Met Office – General Review

Economic Analysis – Final Report

London Economics

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Executive Summary

The Met Office is a unique global institution, delivering integrated weather and climate services. This analysis estimates it will deliver a net economic value[1] of £29.5bn[2] to the UK over the next ten years.

There are additional benefits which have been identified, but for which quantified estimates cannot be produced. These include benefits in the areas of defence and security, international leadership, healthcare, and diplomacy.

In relation to the key sector of civil aviation the analysis has deliberately taken a cautious estimation approach. Alternative methodologies would deliver £175bn over the next five years, as opposed to the £8.4bn included in the estimate above.

There are also very large benefits which accrue globally from the provision of better climate information, which is excluded as this analysis is undertaken from a UK perspective in line with HM Treasury guidance.

The purpose of the study

The Met Office has several distinctive characteristics which make it difficult to compare with other National Meteorological Services (NMS):

- It delivers a unified weather and climate model,
- It is a supplier of processed open data, enabling the UK-based commercial market,
- It supplies bespoke forecast and other services to commercial and private users,
- It delivers under contract the needs of UK civil and military government institutions,
- It is one of only a small number of NMSs who sell services to government institutions in other nations, including supplying services to Australia, South Korea and the US Air Force,
- It is one of only two World Area Forecast Centres, delivering forecasts globally,
- It plays a key role in enabling civil and military aviation, and,
- It is a Trading Fund[3] which in recent years has exceeded its Return on Capital targets set by HMT whilst providing free services to the general public.

This study aims to quantify the benefits to the UK generated by these varied services.

The terms of reference for this analysis were defined by the Review Project Board to include the following questions:

[1] For this study the phrase 'benefit' will mean the socio-economic benefits accrued by the Met Office, whilst 'economic value' or 'value' will refer to benefits minus costs, so the net impact of the Met Office. Because the net impact is positive, it equates to 'net benefits'.

[2] Figures in the text are rounded to the nearest £100m. Figures in tables are rounded to the nearest £10m, as requested by BIS.

[3] A Trading Fund is a particular type of arms-length body established by a trading fund order under the Government Trading Funds Act 1973. The general criteria for establishment is where a majority of the revenue which the body will receive come in the form of revenue in respect of the goods or services delivered by the organisation, and where the responsible minister and HM Treasury are satisfied that the setting up of the trading fund will better enable value for money.

Primary Question

The primary question is to identify the overall net economic value over the next ten years (2015 – 2025) to the UK of having the planned weather and climate services delivered by the Met Office.

Sensitivity Analyses

Three main areas of sensitivity analysis were identified for investigation:

- **Sensitivity One:** How do estimates of net economic value react to variation in the frequency of high impact weather events over the next 10 years?[4]
- **Sensitivity Two:** Sensitivity analysis around the key inputs, outputs, and outcomes relating to weather forecasting and how these impact the total economic benefit identified above.
    - What are the marginal economic benefits, and cost savings of improving or reducing weather forecasting quality?
- **Sensitivity Three:** Sensitivity analysis around levels of investment, including what is the impact if the Met Office does not invest, and will the value of the current infrastructure degrade?

Key Scenarios

Two primary counterfactual scenarios to the base-case were analysed, to identify the marginal benefits and cost (savings) of:

- **Counterfactual One:** A 'standard' versus the current 'world-leading' weather and climate service, taking into account the international influencing role of being 'world-leading', where 'standard' includes meeting only the minimum international requirements, and is taken to mean the quality of service provided by major Western European met services of comparable scale.
- **Counterfactual Two:** Focus the Met Office on weather services, and stop all climate services versus having the weather and climate together as a unified model. This scenario does not take account of the cost of procuring these services from elsewhere.

Methodology

To produce an aggregate estimate of the Met Office's impact on the UK economy over the next ten years, this study brings together multiple benefit streams to capture all elements. The analysis creates a basecase which compares to a 'do-nothing' counterfactual where there is no Met Office. Whilst this is a strong assumption it is consistent with previous studies and allows the full impact

[4] This question originally included a sub-question 'What increase in number or severity of high impact events would justify an increase in investment in national capability? This question was dropped because the literature reviewed demonstrated that the economic case for higher levels of investment had been made, both in terms of NPV and benefit-cost-ratios, for example in relation to the HPC Business Case (2014), which showed the economic value of the rejected £125m option was greater than that of the £97m option selected. This suggested that the binding constraint was affordability, not the economic viability of investment. Therefore, the study presumes that, given this, even greater net present values caused by weather variation would have been unlikely to change decisions.

of the Met Office to be estimated. The analysis uses market-based approaches wherever possible, followed by perception of value estimations. Avoided cost approaches are only used when alternatives are not feasible. The following table gives a high level summary of quantified benefit streams and summarises whether these are estimated using existing or new methodologies and the key literature used. It excludes unquantified benefit streams.

Table 1: Comprehensive listing of all benefit streams identified in the analysis

Stream	Selected approach	Existing or new analysis and key sources
Value to the Public	***Perception of value estimation*** – survey that captures public perceptions of the value of weather forecasting to them	Existing: Buchanan (2012 unpublished); Gray (2015) PA Consulting (2007)
Flood damage prevention	***Avoided cost approach*** – capturing prevented damage to property from fluvial and coastal flooding, uplifted by 50% for health and welfare.	Existing: Gray (2015); PA Consulting (2007); Thieken et al. (2007)
Storm damage prevention	***Avoided cost approach*** – capturing prevented storm damage due to information provided	Existing: Gray (2015); EUMETSAT (2014); Swiss Re (2006)
Aviation industry benefits	▪ ***Market-based estimate***– benefits from reducing flight times due to the WAFC ▪ ***Avoided cost approach*** – prevented costs from weather effects at airports	Existing: Gray (2015); PA Consulting (2007)
Other business sectors benefits	***Market-based estimates*** – high level value chain analysis of Gross Value Added (GVA) by sector, assuming 0.3125%[5] of GVA is attributable to the Met Office.	Existing: EUMETSAT (2014); Gray (2015); LE analysis of the ONS Blue Book data (2013)
Winter Transport benefits	***Avoided cost approach*** – capturing lost output, economic loss from accidents, and welfare losses prevented by providing warning of bad winter weather.	Existing: Quarmby (2010); Gray (2015); Johnston et al. (undated); Nurmi et al. (2013)
Defence and security benefits	***Avoided cost approach*** – based on cost of internal provision if Met Office was not available	New
Government dividend benefits after return on capital	***Market-based estimates*** – the dividend over and above the HMT Minute[6] target 3.5% Return on Capital. Entered via Met Office Revenues and Costs being uploaded into benefits and costs respectively.	MO Finance
European Centre	***Market-based estimates*** – value-chain analysis of benefits of	Existing: General

[5] Calculated as half the average of a high scenario using 1% and a low scenario using 0.25% as the share of GVA attributable to the Met Office.

[6] Every Trading Fund has its return on capital set in a document called an HMT Minute.

for Medium Range Weather Forecasts (ECMWF) benefits	the role Met Office played in attracting ECMWF into the UK	Technology Systems B.V/SET Resource Limited (1995); ECMWF (2013)
International leadership benefits	***Market-based estimates*** – payment in kind of scientist / forecaster time for international research collaborations and fraction of non-UK climate benefits	New
Wider Government avoided cost due to centralised Radioactive Incident Monitoring Network (RIMNET) delivery by Met Office	***Avoided cost approach*** – avoided costs on HM Government (HMG) from RIMNET being delivered by Met Office from RIMNET business case.	Existing: DECC (2014a)
Health effects and lives saved	***Avoided cost approach*** – capturing prevented health costs due to information provided	New. Based on Hajat et al. (2014), NHS (2014); Ebi et al. (2004)
Commercial catalytic benefits	***Market-based estimates*** – This strand attempts to capture the wider influence of the Met office in driving market growth through investment in new commercial products.	New
Climate change information benefits	***Avoided cost approach*** – captures the avoided cost from having better information earlier to enable decisions to be taken to move to the optimal path sooner.	Existing Hope (2011); Gray (2015) Unpublished internal Met Office information

In some cases there are significant benefits which the study has been unable to quantify or which are outside our scope. The following table identifies unquantified benefits and provides any evidence for their potential relative scale.

Table 2: Benefit streams and related unquantified benefits

Stream	Benefit streams which have not been quantified	Indication of potential magnitude
Other business sectors	'Other business sectors' excludes those industries captured elsewhere. Land transport is excluded as 'Winter Transport benefits' would otherwise be a double-count. This means benefits to the land transport sector in the summer-time are excluded.	As total winter transport benefits equal 3.7% of the total benefits, and the impact in summer can be presumed to be significantly less than that of winter, it appears prudent to assume this will equate to not more than 1% of total identified benefits
Defence and security benefits	Because the analysis uses an avoided cost estimate predicated on the Ministry of Defence (MoD) purchasing sufficient in-house capacity to deliver to the same quality as they receive today, this raises a number of unquantified benefits: ▪ The cost of delivery may not equal to benefits the defence sector would receive from this	These unquantified benefits are potentially substantial, but the information is not available to provide a more precise estimate

	service. As such there may be large consumer surpluses which are not captured. ▪ The delivery of this information may save the lives of military personnel. No estimate is made of the value of lives saved, nor of any consequential costs avoided by the family and friends of such personnel.	
International leadership benefits	This benefit stream only captures the quantifiable benefits the UK accrues from other countries providing payment-in-kind for sharing the unified model through our use of their science community and their outputs. It has not proved possible to quantify the wider benefits in terms of diplomacy and international relations from the benefits other countries accrue from the services the Met Office provides, or the leverage better information gives the UK in climate change negotiations.	There is insufficient evidence available to identify the scale of this benefit
Wider Government avoided cost due to centralised RIMNET delivery by the Met Office	This stream measure the costs avoided by other Government Departments because of synergies created by the Met Office taking responsibility for RIMNET, as opposed to the full benefits to the UK of delivering the RIMNET system. These benefits were not estimated due to the requirement on Government to put in place a system, so they would be delivered both in the base-case and the 'do nothing' comparator. These benefits are therefore excluded. There are also a number of intangible benefits described in the RIMNET business case from 2014, which this study similarly does not quantify. Where these relate to additional benefits from the Met Office delivering in an integrated fashion, as opposed to the general benefits of any RIMNET service, these count as unquantified benefits.	Given the relatively low spend on RIMNET by Met Office, it is considered that any unquantified benefits are going to be similarly small.
ECMWF Benefits	The ECMWF delivers benefits to the Met Office the analysis does not quantify, which are not location dependent: ▪ Using ECMWF's model for 7-14 day forecast saves Met Office some HPC capacity but a 'thread' of the overall Met Office model has to run anyway during that 7-14 day period to enable monthly and three month forecasts thereafter. ▪ As an ECMWF member, Met Office gets use of ECMWF's HPC – up to 25% of HPC capacity is available across its member states and Met Office uses 90-100% of its share of that capacity. ▪ As an ECMWF member, Met Office staff can attend ECMWF training – there is also regular interchange of staff between the two institutions ▪ As an ECMWF member, Met Office benefits from ECMWF research, some of which is delivered jointly	These benefits permit savings on HPC investments and generate revenues from sales. They are likely to be worth potentially tens of millions of pounds

	▪ ECMWF generates data which can be sold wholesale by member states.	
Health effects and lives saved	The analysis captures the benefits from avoided deaths. The analysis does not capture any benefits arising from avoided treatment or lifestyle adaptation costs.	Benefits arising from avoided treatment or lifestyle adaptation costs could potentially be substantial
Commercial catalytic benefits	Many nascent markets may also have been captured in a residual category, where economic growth has not been quantified. As such any growth stimulated in these sectors is not included in this analysis. This study also does not attempt to estimate any productivity gains the Met Office receives due to the 'commercial imperative'.	Whilst some investments into new products go on to be transformative in their impact on the economy, other deliver only marginal improvements. As such this unquantified benefit could range between small to substantial in scale.
Climate change information benefits	Benefits accruing outside the UK are not in scope of this analysis.	These benefits are extremely large ($590bn NPV in 2005 prices) but out of scope of this analysis.
Academic benefits	Whilst there is clearly economic benefits to the academic output of the Met Office, the risk of double-counting with the modelled gains in quality across the other streams of benefits mean this study has not estimated a figure. Academic benefits which have wider application than just the Met Office services, therefore, will have been excluded from our analysis.	Because the impact could range from minimal to transformative, as with commercial catalytic investments, it is not possible to assess the likely scale of this unquantified benefit.

