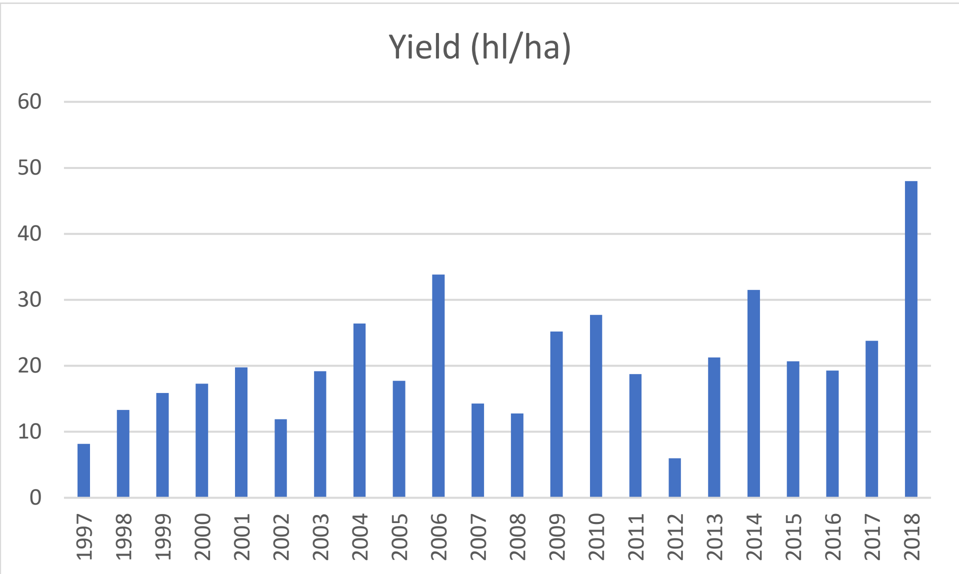


Figure 11 Trends in yield of UK Vineyard Production (1997-2020). Data for 2020 from Wine GB (2021)

The productivity of vines is measured by grape harvest and the quantity of grapes on the vine. In turn, productivity is a major factor in market revenues – quantity multiplied by price - and therefore profitability, given that costs are largely fixed since comprised of planting, pruning, general management, harvesting, processing, bottling and distribution. The complicating factor is that revenue is also affected by quality, which involves both fixed and variable components (what type of wine is grown, and the variability in the quality and vintage of the wine between years).

2.2. Wine and weather

Productivity is directly related to weather conditions over the growing period of the vine. Relevant weather parameters include temperatures and rainfall, in terms of average and daily values, but also extremes, particularly if these arise at key stages of the growing cycle. The latter include the frequency and intensity of mid-winter low temperature, late spring frosts, and the influence of excessive summer heat. Weather conditions are also indirectly related to productivity as a result of their effects on the spread of pests and diseases that impact vine growth and fruiting (Bois et al. (2017)).

There are established relationships between mean temperature and yield that relate to agroclimatic zones. High quality wine grapes grow best in an average growing season temperature in the range 13-21ºC, but the optimum range depends on the grape. For example, Pinot Noir is typically grown in regions that span from cool to lower intermediate climates with mean growing season temperatures (GST) that range from roughly 14.0-16.0°C and have at least 1400 Growing Degree Days (GDD) (Nicholas et al. (2011).

These relationships mean that – as reflected in Table 2 - the most suitable areas of the UK for wine growing are currently the warmer areas of England and Wales, and over 98% of vineyard hectarage is in England (and most in the South-East), with 1.5% in Wales, and the remainder in Scotland and the Channel Islands (Wine GB, 2020).

Table 11 Breakdown of UK Vineyard Production by Region (2020)

Region	% of total area	Total ha (approx)	No of vineyards (approx)
South East	61.5	2147	222
West	8	292	176
Wessex	12	406	104
East Anglia	10	354	108
Midlands and North	4	143	87
Thames and Chilterns	3	97	41
Wales	1.5	51	31
Total		3490	769

Source: Wine GB (2020)

Gape yields vary significantly from year to year due to the weather. Good years occurred in 1996, 2006 and 2010 due to 'optimum' temperatures and weather conditions (warm springs and autumns and the absence of frosts at critical times) and English winemakers described the conditions in the summer of 2018 as "near perfect" (Savills, 2019). Poor years occurred in 1997, 2007, 2008 and 2012 and were due to wet and cold weather during flowering, wet and cold growing seasons, low levels of sunlight, poor summers and spring frosts (Nesbitt A. et al, 2016).

Information on the climate (the long-term average) is important in establishing the suitability of a site for viticulture, and there is also an important role here for climate change information, especially if looking to plant new areas (see Watkiss et al., 2019).

Information on the weather is also important, because of the potential effects on yield and productivity (and also on quality) of weather extremes, and because there are actions that vineyards can take to reduce potentially negative impacts.

2.3 Focus of the case study

The case study starts with current frost related damage and the potential improvements that observations could make in improving current decisions. It then looks at how these observations might also improve future climate model projections and the use in adaptation decisions.

Given the sensitivity of grape production to weather events and patterns, improved observational data (current and historical) could potentially improve the accuracy of forecasting and nowcasting, and so improve viticulture management decisions. This could be from improvements in forecasts that are more site-specific or it could be from improvements in observational (historic data) that provide improved modelling of key variables for wine growing, leading to improved accuracy. The improved accuracy is in turn likely to result in an increased probability of forecasts being correct (and less chance of forecasts being incorrect), and so result in an increased probability of better vine management decisions based, notably with reduced risk of losses/improved output, and overall improved profitability.

More specifically, we investigate two questions relating to observation data:

- Is there value in increasing the frequency of weather variable observations at existing sites?
- Is there value in making weather variable observations at new, additional, sites?

The specific weather parameter investigated is for frost risk.

In England, winter temperatures and frost damage are a key factor for viticulture. During the vegetative growth stage, temperatures below freezing can adversely affect growth, and hard freezes (<-2.2°C) can reduce yield significantly. Nearing maturation, early frost or freezes can lead to the rupture of the grapes, which influences disease development and can result in a significant loss of weight in the fruit. For grapevines, the threshold of frost susceptibility rises from −8 °C in pre-budburst to −2 °C in budburst stage (Reynier 2007). Spring frost is, therefore, a major risk to viticulture in cool-climate regions causing significant crop loss if it occurs after budburst (Mosedale et al. 2015) [24]. For example, the late frosts in 2020 plus the warm conditions early in the season led to lower bunch weights, smaller berries and lower production volumes. A total of 8.7m bottles were produced in 2020, compared to 10.5m bottles in 2019 (Wine GB, 2021).

Nesbitt et al. (2016) identify that the key timing for spring air frost is in April and May, the critical months for budburst and initial shoot growth, from questionnaire responses with producers. They examine Met Office regional air frost (<0°C) data (1961–2013) for days with air frost in these months for key wine growing areas. An imposed linear trend line - **Figure 5** - indicates a reduction in air frost days over time, particularly in April, but no significant decreasing trend in the frequency of air frost days was found in either month. During the period 1989 – 2013, combined April and May air frost days ranged from 0.6 in 2011 to 7.4 days in 2013, with an average of 3.6 days.

[24] Frost and/or freeze occurrence during the spring and fall generally comes in two forms: 1) advection frosts, which occur as cold air masses are brought into a region with the passage of a cold front; and 2) clear sky radiation (or ground) frosts, which occur as the ground and the air in the lower layers of the atmosphere (within and just above a grapevine canopy) gives off heat, warming the air in successive layers upward, and the dew point temperature is low enough (Jones, 2015).

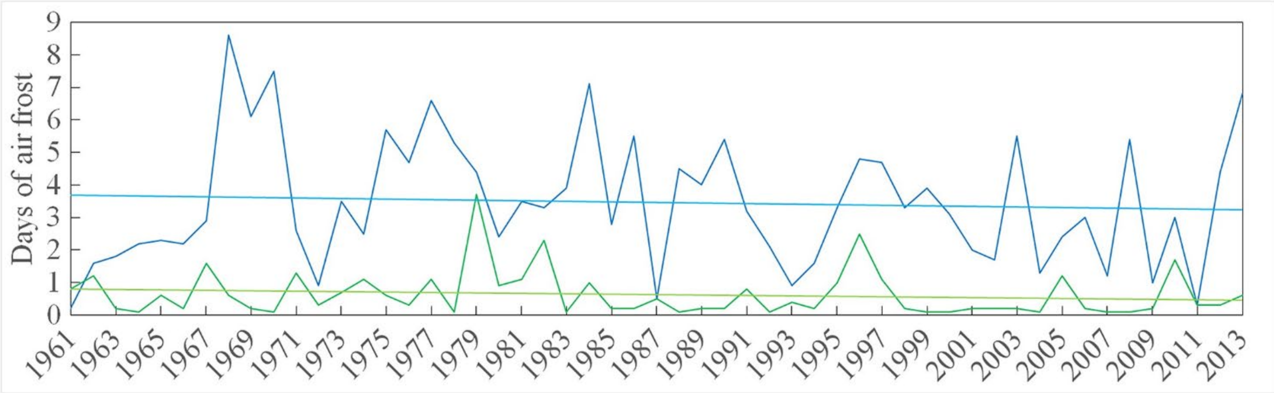


Figure 12 The number of days with air frost in south-east and south-central UK. Source Nesbitt et al., 2016.

April (——) and May (——) air frost frequency (1961–2013) across south-east and south-central United Kingdom with imposed linear trends for April (——) and May (——). April, $y = 0.0087x + 3.6946$, $R^2 = 0.0046$; May, $y = 0.0069x + 0.8171$, $R^2 = 0.0221$.

Climate change will have effects on viticulture, and these include potential positive and negative effects on current production as well as the potential for new opportunities associated with expansion.

Weather conditions are dominant factors in determining the hectarage and volume of wine production in the UK, (ADAS 2019; ADAS 2021). Climate change is likely to be influential in determining future production; in particular, it is projected to lead to more favourable climate conditions for UK wine production, allowing the expansion of hectarage and range of grape varieties that can be grown (Hannah et al., 2013; Wilby et al., 2019; Watkiss et al, 2019).

Historical data - **Figure 6** - suggests that there may be a substantive basis for this assumption. A correlation coefficient of 0.25 between the bioclimatic indicator, mean growing season temperature (GST), and hectares in active grape production indicates that there is the expected positive relationship between the two variables, though the size of the value indicates that the strength of the relationship is low.

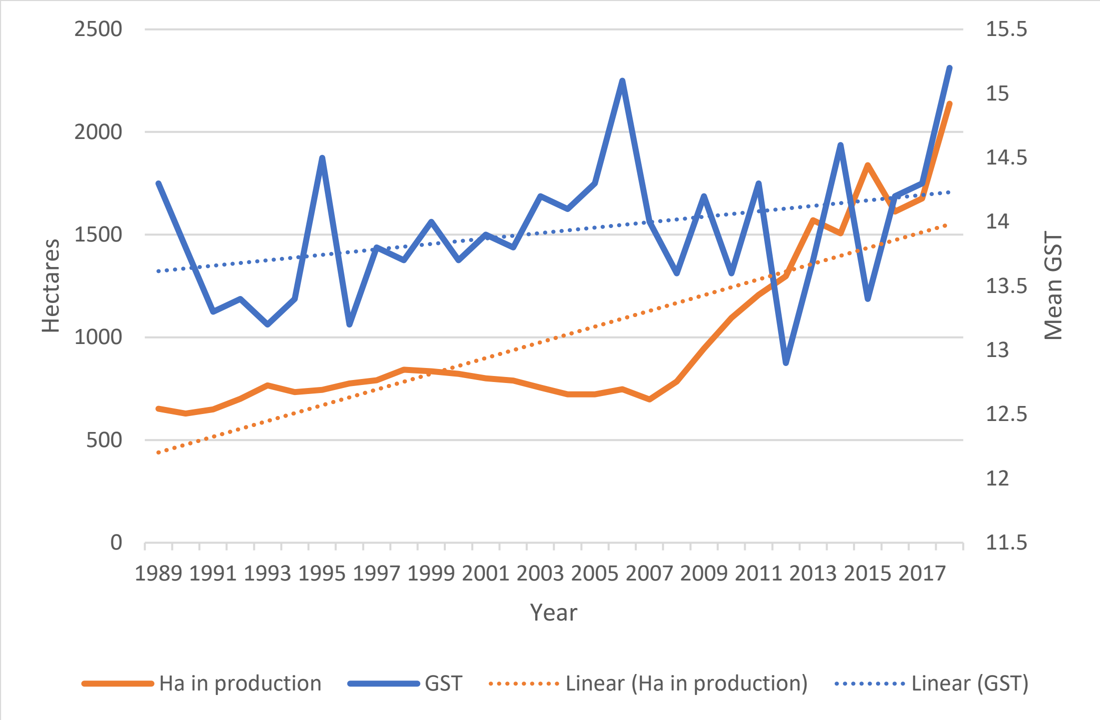


Figure 13. Historical Data on Growing Season Temperatures and Vine Hectarage: England, 1989-2018

Climate change is projected to have major impacts globally in the geographic distribution of wine production in the next half century (Hannah et al., 2013). This will create winners and losers. Figure 7, below shows the relationships between phenological requirements and growing season average temperature in the world's benchmark regions for each variety. Rising temperatures will affect AvGST, and in turn move the suitability areas and thresholds. This will move some regions outside suitability zones.

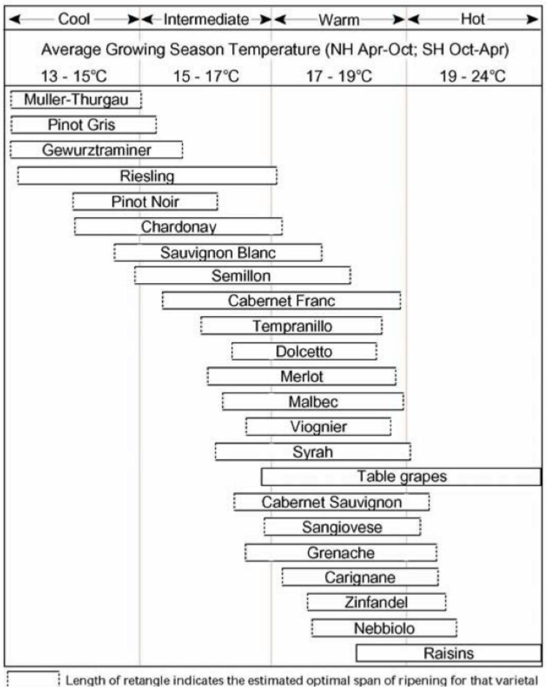


Figure 14 Grapevine Maturity Groupings (Jones, 2006)

Such analysis indicators that England could have a climate that is more suitable for growing wine – as shown by the climate mapping above, and this was reported as an opportunity in the UK CCRA3 report (CCC, 2021). Georgeson and Maslin (2017) project that the UK may move from being a marginal, cool-climate region to become an 'intermediate climate' wine region.

Nesbitt et al. (2022), as part of the UK Research and Innovation SPF UK Climate Resilience programme also looked at future wine suitability in England using the UKCP18 projections. Their results indicate greater potential for Pinot noir for sparkling wines and shifting suitability to still red wine production, due to increased growing season average temperatures.

It is stressed, however, that changes in precipitation and other factors will also be important. Further, while average climate could be potentially beneficial, and there might be reduced spring frosts, this might not reduce risks, due to advancement in the timing of budburst (Mosedale et al., 2015).

In looking at these opportunities, investors can look at climate model projections and so identify potential suitability for new vineyards in relation to location and grape choice, noting that of course other factors are important (i.e., soil type). Information on the potential direction and magnitude of bio-climatic indicators for grape production in future years will help investors to take a more informed view on the grape production volumes that might be expected over vines' lifetime, and thus the likely profitability. This will include information on average growing season temperature, but also downside risks from frost damage.

3. Application of the method

3.1 Study methodology

The project has developed guidance for the valuation of the economic benefits of climate services for climate variability. This aligns with, and builds on, the existing methods in the literature and in existing guidance (WMO, 2015; WISER, 2021). The methodology involves the following steps.

- List the potential economic benefits that the climate service may provide.
- Develop the value chain for the service.
- Review and decide on the potential methods for assessing economic benefits.
- Build a baseline scenario (or counter-factual) without the new climate service.
- Assess the benefits with the climate service in place.
- Assess the costs of the project.
- Compare benefits against costs.
- Undertake sensitivity and bias analysis, then review how benefits could be enhanced.

Step 1: List the potential societal benefits that the climate service may provide.

Given an existing value chain, associated with W&CI services for viticulture, an improved, more accurate weather forecast due to the use of weather observations should result in a lower probability of weather-related losses.

For spring frosts, the threshold of interest is that of air temperature falling below zero, but also specific thresholds for damage (i.e., below 2˚C) at key times of year. The benefits of the improved accuracy of forecast resulting from observation data, and thus sub-zero air temperatures being predicted in the locality of a vineyard, is expected to allow an improved use of information for a number of decisions. The benefits are therefore:

- The enhanced ability of the wine producer to deploy on-site measures that reduce the risk of frost damage to the vine and so reduce the loss of productivity that would otherwise result. Such measures include heat blowers, sprinklers and bougies (paraffin wax candles in pots), described later.
- A reduction in the number of occasions when on-site adaptive measures are employed unnecessarily (i.e., false alarms) and a reduction in associated costs.

If the improved observations also have benefits in improving climate model projections of frost modelling or allow more accurate downscaling of results, they would have additional benefits.

- Reduced uncertainty for wine producers regarding investment decisions (i.e., for current vineyards, for new grape varieties that are more frost sensitive but potentially more profitable, or new plantations of vineyards including in cooler locations). The current variability of productivity and profitability as a result of the incidence of Spring frost events means that producers are less able or less willing to invest in production. The new information would improve the reliability of projections and provide improved confidence in investment decisions. This could also lead in improvements in profitability for these investment decisions.

Step 2: Develop the Value Chain

The next step in the method is to develop a value chain for the service (see **Figure *1***). This relates to the baseline value chain, onto which the improvement in forecast accuracy from improved observations will be applied, as well as the potential improvement to climate projections or information. For this case study, simple value chains have been produced – outlined in **Table *3*** and **Table 4**. This centres on the following steps.

- Foundational activities, including infrastructure or modelling.
- Generation of information, including accuracy of information.
- Communication of information, including timeliness of information, and thus access to information by target end-user groups.
- Understanding of information and trust in the information, affecting ability of users to respond and thus level of use/uptake by end-users.
- Effectiveness of response of users – both positively and negatively – in terms of benefits delivered.

The value chain for improved observations (foundational activities), has to assess this value chain with and without the observation-based improvement in accuracy.

Table 12 Value chain for the baseline and from the improvement in observational information for current forecasts.

Value chain step	**Baseline**	**With weather observation information improvement**
Foundational	Observations, modelling	Enhanced site-specific observations or historic data
Generation	Frost forecast (of damaging levels), including forecast accuracy	Improved accuracy
Communication	Public weather forecast, or specific targeted W&CI service for wine, or site-specific generated forecast	
Uptake and use	Number of vineyards that use the forecast and take action to reduce losses	Improved uptake that may result from perceptions of improved accuracy in the forecast
Action and effectiveness	Use of heat blowers, sprinklers and bougies, that reduce damage (partially or fully)	
Economic benefit	Reduced frost damage (reduced losses to productivity)	Reduced frost damage - from more accurate forecasts leading to more action
Costs	Costs of operating heat blowers, sprinklers and bougies (note also, costs of acting if damaging frost projected that that does not occur, i.e., due to inaccurate forecast).	Reduced unnecessary action (false negatives) and avoided costs (higher accuracy)

This is then extended to look at the potential benefits for adaptation services. In this case, the value chain decision would be associated with an investment decision, i.e., the siting of a new vineyard and choice of grape, taking account of climate change. This has three columns, to reflect the evolution of the potential information available. The first involves an investment decision made today on the basis of current information. The second would use climate model projections. And the third would improve the accuracy of climate model projections from the improved observations.

Table 13 Value chain for the baseline and from the use of climate projection data

Value chain step	Baseline	Use of climate change information	CC plus improved observations
Foundational	Current observations	Climate model development	Improved observational information
Generation	Current forecasts and average climate	Climate model projections of climate variables in the future	Improved accuracy of climate information
Communication	Current weather services	Publication of climate information (potentially tailored wine specific service/information)	Updated tailored information
Uptake and use	Use of information for siting and grape choice of new vineyard	Updated information on future site and grape suitability	Improved information in future site and grape suitability
Action and effectiveness	Investor decision acquisition of land for vineyard and planting	Improved decision (i.e., more profitable grape)	Enhanced confidence in decision
Economic benefit	Revenue/profitability from vineyard	Improved revenue and profitability	Further improvement in revenue
Costs	Cost of investment (high) Cost of weather information (low)	Additional cost of use of climate information in analysis and decision (low)	Additional costs of observations and incorporation in information

Step 3: Selection of method(s)

The next step is to decide on the methods for assessing economic benefits. The potential methods are described in detail in the report: Methodology for Valuing and Monitoring Climate Variability: Deliverable 2 of the contract 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services' and summarised in Box 1, below.

The selection of method depends on two issues: the type of W&CI service and the suitability of various methods to make estimates of benefits; and the capacity, level of expertise, time and resources (including data) available for the SEB analysis.

There have been a number of previous studies of the economic benefits of W&CI services in the wine sector, which provide some examples of the previous applications used (Vigo et al., 2021; Khosravi et al., 2021).

Box 1 ***: Methods used in Economic Benefit studies of weather and climate information services***

Ex ante models

Decision-theory based models that can be applied to estimate potential benefits, for example, using a crop model to assess the possible increases in yield from improved seasonal forecasts. Ex ante models use established relationships between key variables, e.g. precipitation and crop yield, in conjunction with decision models to predict how new information such as on the likelihood of occurrence of anomalous rainfall events will affect the decisions of economic agents and subsequently affect yields.

Integrated economic models

Models that can quantify aggregate effects of changes in one sector or market on others, and include cross-economy, or cross-sectoral, linkages that use, for example, input-output matrices, trade models, and partial or computable general equilibrium economic models.

Cost-loss models

Models used to quantify the effects of extreme weather events and the effectiveness of averting measures such as Early Warning Systems (EWS). These include probability loss curves based on historical event information (e.g. the relationship between flood events of different magnitudes and the economic losses associates with these) that can be extended to look at non-monetary effects e.g. fatalities.

Ex ante surveys

This approach uses survey-based elicitation of individuals' preferences, to assess their willingness to pay (WTP) for potential new services e.g. sailors' WTP to have an enhanced 3-day shipping forecast.

Ex post surveys

These directly survey users to explore actual (or perceived) benefits from climate services following their experience of utilising a given short- or long-term service.

Statistical and econometric analysis

These use statistical analysis (*ex post*) to assess impact/outcomes from the introduction of W&CI services, controlling for other variables to attribute benefits. For example, such analysis may quantify the relationship between winter flood events and the number and/or value of insurance claims. Alternatively, such analysis can quantify the preferences of individuals for a given service (e.g. a customised) weather app by recording their expenditure on the weather app. This latter technique is known as the *Revealed Preference method*.

Impact assessments

These undertake direct measurement of service impact on a group or area, before and after, or relative to a control, e.g. using agriculture field plots to identify differences in crop yields as a result of a change in management practices informed by the climate service, and are complementary to statistical and econometric analysis.

Value (Benefit) transfer

This method takes estimates of benefits developed in one context and applies them in another, rather than undertaking primary studies, adjusting for context where possible. Such a transfer process can be undertaken with findings from studies that use any of the benefit methods outlined in this box.

The selection of method depends on two issues:

- The type of W&CI service and the suitability of various methods to make estimates of benefits.
- The capacity, level of expertise, time and resources (including data) available for the SEB analysis.

For short-term, observation-based, forecasts, the ways in which these two constraints relate to the potential methods described in Box 1 is summarised in Table 4. An indicative ranking of the overall resource/expertise requirements – Low, Medium and/or High - is provided.

Table 14 Potential methods and applications for short-term, observation-based, forecasting valuation

Description of Method	**Resource & Expertise Needs. Limitations.**
Ex ante Surveys of willingness to pay for new or improved services. Not appropriate for commercial operations such as agriculture, apart from estimating the risk-aversion that may be associated with variance in yields and profits.	High. Cost of survey and analysis. High level of expertise involved. Hypothetical survey context may lead to over-bidding WTP.
Revealed preference studies, e.g. averting behaviour. Not appropriate for commercial operations such as agriculture, apart from estimating the risk-aversion that may be associated with variance in yields and profits using, for example, expenditures on insurance payments.	Medium to high. Cost of studies and analysis. High level of expertise involved. May be difficult to isolate weather-related effects from other influences on expenditure decisions.
Ex post Survey/questionnaire of likely beneficiaries (ex post). For example, a survey of viticulturalists of their WTP for an improved observation-based forecast, following a Spring frost episode.	Medium. Cost of survey and processing results but can be included in the baseline and end-line survey. Low -medium expertise required. May be difficult for survey respondents to isolate effects of weather-related events from other events that had similar effects.
Ex ante Modelling of impacts from weather event variations. For example, decision modelling of investment in actions to reduce crop damage with and without an enhanced observation-based forecasting.	Medium to high. Time spent on developing model and data analysis of results. High expertise required. Behavioural decision rules sensitive to modeller's assumptions.
Integrated Economic modelling suitable for larger scale change, e.g. computable general	High. Time spent on developing model and data analysis of results. High expertise required.

equilibrium modelling. For example, the effects of crop variance on associated food products.	Aggregated outputs/results may not be appropriate to local-scale analysis.
Impact assessments, e.g. pilot studies to allow measurement of benefits. For example, crop productivity benefits resulting from enabling action to reduce crop losses inform overall benefit assessment.	Medium to high. Development and analysis of pilot studies and results data. Medium – high expertise required. May depend on decision context arising and impact data being recorded and made available.
Statistical and Econometric analysis (*ex post*), e.g. quantification of income or yield benefits of improved weather forecasting on basis of regression analysis of data. For example, statistical analysis of the relationship between historical incidents of Spring frost events and crop production inform quantification.	High. Time spent on developing econometric analysis and data analysis of results. High expertise required. Depends on decision context having arisen and impact data having been recorded and made available
Value Transfer of results from a previous study to a new decision context. For example, use of quantitative relationships between weather variables and crop yield in other Western European countries, using statistical methods, can be transferred to the UK context.	Low to Medium. As long as data is available from another application the main challenge is to transfer in an appropriate and defensible way, which requires some expertise. Transfer from original study context to current decision context introduces uncertainties that limit accuracy of resulting estimates.

When extending to future climate change, the analysis inevitably focuses on *ex ante* assessments, because of the long time-scales involved.

For this reason, the study has used an approach based on *ex ante* statistical impact assessment and decision modelling results transferred from international studies that provide an impact assessment of GST-yield, and the effects of spring frost incidence (using a loss function of temperature and yields), combined with existing data on UK vineyard yields, production and net returns. The focus has been on the market benefits of current improved accuracy of forecasts as a result of using site-specific observation data and information, and then the extension to climate projection provision. Future research could be more location-specific by further down-scaling of the climate projections and sourcing (if available) more detailed records of spring frosts incidence and vineyard losses per location/region.

Step 4: Build a Baseline Scenario

Improved frost forecasts from better observations. In order to establish the baseline scenario for the initial improvement in frost forecasts from better observations, i.e., the value chain without the improved weather forecast in place, we need to build up an analysis of the current use of frost forecasts and the relationship with vine productivity. For this, we need a loss function that relates the loss of productivity/profitability to exposure to air temperatures. As an example, the range of critical temperatures that result in loss of production at different vine growth stages were estimated in the US context by Snyder and Melo-Abreu (2005), shown in **Figure 8** below, for the Concorde variety of vine. At the crucial budburst stage in spring, the study found that the loss function gives a range from -3.9 °C (10% kill) to -8.9 °C (90% kill).

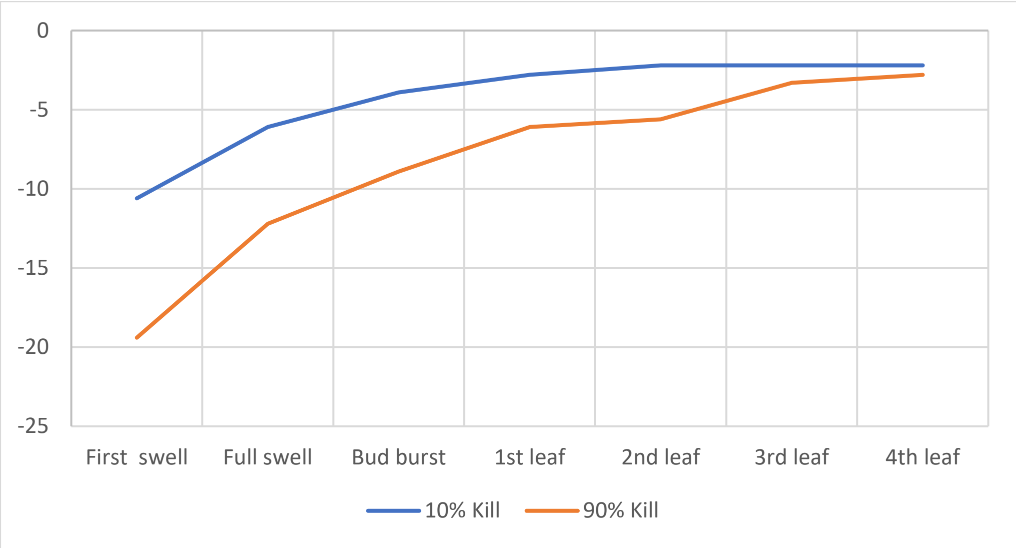


Figure 15 Critical temperatures for grapevines growth stages (°C)**.** *Source: Adapted from table in Richardson (2020) How to prevent vineyard frost damage? – eVineyard blog (evineyardapp.com). Original source: Snyder & Melo-Abreu (2005)*

However, the temperature thresholds for frost damage vary on the phenological phase and grapevine variety (Meier et al, 2018). For the phase of budburst, Snyder and Melo- Abreu (2005) identified 30 minutes exposure at − 3.9 and − 8.9 °C as being lethal to 10 and 90%, respectively for the relatively frost-resistant variety 'Concorde'. Ferguson et al. (2013) reported a temperature of − 1.2 °C as being lethal to 50% of the plant parts in varieties such as Sauvignon Blanc, Chardonnay, Pinot Gris, and Gewürztraminer. Molitor and Junk (2013) and Molitor et al. (2014) used a threshold of 0 °C in their work on frost risk in the Mosel wine regions in Germany and Luxembourg, and Mosedale et al. (2015) considered thresholds of 0 and 2 °C.

For this case study we use the latter studies and adopt a relatively conservative assumption that the key temperature threshold is close to 0 °C (-0.0125 °C). We then adopt the gradient of the loss function identified in Snyder and Melo- Abreu (2005). This loss function is presented in **Figure 9** below.

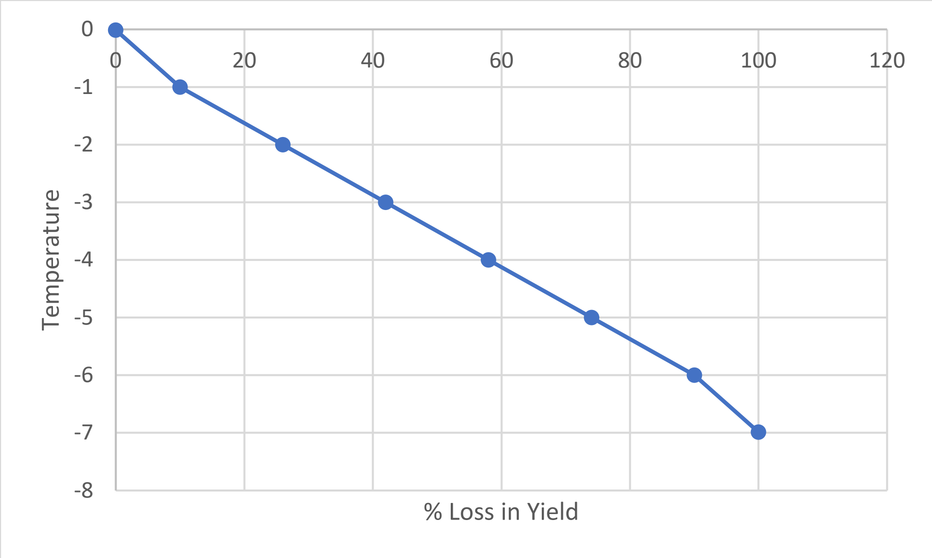


Figure 16 Wine Productivity Loss Function. Source: Adapted from Snyder and Melo- Abreu (2005).

It is highlighted that Nesbitt et al. (2016) applied a standard linear regression for the 1989–2013 period with spring frost and productivity but found no relationship. They hypothesise this may be due to the inability of the air frost data to represent high-resolution spatial occurrence, severity and length, or the potential ability of some producers to protect against frost may go some way to explaining this result. However, the events of 2020 highlight that frost damage is still a major effect in the UK.