The major implications of Table 2 are that the most significant unquantified benefits in scope, given the information available are likely to relate to defence and security, and health effects. Climate change information benefits outside the UK dwarf all other benefits in scope, but are not in scope.

Furthermore, over and above this, climate change and advances in science through collaboration are driving new services. These are not yet large enough to be captured in the base-case analysis but represent growing areas which could become more substantial in the future. For example, changes in the climate are driving increased concern about water resources and risk of droughts and as such Met Office, with partners, have developed a product to bring benefits to Government and industry through more effective management of water usage. Also, on the back of scientific collaboration with the US, the Met Office has developed a new space weather forecasting service which brings benefits to both Government and Industry in terms of avoiding costs from damage to radio communications, GPS and power grids. Further details are provided in Annex 6.

The following table outlines key assumptions which may cause particular benefits streams to be larger or smaller than modelled and why.

Table 3: Key assumptions which may cause benefits to be larger or smaller than estimated

Stream	Key assumptions which may cause benefits to be larger or smaller than estimated	Probable direction
Value to the Public	Assumes a clean distinction between personal and commercial use. At the margin a clean distinction may not always be possible, introducing a risk of double-counting with 'other business sectors'. This effect is	Under-estimate

	difficult to quantify, so we have maintained consistency with previous studies in using the full valuation, but the study addresses this in the sensitivity analysis. This benefit is potentially however under-estimated on a greater scale if one compares it to the $240 per household per year estimates in Lazo et al (2009) in the United States. This estimate, in 2015 real prices of less than £10 ($16), if comparable could be significantly larger. As such, it is presumed that the net position is that an under-estimate is more likely than an over-estimate.	
Aviation industry benefits	The literature review revealed two alternative approaches to quantifying the benefits from the aviation sector. This study uses the more prudent approach, but there are legal requirements compelling a country to make available meteorological information for civil aviation to be permitted. As such, strictly all economic activity in the civil aviation sector could be labelled as a Met Office benefit for at least five years. This would equate to over a hundred billion pounds, dwarfing all other benefit streams. Even within the prudent approach taken, there is still relative uncertainty, and the study addresses this in the sensitivity analysis.	Under-estimate
Other business sectors	In calculating the benefits to 'other business sectors', there is a conflict between two key sources. EUMETSAT (2014) assume between 0.25% and 1% of the GVA of the sector is as a result of weather services, from which we take an average of 0.625%, or which half is attributed to the Met Office, leading to an assumption of 0.3125%. The High Performance Computing (HPC) Business case (2014) assumes 0.2% of GVA for agriculture, which is a high value sector. This study has used the EUMETSAT values to achieve consistency with Gray (2015), but note this may produce an over-estimate. Given the study uses an estimate three times larger than the HPC estimate for agriculture, if the study used the lower estimate this could reduce total discounted benefits by a third. The study addresses this in the sensitivity analysis.	Over-estimate
Defence and security benefits	The modelling is predicated on MoD being willing and able to pay the full cost of maintaining the present quality of service. In reality MoD may be willing to accept a different price/quality trade-off. Any impact of this on the avoided cost is not estimated.	Over-estimate (in relation to the avoided cost approach, noting that unquantified benefits described above may more than compensate for this)
Health effects	Estimates of the impact of weather information on preventing excess deaths related to cold and air quality are not available, so we have applied a factor drawn from American research on heat wave warnings and applied this to estimate excess deaths avoided from excessive heat, excessive cold and poor air quality.	Indeterminate
Climate change information benefits	All results, in line with previous analysis quoted in Gray (2015), assume that adaptation measures are not changed in response to better information about climate change information. The reason for this is that, as adaptation is so cost-effective, the maximum feasible amount is already assumed to occur in the base-case model used in this analysis, so increasing adaptation based on new climate change information is not included. As such this estimate covers abatement values, but this may therefore present an under-estimate.	Under-estimate

The major implications of Table 3 are that this study has attempted to take a prudent approach to assessing benefits and maintaining consistency between options and with previous studies. The four most important areas to note are ‘other business sectors’, ‘value to the public’, ‘aviation’, and ‘defence and security’.

The ‘other business sectors’ estimate maintains consistency with the EUMETSAT business case and Gray (2015) by assuming that only half the calculated benefits to industry are attributable to the Met Office, as opposed to other suppliers. The alternative approach taken by the HPC Business Case delivers a significantly lower estimate for agriculture, which if applied across all industries would reduce benefits from this stream by around a third. In this case the analysis includes sensitivity testing to understand the impact of varying the percentage of gross value added from weather-data dependent industries on the value of the benefit stream. The study uses a range defined by assuming all benefits are attributable to the Met Office in the high case and using the HPC Agriculture weighting at the lower end.

For the ‘value to the public’ estimate the study has assumed that, in line with the phrasing of the original questionnaire, respondents discounted the benefits relating to their business endeavours. However, this is an area of some uncertainty, so we have looked to reflect this in our sensitivity testing.

For ‘aviation’, the study has relied on existing sources, but because this is such a significant benefit stream it has appeared prudent to carry out sensitivity testing to ensure the study adequately reflects the impact of any potential uncertainty on the assumption values used, particularly fuel consumption savings.

The ‘defence and security’ area is one of the most complex, because there are two countervailing potential impacts. There is a risk of over-estimation which relates to the quantified estimate through the assumption of like-for-like purchasing in terms of quality of weather services by MoD either from the Met Office or whatever alternative arrangement they put in place. If however, this was not affordable, there is the potential that the MoD would accept lower quality to control costs. Given our estimate of potential spend by the MoD on weather services is £1.4bn, if they accepted lower quality, this would reduce this avoided costs, but because of the high fixed costs, it is probable this would only change this estimate at the margin. However there is also a risk of under-estimation because we have had to use an approach which fails to capture any downstream benefits, for example of service personnel lives saved. As such the risk of over-estimation appears low, and overall the analysis is more likely to be delivering a net under-estimation of benefits

Findings

The following table outlines the headline findings from the base-case and scenarios.

Table 4: Headline results

Stream	Base-case	Scenario 1 – 'Standard' Met Office	Scenario 2 – No climate Services	Sensitivity 1 – weather effects[7]	Sensitivity 2 – Key factors	Sensitivity 3 – investment options
Total Present Benefits	£31.78bn	£24.70bn	£28.41bn	£29.93bn - £36.45bn	£28.76bn – £39.18bn	£27.82bn- £32.82bn
Total Present Costs	£2.26bn	£1.94bn	£2.13bn	£2.26bn	£2.26bn	£2.00- 2.31bn
Net Present Value	£29.53bn	£22.76bn	£26.28bn	£27.67bn - £34.19bn	£26.50bn - £36.92bn	£25.82bn- £30.51bn
Benefit: Cost Ratio	14.1 : 1	12.7 : 1	13.4 : 1	13.2 – 16.1: 1	12.7 - 17.3:1	13.7:1- – 14.2:1

As this table shows, there are very significant returns to UK from the Met Office, with the base-case delivering a benefit-cost ratio of over 14:1, and even with a smaller Met Office in scenarios 1 and 2 delivering at least 12.7:1. Each scenario is described in greater depth below, with commentary around its particular estimates.

The sensitivities around the base-case provide estimates of the degree of certainty at the 90% level. In the lower range cases the benefit-cost ratio falls to 12.7:1, but in all sensitivities and scenarios the net present value of the Met Office never drops below £22.8bn. In both sensitivity one and two we also see there are is the potential for the benefits to be higher than the base-case, delivering benefit-cost ratios of up to 17.3:1.

Conclusions

This analysis reveals net benefits of £29.5bn to the UK from the Met Office. This analysis identifies that the Met Office delivers value to the public, businesses, government agencies and bodies internationally. Across the spectrum of weather and climate services this picture of positive benefits is consistent.

Over three quarters of the benefits identified are generated by just four streams of benefits:

- Other Business Sectors – 27.4%
- Aviation sector – 26.5%
- Value to the Public – 14.9%
- Climate Change Information Benefits – 10.0%

[7] BCR excluding climate calculated by taking the most extreme values from Figure 12, adding the costs back and deleting the base-case climate present benefit (£3.18bn), and then dividing by present costs (£2.26bn).

Recognising the simplifying assumptions made and the limitations of the data available, the estimated benefits exceed the costs of delivery by a factor of more than 12.7:1[8], after taking account of scenarios and sensitivity tests, and in terms of the base-case more than 14:1, despite being unable to quantify a number of benefits relating to international benefits, defence and security.

Drawing on an WMO published summary of economic assessments of meteorological services around the world (WMO, 2015), we can put these results into context. Taking the benefit-cost ratio of the base-case, excluding climate change information benefits of 12.4:1 this lies at the top-end of the studies quoted above. Whilst there are two studies exceeding 30:1, most of the studies identified lie in the range of 2: 1 to 14:1. Therefore, when comparing this study's result it is necessary to consider whether it is reasonable for this estimate to be marginally higher. There appears to be three reasons why this should be the case:

- The Met Office is an established NMS servicing a developed western economy. Comparisons with Bhutan (3:1), Nepal (10:1) Ethiopia (3:1 to 6:1) or the various countries in World Bank (2008) (2:1 – 14:1) or Hallegatte (2012) (4:1-36:1) appear difficult to defend.
- The Met Office provides the full range of services, and this study attempts to be all-inclusive. Studies which relate either to sector-specific reviews (e.g. Considine et al., 2004) (2:1 to 3:1) or to Met Offices which do not deliver the same breadth of services (e.g. Switzerland (5:1 to 10:1) is not a WAFC) can be expected to provide lower benefit-cost ratios.
- The WMO NWP Index demonstrates that the Met Office delivers forecasts of higher accuracy than NMSs of other countries. If, as we have assumed, accuracy is key component of forecast quality and benefits increase with forecast quality, then it should be expected that the UK Met Office delivers an estimate at the top-end of the range.

The analysis also reveals that alternative estimation approaches in relation to the aviation sector may attribute much larger benefits to the Met Office's contribution. Climate change information benefits also, by definition go wider than just the UK, and these are excluded by design from a UK-focussed cost-benefit analysis.

Alongside the base-case valuation, the valuations from the sensitivity tests and the scenarios also present valuable information. As explained to stakeholders, the scenarios were selected to present pen-pictures of the opposite ends of the three most important 'decision spectrums' along which policy could take the Met Office from its current position; whether or not to remain world-class in relation to quality, and whether or not to focus just on weather, rather than climate services.