In the absence of empirically observed frequencies, we have used indicative estimates to build up a case study analysis. We assume an annual probability distribution across the range of sub-zero frost temperatures as presented in Table 5 below. The average annual expected loss is 4.1% of yield in the absence of action – estimated by multiplying the percentage losses associated with different temperatures by the probability of these temperatures occurring (Table 5) at the time of budburst. Furthermore, we assume that if standard weather forecasts are used to inform decisions relating to the employment of ameliorative measures (frost protection measures), the proportion of forecasts that are correct (i.e. that they predict frost events) is equal to 29% whilst the proportion of forecasts that are incorrect (i.e. that a frost is not forecast but occurs) is 61%. This data is taken from Wilby[25] who regressed daily Tmin at a specific vineyard – Eglantine, in Nottinghamshire, England - against ERA5 2m Tmin (as a proxy for weather forecast model resolution ~30 km) and found that Raw ERA5 Tmin has 29% accuracy in terms of the frequency of spring frosts (Tmin < 0 C) because of an overall warm bias in the model at the site of +1.7C. In the cases where forecasts are incorrect, we assume that no measures are implemented because the wine producer believes the (incorrect) forecast and so does not implement these measures. Given these proportions, the actual average annual loss will be 2.49% of yield since in 29% of the years that such frost events occur the vines will be sufficiently protected such that no damage results.

Table 15 Probability of annual occurrence of frost events

Temp C	Annual prob. Of occurrence	Annual % Expected Loss in Yield
-0.0125	0.7	0
-1	0.4	4
-2	0.2	5.2

[25] Personal communication

-3	0.1	4.2
-4	0.05	2.9
-5	0	0
-6	0	0
-7	0	0
Average annual loss in yield (%)		4.1

Whilst there is not empirical data to corroborate these assumptions, anecdotal evidence appears to broadly support them. For example, in 2020, major frosts were predicted for mid-May as a cold front swept down from Iceland in a south-easterly direction. This brought sudden low night temperatures with major effects. Some weather apps predicted this series of frosts correctly and led vineyards to take precautions. However, other vineyards did not act. As an example, Dunley in Hampshire experienced 50% damages, because they took no action when the climate app predicted positive temperatures. Poulton Hill in Cirencester were similarly affected. Southcott in Wiltshire had 95% of areas affected by ground frost and Durslade in Somerset suffered total damage, as did Kerry Vale in Shropshire and Daws Hill in Oxfordshire and 18 other vineyards. Some vineyards have their own weather stations, but the data from these are not always correlated with operational weather forecasts (Richardson, 2020). It should also be noted that the behavioural relationship between information and action is not always predictable.

Applying the loss of production function during budburst in **Figure 9**, above, to UK vineyard production data, using area under production, 2138 ha, rather than total area, we can estimate potential loss of production during frost events. The vine yield in 2018 is assumed to be the highest current potential yield in the absence of frost, as it was the best year on recent record with a yield of 45.97 hl/ha. The impact of frost events would reduce yield to about 41.4hl/ha at -1 °C down to about 4.6 hl/ha at -6 °C, assuming no preventative action.

Table **7** provides example estimates of the total impact on UK wine production of applying the above yield reductions due to frost at budburst to highest yield (2018) production data. The loss estimates assume frost events at all vineyards which is not realistic for most years, but the significant reductions in yield are consistent with reductions given above for the poorest production years (e.g., average yield in 2012 was only 5.98 hl/ha). The table estimates central and upper-bound losses in net returns assuming averages of £5000 and £15,000 per ha per year (Savills (2019). The estimated upper-bound losses in net returns at the regional level for the two "frost at budburst" temperatures are presented below.**Table 16** Example UK Wine Net returns under scenarios of frosts at budburst using 2018 data (1)

	Ha in production	Total Yield in hector-litres (hl)	Yield hl/ha	Production bottles (million)		Net returns (£) (max)
No frost	2138	98,289	45.97	13.1	10,690,000	32,070,000
Frost at Budburst (°C)						
-0-1		88,460	41.38	11.79	9,621,000	28,863,000
-6		9,829	4.60	1.31	1,069,000	3,207,000

(1) 2018 production data used as the "no frost" scenario as this was the most recent very good year for which production data are available in the Wine GB data. We assume this is maximum potential and then estimate loss ranges as if there had been frost at budburst. This also assumes all vineyards are equally impacted which is not realistic given variation in vulnerabilities to frost due to local variations in landscape and vine management.

Table 17 Example Regional UK Wine Net returns in the event of frosts at budburst (1)

	South East	West	Wessex	East Anglia	Midlands and North	Thames and Chilterns	Wales	Total
	Net returns (£) (1)							
No frost	19,723,050	2565600	3848400	3207000	1282800	962100	481050	32,070,000
Frost at Budburst (°C)								
-1	17,750,745	2,309,040	3,463,560	2,886,300	1,154,520	865,890	432,945	28,863,000
-6	1,972,305	256,560	384,840	320,700	128,280	96,210	48,105	3,207,000

(1) Regional net returns assume regional % split of production ha in 2020

The other key baseline analysis centres on the action taken when a potentially damaging frost is forecast. A summary of the range of these actions is given in Box 2. A survey quoted in Richardson `(2020) found that the most commonly used short term damage limitation systems used in UK vineyards were sprinklers (pre-frost sprays and continual overnight water-sprays) and bougies, followed by blowers and heating cables. We assume that the actions that would potentially benefit from current and improved weather service information would primarily be those short-term damage limitation actions which can be quickly activated in response to weather forecasts (in particular, heating cables, heat burners, fans, bougies and sprinklers).

Box 2: Actions for wine producers to reduce risks of damage from early frosts

Prevention

- *Careful site selection* to avoid frost-prone areas. Considerations include (i) Landscape - closed valleys can trap cold air and create a thick frost zone while open plains tend to thin the frost layer. Slopes can aid airflow while barriers such as walls, hedges or road embankments can interrupt this airflow and result in frost pockets. (ii) Soil types - Dark soils absorb more heat than light soils while gravelly soils absorb more heat than clay soils. (iii) Choice of windbreaks appropriate for the site (solid windbreaks tend to keep in the frost).
- *Choice of variety.* Later-budding varieties in high frost risk areas (e.g. vinifera).

Vineyard management

- *Late pruning* can delay budburst by a few days.
- *Removal of weeds* in between vines can reduce surface area for cooling.
- *Mowing of grass* to reduce population of ice-nucleation active (INA) bacteria in the vineyard which can encourage formation of ice crystals.
- *Choice of trellising* method to keep fruit zone high above frosty ground.

Short term damage limitation

- *Heating cables* which wrap around the fruiting cane and heat is conducted into the sap of the cane. The cables are controlled by thermostat which ensures heat is distributed when it is required.
- *Heat blowers:* e.g. gas burners heating air which is then blown by a large tractor driven fan, across the vineyard. Such machines should be started up before the temperatures drop before freezing.
- *Bougies.* Large paraffin wax candles which can be lit when required. Requires a good warning system. According to Richardson (2020) they have been used in vineyards in the South East region of UK, with mixed success reported.
- *Fires* using vine prunings or straw. Smoke can also help to provide insulation.
- *Sprinklers:* Use of water sprinklers to protect vines as temperature drops. The water freezes around the shoots (releasing latent heat of crystallisation as solid ice forms) and protecting shoots from damage. only possible where pipes and sprinklers have been installed. Can be expensive.
- *Large fans and air blowers* to mix warmer layers of air at higher altitudes with cold air close to the soil (common in California and Ontario). Expensive. A company in New Zealand has developed a frost fan mounted onto a trailer protecting up to 5.5ha, which is available in the UK (example quotation given to a UK vineyard in October 2020: £25,000 plus delivery).
- *Helicopters* have been used, for example in New Zealand, to create a downdraft to mix warmer upper layers of air with cold air at ground level. This is expensive (in New Zealand, one vineyard owner estimated the cost in 2010 at $700 to $800NZ an hour to use 8 helicopters).
- *Weather prediction software:* Commercial software is available, for example: Climatevine app provides (i) Vineyard weather forecasts and extreme weather alerts – including frost alerts (ii) Vineyard, regional and national weather information, through the seasons. Evidence in Richardson (2020) suggest that the app is helpful, but of variable reliability. The anecdotal evidence presented was that UK Met Office was more accurate for next 24 hour forecasts.

Source: Adapted from Richardson (2020) and [Winemaking: Frost in the Vineyards - How Do Growers Cope? (thewinesociety.com)]

The cost of these actions, based on commercial sources, are shown below. These estimates are rather incomplete as operators often only give bespoke quotes by request. Example costs are £2,400 to £4000 per event per ha for bougies. It is difficult to make direct comparisons with costs of other options as these generally only quote capital costs and do not include an estimate of operating (especially energy) costs. For example, the given quote for the cost of an air blower is equivalent to about £875 per ha assuming one use per year, not including operating costs.

Table 18 : Cost of Short-Term Damage Limitation Options for Frost.

Type	Source	Capital cost	Running costs	Note
Heating cables	Vineyard Frost Protection | Gaia Climate Solutions	n/a	n/a	Sources such as vineyard magazine suggest this is a costly option due to energy required.
Heat blowers	https://www.vineyardmagazine.co.uk/grape-growing/giving-frost-the-cold-shoulder/	£20,000 (covers 8 ha)	n/a	Cost of "Frost buster" (mobile heat blower).
Bougies	Vinescapes Ltd - leading vineyards and wineries	£8-10 per candle * 300 – 400 bougies per ha per frost event = £2400 to £4000 per event per ha		This quote comes Vinescapes selling blowers and competing with bougies.
Sprinklers	Not known (Quoted in Richardson, 2020)		£5 per acre per night	
Fans and air blowers	New Zealand company (frost fan mounted onto a trailer protecting up to 5.5ha)	£25,000 plus delivery	n/a	
	Vinescapes Ltd - leading vineyards and wineries	£30,000 to 35,000 (£3,500 pa over 10 year life)	n/a	Does not state number of ha covered[26]. 10 to 12 acres per machine.
Helicopters	New Zealand company (Quoted in Richardson, 2020)		\$700 to \$800NZ an hour to use 8 helicopters (in 2010)	For large vineyards. Did not find reference to use in UK.
Weather prediction software	climatevine.com			ClimateVine app includes frost alerts

There is an important question as to how many vineyards have the equipment to act, as well as around the effectiveness of the actions. Some active protection measures, such as installing heaters, and especially wind machines, have high installation and operating costs and the investment is only justified for large vineyard surfaces. Generally speaking, Neethling et al. (2014) report that winegrowers avoid planting vineyards in frost-prone areas (e.g., low-lying) or select late-ripening varieties for those areas (e.g., Cabernet Sauvignon).

Unfortunately, there is not good information about the use of such actions in the UK wine sector. On the evidence of the amount of frost damage in 2020, we might assume that the level of uptake is modest (though the 2020 event may have led to greater uptake). It is also not clear how effective the

[26] An estimate of 10 to 12 acres per machine (about 4 hectares) is given in https://www.wine-grape-growing.com/wine_grape_growing/vineyard_frost_protection/vineyard_frost_protection_active.htm

actions are in reducing damage. Further work is also being undertaken to investigate effectiveness, including through review of European literature.

In the absence of good information, an initial value chain and efficiency analysis has been undertaken where the baseline assumption for forecast accuracy at vineyard site scale is 29% accuracy. This is indicative only. This is shown below and shows the potential fall across the value chain. The analysis explores the potential outcomes that could arise:

- The forecast of a damaging event is correctly projected, i.e., the event subsequently occurs.
    - Some vineyards take action to reduce losses, leading to benefits from reduced damage.
    - Some vineyards ignore and do not act, leading to damages.

- The forecast of a damaging event is incorrectly projected, i.e., no event occurs.
    - Some vineyards take action to reduce losses and incur costs for an event that did not occur.
    - Some vineyards ignore and do not act (no change).

These are shown in **Figure *10*** with data for value chain efficiency. Overall efficiency is estimated by combining the efficiency losses i.e. 29% accuracy * 80% of producers receiving the forecast * 75% acting as a result of the forecast * 75% effectiveness of those actions. For the positive forecast, this indicates a maximum potential of 13% effectiveness, i.e., due to efficiency losses, the W&CI service can only reduce the theoretical maximum losses of 4.1% of the total yield by around one-seventh.

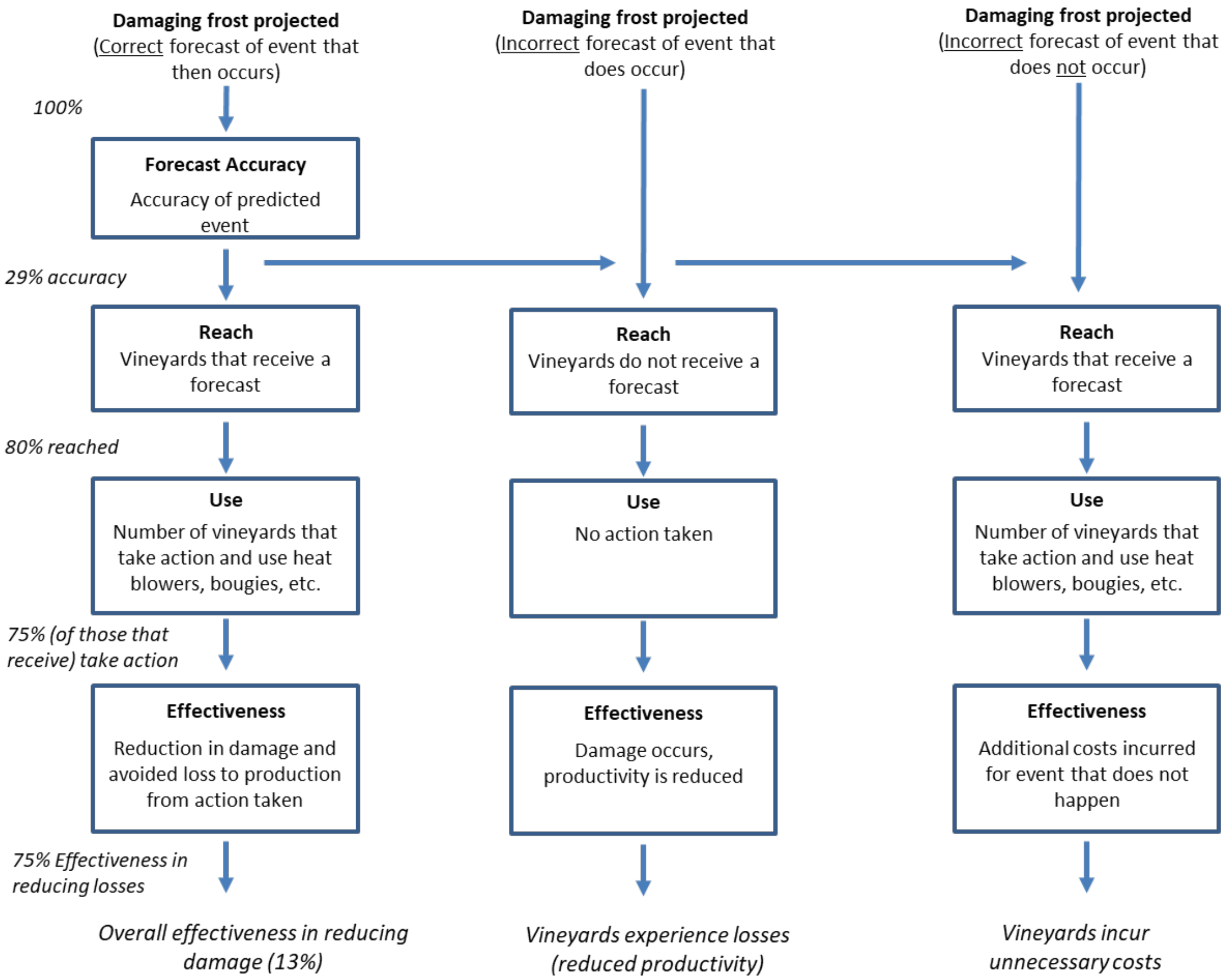


Figure 17 Value chain and efficiency drop off for frost forecasting and vineyard action.

Extension to future climate change investments. A baseline is also needed for the use of these improved frost forecasts (from better observations) in longer-term investment decisions, i.e., for adaptation. The baseline looks at the period out to 2040, to broadly reflect the lifetime of vines planted in the current period and especially the relevant financial period to get back the return on investment.

The starting baseline is over the investment decisions for new vineyards or grape varieties. In the past this would have been based on the historical observed climate. We use the current values that 2,840 hectares are currently in production (assuming 75% of 3,800 ha is in production) and that this hectarage is maintained to 2040. We assume an estimate of annual profit per hectare of £5000. This estimate is taken from the net return estimate given in Savills (2019) who find an average of £5,000 per ha per year after 5 years of establishing the vine, within a range of £15,000 to -£5,000 depending on the performance of the crop in a given year. Adopting this value, annual net returns are estimated to be £14.2 million whilst total returns over the period are approximately £270 million.

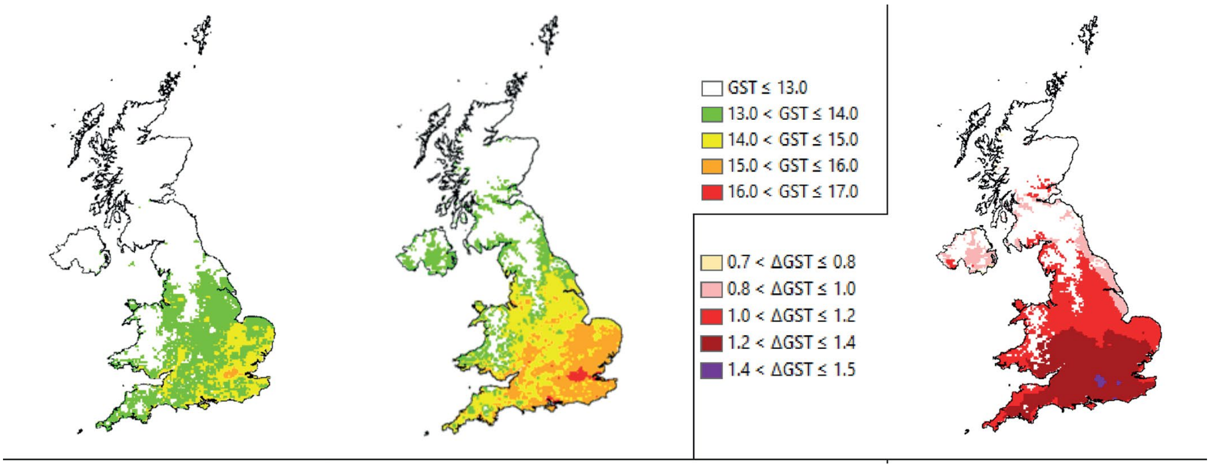
There is then an additional step on the use of climate information and the future baseline under climate change. The analysis has looked at the potential increase in hectares of wine grown in the UK with climate change. In this case, the climate model projection information and sector studies indicate potential opportunities for viticulture will increase and this would be expected to lead to an increase in wine production. There are different information sources that can be used to explore this future increase.

Over the last 30 years, total hectarage in production has increased by approximately 1,500 hectares – equivalent to an annual increase of 50 hectares. Taking a linear extrapolation of this growth trend would generate an estimate of 3,840 hectares by 2040 (under production). Adopting the net return value of £5000/hectare, annual net returns are estimated to be £16.5 million whilst total returns over the period are approximately £314 million.

However, putting this change in a wider context we note that this may well be too low. The anticipated growth under a changing climate is likely to be much higher than the historical average. In 2016, the English Wine Round Table with the Wine and Spirit Trade Association and Defra made pledges to increase the hectares of vineyards from 2,000 to 3,000 ha by 2020, and to increase wine production to reach 10 million bottles in 2020, and Wines of Great Britain has estimated that in 2040 annual production could reach 40 million bottles (Watkiss et al., 2019). This would imply a large increase in likely land under production (i.e., 3000 ha producing 10 million bottles in 2020, increasing to 6000 ha and 20 million bottles in 2030, on a pathway to 12000 ha producing 40 million bottles in 2040). It is noted that this assumes productivity (litres per hectare) stays constant, but current English wine production is much less efficient than that of France; the increase could in practice be a combination of additional land and additional productivity improvements. Recent analysis (Nesbitt et al., 2022) indicates potentially large increases in yields because of climate change for English wines.

A further possible future could be derived from the projected increase in the suitability for wine due to the shift in climate, provided that this would generate more profit compared to alternative use of the land. Hannah et al, 2013) report that net viticulture suitability change in Northern Europe could increase by approximately 100% by 2050, especially under warmer scenarios.

Additional information is available from the recent UK Climate Resilience programme and the project on wine (CREWS-UK). This includes data on regional trends in the GST as a representative bioclimatic indicator. It has undertaken a regression analysis that quantifies the relationship between GST and viticulture hectarage in the UK over the last 30 years – as shown below. The regression results estimate that each 0.1°C increase in GST results in an expansion of viticulture hectarage of just under 200 hectares. We combine this result with those on regional projected GST data presented in Nesbitt et al. (2022). Nesbitt et al. (2022) identify changing spatial patterns of GST across the UK. Their analysis uses a lower threshold of a level of 13°C GST to reflect the mean temperature level below which vines tend not to produce grapes and so allow wine production. They adopt a RCP8.5 climate scenario given the insensitivity of temperature to the choice of scenario in the short-medium term (although this is still likely to lead to a higher warming scenario than RCP2 2.6 to 6.0 in the 2050s). The uncertainties in these projections of GST are show shown below for past and future trends in GST using a range of twelve 5 X 5 km, downscaled, model simulations.



1999-2018 GST Modelled 2021-2040 GST Change between the two periods

Figure 18 Regional Patterns of GST and change under RCP8.5 Climate Change scenario (Source: Nesbitt et al. (2022))

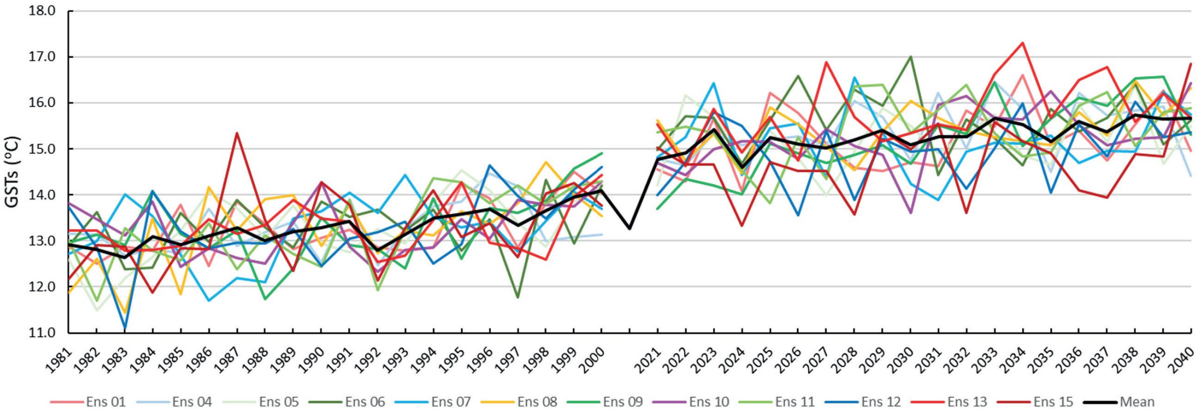


Figure 19 Results for multi-model simulations of GST (1981-2000 and 2021-2040): South-East England (Source: Nesbitt et al. (2022))

On the basis of these data we estimate that hectares under viticulture production could increase by approximately 2,550 hectares by 2040. This assumes a 1.3°C mid-point increase in GST in the Central and Eastern regions of England (with a range of 1.2°C and 1.4°C) and assumes that suitable land and soil availability does not provide constraints. We make the conservative assumption that the increase in GST is a linear one to 2040. We also assume that annual net returns in this 20-year period are at the level, £15,000 per hectare, reached in 2018 – a year characterised by a warm, dry, summer that resulted in exceptional yields and grape quality – since it is projected that these conditions will occur across England in the majority of years to 2040 (Nesbitt et al. 2022). The resulting increase in net returns over the sector, as a consequence of the expansion in hectarage that the rise in GST facilitates, is shown below. The total increase in net returns over the whole period resulting from the 1.3°C (1.2°C - 1.4°C) increase in GST is estimated to be around £400 million (£370 m - £430 m).

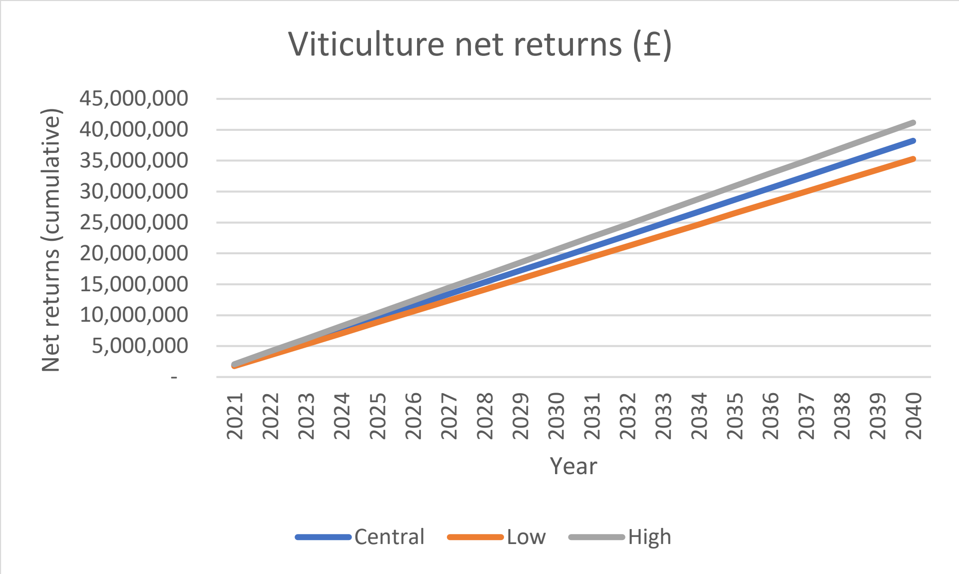


Figure 20 Cumulative net returns, 2021-2040, resulting from viticulture expansion, UK

This central total, and range, effectively constitute the benefit of climate change (2021-2040) above the “no change” baseline. The total annual average net returns over the period equate to £49.5 million – an increase of £17.4 million (54%) on the historical annual average net returns of £32.1 million. In a case where the UK wine industry is using climate information to inform all investment decisions for this increase, this benefit could be attributed to climate information. In practice, however, there will be a considerable efficiency loss along the value chain for such decisions. This could be explored, for example, with surveys of current vineyards (and their awareness on climate projections) as well as discussion with potential new investors.

Step 5: Assessment of Benefits of Improved Service

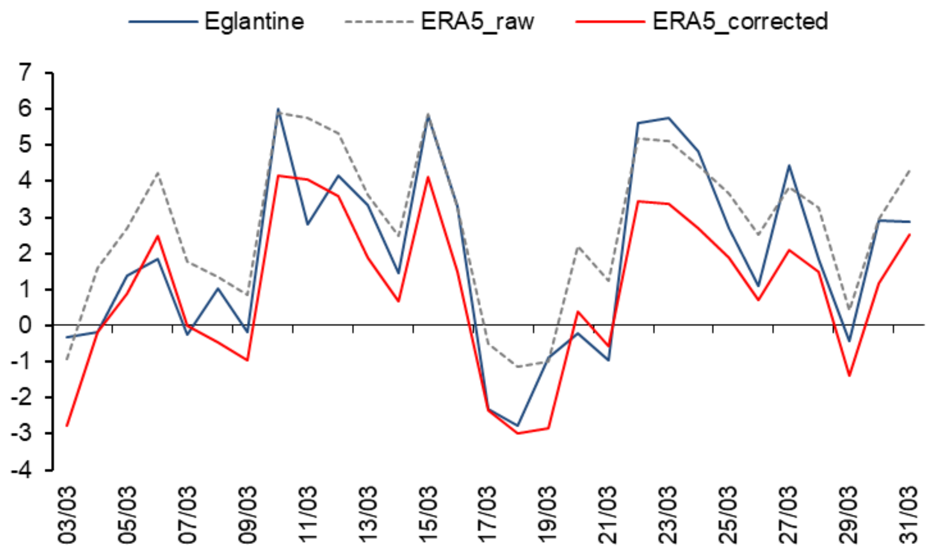
Benefits of observations in current service. This case study has first focused on the benefits of historic or observational data in improving the effectiveness of current W&CI services for wine, through improved accuracy of events, as well as reduced false negatives and false positives.

Building on Step 4, there are a number of possible ways in which improved historic data and observational data could help improve W&CI services for viticulture, specifically for reducing frost damage. These could include, for example:

- More specific correlation of damage with historic observational data to allow more targeted forecasting of specific variables (thresholds) of relevance for wine at the site-specific scale.”
- to allow more targeted modelling and forecasting of specific variables (thresholds) of interest for wine at the site-specific scale.
- Use of historic data and observations to improve **accuracy** of spring frost modelling at vineyards.
- **Downscaling site-specific (local) data** for individual vineyards. This is most readily achieved where there is an on-site meteorological station or an archive of historic weather data.
- Improved **timeliness** of frost forecasts from the Met Office, including length of advance forecast, to give more time to mobilise equipment and personnel to take action in advance.

The approach is illustrated below, assuming an improvement in **site-specific** frost forecasting accuracy from 29% (indicative baseline) to 79%. This is a marked improvement which Wilby estimates on the basis of bias-correction and customisation of down-scaled modelling undertaken for the Eglantine vineyard – see Figure 14.

Figure 21. Correlations between Observed Temperature and Raw & Corrected Forecast Data (Eglantine Vineyard, March 2018)



Clearly, alternative levels of improvement that are judged plausible can be scaled from this. Adopting the assumption of improving from 29% to 79% accuracy, total annual losses in profitability fall from £1.2 million to £0.4 million – see Table below. Thus, the UK-wide benefits of the improved weather forecasting service due to the local calibration to site-specific data is found to be £0.8 million in this case.

These benefits need to be adjusted to account for the efficiency losses in the value chain. For example, moving from 29% to 90% in forecast accuracy moves the overall value chain effectiveness (See Figure above; the calculation is now 79% accuracy * 80% of producers receiving the forecast * 75% acting as a result of the forecast * 75% effectiveness of those actions.) from 13% to 36%. Table 10 shows that the net effect on profit as a result of accounting for value chain efficiency losses is an increase of £0.08 million since the losses are £1.69 million rather than £1.77 million.

Table 19 . UK Wine Profitability under frost event scenarios (maximum likely improvement), theoretical potential.

	% Annual Loss	Loss of Net return (profit, £m)	Actual Net Return (profit, £m)	Loss of Net return (profit, £m, adjusted for value chain losses)
Loss with no frost	0	0	49.5	
Av annual loss with no forecast (%)	4.1	2.02	47.5	
Av annual loss with standard forecast (%)	2.49	1.23	48.3	1.77
Av annual loss with improved forecast (%)	0.86	0.42	49.1	1.69

Our case study can be seen as part of a broader programme of research to investigate how weather and climate risks to viticulture can be managed. For example, the UK Climate Resilience Programme funded a project in this area, Climate Resilience in the UK Wine Sector (CREWS-UK) project[27],[28] that explored these principles in the context of frost risk under future climate change. The research has the following objectives:

1. To produce a very detailed dataset of air frost risk (still a critical hazard for grape growth) to quantify local frost risk more accurately and hence site suitability for growing grapes (viticulture) in the current climate.
2. To develop indicators of climatic risk under future climate change for the 2030s and 2050s based on newly available climate model projections for the UK.
3. To assess decision-making processes with respect to adaptation in the wine sector and examine the role of perceptions of climate change risk and opportunities in decision-making.

The first of these would align to the potential for improved data on air frosts to allow improved local quantification of frost risk, i.e. providing longer-term agroclimatic data for siting decisions. In theory, it would also provide information that could be used to improve the modelling and forecasting of air frost, in terms of early warning as we investigate in this case study.

However, discussion with the CREWS-UK team indicates this information (for 1) is not available, and the team replied to a request for the data that '*the project evolved for many reasons (not least Covid-19) and we had some significant problems with the Hadley data*'.

<u>Benefits for future investment decisions (climate change)</u>. Finally, there is an additional step to assess the value of the improved frost forecasts (from better observations) in improving future adaptation

[27] https://www.lse.ac.uk/granthaminstitute/resilient-wine
[28] There is also one European project looking at climate services for wine, though focusing on long term (decadal) predictions of the main climatic factors which impact on grape growth and quality (MED-GOLD). https://www.med-gold.eu/case-studies-grape-wine/

decisions and the new investment in wine. This is more challenging to do, but it is explored conceptually below.

As estimated above, there is a benefit from climate information to help investment decisions on wine and take advantage of the opportunities of climate change. This economic benefit (annual average net returns over the period equate to £49.5 million) can be attributed in part to climate information, provided that this climate information is used in the investment decisions. This represents the value of information, and helps investors make the decision to invest, and to invest in more suitable locations or varieties, that take account of the changing climate. However, this needs to be factored down to take account of value chain efficiency losses, e.g., not all investors will be aware of the information, only some will use the information in the decision, etc. It is difficult without more information to know how large these efficiency losses are. There is a more general question about how accurate the climate change projection information is, which is explored in a subsequent adaptation case study on climate allowances.

In addition, there is an additional benefit from improved observations in improving the accuracy of climate model projections, which in turn lead to a change in the decisions that investor make - specifically allowing for an improved decision that reduces losses or increases profits. It is the marginal change in profits or losses from the decision that represents the economic benefit (value of information) or the improved observations. This is illustrated below in Figure 15.

For an existing vineyard, new climate projection information may convince the owner to plant new varieties, i.e., to undertake adaptation to the changing climate. This could arise from a shift in suitability for current vines, or because there is a new opportunity to grow more profitable varieties. There is an economic benefit from climate projection information in helping make this adaptation decision if climate projections are used to make this decision (centre column). The benefit of improved observations (for frost) could subsequently help in a number of ways (right column). It could improve the climate model projection (more accurate frost projections) and give greater confidence to the decision to change variety, or the improved frost early warning service might allow a different decision, e.g., to change to warmer varieties that have more frost susceptibility but higher profits, on the basis that frost risks could be reduced from the improvement in the service.

Similarly, there is a series of steps for a new vineyard investment. New climate information might provide an incentive to invest, but it would only be through the use of climate projection information in the decision itself that a benefit is generated, i.e., as part of the adaptation decision. Subsequently, improved observations might help this decision, for example by improving the accuracy of the projections (for frosts) which would give more valuable information on location or varietal choice or give greater investor confidence. It might also be that the improved frost service (from improved observations) might also give an investor greater confidence to invest in more frost sensitive locations or varieties, to advantage of low land costs (e.g., outside of the southeast) or more profitable but more sensitive varieties, both of which could increase the return on investment (see also next section).

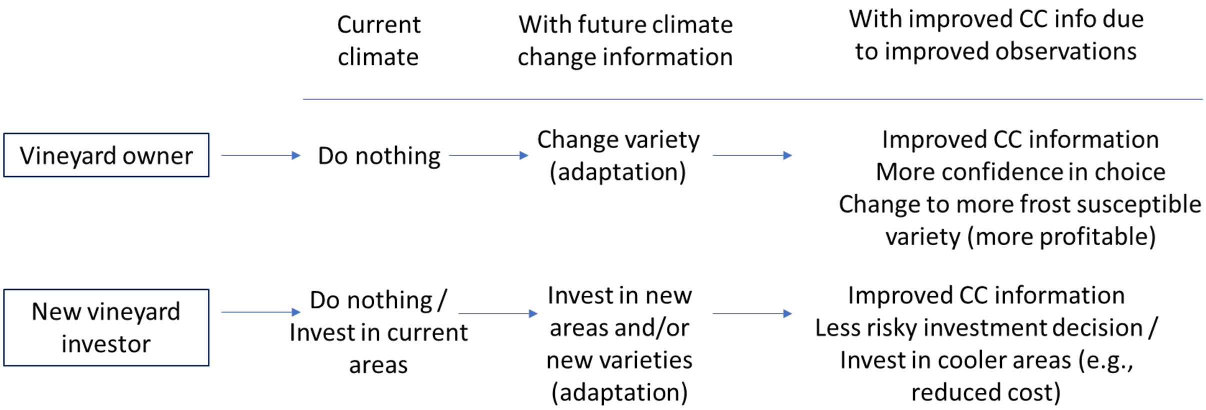


Figure 22 Outline of Investment decisions for future climate change and addition of improved observations

However, it is difficult to attribute a % improvement due to the new observational information. For example, it is not clear by how much improved frost observations might improve climate model projections, or investor confidence, though we judge it to be low. This might mean that a small % of the earlier economic benefits of climate change opportunities (of the annual average net return of £49.5 million) can be attributed to the improved observations (noting also that this value needs to be adjusted down for value chain efficiency losses).

Furthermore, these potential frost related benefits are projected to be largely independent of changes in other bioclimatic indicators such as GST under climate change. It is projected that the incidence of frost days in the March-May period reduces by 2-6 days across many parts of the UK in the period, 2021-2040 (Nesbitt et al., 2022), however, it is also likely that warmer Spring temperatures will lead to earlier vine growth and so the risks of suffering frost damage remain. In effect, the frost risks continue, but are shifted to an earlier time in the year. This may mean that in this particular case there is little additional benefit from improved frost forecasts in climate adaptation decisions, however, this information could be more valuable for early warning services for vineyards in future management decisions to reduce frost risk, as a larger wine sector will have potentially larger losses when early and severe frosts do occur.

Step 6: Assess the costs of the project developing the climate service

There are costs associated with the baseline activities.

Improved frost forecasts. These costs include all activities associated with the set-up and running of the current (baseline) service. This includes recurrent/operating costs associated with staff salaries, modelling and forecasting, and maintenance, etc. These costs are complicated to estimate since the service also includes shared costs with other Met Office activities. For this case study, the important issue is the costs of the additional observations and their use in forecasts, i.e., the costs associated with the activities that lead to the improvement in forecast accuracy. Discussions were held with the Met Office about the service cost, i.e. the operating costs of the prediction and the delivery of such forecasts. This was considered commercially confidential, and it was not possible for Met Office to share this information. However, our own calculations suggest that a notional fee of £995 service charge might be reasonable to: install a thermistor at the vineyard; return and download 2m air temperature data after two frost seasons (at least 15-18 months of data); quality assure and analyse vineyard Tmin with respect to weather forecasts for the nearest model grid cell; then evaluate the added skill of site frost frequency forecasts compared with a standard weather app.

Costs of the investment decisions (future climate). There would be additional costs associated with the production of climate information, and in theory, the additional costs of incorporating improved observational information on frosts into the models.

There is some baseline information on investment costs. Typically, wine investment has quite high capital costs, with £21,000 to £30,000/ha typically required for vineyards (including planting materials and labour for establishment but not the land). In general, the costs of investment would not change – instead the main benefit is in an improved internal rate of return for these investments, i.e., climate change information – and improved information with observations included - would improve the return on investment.

Table 20 Average costs to a commercial enterprise on a suitable site.

	Double Guyot	
	per ha	per acre
Number of Vines	3,000 - 5,000	(1,210 - 2,020)
	£ per ha	£ per acre
Establishment Costs:	over two years	
Materials	14,700	5,950
Labour	12,500	5,059
Total Establishment Costs	**27,200**	**11,009**
Subsequent Annual Costs:		
Materials	1,500	607
Labour (growing)	6,095	2,467
Harvesting*	1,600	648
Total Variable Costs	**9,195**	**3,721**

Source: John Nix farm management pocketbook (2015). Note h*arvesting costs are very yield dependent.*

Step 7: Compare benefits against service costs

Step 6 reports that it was not possible to quantify costs for the service. Thus, Step 7 – required in an economic appraisal – is not possible to undertake in this instance. Given the potential scale of benefits above, however, even with efficiency losses we consider it likely that the service would pass a cost-benefit test, especially as prediction service costs would be shared between various sectors, and the marginal costs associated with the observation-based forecast service would be modest.

It should also be noted that each user – in this case the individual viticulturalists – will have fee costs associated with receipt of the forecast service and its use. It is assumed that – formally or informally – these costs are weighed against the perceived benefits of the service, i.e. the increase in profits as a result of increasing the vine yield.

Looking to future climate information, the baseline costs would include any tailored wine specific climate information and projections, and the additional costs to include the observational information into these. Given the large potential economic benefits from wine in the UK under climate change, the value of improved climate information in this area would be high. This would improve the decisions for new investments, and even though the benefits arise in the future, the low costs of producing tailored information for new wine areas would be likely to result in a high benefit to cost ratio. In terms of maximising such opportunities from climate change, there is a role for the Government to provide the enabling environment for the wine industry to take advantage of the positive changes in suitability and productivity. This could include support to help develop tailored information for viticulture investment. Previous analysis (Watkiss et al., 2019) has found that under a scenario where wine growers are able to realise the benefits of climate change due to better information (and take appropriate investment decisions), and at the same time introduce adaptation measures to address potential variability risks, there would be very large economic benefits and a high benefit to cost ratio.

Step 8: Undertake sensitivity and bias analysis, then review how benefits could be enhanced.

The analysis includes a number of assumptions, rankied from highest to lowest importance as:

- The validity of transfer of temperature-frost damage loss functions related to viticulture productivity impacts from original studies to current study;
- The value chain assumptions, notably that 80% of potential end-users receive the weather forecast information, that 75% of end-users who receive the forecast information consequently act and that end-users are 75% effective in their use of the forecast information;
- The accuracy of standard and customised forecasts, assumed to be 29% and 79% respectively.

There is considerable uncertainty in each of these assumptions, and the results here could be strengthened with better information in these areas.

For the future orientated analysis, the key sensitivity is around that rate of future change in GST across UK regions, as well as the rate of increase in hectarage. Key assumptions adopted – ranked from highest to lowest importance – include the following:

- Validity of transfer of historic GST-hectarage relationship (ex-post impact assessment) to future time period (ex-ante impact assessment)
- The use of a single, high, RCP8.5 climate change scenario from which GST data are derived;
- The use of a single bio-climatic variable with which to identify quantitative linkages with investment in viticulture hectarage;
- The use of the net returns per hectare of £15,000, derived from the 2018 analogue season.

4. Conclusions

This case study uses an 8-step approach to assess the economic benefits of improvements in observations (foundational information) to improve a short-term, observation-based, weather forecasting service. The case study application is focussed on the weather impacts on the production of wine in the UK, specifically the impact of Spring frosts (March – May) on vine productivity. The quantification of impacts is based on data on wine production, combined with frost-vine damage loss functions from the published academic literature.

Future analysis could also look to develop quantitative estimates of the costs of more tailored weather and climate services for wine, which would also allow a cost-benefit analysis. Such an analysis should incorporate a wider range of weather-related metrics of relevance for viticulture. Nevertheless, the existing analysis serves to demonstrate that there is currently significant potential for viticulturalists to make use of observation-based weather forecasts to better target resources and so reduce the risk of losses and increase the cost-effectiveness of their operations.

The case study has also been extended to consider the potential role of observations in providing information for climate services, in this case for adaptation services. The analysis has first looked at the potential additional benefits from climate information in making future wine investments. This indicates the potential increase in hectares under wine production and the total annual average net returns over the period could equate to £49.5 million. In a case where the UK wine industry is using climate information to inform these new investments, this benefit could be attributed to climate information. In practice, however, there will be a considerable efficiency loss along the value chain for such decisions. Nonetheless, the analysis indicates that improvements in climate information for investors would be likely to generate large economic benefits, and relative to the costs of producing this information, would have high benefit to cost ratios.

The improvements in observations, as identified in the current W&CI service example, could also provide additional benefits in relation to these future investments, with economic benefits. There is a potential additional benefit from improved observations if these can help improve the accuracy of climate model projections or contribute to more specific tailored information for viticulture investors. These would support the decisions that investor make, for example in location and grape choice, which could provide additional profits. However, it is difficult to attribute a % improvement due to the new observational information in this case. This is because it is not clear by how much improved frost observations might improve climate model projections or improve investor confidence.

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Methodology for Valuing and Monitoring Climate Services to Manage Climate Variability

Case Study: Economic Valuation of Adaptation Services - Extending Heat Alert Schemes (reactive adaptation)

Deliverable 4 of the project 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services'

Paul Watkiss and Alistair Hunt

Summary

This report presents the third case study for the task 'methodology for monitoring and valuing climate services', as part of the project *Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services*. This case study focuses on the valuation of climate services for early, reactive adaptation decisions.

Valuation of adaptation services

Investing in W&CI services leads to improved information, for example from enhanced early warning or seasonal forecasts. In turn this information provides economic benefits to users, as it leads to positive outcomes from improved decisions. However, for these economic benefits to be realised, there needs to be an effective flow of information along the W&CI value chain, from the production of information through to its uptake and use in a decision.

There are existing approaches for valuing traditional W&CI services, i.e., for weather and seasonal forecasts. These involve identifying potential benefits, developing a value chain, choosing a method, and then analysing the economic value of the service relative to a baseline, including all costs and benefits. These approaches are also potentially applicable to climate services associated with adaptation. However, adaptation involves different information (climate projections) and different timescales and decision types. This case study applies W&CI valuation approaches to an adaptation decision to explore these differences and draw insights on the transferability of methods.

Case study: reactive adaptation to extend heat alert schemes

An early priority for adaptation is to address current adaptation gaps by implementing 'no-regret' or 'low-regret' actions. These actions reduce the risks associated with current climate variability or extremes, as well as emerging climate trends. As such, they are reactive and respond to climate risks already being experienced, rather than projected in future time periods. No- and low-regret actions lead to immediate economic benefits and thus often have positive benefit to cost ratios. Enhanced or new W&CI services are frequently cited as good examples of low- or no-regret adaptation actions. The valuation of these new / enhanced services can help in adaptation decision making, by making the economic case for investment and demonstrating value for money.

For this case study, an analysis was made of the potential costs and benefits of extending the current English heat-health alert system. The current service provides early warning for the impact of prolonged extreme heat on public health, and the alert is published by UK Health Security Agency, based on Met Office information. The case study has first assessed the economic benefits of this current service, in terms of its health benefits including avoided fatalities. This has used economic valuation based on established methods in UK government for appraisal.

The case study has then looked at the potential extension of this system as the adaptation decision. This has focused on extending the scheme to Scotland, as a proposal to do this was included in the recent Glasgow City Region Adaptation Strategy, driven by the recent trend of hot summers and associated heatwaves, and by the new UKCP18 projections (and the significant increase in heatwave risk for Scotland). The case study values the potential economic benefits of this extension, and thus the value of the information used in making an adaptation decision.

Results

The analysis has first assessed the economic benefit of the current heat-health alert system in England. This finds that the system has high economic benefits from the reduction in the risk of heat

related fatalities. However, there are two key factors that influence the size of this benefit. The first is over the effectiveness of the system in reducing mortality risk, as different studies report different findings. To test this, two levels of effectiveness were assessed (10% and 40%). The second is on the valuation of changes in mortality risk, where there are alternative valuation methods which lead to large differences, depending on whether a full value of statistical life (VSL) is used, or an adjusted value such as a value of life year lost (VOLY). These factors were investigated using sensitivity tests. The analysis also looked at the costs of operating the scheme, including the resource costs to the health sector each time an alert is triggered. A key finding is that the current system in England delivers a positive benefit to cost ratio across, under all sensitivity tests, indicating a robust positive finding, though the level of benefits varies significantly. The benefits of the scheme under future climate change have also been assessed, and this finds that economic benefits increase over time.

The analysis has then assessed the value of extending the scheme to Scotland. This has looked at the possible economic benefits of extending the scheme immediately, as well as how these benefits might increase over time with climate change. The analysis finds there are net economic benefits from introducing the scheme now (and a positive benefit to cost ratio), including for all sensitivity tests. These benefits reflect the value of information from the use of climate information in this potential extension decision. The results are presented in the table below.

The analysis has also used data from the UKCP18 projections on heat-wave risk for Scotland (for RCP8.5), to assess how these benefits might increase in the future. These are shown in the table and show the large increase in economic benefits over time. This is important information that could further convince policy makers of the need for the scheme. The additional benefits (future over current) are also shown, to allow a potential attribution of the value of future climate projections versus current information. This shows future additional benefits are as large as current benefits.

Summary of the Economic Benefits and Benefit to Cost ratio for the Adaptation decision to extend the Heat Health Alert System to Scotland (See main report for caveats)

Benefits of scheme in Scotland 2020s	VSL Economic benefit £M /yr and Benefit to Cost Ratio	VOLY Economic benefit £M /yr and Benefit to Cost Ratio
Benefit at 40% effectiveness	£32M/yr (BCR 155:1)	£0.9 /yr (BCR 4.2:1)
Benefit at 10% effectiveness	£7.9 M/yr (BCR 39:1)	£0.2/yr (BCR1.1:1)
Benefits of scheme 2050s (RCP8.5) – note benefits are undiscounted		
Benefit at 40% effectiveness	£69/yr *	£1.9/yr *
Benefit at 10% effectiveness	£17.3/yr *	£0.5/yr *
Increase in benefits of 2050s over 2020s (undiscounted)		
Benefit 40% effectiveness	£37.2/yr (BCR	£1.0/yr
Benefit 10% effectiveness	£9.3/yr (BCR	£0.3

Overall, the case study finds that the methods for valuation of conventional W&CI service valuation are applicable to low- and no-regret adaptation, though some additional steps are required when considering the future climate.

Interestingly, we also find that the application of the W&CI value chain approach is useful for adaptation cost benefit studies more generally, as it introduces a greater focus on real-world benefits, taking account of accuracy, reach, uptake and use. This provides an important insight for adaptation appraisal studies and strategy development.

1. Introduction

Investing in weather and climate information (W&CI) services leads to improved information, such as enhanced early warning or seasonal forecasts. In turn, this information can provide economic benefits to users (individuals/organisations[29]), if it leads to positive outcomes from the actions and decisions that users subsequently take.

This report presents one of the case studies for the project 'methodology for monitoring and valuing climate services', which is part of the contract 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services'. This work is being undertaken by a consortium of JBA Consulting (lead), in association with Climate Sense, Paul Watkiss Associates (PWA), Professor Rob Wilby, and Becky Venton, on behalf of the Met Office. The valuation work is led by PWA.

The project has developed a methodology and draft set of guidance for valuing climate services, as well as method and guidance for analysing value for money (as part of monitoring). These tools are being tested through a series of case studies (Deliverable 4). This case study is focused on adaptation services, focusing on early (no- and low-regret) adaptation decisions.

Defining Adaptation

The starting point is to define adaptation. The IPCC 6th Assessment Report definition is:

Adaptation. In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.

This includes:

Incremental adaptation. Adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale.

Transformational adaptation - Adaptation that changes the fundamental attributes of a system in response to climate and its effects.

Resilience. The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. It also highlights that in the literature, resilience is an entry point commonly used, although under a wide spectrum of meanings.

The Climate Change Risk Assessment 3 Method (CCRA3) (Watkiss and Betts, 2021) included additional definitions for adaptation, as follows:

Reactive adaptation - Adaptation in response to experienced climate and its effects, rather than a pro-active planned approach.

Pro-active planned (anticipatory) adaptation - Planned adaptation to projected climate effects. Note this can be taken by both public and private actors.

It is stressed that climate information used for reactive decisions is likely to be closer in nature to traditional W&CI services. As an example, this might include farmers taking action following a severe

[29] In this report we use "organisations" as being representative of all parties that value weather information.

drought, or a household responding to increasing floods by buying household protection measures. In contrast, planned adaptation is longer-term, and generally uses climate change projections and thus different types of information. It involves different types of decisions, such as climate proofing infrastructure to possible future conditions or developing a new adaptation project in response to anticipated future change. This involves more complexity due to the uncertainty and long-time frames involved.

The most relevant focus here is adaptation information (services) for current or near-term adaptation decisions to address short, medium, or long-term climate change. This aligns with the focus of the UK Climate Change Risk Assessment 3 (CCRA3) on most urgent adaptation decisions. The CCRA3 typology (Watkiss and Betts, 2021) set out three types of early adaptation priorities that can help address risks and opportunities within the next five-years:

- To address any current adaptation gap by implementing 'no-regret' or 'low-regret' actions[30] that reduce risks associated with current climate variability, as well as building future climate resilience.
- To intervene early to ensure that adaptation is considered in near-term decisions that have long lifetimes and therefore reduce the risk of 'lock-in', such as for major infrastructure or land-use change. This often requires the use of decision making under uncertainty (DMUU).
- To fast-track early adaptive management activities, especially for decisions that have long lead times or involve major future change. This can enhance learning and allows the use of evidence in forthcoming future decisions.

These three priorities are not mutually exclusive, and a combination of all three is often needed as part of a portfolio of adaptations.

In this case study, we explore two applications to that relate to the priorities above. This involves one case study that focuses on no- and low regret adaptation, supported by a W&CI service (noting that W&CI services are often cited as examples of no-regret adaptation), and one that is planned, concentrating on future climate proofing.

Defining Adaptation Services

A key issue for this case study is the definition of adaptation services, including their differentiation from weather and climate services more generally. Most existing definitions of climate services incorporate all climate information (including climate projections) and many highlight additional adaptation components. For example:

The Global Framework for Climate Services[31] defines climate services as those that '*provide climate information to help individuals and organizations make climate smart decisions'*. It also explains that '*The data and information collected is transformed into customized products such as projections, trends, economic analysis and services for different user communities*'. The GFCS has an additional

[30] No-regret adaptation is defined as options that 'generate net social and/or economic benefits irrespective of whether or not anthropogenic climate change occurs' (IPCC, 2014). A variation of no-regret options are win-win options, which have positive co-benefits, such as wider social, environmental or ancillary benefits. These are differentiated from low-regret options, which may have relatively low costs or high benefits, or may be no-regret options that have opportunity or transaction costs in practice.

[31] https://gfcs.wmo.int/what-are-climate-services

element that '*Climate services equip decision makers in climate-sensitive sectors with better information to help society* <u>*adapt to climate variability and change*'.</u>

The IPCC WG II Glossary (IPCC, 2022) defines that: *Climate services involve the provision of climate information in such a way as to assist decision-making. The service includes appropriate engagement from users and providers, is based on scientifically credible information and expertise, has an effective access mechanism, and responds to user needs (Hewitt et al. 2012).*

The European Commission roadmap for climate services (2015) defines climate services as '*the transformation of climate-related data — together with other relevant information — into customised products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counselling on best practices, development and evaluation of solutions and any other service in relation to climate that may be of use for the society at large. As such, these services include data, information and knowledge that support* <u>*adaptation*</u>*, mitigation and disaster risk management (DRM)*'.

These definitions treat climate change information and adaptation as part of a temporal continuum from current weather-related forecasts through to information about future projected climate change. This is shown in the figure below (from Hansen et al., 2019).

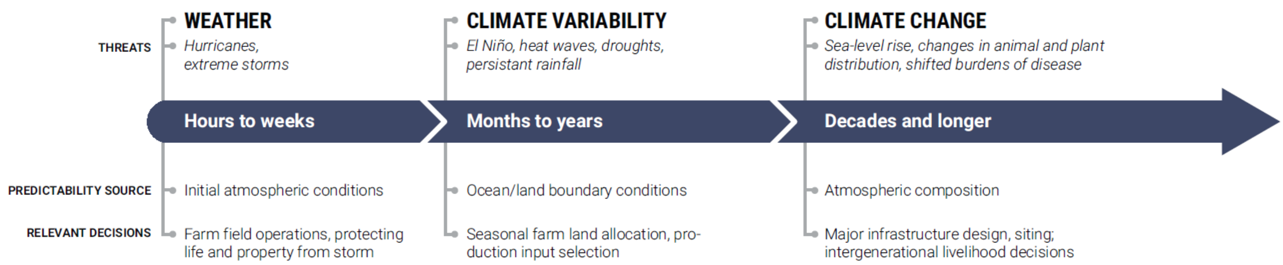

Figure 23 Time scales of atmospheric variation, information, and climate-sensitive decisions. Source Hansen et al. (2019).

A key aspect of this case study is to explore whether adaptation services can be treated as part of the continuum in Figure 1 above, or whether they have different characteristics, especially when used in decisions, and by extension, in their economic valuation.

To be explicit, while climate service providers (e.g., meteorological agencies and meteorologists) seem to consider all the timescales in Figure 1 as part of a common suite of similar climate services (at least based on the definitions above), an adaptation practitioner and especially an economist is likely to consider them to be very different. This is due to the nature of the information and the decisions made. This is important in that it means <u>the framing and method used for valuation of a seasonal forecast (e.g., as in the methods set out in WMO, 2015) is likely to different from the valuation of climate projections in a long-term adaptation decision.</u>

There are a few papers that distinguish and define information related to future climate change information and adaptation services.

Climate services for adaptation have been defined *as all public and private services supporting adaptation to climate change* (Cavelier et al., 2017; Visscher et al., 2020 citing Hewitt et al., 2012).

Visscher et al. (2020) outline four climate services that cover the types of services that might be involved in climate information for adaptation.

Table 21 Typology of climate services. Source Visscher et al., 2020.

	Generic	Customised
Focused	**Maps & Apps** • General climate services • For all users • Made freely or cheaply available	**Expert Analysis** • Mono- or multidisciplinary climate services • Tailored to specific decision-making situations • Offered commercially
Integrated	**Sharing Practices** • Mutual climate- and climate policy services • Among knowledgeable peers • Made freely or cheaply available	**Climate-inclusive Consulting** • Interdisciplinary management, engineering, or policy services including climate data • Tailored to specific decision-making situations • Offered commercially

Visscher et al. give examples of these for climate change and tourism in Europe.

- Maps & Apps, climate data and projections are provided on a national, regional, or local level to groups of civil servants, policy-makers, managers, entrepreneurs and citizens, which they can consider when making decisions on infrastructure, investment portfolios, policy measures, etc.
    - An example is generic information on climate change impacts on tourism (e.g., changes in snow conditions, tourism demand) such as the IMPACT2C Atlas, showing the impacts of +2 °C global warming on the tourism sector, or CLIMAMAP which provides fact sheets on climate change impacts for each Austrian province, using several climate indices.
- Expert Analysis, services are provided by specialized, commercial consultancy firms and market-oriented branches of meteorological and research institutes, which interpret climate models to deliver tailored analyses regarding projections, climate policy, and mitigation arrangements. Users of these services benefit from better risk assessments, design decisions, policy measures, etc., specific for the decision.
    - An example of tailored snow simulations, adding value to investment decisions of an individual ski resort. Compared to generic study results, these tailored services can provide higher spatial resolution and take local data and individual snowmaking capacities into account. Information produced might include changes in average season length, or the probability of ski operation during Christmas holidays, etc
- Climate-inclusive Consulting, commercial, interdisciplinary consultancies, create and deliver climate services by taking climate data and projections into account when advising decision makers on a broad range of subjects, such as infrastructure, investments or corporate strategy. Value for users is created by more robust designs and more prudent and effective decisions, customized to the customer's decision-making situation.
    - An example could include the assessment of a ski area's importance for the regional economy, an assessment of the area's risks to climate change, the analysis of opportunities and challenges, and an economic feasibility study of various investment options. The analysis would be based on tailored snow simulations (i.e., Expert Analysis), accounting for the ski area's specific snowmaking capacities and extension plans. Using

data on current skier days and sales, changes in ski season length can be translated into monetary terms and incorporated into the economic feasibility study of the investment options

- Sharing Practices, users of climate services may also be producers of climate services. The identification of best practices and the sharing of experiences among knowledgeable peers – for instance, local governments within a certain region, or companies within a certain branch. The exchange of services within these communities is facilitated by databases, platforms and events, which are partly sponsored by public bodies, and partly offered by commercial platform providers. These services relate to actual decisions and policy measures, which are integrated in more encompassing contexts of use
    - An example is sharing practice among ski resort operators in another field: neighbouring ski resorts jointly commissioning a market research study, including individual consulting for each ski resort. This could be an example for the use of climate services as well, e.g., joint acquisition of tailored snow simulations for a specific tourism region, and a starting point for sharing practical experiences on how to deal with decreasing snowfall.

An alternative structure for adaptation services is presented by Cavelier et al. (2017), who consider the market uptake of climate services for adaptation in France and present the following figure.

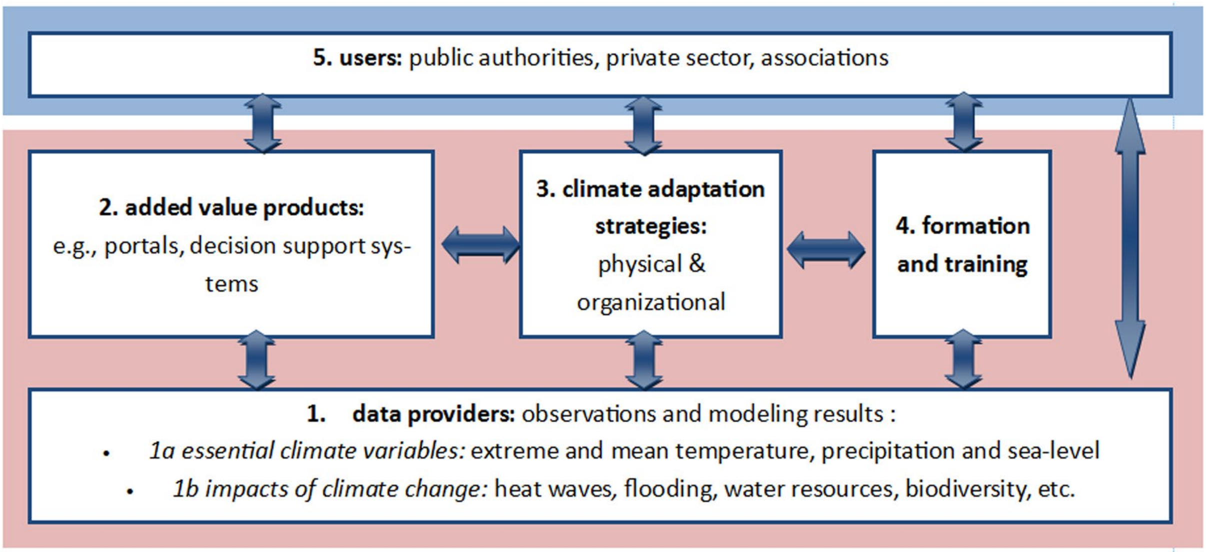

Figure 24 *Climate services providers and users and their interactions. Source Cavelier et al. (2017)*

In their analysis, data providers deliver the observations and modelling results that allow the evaluation of past, present, and future climate change. Cavelier et al. identify three main categories of activity:

- organisations designing added value products such as portals and tools providing impact assessment results.
- design of adaptation strategies and support for decision making on adaptation.
- education and professional training, building capacity to adapt to climate change.

They identify different services:

- Climate observations, models and knowledge.
- Impact studies, portals and advanced products.
- Adaptation studies.

Cavelier et al. use case studies to illustrate information on opportunities and challenges. The paper also highlights that uncertainties in climate projections are a major barrier to the uptake of climate services (adaptation services).

Hansen et al (2019) also identifies that climate information plays a foundational role for adaptation. However, they highlight the challenges around timing, identifying that most climate model projections are for mid to late century. Conversely, few (if any) adaptation decisions have planning horizons that extend to this period, and indeed, most have little use for climate outlooks beyond 20-30 years into the future. They conclude that that this has led to a mismatch between the time-scales for information generation versus needs for support to planning and decision-making. They also argue that the near term (10-30 year timescales), which are most relevant for real-world adaptation are dominated by natural decadal variability. Of high relevance for the case studies below, they also report that climate change projections for mid- and late century can be potentially misused, as uncertainty is downplayed, often at the same time as higher-resolution, downscaled projections are provided: this has consequences for decision-making by focusing on longer-term periods that are not relevant for most short-term decisions, as well as giving misleading appearance of precise local information.

Typology of Adaptation Services

Following from the review above, we identify different types of potential adaptation services, based on a typology of adaptation, rather than a typology of information. This focuses on the adaptation decision that the climate information is used for, recognising that to deliver economic benefits, there needs to be use of information leading to an improved decision. The areas are:

- Information for use in decisions on <u>reactive adaptation or near-term low and no-regret adaptation</u>. This will rely more on current climate observations and short-term trends.
- Information for <u>anticipatory, planned adaptation,</u> which involve decisions taken now (next five years) that are predicated on longer-term climate model projections (i.e., to the 2050s).

The first has a strong overlap with existing W&CI services and can follow similar economic analysis to traditional W&CI services, although there are additional components.

The second is very different, as it involves climate change information, more challenging timescales and uncertainty, as well as other information for the decision.

Study Framing

To help frame the case studies, the analysis also considers three key questions.

1) What is the user decision?

2) What climate information was used in making that decision?

3) What is the value associated with the climate information used in that decision?

2. Valuation of Adaptation Services

Introduction

W&CI services, such as weather forecasts generate information. These services can provide economic benefits for users when this information is used to generate positive outcomes from the actions and decisions that users take (WMO, 2015). This is known as the Value of Information (VoI)[32]. As examples:

- Early warning systems can significantly reduce the damages and losses – and reduce loss of life and injuries – caused by extreme weather and disasters.
- Seasonal forecasts can help improve agricultural production (higher yields) or reduce losses from extreme events.

It is possible to quantify the economic benefits of these W&CI services. Such studies generally look at the activities and outcomes that result from the use of enhanced weather and climate services, then compare these to a baseline or counterfactual without this additional information: the difference between the two is the incremental benefit directly attributable to enhanced services.

The economic benefits of W&CI services are defined in terms of their societal benefits, based on the principles of welfare economics. This aims to assess the ability of a policy, programme or project to improve social welfare or wellbeing (HMT, 2020). Economic analysis is, therefore, carried out from the perspective of society and includes the economic valuation of non-market effects, such as environmental, cultural, social and health benefits. These non-market aspects are sometimes referred to as socio-economic benefits (SEB).

As highlighted by Hansen et al (2019) '*climate services do not contribute economic or social value unless users benefit from better decisions as a result of the information'*. Therefore, the valuation of climate services needs to consider cases where users benefit from better decisions as a result of (climate) information. We highlight that this focus is narrower than the overall CR20-2 study, which is considering standards for climate services.

However, there are two additional issues that are important when looking at adaptation service valuation, which require additional consideration compared with a traditional economic analysis of W&CI services. These are around i) time preference and ii) uncertainty. These are discussed in turn.

Time preference and discounting

In economic analysis, timing matters. This is because individuals and society generally prefer receiving goods and services now rather than later. This means that when undertaking an economic analysis (an appraisal), costs and benefits that occur in different time periods need to be accounted for and adjusted so they can be considered in equivalent terms.

There are routine methods for such adjustments, set out in economic appraisal, such as the UK HMT Green Book (HMT, 2021). Costs and benefits in different time periods are estimated in 'real' base year prices, which means the effects of inflation are removed. Subsequently costs and benefits that arise in different future time periods are adjusted to provide equivalent values using some form of

[32] Keisler et al. (2014) define the value of information (VoI) as the increase in expected value that arises from making the best choice with the benefit of a piece of information compared to the best choice without the benefit of that same information. Hansen et al. (2011) define VoI as the expected improvement in economic outcome of management that incorporates the new information.

discount scheme and discount rates. The UK government (HMT, 2021) uses a 'social time preference rate' (STPR), typically of 3.5% for public policy decisions. The use of these discount rates estimates values (benefits and costs) in equivalent present value terms.