- ***Scenario One*** reducing quality by 20% delivers savings of around £0.35bn, but losses in terms of benefits to the UK of £7.08bn.
- ***Scenario Two*** shows the benefits of delivering unified climate and weather services, something stakeholders saw as an overwhelming strength. Due to quantifying benefits strand-by-strand, this synergistic element may not be immediately apparent. However, when reviewing scenario two, the marginal reduction in costs results in disproportionate

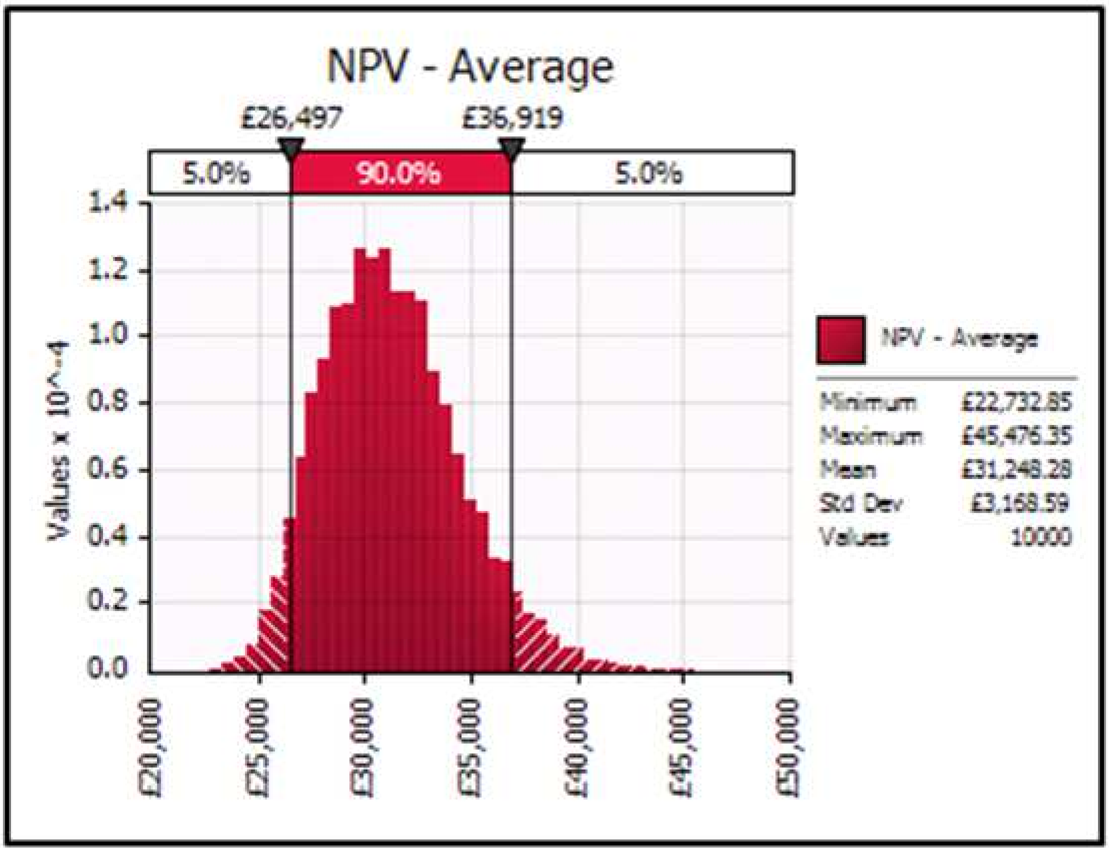
[8] Using the lower end of the 90% CI in sensitivity one.

losses in benefits of £3.4bn, in part driven by this scenario not removing shared elements of the cost base between weather and climate services.

These two scenarios all yield lower net benefits than the base-case, which indicates that in terms of structure[9], the Met Office, at least in terms of these aspects, appears to be delivering more value than the scenarios considered. This analysis makes no assessment of whether this structure is being efficiently delivered in terms of costs, and it is very difficult to find clear international comparators to allow benchmarking. This study does not make any assessment of the *affordability* of the benefits to the Government as a whole.

The sensitivity analysis undertaken reveals that allowing key climate and weather, benefit calculation and investment / disinvestment assumptions to vary causes significant movement in the results, as illustrated in Figure 1, which shows the impact on the net present value of changing key calculation assumptions within realistic ranges from the literature.

Figure 1: Sensitivity Two - Net Present Value (£bn) when varying calculation assumptions



However these still never[10] bring the benefit-cost ratio of the Met Office to the UK below the level of 12:1, including climate benefits and never below 11:1 without climate benefits, still securely in the higher range of international studies. It also reveals how quickly benefits would drop-off in the

[9] Within the constraints put on it by being a Trading Fund

[10] At the 90% confidence interval.

face of cuts to the variable cost base of up to 30%, at which point Met Office feedback suggests the Met Office would no longer be viable.

In relation to future analysis, the areas where further work would be beneficial are:

- Gaining a deeper understanding of the defence and security sectors use of meteorological services would reduce uncertainty in relation to this part of the analysis.
- Further research into the impact of weather forecasts and information on health outcomes would provide more reliable estimates than those used in this study.
- In some sections of the analysis data was used because it is the only consistent data available other the time period required. In particular the Numerical Weather Prediction (NWP) Index created by the World Meteorological Organisation is relied upon as a proxy for quality when it is strictly a measure of forecast accuracy, which is only one dimension of quality. A wider basket of consistent measures relating to other aspects of quality, such as reach and timeliness would provide benefits to future analysis.
- In common with comparable studies (e.g. Hope 2011), the analysis estimates climate change information benefits through estimating savings generated through abatement activity due to climate change information being provided earlier. For a number of reasons outlined in section 4.2.4, we do not include adaptation costs, primarily due to the difficulties in producing an aggregate estimate of adaptation benefits, the consistent treatment of adaptation across both the 'do-nothing comparator' as well as the base-case, (so there is no additionality,) and the question of whether the inclusion of both adaptation and abatement benefits may lead to double-counting. However, as evidenced by Annex 7, there is a significant value of the Met Office's impact on adaptation. Therefore further analysis to identify whether a robust estimate of the value of adaptation efforts in the UK could be produced, and from this the Met Office's impact on adaptation cost reductions across the economy would be a valuable piece of work to enable this benefit stream to be estimated.
- This study has relied on published and internal Met Office literature, particularly key business cases. These business cases are tailored appropriately to meet their immediate need, but there are some issues relating to consistency of assumptions between cases which introduce some uncertainty into the correct method of estimating some benefit streams. Undertaking research into particularly the impact of Met Services across the sectors captured by 'other business sectors' in this study to create standard assumptions which could be used by business cases in the future would provide stronger foundations for the estimation of benefits.
- Possibly the key area of future study is new analysis of key benefit streams, to gain a better understanding of how changes in inputs and quality over time have played through into changes in the benefits accrued. This has been the key area where this study has needed to make assumptions because of the lack of evidence. Repeated studies related to how benefits have grown in key business sectors and, potentially in the area of public valuation of services, would allow a greater degree of certainty in future studies. In undertaking such repeat work, consideration should also be given to how to ensure that the public valuation estimations exclude any business use to prevent the risk of double-counting, and potentially splitting out the impact of new services from improving existing services. Annex 6 mentions two areas where new services are being delivered which have offered the potential to widen the number of areas where Met Office can deliver value, and gaining a better understanding of whether it is improvements in technical quality,

improvement in reach or improvement in the number or types of services which drives the change in value of the Met Office would be valuable in informing future strategy.

1 Background and Objectives

1.1 The Met Office

The Met Office has several distinctive characteristics which make it difficult to compare with other National Meteorological Services (NMS):

- It delivers a unified weather and climate model,
- It is a supplier of processed open data, enabling the UK-based commercial market,
- It supplies bespoke forecast and other services to commercial and private users,
- It delivers under contract the needs of UK civil and military government institutions,
- It is one of only a small number of NMSs who sell services to government institutions in other nations, including supplying services to Australia, South Korea and the US Air Force,
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- It plays a key role in enabling civil and military aviation, and,
- It is a Trading Fund[11] which in recent years has exceeded its Return on Capital targets set by HMT whilst providing free services to the general public.

This study aims to quantify the benefits to the UK generated by these varied services. As with any such study this analysis is constrained by the data available, and on occasion has been forced to use simplifying assumptions to deliver a comprehensive estimate of value and how that value may change in response to shifts in key variables. All data sources used are documented. This report tries in all cases to be explicit when data sources are either relatively weak, or where key assumptions have been made. The literature in relation to this subject is still relatively immature so the analysis has developed new techniques to quantify some benefit streams. These mainly relate to areas the Review has considered key, but for which no relevant literature or analysis existed.

1.2 General Review

The General Review of the Met Office was established by the Department of Business, Innovation, and Skills and the Met Office in late 2014 to provide a strong evidence base for future decisions concerning the role, governance and configuration of the Met Office. As part of the Review, London Economics was commissioned to undertake an economic analysis of the value of the Met Office, testing some key sensitivities and scenarios to provide further insights to the Review. This report provides this analysis.

1.3 Study Objectives

The terms of reference for this analysis were defined by the Review Project Board to include the following questions:

[11] A Trading Fund is a particular type of arms-length body established by a trading fund order under the Government Trading Funds Act 1973. The general criteria for establishment is where a majority of the revenue which the body will receive come in the form of revenue in respect of the goods or services delivered by the organisation, and where the responsible minister and HM Treasury are satisfied that the setting up of the trading fund will better enable value for money.

1.3.1 Primary Question

The primary question is to identify the overall net economic value over the next ten years (2015 – 2025) to the UK of having the planned weather and climate services delivered by the Met Office.

1.3.2 Sensitivity Analyses

Three main areas of sensitivity analysis were identified for investigation:

- **Sensitivity One:** How do estimates of net economic value react to variation in the frequency of high impact weather events over the next 10 years?
- **Sensitivity Two:** Sensitivity analysis around the key inputs, outputs, and outcomes relating to weather forecasting and how these impact the total economic benefit identified above.
  - What are the marginal economic benefits, and cost savings of improving or reducing weather forecasting quality?
- **Sensitivity Three:** Sensitivity analysis around levels of investment, including what is the impact if the Met Office does not invest, and will the value of the current infrastructure degrade?

1.3.3 Key Scenarios

Two primary counterfactual scenarios to the base-case were analysed, to identify the marginal benefits and cost (savings) of:

- **Counterfactual One:** A 'standard' versus the current 'world-leading' weather and climate service, taking into account the international influencing role of being 'world-leading', where 'standard' includes meeting only the minimum international requirements, and is taken to mean the quality of service provided by major Western European met services of comparable scale.
- **Counterfactual Two:** Focus the Met Office on weather services, and stop all climate services versus having the weather and climate together as a unified model. This scenario does not take account of the cost of procuring these services from elsewhere.

2 Over-arching methodology

This section provides greater detail on the analysis used to estimate benefits and costs for the base-case, sensitivity tests and scenarios.

2.1 Framework for the cost-benefit analysis

All analysis is undertaken in 2015 real prices, for costs and benefits. Costs and benefits in future years are discounted at 3.5%, in line with the HM Treasury Green Book[12].

2.2 'Do Nothing' comparator to the base-case

In common with the existing literature, this study compares the base-case against a 'do nothing' scenario, where there is no Met Office provision. All assessments of benefits and costs is undertaken relative to a world where there are no meteorological services provided[13]. This approach has been generally used in reviewed studies in this area. However, there are several aspects of the real world which mean the 'do nothing' is a theoretical concept. These are outlined in Annex 1.

Each of the scenarios is estimated independently, and can be compared to the base-case. The sensitivity testing is done relative to the basecase.

2.3 The economic benefits of meteorological services

Across this project the study has attempted to identify the benefits and costs of the two main areas of the Met Office; weather services and climate services[14]. Within each of these the study has attempted to capture the three main types of benefits we envisage under each heading[15].