The discounting of costs and benefits is moderately important when assessing a typical W&CI project (WMO, 2015), i.e., costs are likely to be borne in the early years as the project is set-up, but benefits will normally not accrue for a year or two later and will run over future years.

However, the influence of discounting becomes much more important for adaptation, especially where this involves benefit streams that arise in the future, especially if large adaptation costs are incurred up front. This means that future benefits (especially in the more distant future, i.e., after 2030) are given lower weight, in present value terms. This can mean it is more difficult to justify a decision that involves large costs today for benefits that occur in the future.

To illustrate, using the social discount rates in UK public policy decisions (3.5%), future adaptation benefits decline in present value terms quite rapidly. The effect of discounting on a £1 benefit/year benefit stream is shown below. The discounted present value of £1 in ten years' time is £0.71 and in twenty years' time is £0.49.

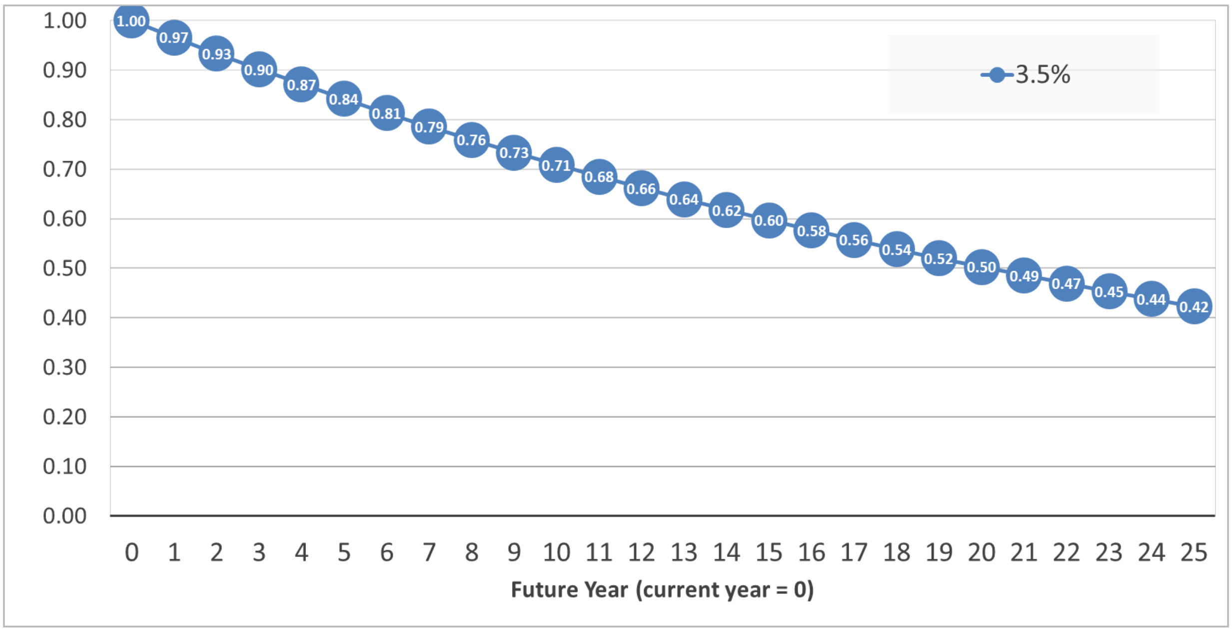

Figure 25 *Value of a future £1 over 25 years, discounted back to current year, using the HMT discount rate (3.5%).*

The discounting of future benefits is particularly important when considering proactive, planned adaptation decisions. This is because proactive adaptation timescales are typically longer than ten years, and often 20+ years in the future. In these cases, discounting is clearly significant, as evidenced in Figure 3.

Uncertainty

Another key challenge for adaptation is uncertainty (Wilby and Dessai, 2010). This uncertainty arises in a number of forms. First, in terms of climate information, it is still known what future emission pathway the world is on, i.e., towards a future 2°C or a 4°C world by 2100 (relative to pre-industrial). This scenario or emission pathway uncertainty makes a major difference to the level of adaptation needed, especially after 2050 when these start to diverge significantly. Second, even if the future emission pathway were known, there is large additional uncertainty from different climate model projections. The range of uncertainty from multi-model ensembles is as large as for scenario uncertainty, and for some climate parameters (e.g., precipitation), different models can even alter the sign of the change (i.e., whether there is an increase or decrease in rainfall). This is evidenced by the large ranges for the 10th to 90th percentile range from UKCP18 (Lowe et al., 2018). Indeed, model uncertainty is much larger than scenario (emission) uncertainty in the next two decades (as evidenced by similar results for RCP2.6, RCP4.5 and RCP6.0, though note RCP8.5 is a little different).

As well as climate projection uncertainty, there is significant uncertainty around future societal, economic and other changes that may take place in the UK and internationally: for example, urbanisation, population change, wealth disparity, net migration. This is often captured through alternative socio-economic projections in climate change modelling analysis, such as the use of the IPCC Shared Socio-economic Pathways (O'Neill et al., 2014).

In the context of W&CI service valuation, this makes it challenging to derive the baseline or counterfactual against which the service is assessed.

This uncertainty makes proactive adaptation decisions challenging. It is relatively easy to design a new investment or project to be resilient to a single future over the next few decades, but it is much more difficult to design it to cope with many unknown futures, especially where there is deep uncertainty (i.e., where there is not a good knowledge of the risk and thus no multi-emission scenario probability distribution[33]).

If a decision is made today to spend resources on adaptation, to prepare for future climate change, this uncertainty increases the risk of economic maladaptation. For example, incurring high costs today by over-designing projects to cope with the highest climate scenario, is unlikely to be a good use of resources because it will almost certainly spend money to adapt to climate scenarios that do not occur. The over-design of projects should therefore be limited to particular cases where there is a need for a precautionary approach (see Watkiss, Wilby and Rodgers, 2020). Conversely, doing nothing or too little on adaptation; for example, by only focusing on the minimal level of change projected, could lead to high damage costs in the future.

There is now a growing use of methods that address these issues through the use of decision making under uncertainty (DMUU) (e.g., Dittrich et al., 2016). These use alternative concepts to a single predict and optimise approach, for example, which focus on maximising flexibility or increasing robustness. However, while these can reduce the potential risks of maladaptation, they are time and resource intensive to use and require expert knowledge.

This also means that the exact way in which information is used in a proactive adaptation decision is important. The approach used will influence the benefits of the decision, compared to the *ex post* outturn that subsequently occurs (under future climate change), and so will lead to differences in economic benefits depending on whether DMUU is used or not. It also means there are additional steps and information used in the decision. These issues have to be factored into the benefit analysis for proactive adaptation services.

[33] UKCP18 includes probabilistic information for individual emission scenarios (or RCPs) but it does not include a single probability distribution for the combination of all scenarios.

Adaptation Service Value Chains

For the economic benefits of W&CI services to be realised, there needs to be a flow of information from the producer to the user and, further, an effective uptake and use of this information in a decision. It is the deployment of this information in a decision that leads to better outcomes than would otherwise be the case, and thus to the economic benefit.

To capture this, economic analysis of W&CI service uses a value chain approach. This maps the sequence of actions that generate the economic benefit. The steps in a value chain include the information provision itself (including climate projections), and supporting infrastructure and foundational activities, including science. It also includes the forecasting capacity and accuracy. The value chain further includes the communication to users, and thus the reach (the number of beneficiaries or users). Finally, it takes account of the uptake, understanding, and effective use of this information by end-users in order to generate value.

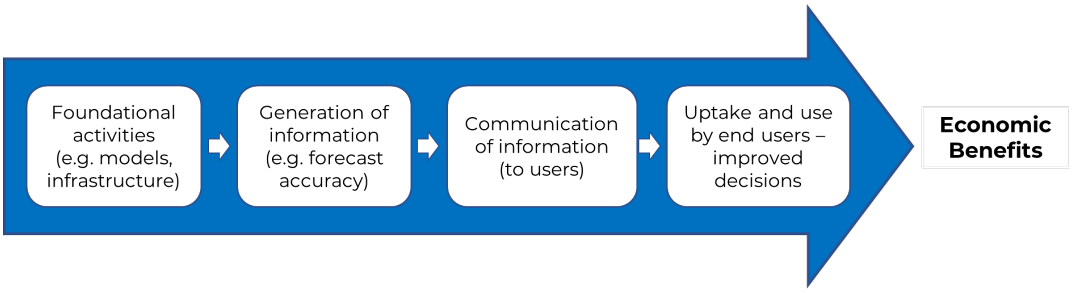

Figure 26. Simple W&CI service chains

Importantly, the economic benefits are generated at the very end of the value chain. This means there are often large efficiency losses (or decay) along the W&CI value chain (Perrels., et al 2013; Nurmi et al., 2013), which lead to much lower actual benefits than potential (maximum) benefits. For example, if a service has a low level of reach (e.g., due to poor dissemination) then the economic benefits will be low, as there will be a smaller number of users. Similarly, if a large number of users receive the information but do not act on it (or do not act effectively), the level of benefits achieved will be lower than the potential benefits. Therefore, to provide a realistic estimation of benefits of W&CI services, a value chain needs to be constructed that considers such efficiency losses.

As highlighted above, the use of information in an adaptation decision is more complex than for a traditional W&CI service. This means that value chains are often different for adaptation decisions, as they involve additional types of climate information (and for example, uncertainty) and they involve longer or more indirect pathways to end-user benefits. This extra complexity and other factors can mean that the efficiency losses that occur along the adaptation service value chain are larger than for more traditional W&CI services.

Furthermore, there are multiple information inputs needed for adaptation – beyond climate hazards. There is also a need for information on adaptive capacity and vulnerability, as well as socio-economic information (see above) when considering future effects. Moreover, it is necessary to consider how the climate information is used in the decision, and whether for example, adaptation decisions include the application of climate information in a decision using DMUU. This raises an issue around the attribution of benefits, and whether they should accrue only to the provision of climate information, or more broadly to other inputs and factors in the decision.

Economic Benefit Quantification Methods of Adaptation

The benefits of climate services can be estimated through different methods. A number of methods exist (e.g., WMO, 2015; WISER, 2017; Vaughan et al., 2019). These approaches can broadly be distinguished between those that assess *potential* benefits of climate services (using *ex ante analysis* before the service is introduced), and those that look at *actual* benefits after implementation (*ex post analysis* after the service is introduced. A summary of methods is presented below.

There is more detailed technical guidance on these methods in WMO (2015) and more technical descriptions and reviews of previous applications for different project types in Soares et al. (2018), Vaughan et al. (2019), and in the Asia Regional Resilience to a Changing Climate (ARRCC) report on Valuing climate services (Suckall and Soares, 2020).

Importantly, not all methods are applicable to adaptation services, or at least not to all types of adaptation services. For example, proactive adaptation will have to use *ex ante* approaches, due to the long timescales involved. To explore this, two different types of adaptation service have been considered in this case study.

Box 1. Methods for analysis of W&CI services.

Ex ante models. Decision-theory based models that estimate potential benefits, for example, using a crop model to assess the possible increases in yield from improved seasonal forecasts.

Integrated economic models. Models that assess aggregate effects, including cross-economy linkages, or wider economic effects for example, input-output, trade, partial or computable general equilibrium models.

Cost-loss models. Models used to analyse extreme events and Early Warning Systems, including probability loss curves based on historical event information that can be extended to look at non-monetary effects e.g., fatalities.

Ex ante surveys. Use survey-based elicitation of individuals' preferences, to assess their willingness to pay (WTP) for potential new services.

Ex post surveys. Survey users to explore actual (or perceived) benefits from climate services.

Statistical and econometric analysis. Use statistical analysis (*ex post*) to assess impact/outcomes from the introduction of W&CI services, controlling for other variables to attribute benefits.

Impact assessments. Undertake direct measurement of service impact on a group or area, before or after, or relative to a control, e.g., using agricultural field plots.

Value (Benefit) transfer. Takes estimates developed in one context and applies them in another context, rather than undertaking primary studies. This can include adjustments to the original figures to account for the new application and context.

3. Case Study on Valuation of an Adaptation Service

The study has developed guidance for the valuation of the economic benefits of weather and climate. This aligns with, and builds on, methods in the literature and in existing guidance (WMO, 2015; WISER, 2021). The methodology involves the following steps.

- List the potential economic benefits that the climate service may provide.
- Develop the value chain for the service.
- Review and decide on the potential methods for assessing economic benefits.
- Build a baseline scenario (or counter-factual) without the new climate service.
- Assess the benefits with the climate service in place.
- Assess the costs of the project.
- Compare benefits against costs.
- Undertake sensitivity and bias analysis, then review how benefits could be enhanced.

These steps have been applied to adaptation services case studies, which reflect different types of adaptation, including reactive (no regret) adaptation and proactive adaptation

Case Study on Reactive Adaptation (Heat health alert)

An early priority for adaptation is to address current adaptation gaps by implementing 'no-regret' or 'low-regret' actions (GCA, 2019: Watkiss and Betts, 2021: IPCC, 2022). These actions reduce the risks associated with current climate variability or extremes, as well as emerging climate trends. As such, they are reactive and respond to climate risks already being experienced, rather than projected in future time periods. No- and low-regret actions lead to immediate economic benefits and thus often have positive benefit to cost ratios.

Enhanced or new W&CI services are frequently cited as good examples of low- or no-regret adaptation actions (GCA, 2019; CCC, 2021). The valuation of these new / enhanced services can help in adaptation decision making, by making the economic case for investment and demonstrating value for money.

The existing approaches for valuing traditional W&CI services, i.e., for weather and seasonal forecasts are also potentially applicable to climate services associated with adaptation, especially these low and no-regret adaptation decision. However, adaptation involves different information (climate projections) and different timescales and decision types. This case study applies W&CI valuation approaches to an adaptation decision to explore these differences and draw insights on the transferability of methods.

This case study focuses on a typical no or low-regret adaptation, centred on extending an existing W&CI service for early warning in England (in this case the heat-health alert system) to Scotland. To do this, the analysis first considers the potential costs and benefits of the current English heat-health alert system. The current service provides early warning for the impact of prolonged extreme heat on public health, and the alert is published by UK Health Security Agency, based on Met Office information. The case study then looks at the potential extension of this system as the adaptation decision. This has focused on extending the scheme to Scotland, in response to warmer trends. The case study values the potential economic benefits of this extension, and thus the value of the use of climate information in an adaptation decision. This case study reflects a recommendation in the recent Glasgow City Region Adaptation Strategy (CRC, 2021) to introduce a heat-alert scheme, though it noted this would be most effective if implemented at the national (Scottish) level.

Step 1. Introduction and list of economic benefits

The current Heatwave plan for England (UKHSA, 2022) is intended to protect the population from heat-related harm to health. The aims of the plan are to prepare, alert and prevent the major avoidable effects on health during periods of severe heat in England. The purpose of the Heatwave Plan is to reduce summer deaths and illness (during severe heat and heatwaves) by raising public awareness and triggering actions in the NHS, public health, social care and other community and voluntary organisations to support people who have health, housing or economic circumstances that increase their vulnerability to heat. The plan is updated each year. The plan includes short-term responses to heat, as well as longer-term strategic planning in response to a changing climate.

The plan is underpinned by a system of heatwave alerts, developed with the Met Office, focused on the heat-health watch system (HHWS) in England, now named the **heat-health alert system** in the latest heatwave plan for England (UKHSA, 2022).

The first step is to identify the benefits of this W&CI service. This is clearly stated in the heat-health alert system (as part of the heatwave plan, UK HAS, 2022) as the reduction in **heat-related mortality (deaths) and morbidity** (ill heath, for example, respiratory and cardiovascular illnesses). These health benefits are the key benefits for economic analysis. It is noted that alongside this heat health alert[34], the Met Office also issues extreme heat warnings[35], which are additional and include potential information for reducing heat related impacts for the public (as well as for other sectors). The two systems are:

- UK Health Security Agency (UKHSA) heat-health alert system – an England only service considering the impact of prolonged extreme heat on public health, especially those with long-term health conditions. Published by UKHSA, based on Met Office information. This targets health professionals and the health care system.
- Extreme Heat Warning – an impact-based warning designed to highlight the potential impacts of extreme heat to protect lives and property, helping people make better decisions (issued by the Met office). This targets the general public as well as public and private organisations.

This step is also extended to consider the benefits of extending the scheme to Scotland. This involves the same benefits (reduced risk of fatalities).

Recent years have seen much higher peak temperatures in Scotland, compared to the historical average, and 2022 saw the highest temperature ever recorded[36], with a temperature of 34.8˚C. These unprecedented temperatures are leading to growing concerns about the potential effects of heat on health. This in turn is leading to the possible extension of the English scheme to Scotland, as proposed in recent adaptation strategies (CRC, 2021).

[34] https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/temperature/heatwave
[35] https://blog.metoffice.gov.uk/2021/06/18/why-the-met-office-is-launching-a-new-extreme-heat-warning/
[36] https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2022/record-high-temperatures-verified

Step 2 Develop the W&CI Service Value chain

The value chain for an adaptation service starts with the same elements as a conventional W&CI service value chain. This includes:

- Foundational activities, including infrastructure, observations or modelling.
- Generation of information, including accuracy of information.
- Communication of information, including timeliness of information, and thus access to information by target end-user groups.
- Understanding of information and trust in the information, affecting ability of users to respond and thus level of use/uptake by end-users.
- Effectiveness of response of users – both positively and negatively – in terms of benefits delivered.
- Redistribution of benefit.

However, to qualify as an adaptation service, there need to be additional steps in the value chain that recognise the difference in application as compared to standard weather or seasonal forecasts. We propose that these additional value chain steps should be:

- An explicit consideration of future climate change.
- An adaptation decision that has some additionality beyond a W&CI decision that might otherwise be taken anyway.

To start, this study has developed a value chain for a **heat-health alert system**. The service acts as an early warning system, forewarning of periods of high temperatures, which may affect the health of the public. The forecasting of heatwaves uses an alert system, which includes some baseline activities (year round), forecasting during the period 1 June to 15 September, and three alert levels. The thresholds for the alert levels vary by region.[37] The thresholds are set at levels known to cause ill health to help ensure healthcare staff and resources are prepared for hot weather periods plus raise awareness amongst individuals who are more vulnerable.

The foundational activities are associated with the existing observation system and the modelling monitoring and forecasting of heatwaves. They also include foundational research involved in assessing the heat alert thresholds, based on public health information. The Met Office forecasts daytime and night-time maximum temperatures, which are monitored regionally.

When these heat thresholds are forecast, an alert is issued and sent (information communication) to relevant health professionals and people working in social care. Heat-health alerts are now published by the UK HSA. Note that, alongside this, there are the forecasts provided by the Met Office Extreme Heat Warning.

The heat-health alert system triggers action for various organisations, which are set out in guidance (UKHSA, 2022) (understanding of information). There are actions for different groups, for professionals, social care staff, but also actions for community, hospitals and care homes, and also community and voluntary sector and individuals. This enables health professionals to take steps to minimise the impact of the heat on people's health. The uptake and delivery of these actions affects the health benefits delivered by the alerts, and the reduction in health risks is conditional on the effectiveness of the actions taken.

[37] https://www.metoffice.gov.uk/public/weather/heat-health/?tab=heatHealth&season=normal

Level	
0	**Year-round planning** All year
1	**Heatwave and summer preparedness and action programme** 1 June to 15 September
2	**Heatwave is forecast – Alert and readiness** 60% or greater risk of heatwave in the next 2 to 3 days
3	**Heatwave action** Temperature reached in one or more Met Office National Severe Weather Warning Service regions
4	**Major incident – Emergency response** Central Government will declare a Level 4 alert in the event of severe or prolonged heatwave affecting sectors other than health.

Figure 27. Heatwave alert levels. Source UK HSA (2022).

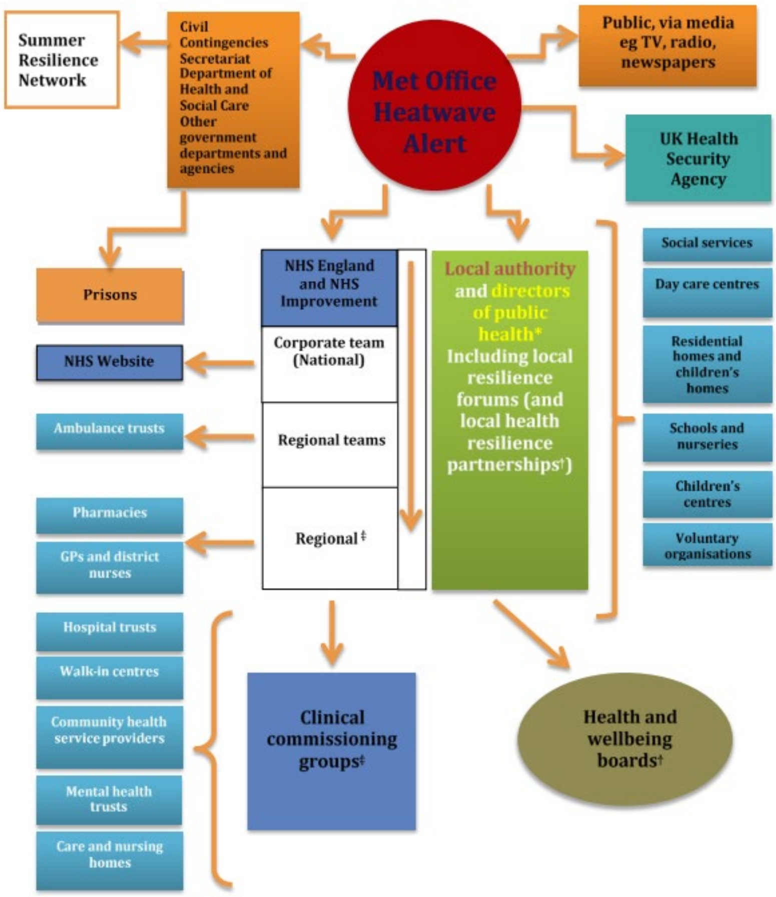

Figure 28- Typical cascade of heat-health alert system flowchart. Source UK HSA (2022).

These steps can be used to develop a W&CI service value chain for the heat-health alert scheme. This is shown in the Table below (left hand column). The efficiency across the value chain – from forecast accuracy to effectiveness of action – determines the actual reduction in health impacts and thus the economic benefits. However, as highlighted above, in order to qualify as an adaptation service, we identify some additional steps in the value chain.

First, additional information on climate change is integrated into this value chain. This involves further steps to assess how the service performs under climate change, with associated change in costs and benefits. This is shown in the third column of the table. This includes the production of climate modelling information, which is then used to estimate potential changes in heat related mortality risks, and in turn, changes in the benefits and costs of the system.

Second, in order to deliver adaptation benefits, there needs to be an adaptation decision. Using the analogy of a typical weather and climate service, this could be an improvement or extension of an existing W&CI service, or the development of a new W&CI service. We consider the example of the extension of the current heat-alert system in England to Scotland, on the basis of changing climate risk and recent adaptation strategy proposals to consider this. This is shown in the right-hand column. We also qualitatively include some discussion of how the English system could be improved, based on information from other countries.

Table 22 heat-health alert system information value chain, baseline, and additional adaptation.

Value chain step	Baseline	Analysis of system under climate change	Adaptation service (adaptation decision)
Foundational	Observational network, monitoring Modelling and forecasting capacity (Foundational public health information on risks/thresholds)	Climate change modelling projections and impact studies	
Generation	Heatwave forecast by Met Office (timeliness, accuracy)		
Communication	Heat-health alert information dissemination by UK HSA– emails, media		
Uptake	Awareness and capacity of health professionals (number who receive information, and understand) + *Awareness and capacity of public from general heatwave forecast*		
Use	Number health professionals who act on information / ability to respond (numbers, trust in forecast) + *Number public who act*	Planning by Department of Health on likely future costs and benefits of the service in future decades	
Action	Effectiveness of action taken by Health care system and professionals + *Effectiveness of action by public*		Use of information in decision to extend scheme to Scotland
Economic benefit	Avoided mortality and morbidity (in health care system + among general public (numbers, economic benefits)	Higher benefits under changing climate	Information on benefits of extending the scheme.
Costs	Analysis of costs of running the scheme, including the costs of heat health alert triggers, i.e. resource costs of health professionals Note also costs incurred if heatwave incorrectly forecast that does not subsequently occur	Higher costs (alerts triggered more frequently). Information on costs and benefits of the system in the future.	Information on costs of extending the scheme. Cost benefit analysis of extending the scheme (and decision to implement now or wait)

Step 3 Review and decide on the potential methods

There are several methods that can be used for assessing baseline health impacts from heatwaves as well as the potential benefits of heat-health alert systems. There is a well-established literature that uses statistical (epidemiological) relationships between daily temperature and daily mortality based on historical observations (see Baccini et al., 2008; PIRU, 2018). These typically show a U- or Jshaped curve, with rising mortality for increasing temperature, above a threshold. The exact shape of the relationship and the threshold varies with country and city. This evidence base can be used to look at the benefits of a heat health alert scheme, i.e., after introduction.

However, when it comes to future climate change, only *ex ante* methods can be used, and the convention has been to apply the same epidemiological relationships for current effects in an *ex ante* modelling framework (e.g., Hajat et al., 2014). This same method can then be used to assess the potential benefits of heat health-alert schemes (e.g., Hunt et al., 2016).

In terms of valuation of benefit, there is an established set of methods for the **valuation of reductions in mortality (fatality) risk** in the UK. This focuses on the 'disutility welfare component': the valuation of changes in the risk of death in a given time period. This is commonly expressed through the metric of a Value of a Prevented Fatality (VPF), also known as the Value of a Statistical Life (VSL). These metrics are already widely used in UK Government appraisal and cost-benefit analysis, for example in transport appraisal. The value of a prevented fatality, (VPF) used in transport appraisal by the Department for Transport (TAG databook, DFT, 2022) is given below.

Table 23 Average value of prevention per casualty. Source DfT WEBTAG.

Table A 4.1.1: Average value of prevention per casualty by severity and element of cost £ (2021 prices and 2021 values)				
Casualty type	**Net output**	**Willingness to pay***	**Medical & ambulance**	**Total**
Fatal	141,851	2,063,940	1,217	2,207,009
Serious	27,325	202,046	16,553	245,924
Slight	2,888	14,790	1,226	18,904
Average, all casualties	8,620	69,977	3,823	82,420

However, there is some debate on the applicability of these values to the heatwave context, because those affected include a large proportion of people that are old or have existing health conditions, and therefore have lower life expectancy than assumed in the typical value of a prevented fatality. The period of life lost – notably for heatwaves – may be small. This is often referred to as displaced mortality, i.e., the number of fatalities that occur in those who have existing ill health and would have died anyway within a short period of time (also known as deaths brought forward). Similar issues to this exist in the air quality context, and previous studies in UK Government appraisal have addressed this by using a different measure, known as the value of a life-year (VOLY). The value of a life year lost due to the chronic effects of air pollution has been used in recent studies to monetise the mortality risk in air pollution damage cost calculations (Defra, 2019). The value used was £42,780 (2017 prices) and is based on life years lost being in normal health. Life years lost due to the acute effects of short-term exposure to air pollution were valued at £22,110 per life year lost (Defra, 2019). However, the standard method for monetising the loss of quality of life due to health conditions is Quality Adjusted Life Years (QALYs). In accordance with the HMT Green Book, QALYs are valued at £60,000 in 2014 prices - this is different from the value of a life year used in the mortality risk pathway and can be explained by the fact that the QALY represents the value of a year lived in perfect health. These values can be transferred to a climate change related context (Hames et al., 2012). However, this requires information about the average period of life lost from heat-related mortality and the quality of life lost. There is no robust evidence on this. Previous studies in this area (e.g., Hunt et al., 2016) have used a range of monetary benefits, representing VSL and VOLY/QALY valuation, although the two approaches lead to very large differences in the size of benefit estimates.

Step 4. Build the baseline and Step 5. Assess benefits with the service

The current baseline starts with the number of heat-related mortality cases (impacts). We have focused on mortality here. There are also potential morbidity benefits from the scheme, which would be additional. The analysis starts with the assessment of the current English scheme.

The average daily outdoor temperature thresholds in England at which populations begin to show heat-related mortality vary regionally from around 17°C to 20°C (Hajat et al., 2014). Daily deaths increase above this level. This is important as a large number of heat-related mortality cases occur outside of heatwaves (at lower temperatures).

Hajat et al. (2014) estimated current heat-related mortality at 2000 fatalities/year on average in the UK. This was based on analysis of deaths in the period 1993 – 2006. This includes all deaths above the threshold of 17 to 20, °C and not just heatwave related deaths. This figure was reported by the Adaptation Committee in the progress report (CCC, 2014) and CCRA2 (Kovats and Osborn., 2016).

In contrast, the English Heatwave Plan focuses on the excess summer deaths that are associated with increasing temperatures in excess of 25ºC (PHE/NHS England, 2018). This therefore focuses on a sub-set of all heat-related mortality.

There is some observational data on heat related deaths (excess mortality) during heatwaves available from epidemiological studies. The 2003 heatwave event in England was attributed with 2234 excess deaths (PHE, 2018) and the 2006 summer heatwave was associated with an estimated 2323 extra deaths. Note that the heat-health alert system scheme was introduced in 2004. The impact on mortality in recent years is reported at 908 excess deaths from heatwaves in 2016, 778 deaths in 2017, and 863 additional deaths in 2018 (PHE, 2018c). Most recently, the total all-cause excess mortality estimated from the 3 heatwaves in the Summer of 2020 was reported at 2,556 deaths (UKHSA, 2022). These figures show that large numbers of excess deaths are occurring during heatwaves, even with the heat health alert scheme in place.

There is no equivalent data on heat related deaths in Scotland, and thus estimating these potential effects, using climate information, can help inform the potential decision to extend the scheme.

The next part of the baseline is to estimate the benefits of the current heat-health alert system. Heatwave plans and heat health alert systems have been in place for many years in other countries and are reported to have benefits in reducing mortality, though they are not 100% effective in reducing deaths.

To look at potential benefits, this case study has applied two different approaches. The first uses a simple top-down analysis based on ex post studies from other countries on the effectiveness of health heat alert schemes, i.e., a form of benefit transfer. The second tries to build up the analysis based on the effectiveness along the value chain using modelling information.

Top down analysis. Internationally, there have been localized studies of the potential benefits of heat alert systems in other countries. A review of the literature by Toloo et al. (2013) identified a small number of studies on heat warning effectiveness. This identified a French study that reports effectiveness (in reducing mortality) of 68%, and a Florentine study with effectiveness of 9%. There was higher effectiveness reported from North America by Toloo et al. at 85% and 88% in two cities. This suggests that are a range of context-specific factors that influence the effectiveness of heat warning systems.

However, other studies, including recent analysis, are less positive. Nitschke et al. (2016) used morbidity and mortality data from two extreme heatwave periods, before and after the introduction of a heatwave warning system in Adelaide, South Australia, to compare the impact. While recognising the limitations of such approaches, the study found significant morbidity reductions were observed with the scheme in place, suggesting that preventive measures contributed to this success, but it did not find there were benefits for mortality. Similarly, an analysis of heat alerts in twenty US cities (Weinberger et al., 2018), between 2001 and 2006, found that NWS heat alerts were not associated with lower mortality in most cities studied, i.e., there was no statistically significant beneficial association. The one exception was in Philadelphia, where heat alerts were associated with a 4.4% lower mortality rate or an estimated 45 deaths averted per year.

There is some information on the English heat-health alert system and some evidence that suggests that the scheme has had some benefits in reducing mortality, noting this is only for temperatures above the heat-health alert system thresholds. Green et al. (2016) developed a linear regression model for heat in England and assessed the observed versus estimated fatalities of the sustained heatwave in England in 2013. They found that the impact on mortality was considerably less than expected, i.e., the 2013 event had much lower mortality than previous large heat events (2003 and 2006), despite a similarly prolonged period of high temperatures (though it is very difficult to compare events). They report that the 2013 event led to 195 cumulative excess deaths, which was only one fifth of those predicted based on observed temperatures, and much lower than in the 2003 and 2006 heatwaves which both led to more than 2000 deaths. However, while the Heatwave plan is a factor in this, the authors report that the reasons for this are unclear and further work needs to be done to understand this.

It is possible to use these effectiveness numbers and transfer them to the English heat-health alert system. This has been done previously (Hunt et al., 2016), using an average of 40% effectiveness based on Toloo et al. (2013). However, some studies reduce heat-related mortality baseline numbers to differentiate between heatwave and non-heatwave periods. For example, one study assumed 50% of total heat-related mortality occurred during heatwaves and the remaining 50% at temperatures below heatwaves (COACCH, 2021).

A detailed evaluation of the England heatwave plan by the Policy Innovation and Evaluation Research Unit (PIRU, 2019) was undertaken. This was not able to conduct a direct comparison of mortality impacts on alert days compared to non-alert days or days. However, it does report that only a small fraction of heat-related deaths occurs on alert days – less than 10% in the case of London and the West Midlands (which indicates that the potential value of 50% - see paragraph above - might be high for the UK).

This provides a relatively simple way to quantify benefits. To illustrate, if baseline heat-related mortality is 2000 cases per year, and 50% of these occur during heatwaves, then a 40% effectiveness of the scheme will lead to 400 avoided heatwave related fatalities/year. This can then be valued using the VPF values above (£2.2 million). Note that if the deaths avoided are valued using an adjusted economic value, to take account of the short period of life lost, e.g., using a value of life year lost and assuming 1 year of life is lost on average (e.g., £60,000 per VOLY and 1 year of life lost), then the benefit is much lower.