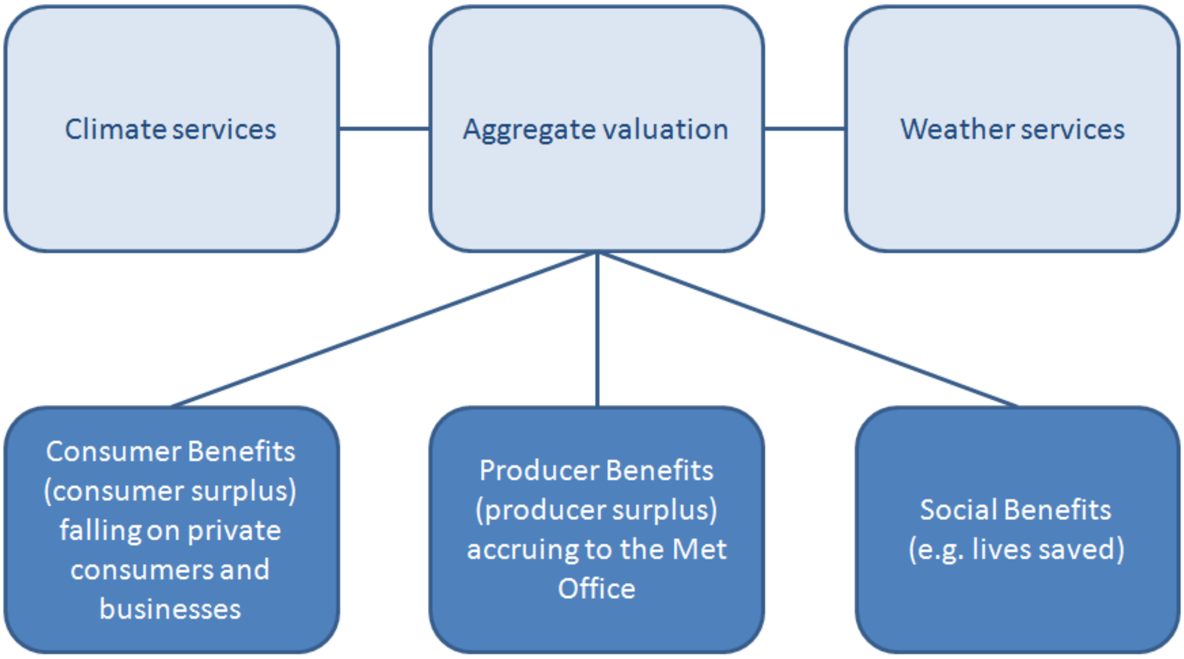
[12] The Green Book: appraisal and evaluation in central government, November 2014 update, available at time of use at https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent

[1313] Whilst there is alternative provision in the market, we make an assumption which is shared by many other studies, at least implicitly, that the Met Office acts as a 'sun' with all activity in the sector ultimately originating in the data gathered and made available by the Met Office, such that without the Met Office there would not be alternative provision. Annex 1 talks about this in more depth..

[14] Including their respective commercial services

[15] We have also considered the question of whether the academic materials the Met Office produces have an intrinsic value in and of themselves, over and above the impact they have on the quality of forecasts and services. We consider this in section 4.4.

Figure 2: Major areas of study



The study uses this approach to map benefit streams and to ensure no major benefit streams are missed or double-counted.

2.3.1 Identified benefit strands

Weather services affect all consumers and all businesses to a greater or lesser degree. In identifying which particular areas to investigate in greater depth the study applies the following criteria:

- The materiality of the value of the costs or benefits, based on the scale of previous estimates;
- The feasibility of gathering information pertinent to estimation, based on our assessment of the existence of literature or data; *or*
- Where it is not feasible to gather information, for key areas the analysis utilises new approaches to estimation.

Table 5 provides a summary of the benefit streams identified for capturing in the study:

Table 5: Benefit and cost streams

	Weather services	Climate services
Consumer benefits falling on the public	Value to the Public	Climate Change information benefits
Prevention of costs falling on both consumers and businesses	Flood damage prevention	
	Storm damage prevention	
Consumer benefits including cost savings and cost prevention falling on the private sector	Aviation industry benefits	
	Other business sector benefits	
	Winter Transport benefits	
	Commercial catalytic benefits	
Consumer benefits including cost savings and cost prevention falling on the state sector	Defence and security benefits	International leadership benefits
	European Centre for Medium-range Weather Forecasts (ECMWF) benefits	
	Wider Government avoided cost due to centralised Radioactive Incident Monitoring Network (RIMNET) delivery by the Met Office	
	International leadership benefits	
Producer benefits falling on the state sector	Government dividend benefits after return on capital	
Social benefits	Health effects and lives saved	

The following table gives a brief description of the benefits captured under stream.

Table 6: Short descriptions of benefit streams in the analysis

Stream	Short description
Value to the Public	The value the public receive from free at the point of delivery weather forecasts and services.
Flood damage prevention	The value the public and businesses receive through flood warnings providing sufficient warning for property to be moved and damage prevented. This also captures the impacts on health of flooding.
Storm damage prevention	The value the public and businesses receive through storm warnings providing sufficient warning for property to be moved and damage prevented.
Aviation industry benefits	The value the aviation industry receives from benefits from reducing flight times due to the WAFC and prevented costs from weather effects at airports.
Other business sectors	The value from the wider economy, excluding sectors otherwise identified, which is attributable to the additional output gained from the improvements in productivity because of services provided by the Met Office .
Winter Transport benefits	The value the public and firms receive from forecasts of winter weather allowing reductions in losses caused by vehicular and pedestrian accidents.
Defence and security benefits	The value of the avoided costs MoD would face if it had to fully fund a standalone defence Met service to meet their needs, if the Met Office was not available to meet MoD’s requirements.
Government dividend benefits after return on capital	The value of the Return on Capital Employed by the Met Office over and above the 3.5% target set by HM Treasury.

European Centre for Medium Range Weather Forecasts (ECMWF) benefits	The value the UK accrues from ECMWF being based in the UK as opposed to elsewhere in Europe. A 40% fraction of this benefit is attributed to the Met Office because of the role its 'world-class status played in attracting the ECMWF to the UK.
International leadership benefits	The value of 'payments in kind' from the international scientist community from joint working in and around the Unified Model.
Wider Government avoided cost due to centralised Radioactive Incident Monitoring Network (RIMNET) delivery by Met Office	The Met Office acts as a service integrator of the pan-Government RIMNET programme. By doing so it delivers the programme at a lower cost than would have been the case if each Department delivered its components separately. This cost saving is the benefit attributed to the Met Office.
Health effects and lives saved	The value of lives saved due to particular weather warnings issued by the Met Office
Commercial catalytic benefits	The value driven by the commercial investments undertaken by the Met Office in creating new products in the commercial sector.
Climate change information benefits	The value to the UK of climate change information being made available sooner than would otherwise be the case. This value is derived from the lower abatement costs incurred because the warnings are available earlier.

2.3.2 Choosing measurement methods for each stream

Meteorological and climate change services are a vital enabler of value across a modern economy. They support better decision-making by a host of economic actors, both in their day-to-day lives and in longer-term planning. This is due to the impact that weather and climate events, particularly high-impact events, can have. Whilst a large number of studies have attempted to estimate the value of weather and climate change, that is not the task of this study. This study is focussed on the value of weather and climate *information*. The distinction is key because the Met Office through its effort does not change weather or climate outcomes, but it provides *information* which other agents can use, or can choose to disregard, to decide how to react. This reaction may include making adaptations to reduce potential damage or altering investment decisions to maximise future returns.

Studies that have focused on the value of weather and climate change information have tended to analyse the public good[16] value of forecasts and warnings, (e.g. Anaman and Lellyett, 1996; Johnson and Holt, 1997). This definition works effectively for the classical 'public weather forecasting services' but when one considers the commercial work the Met Office undertakes under contract, these services are not freely available to all, only to those who have commissioned and paid for them. Therefore weather forecasts are 'quasi-public' goods because of the potential for exclusion. The study therefore assesses public good benefit streams, but also individual benefit streams where actors consume the service as a private good, as described below.

[16] A public good is defined as a good or service which is 'non-rivalrous' and 'non-excludable' in its nature. To draw on clear definitions in Lazo et al (2003): '*Non-rivalry means that one person's consumption of the good does not diminish the ability of others to consume the good (e.g., one person knowing the weather forecast does not diminish anyone else's ability to benefit from knowing the forecast). Non-excludable means that once the good is provided, no one can be excluded from using the good.*'

Within this project it is recognised that, because of the quasi-public good nature of these services, the economic value of weather and climate services are not always directly observed in the market, so a variety of methods to capture the benefits of weather and climate information are used. In some cases, particularly in relation to commercial activity, market data is used to identify the benefits being delivered, whereas for the Public Weather Service the studies reviewed have used a variety of approaches to attempt to generate estimates. The selected approaches generally fall into the following categories:

- ***Market-based estimates*** – where services are sold in private markets, it is normally assumed that the price reflects a profit-maximising decision by the producer and the willingness to pay by the consumer, based on the value they accrue from using the good or service. In the case of Met Office services, because as a Trading Fund the Met Office is not profit-maximising, but instead operates under 'level playing field' obligations[17]. Therefore, the price charged is not necessarily a profit-maximising price so this condition does not hold. As such it is possible that in some cases there may be excess consumer surplus not captured using this approach. Nevertheless, this approach is used wherever appropriate price data is available. For example, in estimating the impact of the Met Office on other business sectors we use standard statistics on the size of these industries when applying the relevant fractions of gross value added to estimate the share attributable to the Met Office. In some instances, where the Met Office is one of a number of contributors to the benefit, a ***value chain approach*** is used. This allocates shares of the total final benefits in proportion to the major inputs into the production function underlying the estimate of benefit. A worked example is given in section 4.3.2.
- ***Perception of value estimation*** – where services are not sold in private markets, the users may still derive a benefit from being able to access that service. This is particularly important in relation to the public task of the PWS, where the public receive this service free at the point of delivery. As such, without a price an alternative non-market method of identifying this benefit is required. This value can be estimated using non-market valuation techniques such as willingness to pay surveys. Willingness to pay services would capture consumer surplus[18], because it captures the full value of the consumer's experience.
- ***Avoided cost approach*** – Weather forecasts and other weather and climate information are often used to provide warning to avoid costs which would otherwise have been incurred, for example in cases of flooding. To determine the share of any avoided costs which are a result of the Met Office a ***value chain approach*** is used, which again, allocates shares in proportion to the major inputs into the production function underlying the estimate of avoided cost. Similarly, where the analysis compares the base-case to a counterfactual where the Met Office does not exist, there are some users who would still require services and who would be compelled to spend resources to ensure delivery. The analysis incorporates these as 'avoided costs' specifically for defence and security and RIMNET. Avoided cost approaches will generally fail to capture consumer surplus.

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[17] For example, whilst the provision of "raw data" via PWS Wholesale is dependent on the Met Office's underpinning infrastructure the pricing policy is aimed primarily at meeting open data obligations, which require marginal cost pricing, putting aside any fixed infrastructure costs, or the marginal costs of the public weather service, outputs from which these services use. Legislation also limits the returns it can deliver, and we have considered such endeavours to be quasi-public task.

[18] Consumer surplus is the extra benefit a consumer receives when what he pays for a good or service is less than the value he puts on it. Each consumer will have a different consumer surplus. If consumer surplus would be negative we would expect the consumer to not purchase that good. Similarly a producer can make such a surplus if the cost of production is less than the price sold. This producer surplus normally broadly equates to profit.

To produce an aggregate estimate of the Met Office's impact on the UK economy over the next ten years, this study brings together multiple benefit streams to capture all elements. The analysis uses market-based approaches wherever possible, followed by perception of value estimations. Avoided cost approaches are only used when alternatives are not feasible. The following table gives a high level summary of quantified benefit streams and summarises whether these are estimated using existing or new methodologies and the key literature used. It excludes unquantified benefit streams.