For this analysis, we derive a low and high value for effectiveness. The high value (40% effectiveness) is based on the international literature and previous studies (Hunt et al., 2016). It is noted that the Green et al. (2016) analysis of the English heat-health alert system might indicate higher benefits than this, but the PIRU evaluation (see below) indicates lower benefits. The low value (10% effectiveness) is approximately based on the 4.4% value from the Philadelphia scheme for total benefits (rounded to 5%), which is equivalent to a reduction of 10% of heatwave related fatalities (assuming heatwaves are responsible for 50% of total heat related fatalities). The results are presented in the table below.

Bottom-up analysis. The evaluation of the England heatwave plan (PIRU, 2019) undertook: 1) a time-series analysis to establish the relationship between hot weather and adverse health outcomes; 2) case studies of local implementation of the heat-health alert system in five areas in England, along with a national survey of nurses in hospital, community and care home settings; and 3) a survey of the general public. The PIRU analysis reports:

- The epidemiological relationship between temperature and mortality and emergency hospital admissions (as indicators of the health impact of hot weather), suggests that hot weather in England is associated with an increase in deaths and emergency hospital admissions.
- There is no evidence that general summertime relationships between temperature and mortality and between temperature and emergency hospital admissions have changed substantially in the years since the introduction of the first heat health alert system in 2004.

More specifically, the report found through an analysis of the general summertime relationships between temperature and mortality or emergency hospital admissions did not provide evidence that the introduction of the heat-health alert system in 2004 has had an effect on these outcomes, although adverse impacts during individual heatwave periods have reduced in recent years, suggesting that there may have been some contribution from the actions encouraged by the system on alert days.

Based on epidemiological evidence, the PIRU reports that there has been very little change in temperature health risk functions in the years since the heat-health alert system has been operational. Conversely, recent (relatively mild) heatwave events have generally not been associated with large excesses in mortality. This may be due to specific measures taken during alert periods and better awareness among the general population. However, even if the heat-health alert system has been effective to some extent in reducing health impacts during extreme hot-days, evidence suggests that the heat-health alert system does not adequately address the larger number of moderately hot days where the biggest health burdens lie. The findings relate back to the earlier point, that excess deaths are associated with heat outside of heatwave alert periods.

There is some information in the PIRU report that allows the development of a value chain efficiency analysis. This allows an investigation of the effectiveness of each step of the chain to try and estimate the potential benefits, as compared to the case of perfect use of information. In the perfect case, there is 100% forecast accuracy, communication, uptake, use and effectiveness, which would result in the reduction of all heatwave related fatalities. In the real world, there will be efficiency losses at each step, which leads to lower levels of overall benefit.

For <u>health professionals</u>, the PIRU undertook a nurse survey that showed that nearly all nurses (92%) reported that they had been aware of the heat-health alerts issued during the summer of 2018 though there was lower awareness of the alert system itself, at less than 50% of nurses (though the survey considered other health professionals, finding higher awareness among managers).

Most received this information from the email alerts in the scheme. The survey also identified the actions that nurses took in response to the alert. This looked at individual actions, rather than a simple aggregation % of whether action was taken, but it found that only 19% took no action at all (and so 81% took some action). This therefore is a low efficiency fall-off (0.92*0.81 =0.75) for these two steps, meaning three quarters of nurses took some action. What is not clear is how effective the various actions were, especially as a wide range of actions were implemented.

With respect to the public, the PIRU finds (for the level 3 event in June 2017) that half of adults (50%) reported hearing hot weather-related publicity/advice during the heatwave, and 43% of those who heard the advice changed their behaviour. Compared to a perfect value chain and communication through to use, these two steps in the value chain would already generate a large efficiency loss (0.5*0.43 = 0.21) meaning only a fifth (20%) of the potential population acted. The information provides evidence that there is a much higher efficiency along the more formal public health heat alert system. These figures can be incorporated in the value chains, looking at the overall efficiency drop off, compared to the perfect case were all mortality and morbidity from a heatwave are prevented. The review has not found any information on the accuracy of the heat-wave forecasts, so in the absence of such data, we assume a 70% accuracy for the heat-health alert system. The reach and uptake numbers are based on the PIRU survey data. There is also not good data on the effectiveness of action taken. To illustrate the approach, we assume that actions by Advanced Nurse Practitioners (ANP) are 75% effective in reducing mortality and morbidity cases, while actions by the general public are only 50% effective. The overall effectiveness of the heat-health alert system (39%) is similar to the upper value above (40%). The figure for the general public is (8%) is close to the lower value above (10%).

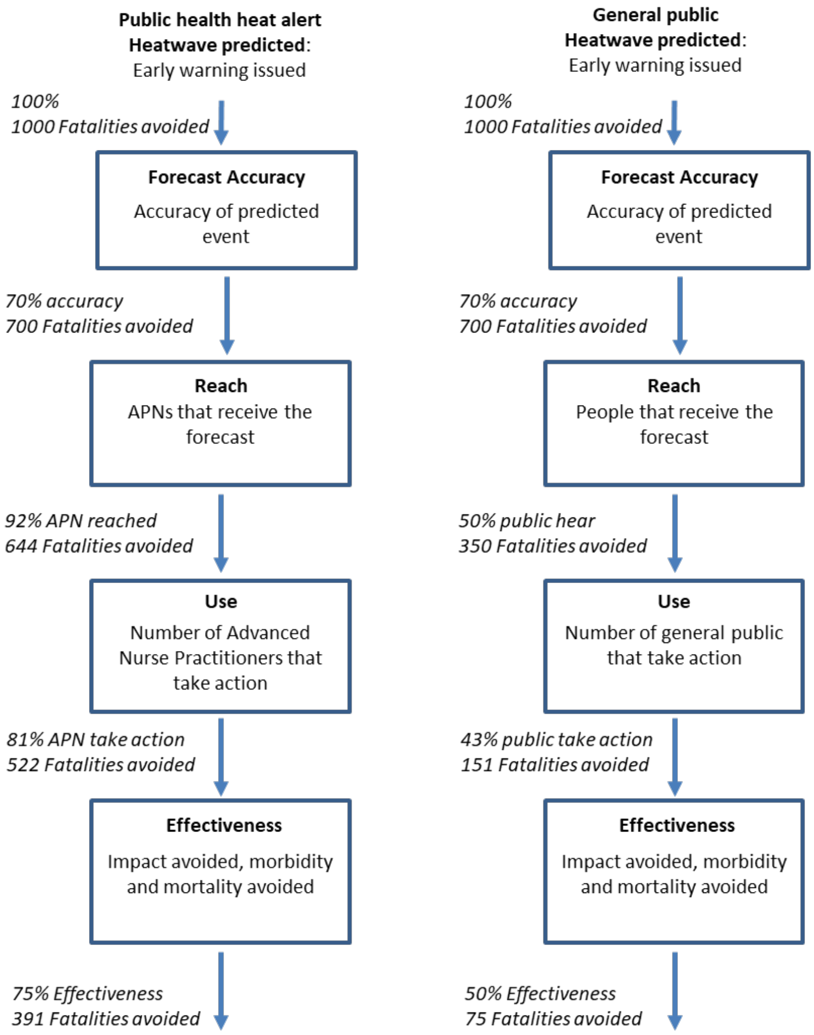

Figure 29 Value chain and efficiency drop off for health system and public heat alerts.

Climate change

The UKCP18 Science Overview (Lowe et al., 2018) reports that hot summers are expected to become more common. In the past (1981-2000), the probability of seeing a summer as hot as 2018 was low (<10%), but this has already increased due to climate change and is now estimated to be between 10-20%. With future warming, hot summers by mid-century could become even more common (with probabilities of the order of 50% depending on the scenarios and projections). Therefore, under a changing climate, mortality risks from heatwaves could increase.

To assess this, we use *ex ante* impact modelling, based on literature estimates. Hajat et al, (2014) estimated the projected change in heat related mortality with climate change. The effects of increased mean temperatures, combined with population growth/age distribution (the aging population), were projected to increase from approximately 2000 UK deaths/year in summer currently (on average) to approximately 3,200 deaths per year in the 2020s and 7,000 per year in the 2050s (central estimates). There was a large range around these central numbers, based on a subset of nine regional climate model variants corresponding to climate sensitivity in the range of 2.6–4.9°C. Note that these values include all heat related fatalities, not just from heatwaves. They also assume the functional relationships stay the same in the future, which may not be the case (see later discussion on acclimatisation).

Table 24 Future Projections of Annual Heat-related mortality with Climate Change for the UK. A1B scenario. Source CCC 2014, based on Hajat et al. (2014). Note that these projections exclude adaptation in terms of the effects of the heatwave plan; they also exclude acclimatisation.

	Mean estimates of increased mortality / year			
	2000-2009	**2020s**	**2050s**	**2080s**
heat- present day	1974			
heat projection - climate only		2882	5310	8468
heat projection - climate and population growth – central		3281	7040	12538
low		1641	3120	6627
high		5332	13440	19255

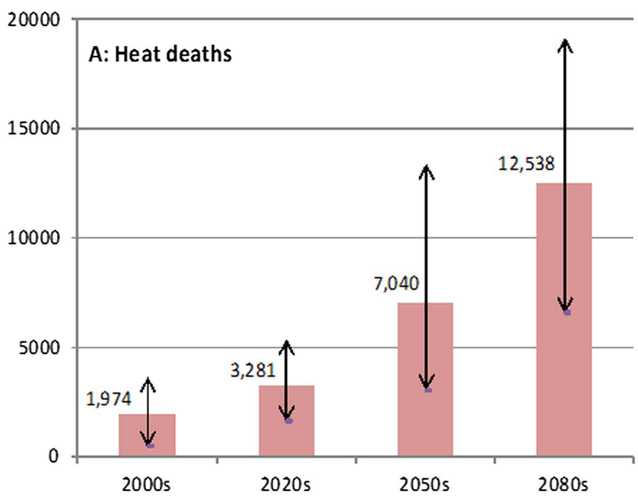

Figure 30 Heat-related deaths in the UK per year for all ages based on an ensemble of nine climate models for a medium emission scenario. Mean estimates across the nine models are shown, and upper and lower limits of arrows represent the maximum and minimum. Source Hajat et al. (2014). Note – excludes any effects of the heatwave plan on mortality and includes all heat related fatalities.

The next step is to estimate the benefit of the heat health alert system in the future, noting this only reduces heat wave related fatalities, and not those that occur below the heatwave thresholds. There is not good data on this split, but as highlighted above, other studies use a value of 50% (heatwave: non-heatwave) and we use this here.

The effectiveness of the value chain then has to be estimated. In line with the previous discussion, we use a simple top-down approach and apply effectiveness from current schemes to assess the future reduced fatalities. This approach has been used by other studies of the economic benefits of heatwave alert systems under climate change in the UK and Europe (e.g., Hunt et al., 2016; Bouwer et al., 2018; Chiabai et al., 2018) but they assume that the effectiveness stays the same.

For this first analysis, the focus is on England, so the England specific values from Hajat et al. (2014) are used for the baseline and the 2020s[38], assuming 50% of these total heat-related fatalities (in both time periods) occur during heatwaves. The benefits are then based on the difference between the two periods, assuming a range of 10% and 40% effectiveness in reducing heatwave related deaths (based on top down and bottom-up analysis as set out above). These are then valued by the VSL value above (£2.2 million) or the VOLY/QALY value (£60,000 and 1 year of life lost). This effectiveness is applied to all heat related mortality above the threshold, so includes people in the health system (care homes, vulnerable people at home reached by health professionals) but also the general public.

This shows the benefits of the scheme will be increased this decade. However, the costs of operating the scheme will also increase, because the thresholds and actions are triggered more frequently (see next section). Note that the sensitivity testing around the level of effectiveness (10 to 40%), as well as the monetary valuation (VPF vs. VOLY), leads to a wide range. This would be further widened if climate model and impact uncertainty was included. For example, the low and high estimates from Hajat et al. (2014) for the 2020s for the UK are 1641 and 5332 fatalities per year, around the central value of 3281.

This analysis provides information on the current W&CI service, the current heat-health alert system, under a changing climate, indicating the economic benefits could be large (especially if valued using a VPF). This demonstrates that the scheme is a likely no-regret adaptation action because it leads to net economic benefits today, and these benefits increase under climate change. However, this only provides information on the current scheme; there is no additional adaptation decision, thus this is investigated in a further step.

There is also some uncertainty about the future health impact level, because of acclimatisation[39]. The inclusion of acclimatisation would reduce the benefits above. While some degree of acclimatization is likely, there is high uncertainty around the exact level.

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[38] Projections for the 2020s are actually a longer time slice but are assumed to be the 2020s decade for simplicity.

[39] Future temperatures in the UK are expected to be higher, but still low compared to Mediterranean countries. These countries have acclimatised to higher heat, i.e., they do not have notably higher baseline heatwave related fatalities than the UK. This is because societal, behavioural and physiological changes have enabled adaptation to these warmer climates. It widely thought that UK citizens will also acclimatize to higher temperatures, through their behaviour, and via changes to buildings, over time. Studies that include acclimatisation estimate that this could reduce future heat related impacts by one third to one half (Kovats, 2011: Watkiss and Hunt, 2012). This effect and similar reductions are cited by Hajat et al. (2014) but are not included in the estimates above. The degree of acclimatisation is likely to dependent on the rate of climate change, i.e., higher acclimatisation levels are anticipated if change is slower. The inclusion of acclimatization could drive down all the values above, so for example, if acclimatisation reduces impacts by one third, then heat related impacts would remain broadly at currently levels (i.e., the 3281 deaths/year projected would be closer to current levels of 2000/deaths per year). Hence, the level of acclimatisation is an important research gap.

Table 25 Potential benefits of the heat-health alert system with rising climate change in England. Total economic cost of heat related mortality in the UK. £Million/year. 2021 prices, no GDP uplift, from central estimates of Hajat et al. (2014) for medium climate change.

Baseline (1980 – 2000)	**Fatalities/year historic**	**Valuation (VSL) £M/year historic**	**Valuation (VOLY) £M/year historic**
All heat related fatalities	1843	4068	111
Proportion arising during heatwaves (50%)	922	2034	55
Assuming effectiveness of scheme is 40% in reducing heatwave related deaths	369	814	22
Assuming 10% effectiveness	92	203	5.5
2020s	**Fatalities/year 2020s**	**Valuation (VSL) £M/year 2020s**	**Valuation (VOLY) £M/year 2020s**
All heat related fatalities	3064	6763	184
Proportion arising during heatwaves (50%)	1532	3382	92
Assuming effectiveness of scheme is 40% in reducing heatwave related deaths	613	1353	37
Assuming 10% effectiveness	153	338	9.2
Benefits of scheme under climate change (2020s – current)	**Avoided fatalities/year**	**Economic benefit/yr (VSL)**	**Economic benefit/yr (VOLY)**
Benefit of scheme at 40% effectiveness	244	539	14.7
Benefit of scheme at 10% effectiveness	61	135	3.7

Adaptation decision

The approach above is common practice for an impact study. However, in the context of an adaptation service, there should be a specific adaptation decision, as it is through the delivery of improved information and improved decisions that economic benefits are produced. Or to put this another way, while the information above highlights the benefits under climate change of the current scheme, there is nothing new happening.

To address this, the case study also looked at a potential adaptation decision for the heat-health alert system. This follows the sort of decision that might be taken when extending an existing W&CI service, or when developing a new service, due to climate change. This would be an adaptation decision, as it involves a change driven by climate trends.

To explore a hypothetical application, we consider a geographical extension of the current heat-health alert system to **Scotland**, which is not currently part of the heat health watch system although it is covered by the broader National Severe Weather Warnings (NSWWS). The UKCP09 projections did not suggest that extreme temperatures in Scotland were likely to lead to high health impacts, and thus heatwave risks would be low. However, there have been much higher temperature peaks in Scotland in recent years, and notably in 2022, the temperature reached almost 35˚C. In response to rising summer temperatures and heatwaves in recent year, the extension of the English scheme was recommended in the recent Glasgow Adaptation Strategy.

This recommendation was also influenced by the new UKCP18 simulations, which indicate higher warming. This was explored in heatwave analyses by Undorf (2018) and O'Neill and Tett (2019), who mapped future Scotland heatwave extremes. This used the current heatwave thresholds for the north of England[40]. The results indicate that a heat wave could occur on average 1 in every 2 years in Scotland by the 2050s (under the RCP8.5 scenario). O'Neill and Tett estimate that the projected number of heatwave days in GCR could rise from zero today to 5 to 10 heatwave days/decade in the 2050s, and the number of days/decade exceeding the temperature criteria (that do not necessarily last for 3 days) rise from 1 to 5 days in the baseline period to 10 to 50 days/decade in the 2050s, i.e., to 1 to 5 days per year.

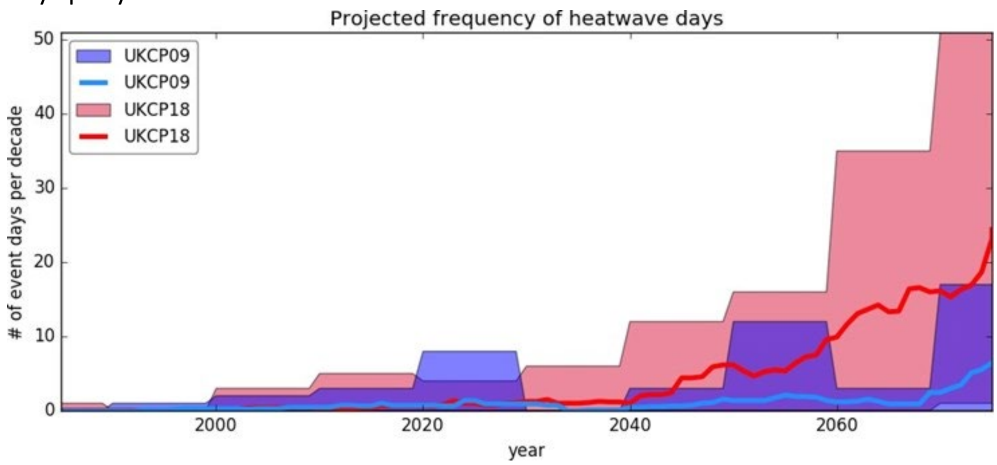

Figure 31 Projected frequency of heat wave days for UKCP09 (blue) and UKCP18 (red) datasets for Scotland. Source: Undorf et al, 2019.The respective shading shows the full plausible range of the number of heatwave days in any one decade, including internal variability. The respective lines show the best estimate for the number of heatwave days per decade with decadal averaging. 12km regional UKCP18 model data and UKCP18 RCP8.5.

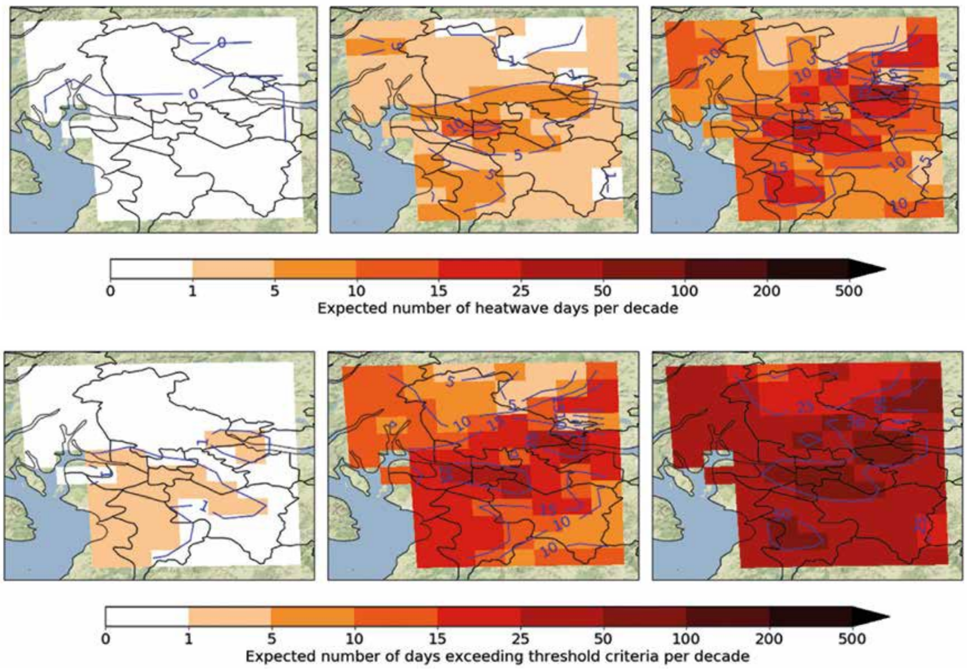

Figure 32 Number of heatwave days and days exceeding day and night-time thresholds projected per decade for the Glasgow City Region (GCR). Current, 2050s, 2070s. Source O'Neill and Tett (2019).

[40] Heatwave days were defined as periods of three or more days where maximum temperatures exceed 28°C and minimum temperatures are above 15°C.

The benefits of extending the scheme are estimated using the same *ex ante* modelling and benefits transfer of effectiveness as for the England scheme above. The estimated current and future heat related fatalities by Devolved Administrations and thus for Scotland are taken from Hajat et al. (2014). These show major increases in rates for the 2050s and 2080s, though more modest impacts in the 2020s. Note that because there is no existing scheme, all avoided fatalities from the heat alert system are additional benefits.

Table 26. Potential benefits of a heat-health alert system in **Scotland**. Total economic cost of heat related mortality. £Million/year. 2021 prices, no GDP uplift, no discounting of future values, from central estimates of Hajat et al. (2014) for medium climate change.

Current period	**Fatalities/year historic**	**Valuation (VSL) £M/year historic**	**Valuation (VOLY) £M/year historic**
All heat fatalities	38	84	2.3
Proportion arising during heatwaves (50%)	19	42	1.1
2020s	**Fatalities/year 2020s**	**Valuation (VSL) £M/year 2020s**	**Valuation (VOLY) £M/year 2020s**
All heat fatalities	73	160	4.4
Proportion arising during heatwaves (50%)	36	80	2.2
Assuming effectiveness of scheme is 40% effective in reducing heatwave related deaths	15	32	0.9
Assuming 10% effectiveness	3.6	8.0	0.2
Benefits of scheme	**Avoided fatalities/year**	**Economic benefit/yr (VSL)**	**Economic benefit/yr (VOLY)**
Benefit of scheme at 40% effectiveness	15	32	0.9
Benefit of scheme at 10% effectiveness	3.6	8	0.2
2050s (note values are undiscounted)	**Fatalities/year 2020s**	**Valuation (VSL) £M/year 2020s**	**Valuation (VOLY) £M/year 2020s**
All heat fatalities	157	347	9.4
Proportion arising during heatwaves (50%)	79	173	5
Assuming effectiveness of scheme is 40% effective in reducing heatwave related deaths	31	69	1.9
Assuming 10% effectiveness	7.9	17.3	0.5
Benefits of scheme (undiscounted)	**Avoided fatalities/year**	**Economic benefit/yr (VSL)**	**Economic benefit/yr (VOLY)**
Benefit of scheme at 40% effectiveness	31	69	1.9
Benefit of scheme at 10% effectiveness	7.9	17.3	0.5
Additional benefits of 2050s over 2020s (undiscounted)	**Avoided fatalities/year**	**Economic benefit/yr (VSL)**	**Economic benefit/yr (VOLY)**
Benefit of scheme at 40% effectiveness	16.9	37.2	1.0
Benefit of scheme at 10% effectiveness	4.2	9.3	0.3

It is noted that a similar approach could be taken to look at extending the England scheme. For example, there have been previous recommendations on enhancing the scheme in the Committee on Climate Change Progress report (2014; 2019) and there are also a set of additional improvements that emerge from the PIRU evaluation of the current scheme (2019) (see these documents for recommendations). There are also more targeted elements, e.g., for care homes (JRF, 2016, Ibbetson et al., 2021)

Step 6 Assess Costs

There are costs of delivering the heat-health alert system. These include all relevant costs across the value chain, so not just the costs of the forecasts and generating the heat-health alerts, but also the costs of delivering the actions associated with the different warning levels, including staff costs.

The different warming levels in the scheme trigger different actions, each of which has resource implications and costs. This includes a large number of organisational responses, see figure 6, from NHS managers through to front line staff.

Hunt et al. (2016) developed some analysis of these potential resource costs, focusing on the warning systems that require action by health professionals, looking specifically at the resource costs associated with Advanced Nurse Practitioners, (ANPs), who are primarily involved in the care of the local population in their homes, rather than in hospitals, and likely to have to take on additional activities when alerts are issued. The study identified resource implications for each of the alert levels. This approach has also been considered here.

Table 27 Roles of health professionals and indicative resource implications for the heat-health alert system implementation. Updated from Hunt et al. (2016).

Heat-health alert system	Role of Health Professionals	Resource Implications
Level 0	Year-round planning	Fixed costs components: - Met Office contract fee; - UK HAS costs
Level 1 – Awareness	Planning at beginning of heatwave season to protect vulnerable people: - Be familiar with the principles and core elements of the Heatwave Plan - Be familiar with the client heatwave advice leaflet and give copies to clients as appropriate. - Consider clients' vulnerability to adverse weather conditions and add to at-risk list	Resource costs at UK Health Security Agency (UKHSA) Health Manager, annually Other Health Professional, annually.
Level 2 – Alert	- Identify list of those from existing caseload who will require daily contact in the event of a heatwave; - Avoid duplicate contact /visits from multiple agencies; - Determine what non-essential activities could cease.	*Each time triggered* Cascade of information UK HAS Cascade of information health manager Health Professional action
Level 3 – Heatwave	- Stop nonessential activities; - Commence daily contact with clients at risk; - Make daily situation reports	*Each time triggered* Cascade of information UK HAS Cascade of information health manager Health Professional action
Level 4 – Emergency	- Continue to do best for caseload; - Provide situation reports upwards, as requested, and raise any concerns they may have;	*Each time triggered* Cascade of information UK HAS Cascade of information health manager Health Professional action

The scheme involves some fixed costs, associated with the Met Office and UKHSA in operating the scheme. Extending the scheme to Scotland would include additional activities for Met Office (though we assume these are low) plus new communication and cascade for information – in the Scottish health service (Public Health Scotland) or from the UK HAS extending the current scheme. We assume that the set-up costs (year 0) would be £250,000, with fixed cost each year of £100,000, though these are just indicative values.

In terms of the additional operating costs incurred from the triggering of different alert levels, we explore these by focusing on ANP nurses, as these nurses are primarily involved in the care of the local population in their homes and likely to have to take on additional activities when alerts are issued (though it is stressed other health care staff in the system will also have additional roles).

- The total number, (full-time equivalents), of ANPs currently working in Scotland are reported as 726 in 2020 (NHS Scotland, 2021).
- The annual cost of employing an ANP is calculated from cost information data in previous analysis (Hunt et al, 2016) for the UK. Cost information includes salary, on-costs, non-capital overheads, capital overheads. These are divided by 220 (annual working days) to give costs of £147/day (Curtis et al., 2010) updated to current prices.

The costs are then calculated for the different alert levels.

- For Level 1, it is assumed that each ANP typically requires one hour per year. This day-fraction, (0.125), is multiplied by the day resource cost identified above, and number of ANPs in Scotland. Note that there would also be additional costs associated with the heat-health alert system for health managers each year, as well as health care professionals responsible for the heat-health alert system in other organizations (e.g., hospitals, care homes).
- For Level 2 and 3. The incidence costs of an event are estimated on the basis of the data from Undorf (2018) and O'Neill and Tett (2019). Their analysis estimates / projected number of heatwave days in GCR rise from zero today to 5 to 10 heatwave days/decade in the 2050s, and the number of days/decade exceeding the temperature criteria (that do not necessarily last for 3 days) rise from 1 to 5 days in the baseline period to 10 to 50 days/decade in the 2050s. We assume the current decade (2020s) is approximately halfway between the baseline and the 2050s, which indicates mid points of 3.75 heatwave days per decade and 13.75 exceedances of the thresholds/decade in the 2020s. These can be used to estimate the number of level 2 and level 3 warnings per year, which we assume map to level 3 (more and long lasting heatwaves) and level 2(less severe heatwaves) thresholds respectively, though this is only indicative. A level 2 event is assumed to take 0.2 days of time for each ANP. A level 3 event, which is longer and more severe (but will be less frequent) is assumed to take 0.75 days (total) over the duration of the heatwave. Again, there would also be additional costs associated with the heat-health alert system for health managers each year, as well as health care professionals responsible for the alert system in other organizations (e.g., hospitals, care homes).
- For Level 4, many actions are associated with the issuing of a broader heat alert (for other sectors) and greater focus on health warnings to the general public. While there would be some additional costs for the health service, costs are assumed to be fairly similar to level 3, as no additional actions are indicated in the heatwave plan.
- It is stressed that the above assumes that the heatwave event would be Scotland-wide. In practice this is unlikely to be the case, given the geographical area. However, as the population is heavily concentrated in Glasgow and Edinburgh and surrounding regions, this is a reasonable proxy.

The indicative costs are shown below. For simplicity, the data are presented as two time-slices, assuming constant likelihood in each period (in practice, there would be an incremental increase over time, with year to year variability). It is noticeable that the costs increase substantially under the 2050s scenarios, as climate change is projected to become more significant, and the alert system is triggered more frequently This assumes the threshold levels are kept the same.

Table 28 Illustration of annual costs (undiscounted) of extending and operating the heat-health alert system to Scotland, based on set up costs and ANPs.

Heat-health alert system Level	Set up	2020s £/year (2020 – 2039)	2050s £/year (2040 – 2059)
Level 1	250,000	116,476	116,476
Level 2		36,248	65,906
Level 3		37,072	74,144
Level 4		N/A	N/A
Total		189,796	256,526

Note there would also be costs associated with incorrect forecasts. For example, in a case where a heat alert is triggered from a forecast of a heatwave, that subsequently does not occur (i.e., the forecast is incorrect), actions will still be taken. As an example, for the Level 2 alert, there would still be action taken by ANPs. These costs should be added to the costs of events that are correctly projected. As highlighted earlier, we have not found information on the accuracy of the heat-wave forecasts from Met Office, and have assumed a value of 70%. This accuracy will relate to cases where a heatwave is not correctly forecast, as well as cases where a heat-wave is forecast that does not subsequently occur. The former are included in the value chain analysis already. To explore the latter, we assume that there is a 10% level of such false positives that are forecast, which would increase the annual costs above.

Step 7 Compare benefits and costs (Cost-benefit analysis)

The costs and benefits of the additional adaptation decision can be compared, i.e., the economic benefits of the extension of an existing system due to the changing climate, using economic appraisal. Previous studies have assessed the economic benefits of the current heat-health alert system in England (Hunt et al., 2016; Watkiss et al., 2019) and these find positive benefit to cost ratios.

In this analysis, benefits and costs that arise in future years are discounted, using the standard HMT Green Book discounting scheme.

Looking at the first twenty years (assuming the climate of the 2020s), then the costs of the scheme, discounted to provide present values (Table 8), can be compared to the benefits (Table 7), again discounted in present values. The resulting benefit to cost ratios are positive in all cases, although only marginally so if the VOLY metric and 10% effectiveness value is used. This indicates that the measure is low-regret or even no-regret in nature (i.e., good to do anyway). However, these values should be treated with caution. The inclusion of avoided morbidity would increase the benefits above, though the costs included are probably a sub-set of total costs as they are focused on ANP only.

Table 29 Illustrative Benefit to cost ratio of extending and operating the heat-health alert system to Scotland (set up costs and ANPs).

2020s		
Effectiveness	Valuation	Benefit to Cost ratio 2020s (2020 – 2039)
40%	VPF	155:1
10%	VPF	39:1
40%	VOLY	4.2:1
10%	VOLY	1.1:1

These BCRs can also be adjusted to take account of the potentially higher costs from the inclusion of incorrect forecasts (false positives) when a heatwave and heat alert warning is issued, that does not subsequently occur. In theory this increases the overall costs of the scheme, as ANP resource costs are still incurred, and this would slightly reduce the BCRs above. Assuming a 10% level of such events, this would have a negligible effect on the results above, though it would reduce the lowest sensitivity value (10%, VOLY) to BCR of 1:1. In practice, however, health impacts are not associated with specific thresholds but rise gradually with temperature and risk levels, and thus costs incurred would still generate health benefits. Nonetheless, it is highlighted that the use of the value chain analysis does raise these issues, and thus there are differences in W&CI service analysis as compared to more traditional impact assessment (as in published heat alert benefits studies undertaken to date, e.g., Hunt et al., 2016). This provides an important lesson on how the use of W&CI valuation methods could improve broader adaptation assessment.

Step 8 Undertake Sensitivity Analysis (including climate change)

The tables above include a sensitivity analysis on the effectiveness (%) of the system in reducing mortality, and on different economic values for valuing the change in mortality (with a full value of a statistical life, or an adjusted value based on the value of a life year lost, reflecting whether account is made of the period of life lost). These two factors alone give a range of two orders of magnitude in the results.

However, the analysis assumed central estimates for climate change, in terms of baseline numbers of heat-related fatalities. As shown in table 5, the baseline projections of heat related fatalities under climate change have a wide range, potentially doubling or halving central values. Furthermore, the assumed value that 50% of these fatalities occur during heatwaves is uncertain, and there is some evidence from the PIRU study that indicates the proportion could be lower than this). The combination of scenario and climate model uncertainty could add a further order of magnitude of uncertainty.

On the benefit side, the inclusion of morbidity benefits would increase benefits, and previous studies (e.g., Watkiss et al., 2019) suggest these could be of a similar order of magnitude to the VOLY estimates of avoided fatalities in monetary terms.