Table 7: Comprehensive listing of all benefit streams identified in the analysis

Stream	Selected approach	Existing or new analysis and key sources
Value to the Public	***Perception of value estimation*** – willingness to pay surveys	Existing: Buchanan (2012 unpublished); Gray (2015) PA Consulting (2007)
Flood damage prevention	***Avoided cost approach*** – capturing prevented damage to property from fluvial and coastal flooding, uplifted by 50% for health and welfare	Existing: Gray (2015); PA Consulting (2007); Thieken et al. (2007)
Storm damage prevention	***Avoided cost approach*** – capturing prevented storm damage due to information provided	Existing: Gray (2015); EUMETSAT (2014); Swiss Re (2006)
Aviation industry benefits	▪ ***Market-based estimate***– benefits from reducing flight times due to the WAFC ▪ ***Avoided cost approach*** – prevented costs from weather effects at airports	Existing: Gray (2015); PA Consulting (2007)
Other business sectors	***Market-based estimates*** – high level value chain analysis of Gross Value Added (GVA) by sector, assuming 0.3125%[19] of GVA is attributable to the Met Office	Existing: EUMETSAT (2014); Gray (2015); LE analysis of the ONS Blue Book data (2013)
Winter Transport benefits	***Avoided cost approach*** – capturing lost output, economic loss from accidents, and welfare losses prevented by providing warning of bad winter weather	Existing: Quarmby (2010); Gray (2015); Johnston et al. (undated); Nurmi et al. (2013)
Defence and security benefits	***Avoided cost approach*** – based on cost of internal provision if Met Office was not available	New
Government dividend benefits after return on	***Market-based estimates*** – the dividend over and above the HMT Minute[20] target 3.5% Return on Capital. Entered via Met Office Revenues and Costs being uploaded into benefits and	MO Finance

[19] Calculated as half the average of a high scenario using 1% and a low scenario using 0.25% as the share of GVA attributable to the Met Office.

[20] Every Trading Fund has its return on capital set in a document called an HMT Minute.

capital	costs respectively	
European Centre for Medium Range Weather Forecasts (ECMWF) benefits	***Market-based estimates*** – value-chain analysis of benefits of the role Met Office played in attracting ECMWF into the UK	Existing: General Technology Systems B.V/SET Resource Limited (1995); ECMWF (2013)
International leadership benefits	***Market-based estimates*** – payment in kind of scientist / forecaster time and fraction of non-UK climate benefits	New
Wider Government avoided cost due to centralised Radioactive Incident Monitoring Network (RIMNET) delivery by Met Office	***Avoided cost approach*** – avoided costs on HM Government (HMG) from RIMNET being delivered by Met Office from RIMNET business case	Existing: DECC (2014a)
Health effects and lives saved	***Avoided cost approach*** – capturing prevented health costs due to information provided	New. Based on Hajat et al. (2014), NHS (2014); Ebi et al. (2004)
Commercial catalytic benefits	***Market-based estimates*** – This strand attempts to capture the wider influence of the Met Office in driving market growth through investment in new commercial products	New
Climate change information benefits	***Avoided cost approach*** – captures the avoided cost from having better information earlier to enable decisions to be taken to move to the optimal path sooner	Existing Hope (2011); Gray (2015) Unpublished internal Met Office information

The following table identifies unquantified benefits and provides any evidence for their potential relative scale.

Table 8: Benefit streams and related unquantified benefits

Stream	Benefit streams which have not been quantified	Indication of potential magnitude
Other business sectors	'Other business sectors' excludes those industries captured elsewhere. Land transport is excluded as 'Winter Transport benefits' would otherwise be a double-count. This means benefits to the land transport sector in the summer-time are excluded.	As total winter transport benefits equal 3.7% of the total benefits, and the impact in summer can be presumed to be significantly less than that of winter, it appears prudent to assume this will equate to not more than 1% of total identified benefits
Defence and security benefits	Because the analysis uses an avoided cost estimate predicated on the Ministry of Defence (MoD) purchasing sufficient in-house capacity to deliver to the same quality as they receive today, this raises a number of unquantified benefits: ▪ The cost of delivery may not equal to benefits the defence sector would receive from this service. As	These unquantified benefits are potentially substantial, but the information is not available to provide a more precise estimate

	such there may be large consumer surpluses which are not captured. ▪ The delivery of this information may save the lives of military personnel. No estimate is made of the value of lives saved, nor of any consequential costs avoided by the family and friends of such personnel.	
International leadership benefits	This benefit stream only captures the quantifiable benefits the UK accrues from other countries providing payment-in-kind for sharing the unified model through our use of their science community and their outputs. It has not proved possible to quantify the wider benefits in terms of diplomacy and international relations from the benefits other countries accrue from the services the Met Office provides, or the leverage better information gives the UK in climate change negotiations.	There is insufficient evidence available to identify the scale of this benefit
Wider Government avoided cost due to centralised RIMNET delivery by the Met Office	This stream measure the costs avoided by other Government Departments because of synergies created by the Met Office taking responsibility for RIMNET, as opposed to the full benefits to the UK of delivering the RIMNET system. These benefits were not estimated due to the requirement on Government to put in place a system, so they would be delivered both in the base-case and the 'do nothing' comparator. These benefits are therefore excluded. There are also a number of intangible benefits described in the RIMNET business case from 2014, which this study similarly does not quantify. Where these relate to additional benefits from the Met Office delivering in an integrated fashion, as opposed to the general benefits of any RIMNET system, these count as unquantified benefits.	Given the relatively low spend on RIMNET by Met Office, it is considered that any unquantified benefits are going to be similarly small.
ECMWF Benefits	The ECMWF delivers benefits to the Met Office the analysis does not quantify, which are not location dependent: ▪ Using ECMWF's model for 7-14 day forecast saves Met Office some HPC capacity but a 'thread' of the overall Met Office model has to run anyway during that 7-14 day period to enable monthly and three month forecasts thereafter. ▪ As an ECMWF member, Met Office gets use of ECMWF's HPC – up to 25% of HPC capacity is available across its member states and Met Office uses 90-100% of its share of that capacity. ▪ As an ECMWF member, Met Office staff can attend ECMWF training – there is also regular interchange of staff between the two institutions ▪ As an ECMWF member, Met Office benefits from ECMWF research, some of which is delivered jointly ECMWF generates data which can be sold wholesale by member states.	These benefits permit savings on HPC investments and generate revenues from sales. They are likely to be worth potentially tens of millions of pounds
Health effects and lives saved	The analysis captures the benefits from avoided deaths. The analysis does not capture any benefits arising from	Benefits arising from avoided treatment or lifestyle adaptation costs could

	avoided treatment or lifestyle adaptation costs.	potentially be substantial
Commercial catalytic benefits	Many nascent markets may also have been captured in a residual category, where economic growth has not been quantified. As such any growth stimulated in these sectors is not included in this analysis. This study also does not attempt to estimate any productivity gains the Met Office receives due to the 'commercial imperative'.	Whilst some investments into new products go on to be transformative in their impact on the economy, other deliver only marginal improvements. As such this unquantified benefit could range between small to substantial in scale.
Climate change information benefits	Benefits accruing outside the UK are not in scope of this analysis.	These benefits are extremely large but out of scope of this analysis.
Academic benefits	Whilst there is clearly economic benefits to the academic output of the Met Office, the risk of double-counting with the modelled gains in quality across the other streams of benefits mean this study has not estimated a figure. Academic benefits which have wider application than just the Met Office services, therefore, are recognised, but have not quantified in the analysis.	Because the impact could range from minimal to transformative, as with commercial catalytic investments, it is not possible to assess the likely scale of this unquantified benefit.

The major implications of Table 8 are that the most significant unquantified benefits in scope, given the information available are likely to relate to defence and security, and health effects. Climate change information benefits outside the UK dwarf all other benefits in scope, but are not in scope.

Furthermore, over and above this, climate change and advances in science through collaboration are driving new services. These are not yet large enough to be captured in the base-case analysis but represent growing areas which could become more substantial in the future. For example, changes in the climate are driving increased concern about water resources and risk of droughts and as such Met Office, with partners, have developed a product to bring benefits to Government and industry through more effective management of water usage. Also, on the back of scientific collaboration with the US, the Met Office has developed a new space weather forecasting service which brings benefits to both Government and Industry in terms of avoiding costs from damage to radio communications, GPS and power grids. Further details are provided in Annex 6.

The following table outlines key assumptions which may cause benefits streams to be larger or smaller than modelled and why.

Table 9: Key assumptions which may cause benefits to be larger or smaller than estimated

Stream	Key assumptions which may cause benefits to be larger or smaller than estimated	Probable direction
Value to the Public	Assumes a clean distinction between personal and commercial use. At the margin a clean distinction may not always be possible, introducing a risk of double-counting with 'other business sectors'. This effect is difficult to quantify, so we have maintained consistency with previous studies in using the full valuation, but the study addresses this in the sensitivity analysis. This benefit is potentially however under-estimated on a greater scale if one compares it to the \$240 per household per year estimates in Lazo et al (2009) in the United States. This estimate, in 2015 real prices of less than £10	Under-estimate

	($16), if comparable could be significantly larger. As such, it is presumed that the net position is that an under-estimate is more likely than an over-estimate.	
Aviation industry benefits	The literature review revealed two alternative approaches to quantifying the benefits from the aviation sector. This study uses the more prudent approach, but there are legal requirements compelling a country to make available meteorological information for civil aviation to be permitted. As such, strictly all economic activity in the civil aviation sector could be labelled as a Met Office benefit for at least five years. This would equate to over a hundred billion pounds, dwarfing all other benefit streams. Even within the prudent approach taken, there is still relative uncertainty, and the study addresses this in the sensitivity analysis.	Under-estimate
Other business sectors	In calculating the benefits to 'other business sectors', there is a conflict between two key sources. EUMETSAT (2014) assume between 0.25% and 1% of the GVA of the sector is as a result of weather services, from which we take an average of 0.625%, or which half is attributed to the Met Office, leading to an assumption of 0.3125%. The High Performance Computing (HPC) Business case (2014) assumes 0.2% of GVA for agriculture, which is a high value sector. This study has used the EUMETSAT values to achieve consistency with Gray (2015), but note this may produce an over-estimate. Given the study uses an estimate three times larger than the HPC estimate for agriculture, if the study used the lower estimate this could reduce total discounted benefits by a third. The study addresses this in the sensitivity analysis.	Over-estimate
Defence and security benefits	The modelling is predicated on MoD being willing and able to pay the full cost of maintaining the present quality of service. In reality MoD may be willing to accept a different price/quality trade-off. Any impact of this on the avoided cost is not estimated.	Over-estimate[21] (in relation to the avoided cost approach, noting that unquantified benefits described above may more than compensate for this)
Health effects	Estimates of the impact of weather information on preventing excess deaths related to cold and air quality are not available, so we have applied a factor drawn from American research on heat wave warnings and applied this to estimate excess deaths avoided from excessive heat, excessive cold and poor air quality.	Indeterminate
Climate change information benefits	All results, in line with previous analysis quoted in Gray (2015), assume that adaptation measures are not changed in response to better information about climate change information. The reason for this is that, as adaptation is so cost-effective, the maximum feasible amount is already assumed to occur in the base-case model used in this analysis, so increasing adaptation based on new climate change information is not included. As such this estimate covers abatement values, but this may therefore present an under-estimate.	Under-estimate

[21] In relation to the avoided cost approach, noting above that other unquantified benefits described above may more than compensate for this.

The major implications of Table 9 are that this study has attempted to take a prudent approach to assessing benefits and maintaining consistency between options and with previous studies. The four most important areas to note are ‘other business sectors’, ‘value to the public’, ‘aviation’, and ‘defence and security’.

The ‘other business sectors’ estimate maintains consistency with the EUMETSAT business case and Gray (2015). The alternative approach taken by the HPC Business Case delivers a significantly lower estimate for agriculture, which if applied across all industries would reduce benefits from this stream by around a third. This base-case however also assumes that only half the benefits to industry are attributable to the Met Office, as opposed to other suppliers. In this case we have carried out sensitivity testing to understand the impact of varying the factors driving this benefit stream on the net present value. The study uses a range defined by assuming all benefits are attributable to the Met Office in the high case and using the HPC Agriculture weighting at the lower end.