On the costs side, the projections of future climate change in Scotland, and the costs of the scheme are based on the UKCP18 RCP8.5 values only and can be considered to be likely overestimates. However, the scheme costs only include ANP costs and there would be additional costs across other core parts of the NHS (hospitals) and for social care.

All of this serves to highlight the multiplication of uncertainty when moving to climate change – and especially impact and valuation. Against this background, the use of sensitivity testing is important. For the case above, even with the sensitivity tests, the BCR still >1, indicating a net economically beneficial scheme (though the full range of uncertainty may include some combinations that would fall below this level). It is also possible to explore decisions using decision making under uncertainty (see the second adaptation case study).

Discussion and Conclusions

This case study has explored the extension of the valuation for W&CI services to adaptation services, focusing on a no- / low-regret option – a heat-health alert system – with the extension of the existing English scheme to Scotland. With respect to the study framing the decision can be summarised as follows.

Table 30 Summary of the Case study.

What is the user decision?	The extension of an existing heatwave forecast and early warning scheme to a new location (Scotland)
What climate information was used in making that decision?	The climate information includes current heatwave forecasts (current scheme), and the extension to use heatwave forecasts in the new scheme in Scotland, as well as climate model projections of future heat waves (UKCP18)
What is the value associated with the climate information used in that decision?	The analysis looks at the economic value of extending the heatwave forecast and heat alert scheme to Scotland (the benefit of this adaptation decision). It also looked at the use of climate information from UKCP18 projections to provide additional information to help inform this decision.

The analysis finds that the current heat health alert system in England generates potentially high economic benefits from the reduction in fatalities. There are two key factors that influence the size of this benefit: the level of effectiveness of the system, and the choice on economic valuation method. For effectiveness, there is some conflicting evidence on how effective heat alert systems are internationally, with some reports indicating high effectiveness, but others much less so. Similarly, some studies indicate that the English scheme could have large positive benefits, but others do not. For the valuation of changes in mortality risk, there are very large differences depending on whether a full value of statistical life is used, or some form of adjusted value such as a value of life year lost taking account the shorter period of life lost on average. The effectiveness and valuation methods were investigated with sensitivity testing and it was found the current English system still delivered a positive benefit to cost ratio across all conditions, indicating a robust positive finding, though the range of benefits varied very significantly. Looking forward, the benefits of the English scheme will increase significantly under climate change, although this also highlights that some extensions to the scheme might be needed, given the overall level of efficiency.

The analysis has then assessed the value of extending the scheme to Scotland. This has looked at the possible current economic benefits of extending the scheme immediately, as well as how these benefits might increase over time with climate change. The analysis finds there are net economic benefits from introducing the scheme now (and a positive benefit to cost ratio), including for all sensitivity tests, though these ratios are lower than the England scheme (reflecting the lower population and lower heat risk levels). These benefits reflect the value of information from the use of climate information, in this case in an adaptation decision. The results are presented in the table below.

The analysis has also used data from the UKCP18 projections on heat-wave risk for Scotland, to assess how these benefits might increase in the future. The new projections have been one factor in Glasgow city region recommending a heatwave alert scheme will be needed. These are shown in the table and show the large increase in economic benefits over time. This is important information that could further convince policy makers of the need for the scheme. The additional benefits (of future over current) are also shown, to allow a potential attribution of the value of future climate projections to the decision. It is highlighted that the additional benefits as large than the baseline benefits, highlighting that a possible high level of attribution to UKCP18 information could be warranted.

Table 31 Summary of the Economic Benefits and Benefit to Cost ratio for the Adaptation decision to extend the Heat Health Alert System to Scotland

Benefits of scheme in Scotland 2020s	**VSL Economic benefit £M /yr and Benefit to Cost Ratio**	**VOLY Economic benefit £M /yr and Benefit to Cost Ratio**
Benefit at 40% effectiveness	£32M/yr (BCR 155:1)	£0.9 /yr (BCR 4.2:1)
Benefit at 10% effectiveness	£7.9 M/yr (BCR 39:1)	£0.2/yr (BCR1.1:1)
Benefits of scheme 2050s (RCP8.5) – note benefits are undiscounted		
Benefit at 40% effectiveness	£69/yr *	£1.9/yr *
Benefit at 10% effectiveness	£17.3/yr *	£0.5/yr *
Increase in benefits of 2050s over 2020s (undiscounted)		
Benefit 40% effectiveness	£37.2/yr (BCR	£1.0/yr
Benefit 10% effectiveness	£9.3/yr (BCR	£0.3

Overall, this case study finds that the methods for valuation of conventional W&CI service valuation are applicable to low- and no-regret adaptation, though some additional steps are required when considering the future climate information.

Interestingly, we also find that the application of the W&CI value chain approach is useful for adaptation cost benefit studies more generally, as it introduces a greater focus on real-world benefits, taking account of accuracy, reach, uptake and use. This provides an important insight for adaptation assessment studies.

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Methodology for Valuing and Monitoring Climate Services to Manage Climate Variability

Case Study: Economic Valuation of Adaptation Services – Climate Allowances (proactive adaptation)

'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services'

Paul Watkiss, Pieter Sayer and Alistair Hunt

Summary

This report presents the fourth case study for the task 'methodology for monitoring and valuing climate services', which is part of the contract *Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services*. This case study focuses on the valuation of climate services for proactive adaptation decisions.

Valuation of adaptation services

Investing in W&CI services leads to improved information, for example from enhanced early warning or seasonal forecasts. In turn, this information provides economic benefits to users, as it leads to positive outcomes from improved decisions. However, for these economic benefits to be realised, there needs to be an effective flow of information along the W&CI value chain, from the production of information through to its uptake and use in a decision.

There are existing approaches for valuing traditional W&CI services, i.e., for weather and seasonal forecasts. These involve identifying potential benefits, developing a value chain, choosing a method, and then analysing the economic value of the service relative to a baseline, including all costs and benefits. These approaches are also potentially applicable to climate services associated with adaptation. However, adaptation involves different information (climate projections) and different timescales and decision types. This case study applies W&CI valuation approaches to an adaptation decision to explore these differences and draw insights on the transferability of methods.

Case study: proactive adaptation using climate allowances

Proactive adaptation involves anticipatory, planned adaptation. Such decisions are based on climate model projections of the future climate. However, in order to produce an economic benefit, there needs to be the application of this climate information in a decision.

This case study focuses on climate allowances (the adaptation service) and their use in climate proofing of current infrastructure. These allowances are approximations of anticipated climate change for key variables, based on underlying detailed analysis, which can be used as a 'ready reckoner' in decisions. They can be used in one-off decisions that have to be made now, such as a new drainage infrastructure project, and can be used to adjust the design (climate proof) to take account of future climate change.

The use of a climate allowance leads to potential economic benefits, from the reduced risk or enhanced performance under climate change over future decades. However, it also includes an additional cost, from the additional climate proofing measures or design standards when the infrastructure is built today. This involves more complex issues than for traditional W&CI services and for no- or low-regret adaptation for two reasons. First, because of the difference in the timing of costs (which occur now) versus adaptation benefits (which are in the future, rising over time) and thus the effects of discounting. Second, due to the uncertainty around future climate change and so the 'accuracy' of information, and how this affect actual versus anticipated benefits.

The case study has looked at two examples of the use of allowances to explore these issues, and the use of W&CI valuation methods for proactive adaptation. The first example looks at the potential economic benefits of improved climate model information, and its use in updating allowances, assessing the potential benefits of moving from UKCP09 to UKCP18. The second looks at how the accuracy of climate model projections and allowances affects the economic benefits of climate proofing, considering the influence of discounting and uncertainty.

Results

The first example assessed the potential economic benefits in updating allowances with the new climate information, looking at the potential benefits of changing the uplifts (% values) in going from UKCP09 to UKCP18. Based on the assumption that that the latter are more accurate, the potential economic benefits from this change has been assessed in the context of the Long-Term Investment Scenarios (LTIS) for flood and coastal erosion risk management. This case study finds that improved information from the updated projections could have large economic benefits. This additional economic benefit applies in cases where the allowance increases the uplift (%) but also when it reduces the uplift, as in both cases the new information improves the decision. However, it is difficult to assess the relative improvement in accuracy, and thus the likely benefit outturn, because there is no information on how much of an improvement in accuracy arises (in going from UKCP09 to UKC18) but also because considerable uncertainty remains over future emission scenarios (and RCPs) as well as climate model uncertainty for each scenario/RCP. The case study has also considered what would have happened if UKCP09 data and allowances had been used in decisions, which were now updates by UKCP18 and updated allowances. This identifies different outcomes arise according to whether the new information increases or decreases the previous allowances. When uplift (%) values in the allowances increase with the new UKCP18 information, then schemes designed using the previous allowances (based on UKCO09) will be under-designed to likely risks, meaning they have a likely higher residual damage. When uplift (%) values fall with the new information (UPCK18), then schemes designed using the previous allowances (UKCP09) will be over-designed to likely risks, i.e., costs will be higher than needed.

The second example looks at these issues of choice and 'regret' in more detail, looking at the economic benefits from the use of allowances as applied to an illustrative sea wall investment design. This considers the potential influence of uncertainty, in relation to the projected sea level rise forecast in an allowance and its use in a single immediate decision for long-term protection. The case study looks at the implications of forecast (projection) accuracy by comparing the use of information in design versus different possible (ex post) out-turns. This finds that the economic benefits from allowances are lower when uncertainty and ex post outcomes are taken into account, as compared to a simple 'if-then' analysis (which assumes that the projections will be fully accurate). It also finds that the decision support methods used to make the adaptation decision influences the value of information and economic benefits. The benefits of allowances might be increased if a range of possible allowances were able to be considered, reflecting climate change uncertainty, or if decision making under uncertainty was applied. However, the downside of this is that it would reduce the simplicity of the allowances and could act as a barrier to their use.

These case studies show that while the methods for valuing weather and climate services can be applied to adaptation services, there are some important differences, especially with respect to accuracy, as well as how the information is taken up and used in the decision.

Insights

The application of methods for the valuation of traditional weather and climate information services to proactive adaptation involves additional issues and challenges to the other case studies in this project.

The case study first applied the valuation methods to a static example, with the use of climate allowances in flood management, looking at the potential economic benefits from improved climate projections. This shows that in theory, providing the improved climate projections are more accurate, this will lead to economic benefits (for both decreasing as well as increasing risks). However, there is no information on how much more accurate the improved climate projections are, and this makes it difficult to assess the likely level of economic benefits that are likely to be realised.

The case study then undertook an analysis and comparison of different decision approaches for proactive adaptatoin, contrasting static (if-then) methods with the use of outcome mapping (decision trees) and decision making under uncertainty. This found that while it is possible to use a theoretical if-then framework and apply standard valuation methods to proactive adaptation, the uncertainty around climate scenario / models outputs, means that this standard approach does not provide information on the 'accuracy' of the adaptation service, and thus the real (ex post) economic benefits. However, it is possible to extend these methods and consider uncertainty and its influence on subsequent outcomes, using decision trees and decision making under uncertainty. When such an analysis was undertaken, it was found that the estimated economic benefits from adaptation services are lower when uncertainty and ex post outcomes are taken into account (then when assessed using a theoretical 'if-then' analysis that assumes that the projections are completely accurate) but such an approach would be more likelky to lead to greater real-world benefits (ex post), because it minimises 'regrets'.

The analysis therefore finds that the decision support method used, as well as the type of climate information, is important in valuing adaptation services. This means that some of the 'value of information' generated by adaptation services should be attributed to the decision support services, and not just to the climate information provision (in this case the climate model projection and climate allowances).

The case study application found that the use of a value chain approach was a useful addition to adaptation assessment more generally, and these approaches could be used to improve studies on the economics of proactive adaptation.

Considering the case study on climate allowances specifically, the findings may mean that the economic benefits of allowances might be increased if decision making under uncertainty was recommended, at least for more standard decisions (where a precautionary approach was not needed). However, the downside of this is that it would reduce the simplicity of the allowances and could act as a barrier to their use.

Introduction

Investing in weather and climate information (W&CI) services leads to improved information, such as enhanced early warning or seasonal forecasts. In turn, this information can provide economic benefits to users (individuals/organisations), if it leads to positive outcomes from the actions and decisions that users subsequently take.

This report presents one of the case studies for the project 'methodology for monitoring and valuing climate services', which is part of the contract 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services'. This work is being undertaken by a consortium of JBA Consulting (lead), in association with Climate Sense, Paul Watkiss Associates (PWA), Professor Rob Wilby, and Becky Venton, on behalf of the Met Office. The valuation work is led by PWA.

The project has developed a methodology and draft set of guidance for valuing climate services, as well as method and guidance for analysing value for money (as part of monitoring). These tools are being tested through a series of case studies (Deliverable 4). This case study is focused on adaptation services, focusing on proactive adaptation decisions.

Proactive, Planned Adaptation: Climate Allowances

This adaptation service case study focuses on proactive, planned adaptation. This is focused on decisions that use future climate change projections and information. This involves different issues to the economic valuation of no-regret adaptation (the previous heat health alert scheme case study). This because the value of information (the economic benefit) generated by the service arises in the future, it is subject to high uncertainty, and because involves differences in the timing of costs and benefits over time.

The case study focuses on climate allowances (the adaptation service). These are approximations of anticipated climate change for key variables, based on detailed analysis, which can be used as a 'ready reckoner' in decisions. For example, they can provide indicative changes in peak river flow, peak rainfall intensity, sea level rise, etc. associated with future climate change, which can be used in (some) design or planning decisions. The use of allowances avoids the need for very detailed climate analysis for every individual scheme, and thus can help with implementation of climate risk assessment and adaptation decisions.

The case study explores the economic benefits from the use of climate allowances in climate risk management of infrastructure projects, and the changes in design to take account of climate risks using these allowances (the adaptation decision). It investigates the additional economic benefits from improved climate information for allowancing, and also the benefits taking account of the accuracy of climate allowances and the decisions they lead to.

To help frame the case studies, the analysis also considers three key questions.

1) What is the user decision? This is the design of new infrastructure that takes account of climate change

2) What climate information was used in making that decision? UKCP projections and their use in climate allowances.

3) What is the value associated with the climate information used in that decision? Reduced impacts from climate change on infrastructure / improved performance of adaptation projects.

The value of information from adaptation services for proactive adaptation

In order to generate an economic benefit, an adaptation service needs to do more than generate information or guidance. This information also needs to be used in a decision, because it is the improvement in outcomes (from the use of the information) that leads to the economic benefit when compared to a baseline (without the use of this information).

In this case study, we focus on proactive adaptation services for infrastructure to work through this analysis. The reason for this choice is included in the box, along with a differentiation between types of adaptation infrastructure, highlighting the differences between climate proofing of planned infrastructure and targeted adaptation investments.

Box. Why infrastructure? And what types of adaptation investments?

Infrastructure is a priority for climate adaptation because:

- Infrastructure has a long lifetime and thus investments made today will be exposed to future climate change. This may result in climate change affecting the operating costs, performance or anticipated service or benefits of the infrastructure, and in turn the rate of return (ADB, 2021). It could also result in changing patterns of extreme events from climate change affecting the infrastructure or exceeding the design criteria, causing damage or failure.
- Many infrastructure projects involve lock-in, or (quasi) irreversibility. This was defined in CCRA3 (Watkiss and Betts, 2021) as an action or decision today that 'locks-in' the potential for future climate risk and is difficult or costly to reverse or change later. This can be from an action or decision taken that is business-as-usual', from a lack of an action or decision, or from a mal-adaptative action or decision. These decisions a degree of path dependency. For infrastructure, this includes decisions made today on design and siting, and whether these include consideration of changing climate risks.

For adaptation, there are two types of infrastructure investment decisions (Watkiss, Wilby and Rodgers, 2020).

- Climate proofing or climate smart design. This adjusts planned infrastructure investments to take account of climate change, often referred to as climate proofing (though note many commentators do not like the term climate proofing, as it likely to be impossible and certainly not economically efficient to reduce all risks to zero). This is associated with climate risk screening and involves a decision on the additional adaptation to include to make a planned infrastructure project more climate resilient. Note this can also apply to major refurbishment or renewal infrastructure projects.
- Targeted adaptation projects. This focuses on new investments where adaptation is the primary objective, such as new coastal flood defences to address rising sea level.

The difference between the two is important, because in the first, the decision and the benefit of the adaptation services only relates to the marginal change due to climate (on top of an existing decision), whereas in the second, the decision/benefit is directly targeting climate change and it is the primary purpose of the project.

The conceptual framework for valuation can be described by using a simple example, presented below for the generation of climate information (the adaptation services) and its application to climate proof e.g., a new road project (the decision). This might involve the following considerations to assess the benefits of an adaptation service and is summarised in the schematic below.

- In the baseline, the road would be built without taking account of climate change.
- Climate change would lead to impacts to this road that lead to economic costs such as damage to the road structure or travel time delays from flooding.

- The adaptation service would involve a climate risk assessment, which would identify the risks to the road from climate change, i.e., the level of impacts that will arise.
- This information would be used in an adaptation decision, which changes the design of the road to take account of future climate change, e.g., including enhanced flood protection. This would reduce the climate change impacts relative to the baseline (though note it would be unlikely to reduce them to zero, so there would still be residual damages).
- The economic benefit of the adaptation, and thus the value of information of the adaptation service, would be the reduction in impacts from the use of the improved information in the climate smart design decision (with adaptation), relative to the baseline (without adaptation). The economic benefits would subsequently be compared to the costs of adaptation, to look at the overall economic outcomes that results from the decision.

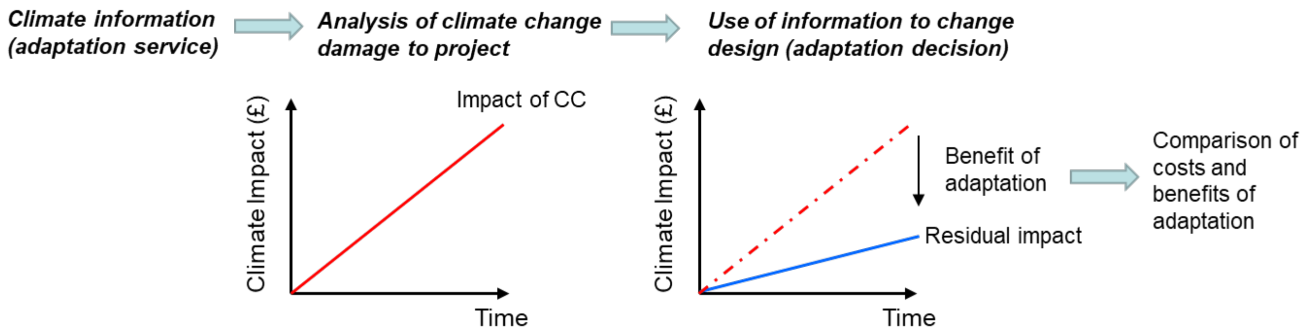

Figure 33 Simple schematic of the potential value of information from adaptation services.

There is existing literature on climate risk assessments that provide the basis for such analysis, see box. These typically involve a series of steps based around an impact assessment methodology.

Box 1. Climate risk assessments

There is a wide existing literature on vulnerability, risk and adaptation assessments, which generate information of relevance for adaptation, e.g., as in the Climate Change Risk Assessment (Watkiss and Betts, 2021: Sayers et al., 2020), or for climate risk assessment at the detailed project level (e.g., ADB, 2020). The generation of this information involves a number of steps (simplified here for conciseness):

- Future climate change model projections and socio-economic projections for a future period (i.e., the 2050s) are identified, relative to a baseline period, as well as the stock at risk (population, housing), normally at a defined gridded level.
- This information is then input into an impact model (or similar), for example a coastal or river flooding model, to estimate future flood impacts (in the 2050s) using established relationships (e.g., depth damage curves).
- This same framework is then used to examine technical adaptation options, e.g., dikes, that can reduce future impacts and so result in adaptation benefits, which are sometimes also compared to the costs of adaptation.
- This analysis can be put into a decision support analysis such as least-cost, cost-effectiveness or cost-benefit analysis to prioritise options or even adaptation levels.

In this standard assessment framework, the analysis is repeated for different futures, typically assessing scenario combination for different Representative Concentration Pathways (RCP) - Shared Socio-economic Pathways (SSPs) combinations. The analysis is repeated for each scenario, using what is often called an 'if-then' framework, i.e., if sea level rise is A metres by 2050 under RCP2.6-SSP2, the optimal adaptation decision involves a dike height of X, if the rise is B metres under RCP6.0-SSP2, the optimal dike height is Y.

Real-world applications and uncertainty.

Most of the earlier literature, e.g., the impact assessment studies described in box 1, have focused on stylised adaptation assessments for future time periods (e.g., the 2050s) using an 'if-then' framework that samples different futures. These provide valuable information, but they do not inform real adaptation, nor generate economic benefits per se.

For economic benefits to be generated, there needs to be the application of this climate information to a real-world adaptation decision. For example, this requires the application of climate information on current and future time periods to an immediate investment decision (today). This involves different issues to the theoretical framework set out in Figure 1 above and the 'if-then' framework, because a single decision has to be taken now (the decision) to address a wide range of uncertain future impacts from climate change (from the adaptation service).

Taking the road project example above, and applying to the real-world context:

- In the baseline case, the road would be built without taking account of climate change and there will be potential consequent future damages from climate change.
- The adaptation service would involve a climate risk assessment to assess these risks. This would start with existing climate risks (from current climate variability and extremes) which would normally already be included in the design. There would be increasing climate risks over the lifetime of the road though there is high uncertainty around the exact future climate change and the level of climate risks, due to scenario and climate model uncertainty. The level of future risks/damages is therefore not known with confidence. There are alternative ways to communicate these possible future changes in risks, and to provide information on how climate risks change over time and across the uncertainty space.
- The information from the climate risk assessment would then be used to change the design of the road to take account of future change. However, this decision is complex and involves choices because it involves a one-off decision today. Different decision approaches can be used to address uncertain future risks, e.g., to protect against the central level of expected future damages, to design for the worst case, or to plan decisions that take account of uncertainty in other ways including design that allows for adjustment over time.
- The economic benefit of the adaptation service is the difference between the 'with' and 'without' case. It is possible to estimate the ex-ante (potential) benefit from the application of the adaptation service in a decision, i.e., using models to estimate the benefits of adaptation to the road project from the use of information in the design. Note that it is not possible to measure or estimate the actual ex post actual benefit from the adaptation service for proactive planned adaptation, as this would require information on the actual climate change outcome over long time periods (i.e., the lifetime of the project).

Importantly, there are choices on how to use the adaptation service in a real-world decision and how then to estimate the benefits, i.e., on the approach used for the ex-ante benefit analysis. This can be best illustrated by taking different approaches and highlighting some strengths and weaknesses.

Designing for the average or the worst case. If the average central climate risk scenario (or the 50th percentile) and associated damage profile over time is used for the road design climate proofing decision, then it is possible to model the ex-ante baseline damages, and then model the ex ante benefits from the change in design. This would look like Figure 1. However, this does not provide the real economic benefit, only the benefits as predicted in a central modelled decision (which assumes the central climate projection is 100% accurate). To partially address this, it is possible to take multiple ex ante baseline scenarios and model the ex-ante benefits of the single central design choice against each of these different futures (one at a time) and see how these vary. An alternative approach is to design for the worst case, i.e., adopt a precautionary approach. In this case there are likely to be benefits whatever the actual outcome, and this can be modelled, but as discussed later, this may involve higher and quite possibly excessive costs.

Decision making under uncertainty. Recognising the limitations above, and the potential for mal-adaptation, more recent literature has moved to a focus on decision-making under uncertainty (DMUU) for adaptation decisions. This includes techniques such as adaptive management, real options analysis, robust decision making, portfolio analysis; decision scaling and decision rules (Watkiss et al., 2014: Dittrich et al., 2016). These methods address uncertainty by using various principles (learning, flexibility, robustness, hedging and minimising regrets). However, these methods can be complex to apply, require detailed data, and are time consuming and resource-intensive when applied formally.

For the road project example, the use of DMUU might involve the following.

- Identifying potential future baseline climate risks, the range of which capture uncertainty. This might include multiple scenarios (RCPs) and multi-model ensemble results. This could involve the UKCP18 probabilistic projections, but as these are for individual RCPs only, it would need to consider multiple RCPs to capture scenario uncertainty. These alternative futures have to be modelled in terms of the baseline damage they would lead to, as part of a more complex climate risk assessment.

- The information from the climate risk assessment would be used to change the design of the road to take account of future change, taking account of uncertainty. For example, it could identify design changes that provide reductions in benefits across the full range of multiple futures (robust), or it could include design changes that provide the flexibility to retrofit later more easily (real options).

- The economic benefit of the adaptation service is again the difference between the with and without case. This analysis is again ex ante and modelled. However, in this case there is no one single counterfactual baseline. The baseline depends on the DMUU method taken. In a robust decision-making analysis, the design option may be compared to multiple baselines (note RDM does not tend to use probabilities). For a real options analysis, the baselines might have a probability distribution to them. This means there is additional analysis required to derive the economic benefits.

- It is also possible to compare the benefits of DMUU to the use of an 'if-then' approach, i.e., to look at the additional ex ante benefits of using DMUU over and above a static approach.

Therefore, the estimated benefits generated from the use of an adaptation service will depend on the decision method used, i.e., they will be different within a DMUU framework than for an 'if-then' framework. This highlights that it is not just the adaptation service (information) that generates the value of information, but also the decision support analysis, noting that the decision support is also a form of service. This is therefore different to standard economic analysis of weather and climate information services, where all the value is assumed to be generated simply by the availability of climate information. This suggests that the value of information for proactive adaptation services will vary with the decision support method used, and also that it might be appropriate to attribute the benefits between the adaptation service and the decision support method (service), rather than just to the climate information itself.

There are approaches that have been developed to look at the economics of adaptation decisions for climate-smart design of projects (sometimes called climate proofing) (Watkiss et al., 2014; ADB, 2015; ADB, 2020). In simple terms, these approaches can be applied to the approach in figure 1 of a central scenario, which the project is designed to address. The first step is to estimate the net economic benefits of the project before climate change in the baseline (the net present value, i.e., present value of benefits minus present value of costs). The analysis is then repeated with the analysis of climate change to look at the impact of climate change on the project. The final step is to look at the costs and benefits of adaptation in reducing these additional impacts. The schematic for this analysis framework is shown below, using the example of a road project.

Road project → Costs and benefits of project (baseline, no CC)
Economic benefit of road project (NPV)

↓ *Impact of climate change*

Future climate change impact → Costs and benefits of project under climate change with no adaptation
- climate change impacts will reduce NPV

↓ *Cost and benefits of adaptation*

Adaptation included in road project → Costs and benefits of project with climate proofing
Reduction in impact of climate change from adaptation (benefit) (noting may still be some residual damage) but additional costs of adaptation (cost)
Economic benefit of road project with climate proofing (NPV CP)

Figure 34 Economic analysis of climate proofing.

However, this central single scenario approach does not provide the likely economic benefits, because of uncertainty. Accounting for uncertainty can be considered in terms of the value of information from the use of climate services in the decision, and value chains, with the issue of forecast accuracy.

For traditional weather and climate services, such as daily or seasonal forecasts, it is possible to evaluate accuracy, for example by looking at the predicted versus actual outcomes. This is then used in the value chain analysis. The level of accuracy for W&CI services is normally relatively high.

It is much more difficult to assess forecast accuracy for adaptation services, especially for proactive adaptation decisions, because these services are usually projecting across time periods of years and/or decades into the future. The accuracy of climate projections is therefore much more uncertain and, by implication, lower than for W&CI services. The accuracy also varies because of uncertainty.

This question over the level of accuracy of the adaptation services has consequences for the benefits of the decision. Taking the road example above, the issue of uncertainty and accuracy in the climate projections, or services, (e.g., allowances), can lead to different economic consequences, including under- or over-investment in adaptation, as compared to the actual (real) outcome of climate change over the next 20 – 30 years. This is shown in the figure below for a one-off fixed decision, e.g., using a single average scenario and design response.

If a central figure is used in the allowance, and the scheme is designed to this, then a number of possible outcomes can arise depending on how climate change emerges in practice. If the climate model projection turns out to be an underestimate, e.g., rainfall intensity (left hand side of figure), then the scheme will not be designed to cope with all risks that emerge and there could be higher damage to the scheme. However, if the climate projection turns out to be an overestimate (central right hand side of figure) then the scheme will have invested money in changes that are not needed, i.e., costs will be higher than needed. If the worst case scenario is used (far right hand side), then it is almost certain that in most future, the scheme will be overdesigned, and so costs will be higher than needed.

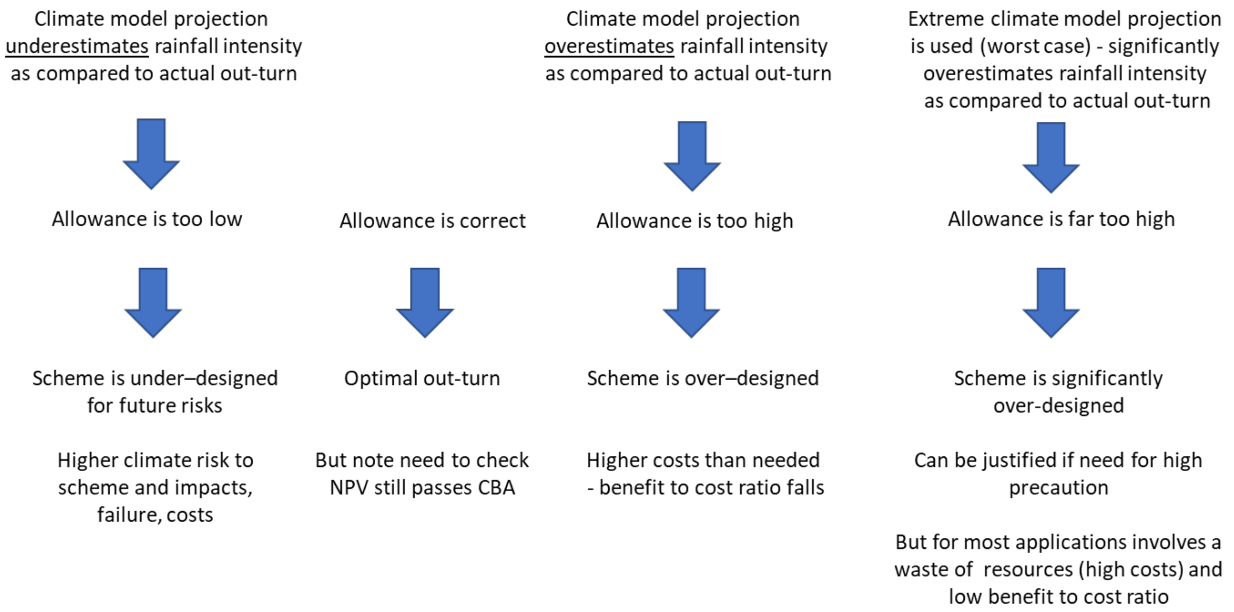

Figure 35 Implications from use of climate projections in one-off fixed decision during design (if-then), depending on the accuracy of the climate information.

This means there are potential ‘regrets’ from making the decision, but these will vary according to the scheme design criteria and the outturn. These involve potentially higher risks or higher design costs. The economic benefits of the service will therefore be influenced by these factors.

These design issues can be reduced by using a decision making under uncertainty approach and thus the economic efficiency and effectiveness of the adaptation decision may be higher when these DMUU methods are applied. However, there may also be a cost penalty from addressing uncertainty, for example the additional costs for a flexible option, or the additional costs of an iterative approach that requires additional monitoring and then later action.

When moving to a decision making under uncertainty approach, a much more complex landscape of decision emerges. From an economic perspective, in a case where there is uncertainty, a number of possible choices are possible for the road project example (adapted from ADB, 2016; Watkiss et al., 2020):

- Do nothing, i.e., accept the climate risks to the project (note this can also be complemented by a risk spreading strategy, e.g., insurance).
- Climate-proof the project today with a ‘fit and forget’ approach. This could be based on analysis of central values or worst-case scenarios.

- Climate-proof the project later in time (retrofit), when more information on risks emerge.
- Climate-proof the project today with decision making under uncertainty, as examples:
    - Climate-proofing the project today using decision scaling or robust decision making (changing design so that project performs well against multiple futures).
    - Climate-proofing the project so it is ready / easier to climate proof in the future, if needed, for example with flexibility (which can include the use of real options analysis).
    - Climate-proof the project later as new information, e.g., based on iterative approaches, including dynamic adaptation pathways.

In an economic analysis, the decision on which of this to do is influenced by:

- The impacts and economic / financial costs of climate change on the project now and projected over time, across different futures.
- The costs of taking action (climate proofing) today.
- The costs of taking action later (e.g., retrofitting).
- The level of irreversibility of the decision.
- The benefits (reduced climate impacts) of taking action today.
- The expected benefits (reduced climate impacts) in the future.
- Any co-benefits of the project (now and/or in the future).
- The level of precaution needed (e.g., some projects need to avoid downside risks such as critical infrastructure).
- Whether better information will become available and support improved future decisions.

In general terms, it will make more sense to climate proof a project today (ADB, 2015: ADB, 2020) if:

- Climate proofing today generates immediate economic benefits that outweigh costs, even without future climate change (no-regret options), i.e., climate proofing reduces current climate risks or when climate proofing leads to positive co-benefits (e.g., ecosystem-based adaptation).

- The costs of climate proofing today are low, and the likely benefits (avoided impacts) are large under future climate change (and thus offset costs today, even when discounted).

- If there is <u>not</u> a cost penalty for an option that is more robust or provides flexibility, then it may make sense to climate proof today.

- Climate proofing later (retrofitting) is not possible or difficult (irreversibility).

Conversely, if costs of climate proofing today are high, and/or there are not immediate benefits, then it may be economically rationale to climate proof later, especially if improved information will emerge, and/or if the costs of retrofitting later are similar to today. In such cases, it makes more sense to wait and climate proof in the future, if needed.

Introduction to the case study: climate change allowances

This case study is focused on climate change allowances as an example of an adaptation service. These allowances are approximations of anticipated climate change for key variables, based on detailed analysis, which can be used as a 'ready reckoner' in decisions. These allowances can be used to help change the design of infrastructure projects (among other uses), and thus in adaptation decisions.

The use of allowances avoids the need for very detailed analysis for every individual scheme, and thus can help with climate risk assessment and adaptation decisions at scale. However, given their simplicity, they are not so applicable for major adaptation investments, or where there are risks of major regrets, e.g., one would not use allowances to design the next Thames Barrier. In the latter case, a more detailed climate risk analysis is needed and given the very high capital costs, it would also be more appropriate to design with uncertainty.

The focus of the case study is to explore the economic benefits of climate allowances, from their application in current design decisions for new infrastructure. This could, in theory, be a climate proofing decision (e.g., the climate allowance on peak rainfall in the design of a new road or a new drainage scheme), or for modest adaptation investment (e.g., a small coastal protection project). The aim is to look at the economic benefit from the use of allowances as an adaptation service. In line with the discussion above, this would identify the impacts of climate change on the infrastructure investment in the baseline, then identify the benefits in reducing the future impacts of climate change from the use of the allowance to change design (adaptation).

There are climate change allowances for flood risk assessments (EA, 2022a: 2022b), which can be used for flood and coastal risk projects, schemes and strategies (EA, 2022b). A set of climate change allowances have been produced for:

- peak river flow.
- peak rainfall intensity.
- sea level rise.
- offshore wind speed and extreme wave height.

The guidance on climate change allowances highlights that such allowances can help to understand how flood or coastal erosion risk may change over time and enable the user to develop projects, schemes and strategies that adapt to a range of future climate change scenarios. Guidance is for local planning authorities preparing strategic flood risk assessments, developers and their agents preparing flood risk assessments for planning applications, and development consent orders for nationally significant infrastructure projects. The guidance highlights that making allowances for climate change in a flood risk assessment will help minimise vulnerability and provide resilience to flooding and coastal change. The guidance for use of allowances outlines a series of steps that need to be taken:

1. Apply the 'design' climate change allowances to each appraisal option.
2. Apply climate change allowances for severe climate change.
3. Apply extreme climate change allowances to your recommended option[41].

For sea level allowances, the guidance emphasises that the approach should use site specific sea-level rise values from the UKCP18 user interface, which provides a range of allowances based on

[41] The guidance sets out that the user must include the extreme scenario where: the scale of flooding or coastal erosion risk impacts are extreme; management options involve very high value or low adaptability assets. It is not usually necessary to include the extreme scenario in: the design of your recommended option; your appraisal's economic and financial assessment.

percentiles. It recommends the UKCP18 Representative Concentration Pathway (RCP) 8.5[42] and the 70th percentile (higher central) as the design allowance, and the 95th percentile (upper end) allowance in planning for more severe climate impacts[43]. To calculate sea level, the guidance recommends adding together the climate change allowances from the UKCP18 user interface with the present day extreme sea levels from Coastal design sea levels - coastal flood boundary extreme sea levels (2018).

For peak river flow allowance, the allowances are provided by management catchment. The allowances show the anticipated changes to peak flow by management catchment. The range of allowances included is based on percentiles (Defra 2022): a percentile describes the proportion of possible scenarios that fall below an allowance level. The 50th percentile is the point at which half of the possible scenarios for peak flows fall below it, and half fall above it. The allowances are based on percentiles from the UKCP18 data:

- The central allowance is based on the 50th percentile
- The higher central allowance is based on the 70th percentile
- The extreme allowance is based on the 95th percentile

Allowances are included for three future time-frames, labelled 2020s, 2050s and 2080s. An example is shown below[44].

Table 32 Gloucestershire and the Vale Management Catchment peak river flow allowances.

	Central	Higher	Upper
2020s	11%	17%	33%
2050s	11%	19%	43%
2080s	26%	41%	84%

The peak rainfall intensity allowances also show the anticipated changes to peak rainfall by management catchment. Again, the allowances are based on percentiles from the UKCP18 data:

- central allowance is based on the 50th percentile
- upper end allowance is based on the 95th percentile

Allowances are included for two future time-frames, labelled 2050s and 2070s.

[42] The RCP8.5 scenario is specified in the guidance https://www.gov.uk/guidance/flood-and-coastal-risk-projects-schemes-and-strategies-climate-change-allowances

[43] An allowance based on the 70th percentile is exceeded by 30% of the projections in the range. At the 95th percentile it is exceeded by 5% of the projections in the range.

[44] https://environment.data.gov.uk/hydrology/climate-change-allowances/rainfall

Table 33 Gloucestershire and the Vale Management Catchment peak river flow allowances

3.3% annual exceedance rainfall event

Epoch	Central allowance	Upper end allowance
2050s	20%	35%
2070s	25%	35%

1% annual exceedance rainfall event

Epoch	Central allowance	Upper end allowance
2050s	20%	40%
2070s	25%	40%

*Use '2050s' for development with a lifetime up 2060 and use the 2070s epoch for development with a lifetime between 2061 and 2125.

PLUVIAL FLOODING: FUTURE DRAINAGE

A set of climate change allowances has been produced by the UK Climate Resilience project, FUTURE-DRAINAGE: Ensemble Climate Change Rainfall Estimates for Sustainable Drainage[45]. The project (Dale, 2021) used the new UK Climate Projections (UKCP) high resolution 2.2km data (UKCP Local) to derive rainfall uplift estimates using the high greenhouse gas emissions scenario RCP8.5. These (2.2km) projections provide a spatially disaggregated basis on which to project future changes in hourly precipitation extremes, which are important for surface water flooding. The climate projections were combined with advanced statistical modelling to provide new estimates of short-duration precipitation extremes. Results were tailored to stakeholder needs, to help inform flood management and urban drainage design in a changing climate.

Rainfall flood damage estimates were made using standard Flood Estimation Handbook (FEH) data to test the resilience of existing drainage systems and flood resilience schemes, and to help design those of the future. To allow for climate change, the rainfall uplifts produced by FUTURE-DRAINAGE can therefore be applied to FEH data to allow for future projected increases in rainfall. The uplifts produced vary by location, rainfall event duration and event rarity (return period) and the project considers that these uplifts supersede those produced on a UK Water Industry Research project in 2017 Dales, 2021).

[45] https://www.ukclimateresilience.org/projects/future-drainage-ensemble-climate-change-rainfall-estimates-for-sustainable-drainage/

Box 1. Comparisons of FUTURE-DRAINAGE to UKWIR (from Dale, 2021)

The FUTURE-DRAINAGE project (Dale, 2021) considers its uplifts to be more reliable and supersede the UKWIR 2017 values. Interestingly, FUTURE-DRAINAGE did undertake a comparison of the uplift values with those produced by the UKWIR 2017 project, although the comparison is limited since the regions over which the two sets of uplifts apply are different. An approximate comparison is provided below. The analysis compared UKWIR 2017 guidance uplift values for the 30-year return period, 2050 case with the range of values from FUTURE-DRAINAGE for the 30-year return period, 2050 case. The regions referred to in this table are those used in the 2017 UKWIR project. In general, the lower values in the FUTURE-DRAINAGE range are from the 24-hour duration and the higher values in the range are from the 1-hour and 3-hour duration. For the high estimate, it can be seen that FUTURE-DRAINAGE results are lower than UKWIR 2017 values in all regions except South UK. For the central estimate, FUTURE-DRAINAGE results are lower in the North-West and higher in the South UK.

Table 1 – Approximate comparison of uplifts to the UKWIR 2017 values for 2050, 30-year return period.

UKWIR 2017 values			FUTURE-DRAINAGE Range	
			From	To
North West UK	Central estimate	35%	15%	30%
	High estimate	*65%*	*35%*	*45%*
North East UK	Central estimate	20%	10%	30%
	High estimate	*50%*	*25%*	*45%*
South UK	Central estimate	15%	20%	25%
	High estimate	*35%*	*25%*	*35%*

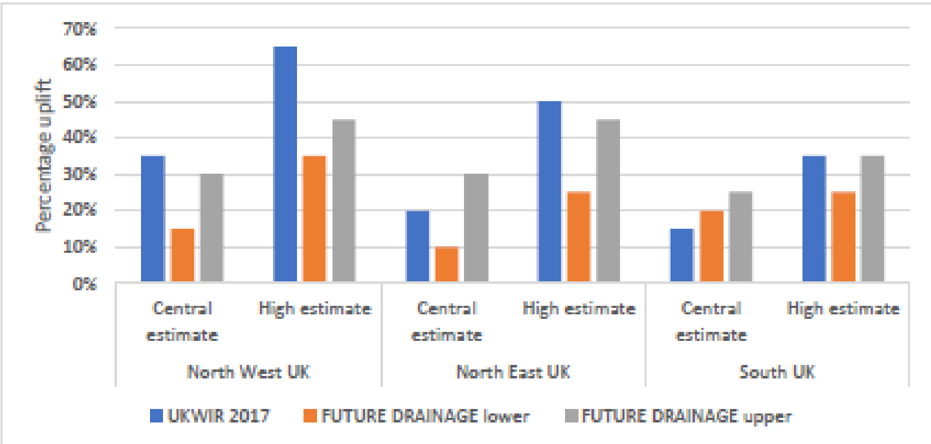

Figure 3 - Approximate comparison of uplifts to the UKWIR 2017 values for 2050, 30-year return period.

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Discussion of the benefits of allowances

The use of allowances simplifies the consideration of climate change, but it of course reduces the level of detail. There are a number of issues in considering the consequences of this reduced detail. We identify three issues:

- The level of precision in the estimation process.
- The treatment of uncertainty resulting from alternative possible climate and socio-economic futures.
- The recommendations on how to use and decision support method.

The first of these – measurement and modelling errors - is a minor issue, given the issues of uncertainty more generally. Most of the allowances avoid over-precision by rounding uplifts to the nearest 5%.

The second and third points are important. When the downscaled UKCP18 projections (e.g., 2.2 km) are used for allowances, these have advantages in respect to the quality of the model and its ability to capture local processes, but they only use variants of the Met Office Hadley Centre climate model (an issue acknowledged by Dale, 2021). This therefore does not capture the uncertainty range that is present from multi-model ensembles, for example, as captured in the UKCP18 probabilistic projections. This will mean that the use of the downscaled data is unlikely to capture the full uncertainty range. This is important because allowances are normally used with an if-then approach, with sensitivity testing, rather than with decision making under uncertainty.

It is also noted that the EA guidance recommends the use of the RCP8.5, for example with the 70th percentile (higher central) as the design allowance, and the 95th percentile (upper end) allowance in planning for more severe climate impact. RCP8.5 is a worst-case high emission scenario (reported as the 90 - 98th percentile of all scenarios[46]), and thus its use does involve a highly precautionary approach. Such a scenario would definitely be appropriate for major decisions, e.g., siting and protection of a nuclear site, but would lead to higher costs in design for more routine decisions, especially with short lifetimes of 20 or 30 years.

Application of the W&CI services valuation method

Our study has developed guidance for the valuation of the economic benefits of weather and climate. This aligns with, and builds on, methods in the literature and in existing guidance (WMO, 2015; WISER, 2021). The methodology involves the following steps.

- List the potential economic benefits that the climate service may provide.
- Develop the value chain for the service.
- Review and decide on the potential methods for assessing economic benefits.
- Build a baseline scenario (or counter-factual) without the new climate service.
- Assess the benefits with the climate service in place.
- Assess the costs of the project.
- Compare benefits against costs.
- Undertake sensitivity and bias analysis, then review how benefits could be enhanced.

The second step – and an important part of the economic analysis of W&CI service – is the use of a value chain approach. This maps the sequence of actions that generate the economic benefit. The steps in a value chain include the information provision itself (including climate projections), and supporting infrastructure and foundational activities, including science. It also includes the forecasting capacity and accuracy. The value chain further includes the communication to users, and thus the reach (the number of beneficiaries or users). Finally, it takes account of the uptake, understanding, and effective use of this information by end-users in order to generate value.

[46] carbon brief, https://www.carbonbrief.org/explainer-the-high-emissions-rcp8-5-global-warming-scenario/).

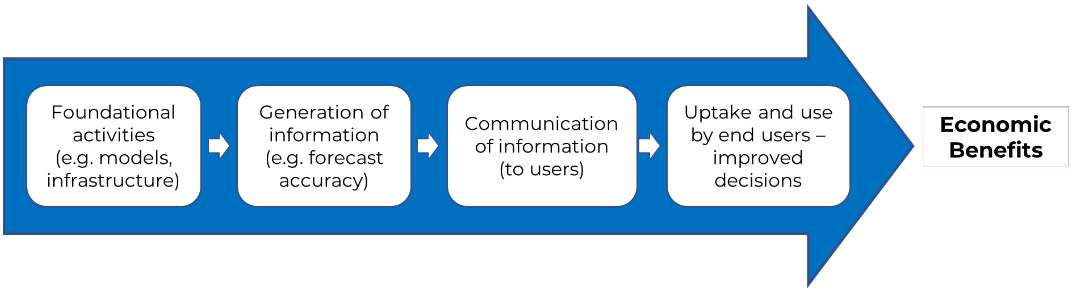


Figure 36. Simple W&CI service chains

The use of climate model information and climate allowances relate to the foundational activities and the generation of the allowances (the first two steps) – but then there is also a need to see how these are communicated to users, and most importantly, to consider how they are used in improved decision by these users to generate economic benefits.

These steps have been applied to a series of mini-case studies on climate allowances.

- The analysis of the additional benefits in moving from UKCO09 to UKCP18 for drainage decisions, i.e., economic benefit of improved projections.
- The analysis of accuracy and how this affects benefits ex post using some analysis for sea walls.

The first case study looks at the improvement in foundational activities and improved accuracy of information from improved climate projections. These then improve the overall economic benefits from the use of this information (in climate allowances) along the value chain. The second case study also looks at accuracy, but in terms of the use in adaptation decisions, and how economic benefits differ in the case of climate projections because of uncertainty.

Benefits of UKCP18 in Update Allowances (FUTURE DRAINAGE)

The case study takes a national perspective and primarily utilises data from the Long-Term Investment Scenarios (LTIS) for flood and coastal erosion risk management (FCERM) developed by the Environment Agency. We utilise the economic data that results from application of the flood management investment modelling to simulate the possible effects of introducing climate change allowances for a range of climate change scenarios.

Step 1. List of economic benefits

The first step in the approach is to identify and list the potential benefits of the service. Climate change can affect the financial and economic performance of infrastructure. It can have an important influence on key financial parameters, including asset values (capital), current expenditures (operating and maintenance costs), and revenues (ADB 2020). These changes affect:

- Economic returns delivered by the investment—whether the total economic and social benefits generated by the asset are sufficient to justify the costs.
- The cash flows (cost and revenues) and hence financial returns delivered by the project—and, in some cases, whether cash flows generated by the asset are sufficient to meet the return requirements of investors.

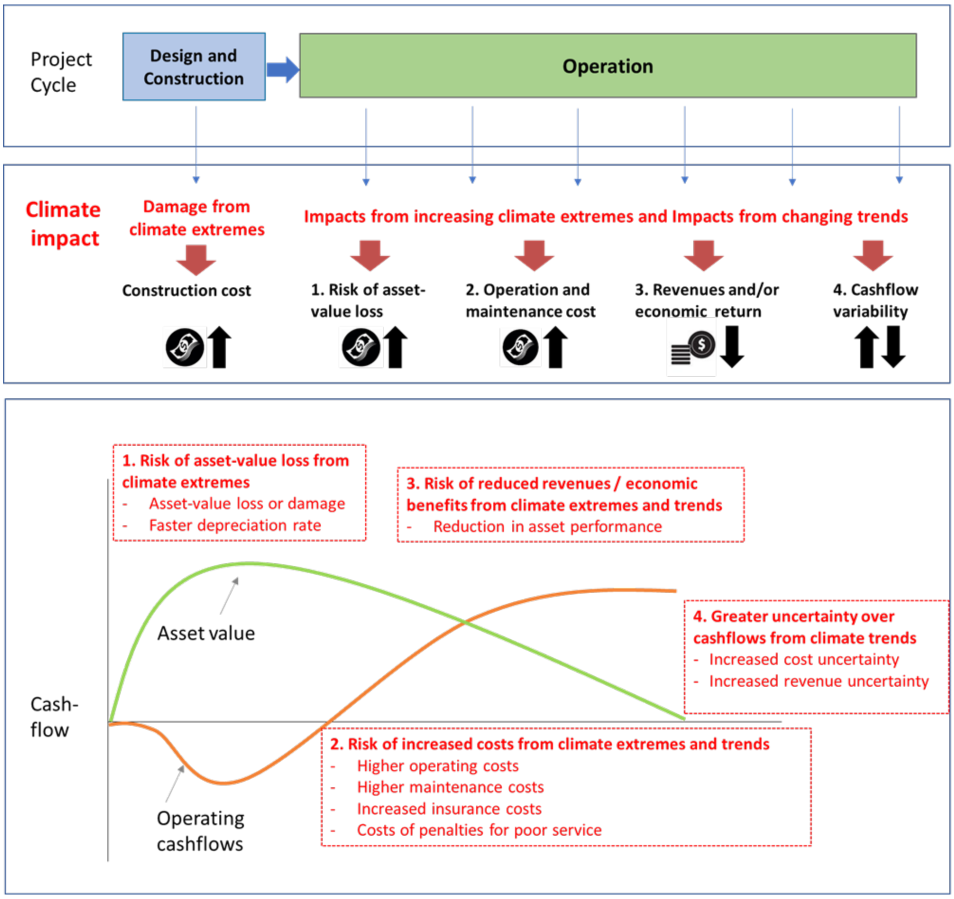


Figure 37 Impacts of climate change on Investment financing for climate proofing. ADB, 2021.

ADB (2021) identifies four separate channels through which damage costs can be identified:

- The direct damage to capital (assets) from extreme weather events that either require additional spending or lead to a deterioration in the performance and/or value of the asset and services it provides.
- The increase in operating costs that may result from climate change impacts, e.g., from changing average climate.
- The possibility that climate change will reduce the function or services (the benefits) provided by the assets, and their revenue generation potential or the socioeconomic benefits that they are expected to produce.
- The increased variability of asset performance and hence the greater uncertainty in the financial returns that an asset will provide.

Improved information – in the form of a climate allowance used in an infrastructure decision – can therefore reduce or avoid these impacts (and in theory, take advantage of any upsides).

In this case, we will look at the general benefits from the use of allowances and compare to the baseline where no allowance is included, i.e., no climate information is used. The analysis also explores if it is possible to value the benefits of the improved information from climate projections for deriving allowances, in moving from UKCP09 to UKCP18, and the comparison of FUTURE-DRAINAGE with UKWIR 2017.

Step 2: Develop the W&CI Service Value chain

The value chain for the adaptation service for proactive adaptation for climate proofing involves.

- A set of design considerations, built around the project objectives, e.g., the project design of a new road and core road appraisal, or the design of a new drainage system based on volume (demand), or the design of a new sea wall.
- A set of baseline weather and climate considerations that would be included in the scheme design typically, i.e., the existing standard design criteria for coping with peak rainfall intensity, or floods, or peak wave height. These do not consider climate change.
- Finally, there is the adaptation service, and the climate change information in the form of allowances, which are used to future-proof the project (changes to design) against climate change.

The value chain aspects for current W&CI information and future climate change are shown in the table below. In line with the earlier discussion, there are a number of steps in the value chain analysis which are challenging when looking at climate change allowances. These include an assessment of the forecast accuracy of the allowances and an assessment of their effectiveness, especially in the context of uncertainty, noting as above, this will depend on the decision support method used (normal or DMUU).

An extension of the value chain above is to look at the improved information when moving from UKWIR 2017 to FUTURE-DRAINAGE. In this case, the value chain is the same, but the accuracy (generation) of the allowances is improved. In turn, the improved accuracy leads to higher benefits down the value chain, from the improved effectiveness of the information.

Table 34. Value chain for baseline and climate allowances.

Value chain step	Infrastructure baseline – example of weather and climate aspects	Future climate change (adaptation service)
Foundational	Monitoring, observations and historical records	Climate model projections. *Accuracy of modelling.*
Generation	Historical weather data on peak flow, flood frequencies and intensities, wave heights, etc.	Production of climate allowance values (accuracy of allowances) that include % allowance for same parameters. *Accuracy of allowances.*
Communication	Dissemination of data, e.g., portals, guidance to engineers	Dissemination of allowances through EA guidance and regulatory requirements for application. *Number of design decision makers reached*
Uptake and use	FCERM[47] appraisal guidance and application (EA, 2022) (note assume use as good practice)	Guidance for use. *Number / % of schemes which use the allowance*
Decision	Inclusion of information on peak flows, flood probability data and observations (might include hydrological analysis and modelling, flood probability curve, annual average loss (AAL), or equivalent annual damage (EAD)). Design of scheme	Application of allowance to current drainage investment decisions, including the allowance in hydrological analysis and modelling, and estimation of updated AAL or EAD under climate change Amended scheme design *Effectiveness of schemes amended*
Economic benefit		Reduced AAL/EAD under climate change
Costs		Additional costs of change in design, and comparison to benefits generated.

Step 3 Review and decide on the potential methods

The selection of method depends on two issues:

- The type of W&CI service and the suitability of various methods to make estimates of benefits.
- The capacity, level of expertise, time and resources (including data) available for the SEB analysis.

For climate change projections, the report: Methodology for Valuing and Monitoring Climate Variability: Deliverable 2 of the contract 'Climate Resilience – CR20-2 Standards for climate services and monitoring and valuing climate services' sets out the potential methods and needs. These have been adapted to the adaptation service context.

[47] The Environment Agency's Flood and Coastal Erosion Risk Management (FCERM) guidance at: FCERM appraisal guidance - GOV.UK (www.gov.uk)

Table 35 Potential methods and applications.

Description of Method	Resource & Expertise Needs. Limitations.
Ex ante Surveys of willingness to pay for new or improved services. For example, a survey of local authority personnel responsible for drainage management of their WTP for reliable climate allowance estimates and attendant benefits.	High. Cost of survey and analysis. High level of expertise involved.
Revealed preference studies, e.g. averting behaviour. For example, additional expenditures on drainage systems that accommodate perceived climate change risk.	Medium to high. Cost of studies and analysis. High level of expertise involved. May be difficult to isolate climate-related effects from other influences on expenditure decisions.
Ex post Survey/questionnaire of likely beneficiaries (ex post). For example, a survey of local authority personnel responsible for drainage management of their WTP for a reliable climate risk allowance and attendant benefits, following a serious local flood event.	Medium. Cost of survey and processing results. Low -medium expertise required. May be difficult for survey respondents to isolate effects of climate-related events from other events.
Ex ante Modelling of flooding impacts from climate change risks. For example, decision modelling of road damage with and without allowances of different magnitudes.	Medium to high. Time spent on developing model and data analysis of results. High expertise required. Behavioural decision rules sensitive to modeller's assumptions.
Ex post Impact assessments, e.g. studies to allow measurement of benefits (whether pilots or full schemes). For example, time and accident benefits resulting from enabling action to reduce road flood risk inform overall benefit assessment.	Medium to high. Development and analysis of studies and results data. Medium – high expertise required. Would need to have long time frames to generate robust findings.
Ex post statistical and Econometric analysis, e.g. quantification of reduction of flood risk on basis of regression analysis of historical data. For example, statistical analysis of the relationship between historical incidents of flooding and road disruption inform quantification.	High. Time spent on developing econometric analysis and data analysis of results. High expertise required. Would need to have long time frames to generate robust findings.
Value Transfer of results from a previous study to a new decision context. For example, use of flood risk-damage cost relationships estimated by DfT in surveys can be transferred to the road delay context.	Low to Medium. Transfer from original study context to current decision context introduces uncertainties that limit accuracy of resulting estimates.

Given the proactive nature of the climate change allowance climate services, only *ex ante* methods can be used, though these can be used in different ways. While most literature uses ex ante modelling, it might be possible to do ex ante willingness to pay surveys, for example. An alternative approach might be to use benefit transfer, i.e. analysis from existing climate proofing schemes that are similar, though this transfer is likely to be based on other ex-ante modelling studies, rather than ex post information. For example, it would be possible to use existing impact assessment-based modelling – transferred from Centre For Ecology & Hydrology [1999[48]] and benefit transfer of appropriate economic unit values (i.e. transfer of values derived in previous studies but judged to be suitable for use in the current context) given in the Multi-Coloured Manual (Penning-Rowsell (2013))[49]. The

[48] Centre for Ecology & Hydrology, (1999), *Flood Estimation **Handbook***. Wallingford HydroSolutions. ISBN: 9781906698003

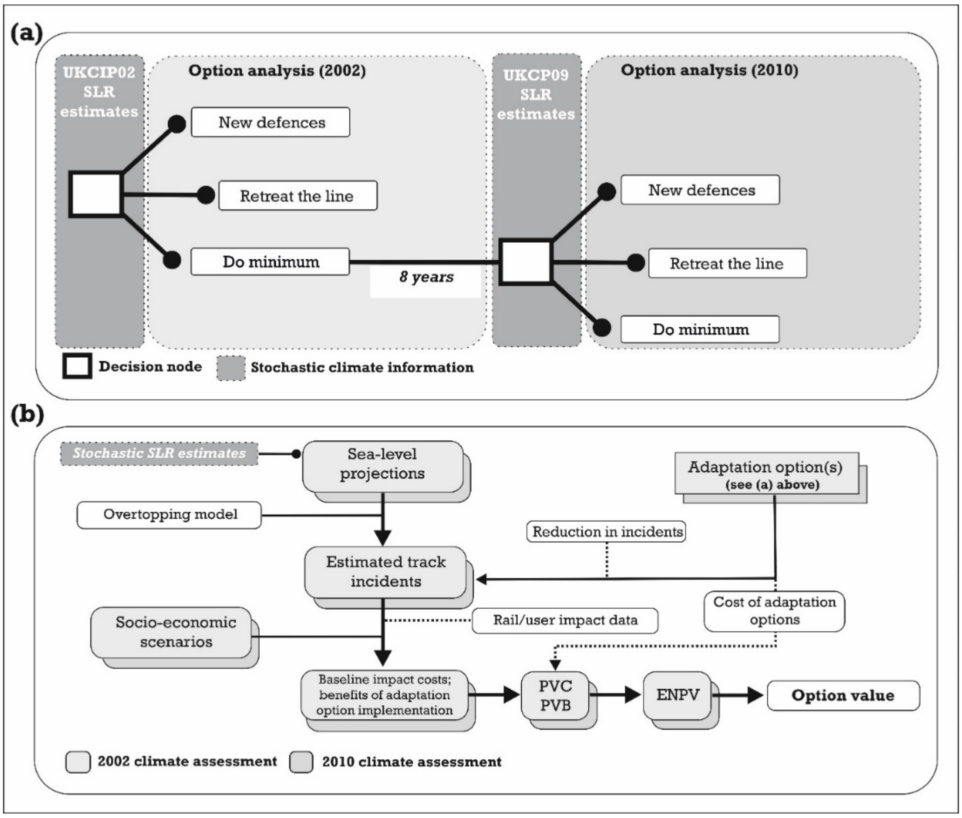
[49] Penning-Rowsell, E. Priest, S., Parker, D., Morris, J., Tunstall, S., Viavattene, C., Chatterton, J., and D. Owen (2013) Flood and Coastal Erosion Risk Management: A Manual for Economic Appraisal.

imposition of allowances is an explicit way of transferring the findings of detailed hydrological impact modelling at the national scale to generate typical mark-ups – or allowances – at the regional scale. They therefore provide an indication of the change to the hydrological system – whether fluvial, pluvial or coastal flooding-related – projected to result from climate change scenarios. In this study the valuation of the related impacts is undertaken using benefit transfer.

Box 3. Previous analysis of the economic benefits of moving from UKCP02 to UKCP09

In a previous application, Dawson et al (2018) explored the value for management decisions relating to coastal rail infrastructure from updated climate scenarios. This modelled the effect of moving from the UKCP02 sea-level rise scenarios to the UKCP09 scenarios on the economic performance of alternative management options open to Network Rail when considering the future of the 4.2 miles Dawlish-Teignmouth stretch of rail line. The method is outlined in the two parts of the figure below.

The new SLR data (UKCP09 in (a)) allows the cost-benefit analysis for the management options to be updated from the use of UKCP02. The modelling components that input into these CBAs are indicated in (b). In practice, objective probabilities are not known for alternative, stochastic, SLR scenarios. Therefore, in their absence we assume a range of alternative subjective probabilities corresponding to a range of attitudes to risk that decision-makers might have (characterised as pessimists, neutralists and optimists) and these allow us to calculate Expected Net Present Values (ENPVs). The change in the ENPVs as a result of moving from UKCP02 to UCKP09 is known as the Option Value, or Value of Information. The value gained by delaying the decision, and therefore giving the decision maker the opportunity to re-evaluate the adaptation measures is estimated to be equivalent, using central and neutralist valuation parameters, to be approximately 6%-20% of the capital cost of adaptations on the railway line.



Step 4. Build the baseline

We utilise the economic data provided in the Environment Agency Long-Term Investment Scenario (LTIS) analysis[50] in order to identify baseline riverine and coastal flood impacts on infrastructure and property, plus flood impacts from surface water flooding in urban areas. We make the following calculation steps, summarised in the 5 below:

- Total property flood damages (present value, i.e., discounted, over 100 years) and infrastructure damages, for coastal and fluvial flooding, under a medium climate change scenario are estimated to be £1050 billion and £992 billion, respectively. LTIS reports do not provide a baseline explicitly, so we derive these baseline totals by working back from the benefit estimates. The benefit estimates – the data presented in LTIS - are 12% of the total damages and equate to £126 billion and £119 billion, respectively. Total surface water damages have a present value cost of £143 billion.
- The average discount factor over the 100-year period of 0.3 is removed in order to estimate undiscounted total damage costs for the whole period and on an annual basis;
- An indicative climate change risk factor of 20% is used – estimated from a rough mid-point of the values given in Table 1 and Table 2, above – in order to calculate climate change damage costs. Annual average undiscounted climate change-induced damage costs under a Medium scenario are found to be £7 billion and £6.6 billion for property and infrastructure, respectively, and £1 billion for surface water costs. These estimates are then converted to undiscounted 100-year damage totals and their Present Value-equivalents – see the final two rows in Table 5, respectively. The annual, and undiscounted and discounted, 100-year totals therefore constitute the baseline risk estimates.

Table 36. Property & Infrastructure Fluvial and Coastal and Surface Flood Damage Costs – LTIS-derived.

	Fluvial & Coastal		Surface	
	Property	Infrastructure		Total
	Billion £	Billion £	Billion £	Billion £
PV Benefits (100 years)	126	119	17	262
Risk reduction	0.12	0.12	0.12	
PV damages (100 years)	1050	992	143	2185
Discount factor (average	0.3	0.3	0.3	
Undiscounted damages (100 years)	3500	3306	476	7282
Total annual damages	35	33	5	73
CC-induced factor	0.2	0.2	0.22	
CC-induced annual total damages	7	6.6	1.0	15
CC-induced total damages (100 years)	700	661	105	1466
CC-induced PV total damages	210	198	31	440

[50] Long-term investment scenarios (LTIS) 2019 - GOV.UK (www.gov.uk)

Step 5. Assess benefits with the service

The monetary estimates presented show that the annual climate change-induced damage costs under a Medium scenario are estimated to be £7 billion and £6.6 billion for property and infrastructure, respectively, for coastal and fluvial flooding. The medium climate change scenario is equivalent to the central allowance given in the Environment Agency guidance for these forms of flooding. The central allowance effectively signals that with the inclusion of climate change the baseline flood risks will be 20% higher than they would be in the absence of climate change. Therefore, the benefit of introducing the allowance is derived from the fact that adaptation to climate change-induced flood risk is now incorporated into the overall management of flood risk. The resulting changes in investment costs, benefits, their net present value (NPV) balances (benefits minus costs), and residual damage costs, are presented in Table 7 below and are derived from the data given in LTIS.

The results show that without the allowance, the total net present value of flood risk management under the Medium climate change scenario is £155 billion whilst the residual flood risk damage cost is £1,993 billion. In contrast, when adaptation to climate change is incorporated into flood risk management the net present value of investment is higher – at £193 billion – and the residual damage costs are lower – at £1,797 billion. This takes account of the higher benefits but also the higher costs involved. The benefit of the allowance is therefore the sum of the improved NPV ((£193bn - £155 bn = £38 billion) and the reduction in residual damage costs (£1,993 bn - £1,797 bn = £196 billion), which equates to a present value of £234 billion over the 100-year time-period.