For the ‘value to the public’ estimate the study has assumed that, in line with the phrasing of the original questionnaire, respondents discounted the benefits relating to their business endeavours. However, this is an area of some uncertainty, so we have looked to reflect this in our sensitivity testing.

For aviation, the study have relied on existing sources, but because this is such a significant benefit stream it has appeared prudent to carry out sensitivity testing to ensure the study adequately reflects the impact of any potential uncertainty on the assumption values used.

The defence and security risk of over-estimation is likely to be far lower. The analysis assumes like-for-like purchasing in terms of quality of weather services by MoD either from the Met Office or whatever alternative arrangement they put in place. If however, this was not affordable, there is the potential that the MoD would accept lower quality to control costs. Given our estimate of potential spend by the MoD on weather services is £1.4bn, if they accepted lower quality, this would reduce this avoided costs, but because of the high fixed costs, it is probable this would only change this estimate at the margin.

2.4 Framework for assessing costs

This study utilises Met Office financial expenditure data to derive a forecast of spend throughout the period of interest (2015 – 2024). These costs have been structured to enable sensitivity testing in line with the project requirements. As such these may not be easily married to published accounts. The following headline assumptions are made:

- The Met Office is a Trading Fund. As such, its pricing for goods and services is established to deliver a return on capital to HM Treasury, delivered in the form of a dividend.
- The Met Office receives no recurrent delegated expenditure limit (DEL) or annually managed expenditure (AME) budgets from HM Government. All revenue is gained through contracts or contractual-style relationships with public and private bodies, domestically or internationally. As such all revenues are treated as a benefit, not a transfer, even if these have been accrued from Government bodies.
- The Met Office has received a capital grant from the Department for Business Innovation and Skills (BIS) of £97m to fund the capital investment for the High Performance Computing (HPC) from 2015-2017, which this study treats as income. This is an unusual form of funding for the Met Office. It primarily funds capital requirements through apportioning depreciation charges onto its contract revenues. Therefore the satellite

arrays purchased through EUMETSAT are paid for through recurrent revenue from contracts.[22]

[22] To prevent ambiguity, the satellite depreciation charges which are integral to the charging mechanism and cost allocation of the Met Office's costs are strictly not applicable to a CBA . If we were strictly applying the Green Book we should score the satellite at the point of time they are put into action, rather than the stream of financial payments to pay for these over subsequent years. We have chosen to not apply this approach because satellites are long-term investments and some have been launched in periods before that which we are analysing and would therefore be treated as sunk costs. Equally, to include the full cost would be to disproportionately apply costs to the Met Office in the period in question and again distort the case. Given the relative scale of the impact of this decision we do not consider this will introduce a first order error. As such, we treat the depreciation costs as a real use of resources / cost, despite being aware of their true nature.

3 Literature Review

3.1 Approach

This section provides a description of the methodological approach which London Economics adopted for the systematic literature review relating to the economic benefits of meteorological service provision, reflecting the guidance that has been set down in the Magenta Book (HM Treasury, 2011) which offers a checklist for undertaking a systematic review.

The key substantive challenge associated with this review of the literature was that studies on the economic benefits of meteorological services are relatively rare, and often limited to an analysis of weather forecast and warning services or qualitative assessments. The benefits of climate change research, or the health impacts of air pollution and extreme temperature forecasts, for example, remain relatively unexplored. In addition, quantitative assessments of the benefits of meteorological services are often very assumption driven, and the results of different studies therefore not always consistent. Methodologically challenging was establishing the information sources to be trawled for research material, and the inclusion and exclusion criterion to ensure that the most recent and relevant research work proceeded to the full in depth review underlying the model and final report.

Conducting a literature review as part of an economic cost-benefit evaluation can be broken down into four key phases, which London Economics follows in answering all research questions sought to be answered on the basis of secondary literature. In this study London Economics' standard literature review process has been amended to incorporate internal Met Office information provided to us by the General Review team. The resulting literature review approach is depicted in Figure 3.

3.1.1 Stage 1: Development of parameters and identification of potential sources

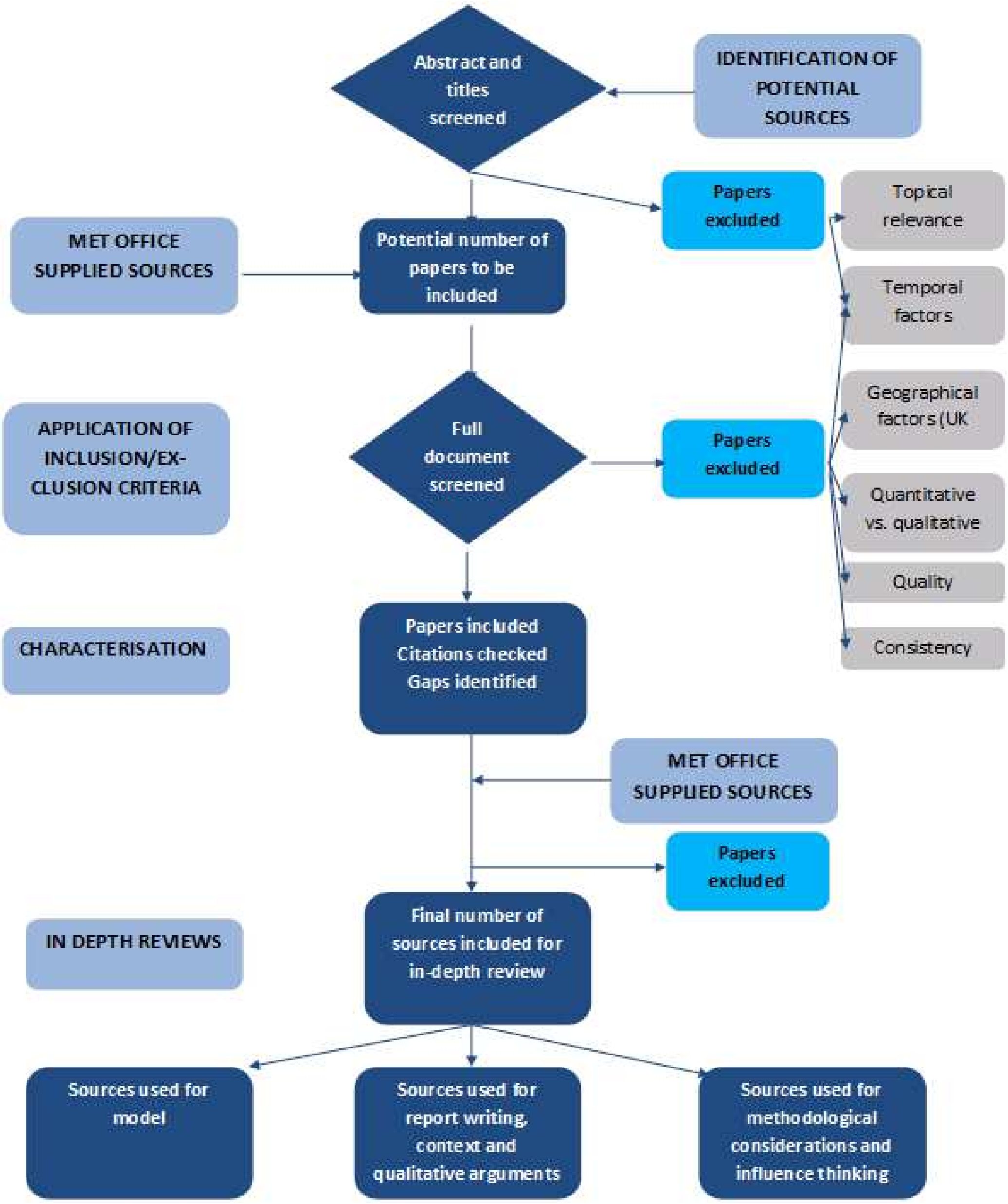
The first stage involved establishing the information sources to be trawled for research material and defining the initial parameters for the literature review. These initial parameters included topical relevance to the research specification and temporal factors (i.e. only empirical studies undertaken since 2005 were considered in detail).

The second stage was to identify a wide range of research sources. The identified sources included academic journals in the social sciences, research material commissioned and published by government departments and other non-departmental public bodies and representative organisations/associations, academic work that was either in progress or presented as part of university or research discussion paper series, and finally internal, unpublished or 'grey' sources that were available.

A large share of this material came via the Met Office itself. Met Office experts and employees of the General Review team were able to assist us in the search of unpublished, internal evaluations and business cases, previous qualitative and quantitative evaluations of parts of the Met Office (e.g. PWS, Hadley Centre) as well as general information about the Met Office (e.g. funding structures, stakeholders, performance measures etc.).

The sources identified in Stage 1 were then trawled to gather a large pool of over 300 individual documents) of literature.

Figure 3: Approach to undertaking systematic review of literature



3.1.2 Stage 2: Development and application of exclusion criteria and initial filter of articles

Having applied broad selection parameters in Stage 1, the next step was to establish further exclusion criteria to identify which elements of the literature were to be analysed in detail and included in the final research report. Those criteria addressed the relevance and appropriateness of the questions, methodologies and results presented in each study, the nature of the study (quantitative vs. qualitative studies), geographical factors (i.e. international sources were excluded unless there was no pertinent UK source available) and again temporal factors (inclusion of the newest possible estimates). In addition, all sources were sifted for quality aspects and internal as well as external consistency.

There was then a full review (rather than abstracts and titles as in the first stage) of each document, to ensure they were pertinent to the detailed research questions of our study.

3.1.3 Stage 3: Second filter of articles

Each of the studies identified as meriting inclusion were then assessed for additional citations. Given that many of the sensitivities and scenarios defined in section 1.3 have, to our knowledge, not been assessed in a quantitative way before, the team worked closely with the General Review team to fill gaps in our understanding of the relevant factors in play and to obtain monetised estimates of key values by consulting further internal and external sources known to the Met Office General Review team.

The entire process was applied to the additional references identified via citations and gap identification (and duplications were excluded) for possible inclusion in the final list of articles brought forward for final full and in-depth review in Stage 4.

Stage 4: Full scale review of articles selected for inclusion

This final stage involved an in-depth review of the remaining articles and documents that were not excluded at any of the previous stages and a synthesis of the information collected. The final sources can be categorized as follows:

- Sources used for the model
- Sources used for contextual and qualitative arguments
- Sources used for methodological considerations

3.2 Summary of key papers

Whilst the study draws on a number of sources, the following are of particular importance in terms of the degree to which they are referred to in this study, mainly driven by the particular relevance of their subject matter to our analysis. There are numerous other key studies, such as, for example Stern (2006), which are vital to understanding this subject, but which are not detailed below because they do not directly focus on the value of climate and weather *information* benefits.

Box 1: Public Weather Service Value for Money Review (2015)

In parallel to our economic analysis of the overall economic value of the Met Office to the UK economy, Dr. Mike Gray has been preparing a review of the value for money of the Met Office's Public Weather Service (PWS) to inform future internal government funding decisions (Gray (2015). Drawing on pre-existing studies on the economic value of weather forecasts, in the UK and internationally, and updating the figures to 2012 prices, Dr. Gray found that the annual benefits of the PWS to the UK are likely to lie between £1-1.5bn per year, with the higher end values being more likely. Comparing this to the 2014/15 costs of the PWS of £120m, this represents a benefit-cost ratio of at least 10 to 1.

The sectors considered in the review were:

- Value to the public (£460m p.a.)
- Value to aviation (£400m p.a.)
- Added value to all non-aviation industries of the economy (£400m p.a.)
- Storm damage avoidance (£80m p.a.)
- Value to land transport (£70m p.a.)
- Flood damage avoidance (£64m p.a.)