Table 37 Economic Appraisal Results: Property & Infrastructure Fluvial and Coastal Flood – LTIS-derived

	Fluvial & Coastal		
	Property	Infrastructure	Total
	Billion £	Billion £	Billion £
Annual Iv costs medium CC	0.9	0.9	1.7
Annual Iv costs without CC	0.7	0.7	1.4
PV costs medium CC	26	26	52
PV Costs without CC	21	21	41
NPV Medium CC	100	93	193
NPV without CC	80	75	155
PV residual damages including adaptation	924	873	1,797
PV residual damages without adaptation	1,025	968	1,993

In order to identify the economic benefit of moving from the UKWIR (2017) allowances to those derived from the FUTURE-DRAINAGE project modelling for the South UK region we adopt a similar approach as the aggregate flood risk management analysis. As shown in Box 1, the allowance given in UKWIR for South UK is 15% whilst in FUTURE-DRAINAGE the allowance derived is 22.5% - the range mid-point. The resulting estimates are presented in Table 8. The results show that with the UKWIR allowance, the total net present value of surface flood risk management is £6.4 billion whilst the residual flood risk damage cost is £59 billion. In contrast, when the up-dated FUTURE-DRAINAGE allowance for climate change is incorporated into surface water flood risk management the net present value is higher – at £6.8 billion – as are the residual damage costs – at £63 billion. The benefit of the updated FUTURE-DRAINAGE allowance compared to the original UKWIR allowance is therefore the sum of the change in NPV (£0.4 billion) and the change in residual damage costs (£4 billion), which equates to a present value of £4.4 billion over the 100-year time-period.

Note that precisely the same method is adopted irrespective of the direction of change in the allowance. For example, Box 1 shows that in North-West UK, the allowance is 35% in the earlier UKWIR analysis and 22.5% in the subsequent FUTURE-DRAINAGE analysis. In this case, with the UKWIR allowance, the total net present value of surface flood risk management is £3.2 billion whilst the residual flood risk damage cost is £30 billion. In contrast, the FUTURE-DRAINAGE allowance for climate change generates a lower net present value of £3.4 billion, with residual damage costs of £31 billion. The benefit of the updated FUTURE-DRAINAGE allowance compared to the original UKWIR allowance is therefore the sum of the change in NPV (£0.2 billion) and the change in residual damage costs (£1 billion), which equates to a present value benefit of £1.2 billion over the 100-year time-period.

Table 38 Economic Appraisal Results using UKWIR and FUTURE-DRAINAGE Allowances: Southern UK

Calculation Data	FUTURE-DRAINAGE (2021)	UKWIR (2017)
Annual Iv costs medium CC	0.059	0.055
Annual Iv costs without CC	0.046	0.047
PV costs medium CC	1.8	1.7
PV Costs without CC	1.4	1.4
NPV Medium CC	6.8	6.4
NPV without CC	5.3	5.5
PV residual damages including adaptation	63	59
PV residual damages without adaptation	70	66

Table 39 Economic Appraisal Results using UKWIR and FUTURE-DRAINAGE Allowances: North-West UK

Calculation Data	FUTURE-DRAINAGE (2021)	UKWIR (2017)
Annual Iv costs medium CC	0.029	0.028
Annual Iv costs without CC	0.023	0.018
PV costs medium CC	0.9	0.8
PV Costs without CC	0.7	0.5
NPV Medium CC	3.4	3.2
NPV without CC	2.6	2.1
PV residual damages including adaptation	31	30
PV residual damages without adaptation	35	32

A different – but equivalent - way of thinking about this is to consider the ex post up- and downsides of acting on the information, i.e., using the allowances. In this case, a capital expenditure is made, i.e., a flood scheme is designed and built using UKWIR allowances, and then subsequently this information is updated by FUTURE DRAINAGE. This is shown below.

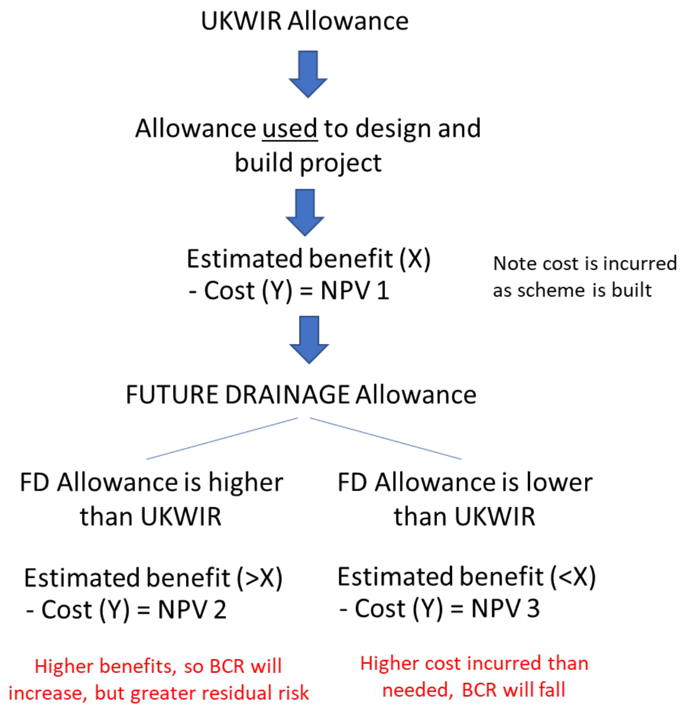


Figure 38 Analysis of outcomes of improved information UKWIR to FUTURE DRAINAGE

In this case, the actual use of the allowance data in a decision, that is later superseded by improved information leads to different outcomes. In the case where the risks are higher with the new information, and a higher allowance replaces the previous one (as in Southern UK above), then benefits would be expected to also be higher (as risks are higher), and thus the NPV may increase, but there is a danger of higher residual damages (or even a risk of scheme failure). In the case where the risks are lower from the new allowance (as with the North West), then the benefits will be lower, but as the costs are already incurred, so the NPV will fall. Note that in both cases it is assumed that new science ensures that the new allowance is more accurate. This shows that both previous decisions (based on UKWIR) involve regrets, but they are different in nature, depending on the subsequent direction of change.

The benefits of introducing allowances need to be adjusted to account for the efficiency losses in the value chain. In this context, given the new nature of the product it is not possible to quantify the changes in accuracy of modelling and the resulting climate change allowances. It is also the case that since the allowances form part of the regulatory guidance published by the Government and implemented by the Environment Agency, the mandatory nature of this guidance implies that their effectiveness in adoption by those responsible for the development of the flood risk management scheme (developers, land-owners, the EA) may be assumed to be close to 100%. Therefore, we do not envisage a further loss of efficiency in the value chain.

Step 6: Assess the costs of the project developing the climate service

There are costs associated with introducing allowances. These costs include those associated with the hydrological and impact modelling entailed in establishing the extent of the damage costs associated with climate change, additional to those that would result in the absence of climate change. The costs incurred in bringing these allowances into existence are those borne by the Met Office – the capital and recurrent costs associated with generating and processing climate change projections – as well as the organisations responsible for the hydrological and physical impact modelling, and the Environment Agency who take the lead in interpreting the modelled output data so as to express it in terms of allowances, and the dissemination of the allowances. These costs are complicated to estimate since the service also includes shared costs with other Met Office activities. However, an example of the cost of one component of these resource requirements is the cost of generating the up-dated set of allowances for surface water flooding. The cost of the contract for the FUTURE-DRAINAGE research, undertaken by JBA Consulting, with partners, was £250,000.[51]

Step 7: Compare benefits against service costs

Step 6 reports that it was not possible to quantify costs for the service. Thus, Step 7 – required in an economic appraisal – is not possible to undertake in this instance. Given the potential scale of benefits above, however, we consider it very likely that the service that brings about the allowance and provides for an improvement in the allowance, would pass a cost-benefit test, given the scale of flood risk that these allowances are able to affect through flood risk management.

Step 8: Undertake sensitivity and bias analysis, then review how benefits could be enhanced.

In the absence of service cost data there is no sense in undertaking a sensitivity analysis of cost-benefit analysis. However, it should be noted that were such a Cost-Benefit Analysis (CBA) to be possible we would explore how the uncertainties in the baseline cost assessment (Step 4) and those in the benefits assessment (Step 5) could be tested through the adoption of a range of baseline cost estimates that explore whether and how the outcome of a CBA changes. The principal parameters in the baseline costs and benefits assessment to which uncertainty is attached include:

- The hydrological flood modelling projections.
- The flood damage cost functions.
- The effectiveness of flood risk management.

Decisions relating to the investment in, and promotion of, flood risk allowances based on modelled data by the Environment Agency will be dependent on making defensible projections of future baseline impact costs, and the benefits that would result from the reduction of these impact costs. In the most basic analysis, the average potential benefits estimated in Step 5 can be extrapolated. These extrapolations would need to be augmented by data on projected land use patterns that themselves determine exposure of people and assets to flood risk. Projections of these land use patterns can be found in LTIS.

Discussion

There are several assumptions in this analysis. The most important of these are

- Climate change allowances are understood and accepted as reflecting the risk preferences of specific stakeholders and wider society.
- End-users are 100% effective in their use of the forecast information.
- Updated projections are more accurate than previous projections.

[51] : https://www.ukclimateresilience.org/projects/future-drainage-ensemble-climate-change-rainfall-estimates-for-sustainable-drainage/

These assumptions are required to generate quantitative measures of benefits, but they highlight that there is considerable uncertainty involved. In this case, regulatory requirements are likely to bring about an uptake and efficient use of the information at something close to 100%. This assumption might be challenged, however, if – for example – the users of this information believed that the information was unreliable, made planning overly complicated, or were constantly changing.

A key feature of these allowances is that there is a single, specific, allowance suggested for a given development, which is determined by an assessment of the area's modelled vulnerability to flood risk. Implicit in this approach is that the values in the allowances reflects current social attitudes to flood risk and vulnerability, i.e. levels of social risk aversion.

As noted above, the adoption of allowances that are based on high percentiles within the RCP8.5 climate change scenario suggest that the Environment Agency is utilising a precautionary approach, reflecting a relatively high degree of social risk aversion, which will lead to relatively high-cost management options. This contrasts with existing flood risk management, which have tended to use a benefit to cost ratio (5 to 1 return) threshold for a justification for investment. This means climate change is being implemented to a higher level of protection that for current flood management.

The use of a single allowance (and sensitivity test) could also introduce a false sense of the certainty on future climate change flood risks. This may lead to a lack of flexibility in the flood risk management design or a reliance on utilising a single option to respond to the flood risk rather than considering a wider range of options or the use of decision making under uncertainty.

Future analysis could also look to develop quantitative estimates of the service costs in order to be able to undertake a complete cost-benefit analysis and so comment on the economic justification for the climate modelling service.

Case study on Seawalls, Allowances and Uncertainty

A second case study has been used to explore the economic benefits of the use of allowances, based on possible ex post outcomes. This is centred on a simple new coastal protection scheme (seawall) as an example.

The seawall is assumed to be a one-off decision and can be designed to different heights, based on climate information from the allowances. The analysis then looks at the benefits and costs associated with combinations of seawalls of varying heights against different sea level rise outcomes. The 5 climate change scenarios which are used as a basis for expected changes in sea level are:

- No change from 2022 levels.
- RCP 2.6, 50th percentile.
- RCP 4.5, 50th percentile.
- RCP 8.5, 70th percentile (upper central).
- RCP 8.5, 95th percentile (extreme).

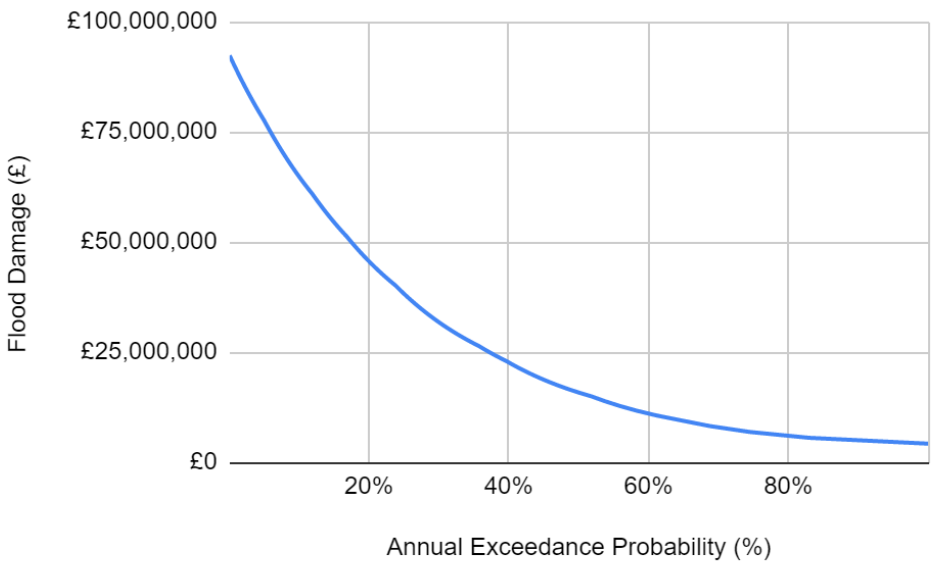
To link to the allowances, which are geographically specific, it is assumed the seawall is built in Bristol. The changes in sea level which are projected by UKCP18 through to 2072 under each of these scenarios are then used to inform the build height for a seawall. It is assumed that the seawall is designed to withstand floods which have a return period of up to 1 in 100 years.

The potential tidal flood damages are estimated using a simple flood damage curve. This curve was constructed using a combination of McKinsey (2020)[52] estimate for the damage of a 1 in 200 year flood in Bristol of £92 million and the gradient of the flood damage curve for England (Penning-Rowsell, 2020[53])[54].

The total expected annual damages (EAD) according to this curve are £25.7 million and the EAD for events with a return period of 1 in 100 or less is £16.8 million which implies that a seawall which can withstand floods with a return period of up to 100 years will reduce EAD by 65%.

[52] https://www.mckinsey.com/~/media/mckinsey/business functions/sustainability/our insights/can coastal cities turn the tide on rising flood risk/mgi-can-coastal-cities-turn-the-tide-on-rising-flood-risk.pdf
[53] https://eprints.mdx.ac.uk/31511/2/jfr3.12685_VoR.pdf
[54] £92 million is derived from the average of their $45 million to $195 million range converted from USD to GBP using the average USD/GBP exchange rate for 2020 of 1.3. The damage curve for England can be found in Table 8 of Penning-Rowsell (2020).

Figure 39. Illustrative flood damage curve for Bristol.



This analysis also looks the 'regrets' from under or over-sizing the seawall, as compared to the actual sea level rise that later emerges. For example, it may be that a seawall which would be appropriate for an RCP 2.6 expectation for sea level rise is built, but sea level rise follows a pathway that is consistent with the RCP 4.5 scenario. In this scenario the seawall would be defined as 'insufficient' and would not reduce the expected damage associated with tidal flooding as much as an optimal seawall would. Equally, there may be a case in which a seawall is built for an RCP 8.5 (extreme) scenario, but sea level rise turns out to be consistent with an RCP 4.5 scenario. In that scenario the seawall would be defined as 'excessive' and would incur much higher costs, even though it would reduce the expected damage associated with tidal flooding more than an 'appropriate' seawall.

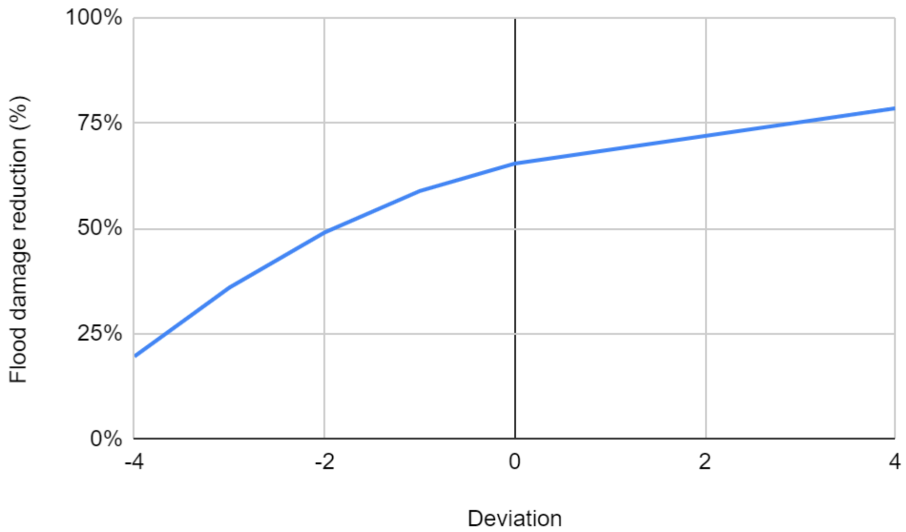
The combination of seawalls and climate change scenarios is best set out by the matrix below. The numbers refer to the increments in level of under (insufficient) or under (excessive) design.

These combinations are then translated into differing levels of flood protection using a combination of the baseline estimate of 65% damage reduction for an 'appropriate' seawall. For this example, we use a simple effectiveness curve below, that provides indicative values that translate the matrix above into potential flood damage reduction. The curve is constructed with the assumptions that the losses in effectiveness from having an 'insufficient' seawall are larger than the gains in effectiveness from having an 'excessive' seawall and that as walls are deemed increasingly 'insufficient' the drop-off in effectiveness accelerates. The aim is just to illustrate the concepts of the regrets of decisions, in the absence of specific information.

Table 40 Seawall height and sea level rise scenario compatibility matrix.

		Sea Level Rise by 2072				
		Base (2022)	RCP 2.6 (50th)	RCP 4.5 (50th)	RCP 8.5 (70th)	RCP 8.5 (95th)
Seawall Height	Base (2022)	Appropriate	Insufficient (-1)	Insufficient (-2)	Insufficient (-3)	Insufficient (-4)
	RCP 2.6 (50th)	Excessive (+1)	Appropriate	Insufficient (-1)	Insufficient (-2)	Insufficient (-3)
	RCP 4.5 (50th)	Excessive (+2)	Excessive (+1)	Appropriate	Insufficient (-1)	Insufficient (-2)
	RCP 8.5 (70th)	Excessive (+3)	Excessive (+2)	Excessive (+1)	Appropriate	Insufficient (-1)
	RCP 8.5 (95th)	Excessive (+4)	Excessive (+3)	Excessive (+2)	Excessive (+1)	Appropriate

Figure 40 Illustrative Rate of protection against flood damage by scenario. Deviation refers to the degree seawall height is 'excessive' (positive values) or 'insufficient' (negative values) – see matrix.



Bristol was chosen as the geographical context and the UKCP18[55] provides expected sea level rise for each of our 5 scenarios. The values are compared to a 1980-2000 baseline and so, to compare them to a scenario of no further sea level rise from this point onwards (in 2022), one must subtract the amount of sea level rise which has occurred in the past 20 to 40 years which is 0.11m.

[55] https://ukclimateprojections-ui.metoffice.gov.uk/ui/home

Table 41 Sea level rise by climate change scenario: Bristol.

Scenario	Sea level rise by 2072 compared to 1980-2000 baseline (m)
2022 (no further rise to 2072)	0.11
RCP 2.6, 50th percentile	0.32
RCP 4.5, 50th percentile	0.37
RCP 8.5, 70th percentile (upper central)	0.53
RCP 8.5, 95th percentile (extreme)	0.67

Counterfactual

In order to create a counterfactual scenario, the expected tidal flood damages under each of the 5 scenarios was estimated. This used the return period - surge height curve from (Department for Transport 2014[56], based on EA).

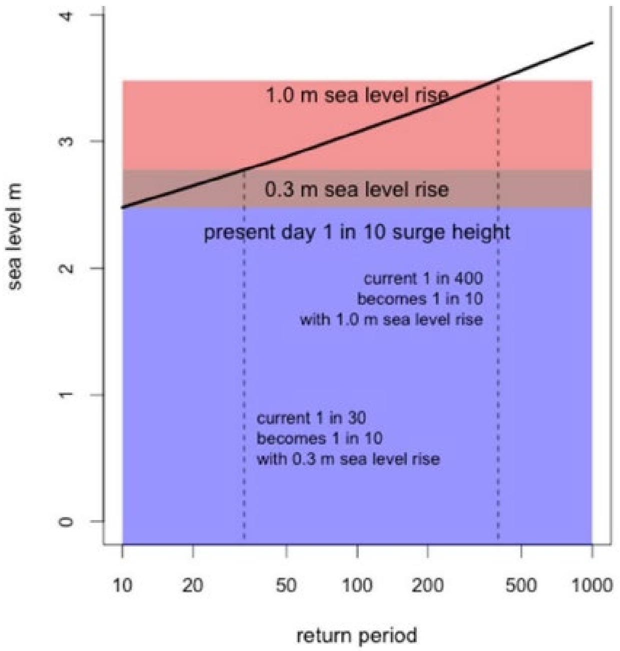


Figure 41 Chart shows relationship between rising sea level and more frequent return-period for a tidal surge at a UK coast port. The solid black line is the current return period -surge height curve. The blue box is the height of the current event with an annual probability of 0.1 (1 in 10). The pink bars represent 0.3 and 1.0m sea level rise.

[56] Department for Transport. (2014). Transport Resilience Review: A Review of the resilience of the transport network to extreme weather events. Retrieved August 16, 2021, from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/335115/transport-resilience-review-web.pdf

This curve allows us to translate the sea level rise in the table above into expectations for how the intensity of tidal storm surges could evolve between 2022 and 2072 using the intensity of 1 in 10 year events as a proxy for all tidal flood events.

Table 42 Relative intensity of a 1 in 10 year flood by climate change scenario.

Scenario	Sea level rise by 2072 compared to 2022 baseline (m)	Multiple of 1 in 10 year flood by 2072 (compared to 2022)
2022 (no further rise to 2072)	0.00	1.00
RCP 2.6, 50th percentile	0.21	2.30
RCP 4.5, 50th percentile	0.26	2.70
RCP 8.5, 70th percentile (upper central)	0.42	9.30
RCP 8.5, 95th percentile (extreme)	0.56	17.20

Using the estimate that in 2022, the EAD of coastal flooding in Bristol is £25.7 million one can generate estimates for the average annual cost of coastal flooding in Bristol by 2072, by multiplying by the factors above. It is assumed that the change between expected annual damages in 2022 and 2072 occurs linearly so, if the value is £25,700,000 per year in 2022 and £77,100,000 in 2072, the value in 2047 would be £51,400,000 per year.

Benefit

To calculate the benefit of the seawall, i.e., the avoided economic damage associated with storm surges, the damage values are multiplied by the avoidance percentages outlined earlier (20% to 78%). For example, for the RCP 8.5 (upper central) scenario where EAD reaches £239 million by 2072, and where a seawall was built to an RCP 2.6 scenario, the damage avoided in 2072 would be 49% of £239 million which is £117 million.

This calculation is done for each seawall vs. sea level rise scenario combination for each year between 2022 and 2072 with the Present Value (PV) of this benefit stream being discounted using the HMT Green Book social discount rate regime.

Costs (Version 1)

Costs vary by the height of seawall constructed and so there are 5 cost scenarios, one for each of the seawall heights. In each case, the amount of sea level rise which is estimated in the scenario is added to the baseline crest height (7m) to give the height of the seawall which is to be constructed. The 7m baseline height is based on the average height of current seawalls in the area (Living levels, 2018[57]). Capex costs are calculated using the estimates below.

[57] https://www.livinglevels.org.uk/stories/2018/12/10/sea-wall

BOX. Cost calculations

RCP 2.6 (0.32m SLR) - it is assumed that 10km of seawall of 7.32m in height would need to be constructed in this scenario. This scale of wall is costed using findings from Tamura et al. (2019[58]) which finds that the average cost per kilometre (length) per metre (height) can be calculated using the formula below. The GDP per capita in the UK was £30,246 which leads to a cost of £4.5 million per km per m. Multiplied by the scale of the wall, this provides a capex requirement of £327 million.

RCP 4.5 (0.37m SLR) - In this scenario it is expected that the wall will need to be both taller and longer than in the RCP 2.6 case and so the RCP 2.6 cost is multiplied by the relative costs of flood adaptation for RCP 4.5 as compared to RCP 2.6 set out in Supplementary Table 1 of Ward et al. (2017[59]) are used as a proxy for these increased costs. Costs are estimated to be 12.8% higher than for RCP 2.6 which leads to a capex requirement of £369 million.

RCP 8.5 (70th) (0.53m SLR) - The costs for this scenario are estimated in the same way as for RCP 4.5. As there is no 70th percentile value in the source, the central RCP 8.5 cost value is taken. Costs are estimated to be 38.3% higher than for RCP 2.6 which leads to a capex requirement of £452 million.

RCP 8.5 (95th) (0.67m SLR) -The costs for this scenario are estimated in the same way as for RCP 4.5. As there is no 95th percentile value in the source, the central RCP 8.5 cost value is uplifted by the ratio of SLR in the 95th percentile compared to the 70th percentile scenario (0.67/0.53). Costs are estimated to be 48.8% higher than for RCP 2.6 which leads to a capex requirement of £487 million.

2022 (no further rise to 2072) (0.11m SLR) - Ward et al. (2017) does not contain costs for a no further SLR scenario and so it is crudely assumed that the percentage difference in costs between RCP 2.6 and no further rise is equal to that between RCP 2.6 and RCP 4.5. This implies that costs are 12.8% higher in RCP 2.6 than in a no further SLR scenario and an estimate for the capex requirement in a no further SLR of £290 million.

Annual opex costs are assumed to be 1% of capex costs (Tiggeloven, 2020[60]).

The result of these assumptions are 5 cost scenarios.

Table 43 Capex and opex costs by seawall height scenario.

Scenario	Capex (one off in 2022)	Opex (annual)
2022 (no further rise to 2072)	£289,906,540	£2,899,065
RCP 2.6, 50th percentile	£326,915,885	£3,269,159
RCP 4.5, 50th percentile	£368,649,828	£3,686,498
RCP 8.5, 70th percentile (upper central)	£452,117,714	£4,521,177
RCP 8.5, 95th percentile (extreme)	£486,555,854	£4,865,559

[58] https://link.springer.com/article/10.1007/s10584-018-2356-2#Sec10
[59] https://static-content.springer.com/esm/art%3A10.1038%2Fnclimate3350/MediaObjects/41558_2017_BFnclimate3350_MOESM1_ESM.pdf
[60] https://nhess.copernicus.org/articles/20/1025/2020/

These capex and opex numbers are combined to form a time series of costs which is discounted to calculate the 50-year NPV using the same discount rate as is the case for the benefit streams (3.5%).

Benefit Cost Ratios

The BCRs for each of the seawall vs. sea level rise scenario combinations is set out below. It is found that BCRs are generally higher for more extreme RCP scenarios which is consistent with the increases in EAD for the counterfactuals (baselines) in the higher RCP scenarios. This just means that if climate change is higher, then baseline damages are higher, and so in turn adaptation benefits will be larger. However, this assumes that for each cell in the matrix, the projection turns out to be correct.

Table 44 BCR by seawall height and sea level rise scenario combination.

		Sea Level Rise by 2072				
		2022 level sea rise	RCP 2.6 (50th)	RCP 4.5 (50th)	RCP 8.5 (70th)	RCP 8.5 (95th)
Seawall Height	2022 level	1.15	1.51	1.38	2.50	2.34
	RCP 2.6 (50th)	1.07	1.49	1.47	3.03	3.80
	RCP 4.5 (50th)	0.99	1.39	1.45	3.22	4.60
	RCP 8.5 (70th)	0.85	1.18	1.24	2.92	4.50
	RCP 8.5 (95th)	0.82	1.15	1.21	2.85	4.64

What is important is to look at the 'regrets' if the projection is not correct. To do this, we need to take into account their relative probabilities and derive expected values, and then look at the change in outcomes.

We assume that RCP2.6, 4.5 and 6.0 are all equally likely, but that the RCP 8.5 scenario is much less likely. For the latter, we use the reports from Hausfather (2019[61]) that the RCP 8.5 scenario actually represents the 90th percentile of all scenarios, and thus has a lower probability.

This is shown in the table below. In the 'Even' version we have simply weighted each of the four RCP scenarios considered in this analysis as equally likely. For the 'Proportionate' version we have assigned the RCP 8.5 scenario as having a 10% likelihood and we have assigned the RCP 2.6, 4.5 and 6.0 equal likelihood of 30%.

To adjust for the fact that our two RCP 8.5 scenarios represent the 70th and 95th percentiles of the scenario's outcomes respectively, we have assigned the 70th percentile outcome as representing 82.5% of the RCP 8.5 scenarios and the 95th percentile outcome as representing the remaining 17.5% of RCP 8.5 scenarios. Note that RCP6.0 is not available in the UKCP18 marine projections, so

[61] https://www.carbonbrief.org/explainer-the-high-emissions-rcp8-5-global-warming-scenario/

this is not included, but by default we consider this would have a 30% likelihood. Note that because of this we have excluded this 30% of outcomes from our weighted average calculation (the total is divided by 70% rather than 100%).

Table 45 Probability weighted BCR by seawall height scenario.

Seawall Height built	Probability Weighted BCR (Even)	Probability Weighted BCR (Proportionate)
Basic Seawall (2022 level)	1.93	1.59
RCP 2.6 (50th)	2.45	1.72
RCP 4.5 (50th)	2.66	1.71
RCP 8.5 (70th)	2.46	1.50
RCP 8.5 (95th)	2.46	1.46

The proportionately weighted BCRs show that for this case, when probabilities are considered, the midrange (RCP 2.6 and 4.5) seawalls are shown to represent the best value for money. Over designing (RCP8.5) is not optimal, as the increase in costs relative to the weighted benefits. The approach will also be influenced by risk appetite. If a policy maker wants to produce the economically optimal approach, then they would not use the highly precautionary approach and use RCP8.5. This would mean that available 'adaptation' resources could go further, e.g., it would be possible to build more seawalls. However, if the policy make is risk averse (e.g., if the seawall protects critical infrastructure or has the potential to lead to loss of life in the case of failure), higher sea walls may be justified, even though they may have a lower benefit to cost ration.

Note that the specific BCRs should not be over interpreted, as they depend on assumptions, for example, a sensitivity run with lower cost increments provides different results. This highlights the earlier point that if the costs of climate proofing or adaptation are low, then it can make sense to do more adaptation earlier.

Table 46 Probability weighted BCR by seawall height scenario. Low incremental cost scenario

Seawall Height built	Probability Weighted BCR (Proportionate)
Basic Seawall (2022 level)	1.69
RCP 2.6 (50th)	1.72
RCP 4.5 (50th)	1.85
RCP 8.5 (70th)	1.88
RCP 8.5 (95th)	1.91

The analysis above focuses on how uncertainty affects accuracy and thus affects benefits and costs. However, it is also useful to think about the efficiency drop off along the rest of the value chain.

In terms of communication and reach, as highlighted above, there is likely to be a high level of awareness on the need to include climate risk assessment and either detailed analysis or allowances when designing new coastal infrastructure.

The efficiency drop off is likely to be greater when considering the use (and also the effectiveness of use) of the climate allowances in decisions, because of the potential for regrets.

Finally, the benefits of decision choice will depend on the specific context. In some cases, economic benefits will be largest if central projections are used, because of the trade-off between damages and adaptation costs, while in others, it can make sense to adopt a precautionary approach. This highlights that the 'best approach' will be context and decision specific, and will also depend on the risk appetite of the policy maker and the decision. The presentation of a range of allowances could allow the developer/other local stakeholders to determine their risk appetite for themselves.

Discussion

This case study has applied the valuation method developed in the study to proactive adaptation. This is adaptation that involves anticipatory, planned adaptation decisions, where economic benefits may arise primarily in the future under climate change. Such decisions are based on climate model projections of the future climate, and thus are also subject to high levels of uncertainty. While there are numerous theoretical studies of such action, including economic analysis, there are less studies of case where adaptation services are used in real-world decisions, noting it is the application of the adaptation service in practice that generates the economic benefit.

The case study finds that the application of methods for the valuation of traditional weather and climate information services to proactive adaptation involves additional issues and challenges to the other case studies in this project.

The case study first applied the valuation methods to a static example, with the use of climate allowances in flood management, looking at the potential economic benefits from improved climate projections. This shows that in theory, providing the improved climate projections are more accurate, this will lead to economic benefits (for both decreasing as well as increasing risks). However, there is no information on how much more accurate the improved climate projections are, and this makes it difficult to assess the likely level of economic benefits that are likely to be realised.

The case study then undertook an analysis and comparison of different decision approaches for proactive adaptatoin, contrasting static (if-then) methods with the use of outcome mapping (decision trees) and decision making under uncertainty. This found that while it is possible to use a theoretical if-then framework and apply standard valuation methods to proactive adaptation, the uncertainty around climate scenario / models outputs, means that this standard approach does not provide information on the 'accuracy' of the adaptation service, and thus the real (ex post) economic benefits. However, it is possible to extend these methods and consider uncertainty and its influence on subsequent outcomes, using decision trees and decision making under uncertainty. When such an analysis was undertaken, it was found that the estimated economic benefits from adaptation services are lower when uncertainty and ex post outcomes are taken into account (then when assessed using a theoretical 'if-then' analysis that assumes that the projections are completely accurate) but such an approach would be more likelky to lead to greater real-world benefits (ex post), because it minimises 'regrets'.

The analysis therefore finds that the decision support method used, as well as the type of climate information, is important in valuing adaptation services. This means that some of the 'value of information' generated by adaptation services should be attributed to the decision support services, and not just to the climate information provision (in this case the climate model projection and climate allowances).

The case study application found that the use of a value chain approach was a useful addition to adaptation assessment more generally, and these approaches could be used to improve studies on the economics of proactive adaptation.

Considering the case study on climate allowances specifically, the findings may mean that the economic benefits of allowances might be increased if decision making under uncertainty was recommended, at least for more standard decisions (where a precautionary approach was not needed). However, the downside of this is that it would reduce the simplicity of the allowances and could act as a barrier to their use.