The underlying sources used three broad methodological approaches to determine the respective sectoral values:

- Value perception studies (willingness to pay): Surveys asking users what they would be prepared to pay to use the service
- Cost-Loss model: Assessment of the benefits of taking a specific mitigation action against a weather event. Requires knowledge of the economic impact of a weather event on a commercial activity if no action is taken, and an understanding of the costs and effects of mitigation. This is similar to our definition of avoided cost.
- Value chain analysis: For weather events where data on the economic loss due to weather impacts exists (e.g. hazard damage), this approach looks at the benefits of a weather service from the angle of possible cost avoidance. In addition to records of the economic damage of weather impacts this requires data on the accuracy and reach (how many people obtain and understand the forecast) of the service.

Given the Met Office specific focus and the timeliness of Dr. Gray's analysis, and only after careful consultation of the underlying primary studies, we have directly incorporated some of Dr. Gray's quantified benefits of the PWS to the UK economy into the weather section of our model, while maintaining some important differences:

- Dr Gray's analysis is in 2012 prices and ours is in 2015 prices.
- Dr Gray's analysis was focused on the benefits of the PWS's work to produce weather forecasts. Non-weather forecast benefits of the PWS are included in our analysis .
- This analysis has a wider scope, also covering the value of climate change information.

Methodologically we have worked to compare and contrast with Dr Gray, and this has led to refinements of both of our approaches, where we have agreed methodologies. Some minor differences remain at this point:

- In calculating public value benefits Dr. Gray rounds to the nearest pound, whereas we round to the nearest penny. Doing this allows us to better capture the quality effect on public value through time.
- For the value to winter transport calculations, for the lowest band (0-£10m) we use range mid-points (£5m), whereas Dr Gray used £10m, delivering a slightly smaller estimate.
- In calculating the benefits to 'other business sectors', there is a conflict between two primary studies. EUMETSAT (2014) assume between 0.25% and 1% of the GVA of the sector is as a result of weather services. The HPC Business case assumes 0.2% of GVA for agriculture, which is a high value sector. We have used the EUMETSAT values to achieve consistency with Dr Gray's work, as this covered all sectors on a consistent basis, but note this may produce an over-estimate. As such we have taken this into account in our sensitivity testing.

Box 2: High Performance Computing 2015 Onwards: Full Business Case and underlying case studies (2014)

In 2014, funding has been confirmed for a new £97m supercomputer to improve the Met Office's weather forecasting and climate modelling. The business case supporting/underlying this decision (Met Office, 2014) set out the socio-economic benefits (SEBs) of different high-performance computing investment options. For the option that was chosen eventually, the benefits were assessed at £2.2bn (5 year net present benefit), equivalent to a benefit cost ratio of 22:1.

The approach was to estimate the socioeconomic benefits of relevant Met Office services to the sectors, and to attribute a percentage of those benefits to high-performance computing. This central SEB estimate was then weighted by different capability weights depending on the sector (different sectors require different capability areas) and the investment option (different capability upgrades achieved through different investments).

HPC Estimates	Civil aviation (£m)	Renewable energy (£m)	Food supply (£m)	Flooding (£m)	Winter travel disruption (£m)	Climate change (£m)
	295	526	104	242	75	933

The estimates of the socio-economic benefits of the Met Office's decadal to centennial climate projections used in the 2014 HPC business case (see Box 2) were derived by Dr. Chris Hope from the University of Cambridge.

They were based on PAGE09, (described in Hope (2011), an integrated assessment model developed by Dr. Hope that calculates the impacts of climate change and the costs of policies to abate and adapt to it. The model can be used to find the optimal emission path, which is the emission path over time that minimises the mean net present value of the sum of climate change impacts[23] and abatement costs, for any ranges of scientific and economic inputs, among them climate change information of the sort provided by the Met Office Hadley Centre.

For the HPC business case, Dr Hope estimated the total global benefits from important climate change information being delivered ten years earlier (from 2030 to 2020). The assumption is that if the new information is received earlier, emission paths can be re-optimised earlier, bringing benefits through a combination of lower impacts and lower abatement costs. To account for the fact that earlier information is not certain to be used to adjust optimal emission paths, it is assumed that 70% of the better information is used (central estimate); if the information is not used in this way, it is assumed to have no value.

Box 3: Full business case EUMETSAT Polar System – Second Generation (Turner 2014)

The business case for funding the next generation of European Polar orbiting meteorological

[23] All results derived from Hope's study assume that adaptation measures are not changed in response to better information about climate change information. The reason for this is that, as adaptation is so cost-effective, the maximum feasible amount is already assumed to occur in the default PAGE09 model, so the justification for increasing adaptation after new climate change information is released would be unlikely to be prudent.

satellites (Turner et al., 2014) allocated a fraction of previously existing estimates of the benefits of weather information to one input of the meteorological information production chain.

Assuming that observations and NWP models each contribute around 50% to the accuracy of NWP forecasts, and using advanced numerical methods to evaluate the level of contribution of the current EUMETSAT Polar System (EPS) satellite (Metop) to the accuracy of global forecasts at 25% out of all observations assimilated, the study concluded that Metop contributes about 12.5% of the economic benefits of the Met Office.

This was found to be broadly consistent with results from the ECMWF, which showed an average degradation of forecast performance of 8% when Metop data was not used.

Note that the 50% attribution to observations is inconsistent with the 50% attribution to HPC assumed in the HPC business case, unless there is no contribution from the science community. This is because these cases were delivered at different times for different purposes. For this reason, our analysis did not use up the HPC or satellite contribution factors from either of these sources, with this study instead creating new factor weightings.

Box 4: The Public Weather Service's Contribution to the UK economy (2007)

In 2007, the Public Weather Service Customer Group (PWSCG) commissioned a study on the economic benefits of the PWS from PA Consulting, which considered the value of the PWS based on the perceived value of the public and cases studies from the Cabinet Office, Environment Agency and Civil Aviation Authority.

The PA study quoted an estimated overall benefit of £614m p.a.

Their estimate of the value of the PWS to the public was based on work previously carried out by ORC International which asked a survey group of 2,833 UK adults how much they felt the PWS was worth to them in monetary terms per year. The average amount was £7.30 per year. By multiplying this by the UK adult population of 48.4m (2006 estimates) this gave a value of £353.2m.

The three government agencies reviewed in case studies gave a value of £260.5m p.a., discounted to take into account a proportioned direct service payment.

Department	Lives saved	Financial equivalent of lives saved*	Property savings/efficiency gains	Total fiscal benefit
Cabinet Office[24]	54	£79.8m	£4.1m	£83.9m
Environment Agency	-	-	£47.9m	£47.9m
Civil Aviation Authority	20	£29.6m	£99.1m	£128.7m
Total	**74**	**£109.4m**	**£151.1m**	**£260.5m**

Source: PA Consulting (2007), p. 1-3. Note: Cost of a life is estimated at £1.478m

[24] Responsibilities cover disaster response.

The Environment Agency case study focused on the benefits of the EA's use of weather and storm tide information to provide its Flood Forecasting Service.

Calculations were:

- Annual average flood damage (£2,117m) x performance factors (10.3%) = Flood damage avoided (PV £218m)
- Flood damage avoided (PV £218m) – Investment (£21.8m) = Flood Warning Service Benefit (£197m)

25% of this estimate were attributed to the Met Office, and then multiplied by 97.65% to take into account a proportioned direct service payment.

The Cabinet Office estimate was based on Met Office information that enables emergency responders to make critical decisions. The examples used were

- lives saved on construction sites thanks to the National Severe Weather Warning Service (23 lives)
- efficiency savings from making more informed resource decisions during periods of adverse weather conditions (£4.1m)
- lives saved from heat wave forecasts (31 lives)

For the Civil Aviation Authority, on whose behalf the Met Office provides weather information to aircraft in UK airspace and acts as one of two global en-route weather data providers (WAFC) and specialist regional volcanic ash advisory centre, and operates a meteorological information satellite dissemination system , the following benefits were calculated:

- Lives saved through improved weather services (20 lives)
- Efficiency savings through improved routeing (£95.5m)
- Reduction in flight delays for the UK (£3.6m)

Box 5: The case for EPS/Metop second generation: Cost benefit analysis (2014)

In order to make the case for the second generation EPS/Metop, EUMETSAT (2014) analysed the contribution of satellite data inputs to weather analyses and forecasts generated by the National Meteorological Services of EUMETSAT members and cooperating states. In order to do so, the EUMETSAT study assessed the socio-economic benefits of forecasts in the European Union for three benefit areas: protection of property and infrastructure, added value to the European economy and private use by European citizens.

Benefits in terms of property and infrastructure protection were estimated in form of avoided costs from flood and storm damage. Assuming possible damage cost reductions of 10-37.5% for floods and 10-50 % for storms, the study derived forecasting benefits of €0.26 bn – €1.2 bn per year for floods and storms alone. Assuming that forecasts of other severe phenomena (snow, heat waves, cold spells, etc.) bring benefits of similar order, they doubled the estimate leading to €1.32 – €5.4 bn per year.

For the overall estimate of direct benefits of weather forecasts to the European economy in the form of added value, the study estimated that about one third[25] of the European GDP is sensitive

[25] Whilst this study has used this result as a quality assured business case which has been approved by multiple Governments to justify the investment, external peer review proposed we used a different approach which gives a base value of 17% of GDP, rather than one-third. Therefore this study have attempted to control for this issue through applying wider than usual sensitivity bands around the key elements of our model which use this assumption. The impact of this is shown in Sensitivity Two.

to weather, and assumed 0.25-1% value-added due to weather forecasts. This results in benefits between €10.23 – 41bn.

The benefit estimates of the private use of forecasts were based on a willingness to pay survey of US households conducted by Lazo, Morss and Demuth (2009). The survey arrived at a median estimate of $280 per year per household, with above 80% of households ready to pay at least $30. The EUMETSAT study assumed more conservative estimates of €20-80 per household per year.

Benefit area	Minimum	Likely
Protection of property and infrastructure	€1.32bn	€5.4bn
Added value to European economy	€10.23bn	€41bn
Private use by European citizens	€4bn	€15bn
TOTAL	**€15.55bn**	**€ 61.4bn**

4 Detailed definitions and methodology of the base-case

4.1 Defining the base-case scenario

One key difference between this analysis and other previous studies is that it has been agreed that the base-case cannot simply describe the 'current capability' of the Met Office because of a number of key investment decisions which have already been made that will change the capabilities, costs and benefits of the Met Office into the medium term. The study therefore delivers a ten year estimate because the Met Office & HMG are committed to significant investments[26] on:

- The High Performance Computer (HPC) (launched in 2015 and fully operational 2017)
- The next generation of polar satellites via EUMETSAT (fully operational 2022) to accompany the geostationary array in Equatorial orbit.

The analysis therefore focuses on '*planned weather forecast service and climate modelling capability*' covering a ten year scenario from 2015-2024, which caters for these changes, and recognises:

- **Expected changes in the quality of services delivered:** the same system will have greater benefits in future years if quality improves. Section 4.5 provides information on how quality has improved consistently in recent years and how the analysis takes account of this.
- The Met Office reviewed for foreseen **major policy changes**[27] which may impact over the time window. No additional policies for inclusion were identified.
- **Planned life expectancy of assets:** Assuming the Met Office continues the current policy of investing in a replacement supercomputer every five years the analysis models a new supercomputer purchase in 2020.

As such, the base-case assumes all inputs remain constant except the capital investments into satellite and supercomputer technologies. The investments included in the base case are:

- The HPC investment agreed for 2015-2017, with full operation from 2017, is included. This investment costs £97m.
- An assumption of a further supercomputer purchased in 2020. The analysis assumes this supercomputer has the functionality of a larger supercomputer option which was not taken forward as part of the HPC decision-making process, and delivers the same expected benefits. However, due to 'Moore's Law' about the development of supercomputing capacity per pound it is assumed that this supercomputer can be purchased in 2020 at the same price (£97m) as the present supercomputer. This assumption requires an improvement in price per unit of computing power of approximately 5% p.a. This assumption appears prudent in the light of stakeholder views.
- The satellite arrays are included on the basis of the planned scheduled roll-out.

[26] There is also a jointly funded upgraded radar system with Environment Agency, but the value of this is significantly smaller.

[27] Defined as those policies signed-off, costed, and having scheduled dates for commencement.

A key aspect of the study is ensuring additionality is identified without over-lap or double-counting. Reviewing the business cases for these investments indicate the following:

- PA (2007) captured the value of the PWS at a point in time, including:
  - The satellites in operation at the time, which are due to be replaced by EUMETSAT on a like-for-like basis.
  - The supercomputer in operation at the time, which is replaced in 2017 by a step increase in high performance computing.
- EUMETSAT (2014) calculates socio-economic benefits on the basis of replacing the existing satellites, on a like-for-like benefit basis. Therefore there is no additionality.
- The HPC Business case (2014) calculates socio-economic benefits of the computer covering both weather and climate change, taking account that some of these benefits are delivered by the existing supercomputer. As such, the HPC case is designed so that its benefits are additional to the base-case, driven by the upgrading of the supercomputer.

The following sections outline the key methodological points by strand.

4.2 First order benefit streams

Benefit streams are classed as first or second order according to the magnitude of the benefits they generate in the base-case. This definition is used to allow clear identification of the most important benefit streams.

4.2.1 Value to the public

This strand captures the value the public receive from free at the point of delivery weather forecasts and services.

The methodology to measure the value the public receive from weather services refreshes the analysis delivered in PA Consulting (2007), which collected data from willingness to pay surveys of the general public asking questions relating to the valuation of these services. The approach taken to update this is consistent with that used by Gray (2015), as described in section 3.2.

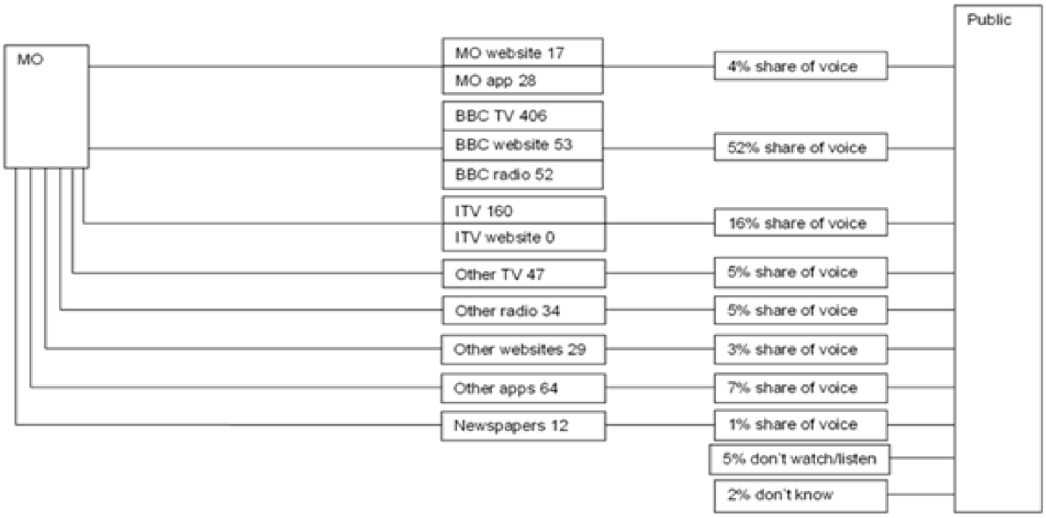
Surveys of the public have been repeated in recent years, most recently by GfK NOP Social in 2012[28]. This survey has the following key characteristics:

- The value for the public estimated relates to Meteorological services, such as 'weather forecasts' not the Met Office and its contribution, and thus may catch competitors and any value added created by these providers.
- Whilst the study was commissioned by the Met Office and aims to measure the effectiveness of the Public Weather Service, some questions refer to other competitors or source mediums such as the BBC or Google, as these use Met Office data.
- Further detail on this survey is provided at Annex 5.

[28] This is the article we otherwise refer to as Buchanan (2012)

The following figure from Buchanan (2012 unpublished) shows the main means by which consumers source weather information:

Figure 4: Met Office relationship with other major Met services providers[29]



Source Buchanan (2012 unpublished)

For our base-case, after adjusting for inflation, the analysis uses the 2012 valuation, applying the growth rate in public valuation from 2007-2012 to generate an estimate of benefits in a consistent base year to the rest of our study.

Because there is always uncertainty relating to whether respondents can cleanly differentiate between personal and business benefits from weather forecasts in their valuation the sensitivity analysis tests varying the estimation of benefits by ±50%.

This benefit is potentially however under-estimated on a greater scale if one compares it to the \$240 per household per year estimates in Lazo et al (2009) in the United States. This estimate, in 2015 real prices of less than £10 (\$16), if comparable could be significantly larger. As such, it is presumed that the net position is that an under-estimate is more likely than an over-estimate.

4.2.2 Aviation

The value the aviation industry receives from benefits from reducing flight times due to the WAFC and prevented costs from weather effects at airports, as discussed in Gray (2015) using sources gathered for the HPC business case.

There are two key aspects in relation to this sector to be aware of:

- Helios (2014 unpublished) notes: '*Accurate weather forecasting is essential for efficient and safe operation of aviation (civil and military). Indeed, the United Nations specialised agency which regulates civil aviation, the International Civil Aviation Organisation (ICAO), defines a minimum set of meteorological services which must be provided by its States for*

[29] At Annex 1, we refer to the 'Sun' theory of the Met Office as the point of origin for the whole of the meteorological services sector, which in part justifies our use of a 'do nothing' comparator. This figure is a useful indicator of the type of relationship we attempt to describe the Met Office as a 'Sun'.

them to operate civil aviation. In principle, therefore, without the National Capability provided by the PWS it would be impossible to run safe and efficient civil aviation in the UK...The British Air Transport Association (BATA) outlines the economic value of aviation to the UK. This includes £18bn of direct economic output from the airline industry, £17.5bn of benefits from inwards tourism, and £116m worth of trade to non-EU countries.'

- Treating the Met Office as one of a number of contributors to the aviation sector, rather than as an absolute enabler yields a more moderate assessment of value. The analysis considers two elements to estimate the value of the Met Office to the aviation sector, namely, the international benefits as a World Area Forecast Centre (WAFC) and the national benefits of Met Office forecasts for weather impact events on UK airports. PA Consulting (2007) uses a value chain analysis to estimate the annual net benefits of the reduction in flight time due to the WAFC service provided by the Met Office. Helios (2014 unpublished) uses a sector specific avoided cost model to capturing weather impacts at airports. Using a value chain approach in line with Gray (2015) the analysis captures the benefits to both airports and airlines, as shown in the following figure.[30]

The study uses the second of these approaches, but notes that there is a risk this could lead to a very significant under-estimate of the benefits from this stream. In part because of this we have chosen this to be one of the areas selected for wider ranges for sensitivity testing in Sensitivity Two.

Figure 5: Aviation calculations

Value to the Aviation Sector =	Value of WAFC service	+	Value of weather forecasts to airports					
Value of WAFC service =	*Global operating cost for 1 minute reduction in flight time*	*x*	*Proportion of flights using WAFC London data*	*x*	*Proportion of flights using data effectively*	*x*	*Proportion attributable to PWS*	*x*	*Direct service discount factor (accounting for CAA's direct service spend)*
Value of weather forecasts to airports =	*Total cost impact of no Met Office services to aviation*	*-*	*Total cost impact of current Met Office services to aviation*					

4.2.3 Non-aviation industries

This benefit stream captures the value from the wider economy, excluding sectors otherwise identified, created due to the additional output gained from the improvements in productivity which is attributable to the Met Office because of the forecasts and services it provides. This includes the following, but we have not attempted to individually estimate the benefits from each of these:

- PWS free data used for business use
- Met Office commercial products
- Other commercial data which relies on Met Office information

[30] 25% of benefits are attributed to Met Office for WAFC services. 100% of services to airports are attributed to the Met Office. Also, to note, for the forecast of global flights the study uses the IATA 2015 estimate, rather than generating a forecast for that year. Subsequent forecasts are London Economics forecasts using this IATA 2015 forecast as a base. Whilst there is a case for the use of passenger numbers because of the increasing use of larger and more fuel efficient vehicles, this analysis has maintained consistency with previous studies. In relation to travel time estimates, this study has maintained consistency with previous approaches. Future studies may look to use WebTAG Databook values, (www.dft.gov.uk/webtag) as the most up to date monetary values of time.

The analysis estimates the value of the Met Office to the rest of the economy using a value chain approach based on that used in Gray (2015). The percentage of weather-dependent industries is calculated using data on the gross value-added (GVA)[31] for each sector weighted according to their dependence on weather forecasts. Weights are sourced from Gray (2015), as outlined in Table 10, except where the analysis captures alternative estimations for the sector. In these cases the weight is set to 'nil impact' to prevent double-counting[32]. Taking this weather dependent GVA as a proportion of total UK GVA provides an estimate of weather dependent industries in the UK. This delivers around 17% of the economy as weather dependent.

Total gross domestic product (GDP) in the UK is sourced from the Office of National Statistics (ONS). Gray (2015) provides an estimate forecast of the 'value-add' to the economy from weather forecasts for each sector, and assumes 0.3125% of the value of these sectors is attributable to the Met Office.[33]

Table 10: Other business sectors – high / low and nil weather impact categorisation

High weather impact sectors (weighting of 1)	Low weather impact sectors (weighting of 0.1)	Nil weather effects (weighting of 0)
Agriculture	Manufacturing	Education
Construction	Health and social work	Financial & Business Services
Electricity, gas, and water supply	Hotels and Restaurants	Public administration and defence[34]
Mining and quarrying	Wholesale and retail trade	Real Estate and renting
		Art and other
		Land Transport[35]
		Admin and support services
		Information and Communication
		Professional, scientific and technical

Source- Gray (2015) with amendments by London Economics

[31] Gross Value Added is a measure in economics of the value of goods and services produced in an industry sector after taking account of the value of inputs consumed. GVA plus taxes on products less subsidies on products equals GDP

[32] We have excluded aviation, defence and security, and land transport because these have been separately calculated. We have excluded financial and business services to prevent a double-count between the insurance sector and the direct estimates of flood damage, storm damage, and winter transport. We have retained 'Health and social work' despite having a health calculation because we have no separate estimate for social work, but to compensate have scored the impact as 'low'. One can query some of the weightings, for example education is given a nil weight in Gray (2015). We have reviewed this and considered potential scenarios, for example, if we set Health and Social Work to nil, because it is included elsewhere and made Education 'low' rather than 'nil' impact the proportion of UK industries which are weather dependent would move from 16.98 to 16.83. We therefore consider the sensitivity analysis we have applied adequately copes with this.

[33] The approach takes half of the average of a high and low scenario. The high scenario assumes 1% of the overall value of weather dependent sectors, whilst the low scenario assumes 0.25%.

[34] This sector is excluded because defence is caught elsewhere, as are the major public sector response impacts around flooding, storms and winter transport.

[35] Land transport is excluded because of the valuation for winter transport identified elsewhere. As noted previously, this does imply that any benefits from forecasts which do not relate to winter are not captured in our analysis, introducing a risk of under-estimation of this benefit stream. It is considered this risk is acceptable as the anticipated impact is likely to be small relative to the estimate for winter transport impacts.

As noted earlier in this study, an alternative set of weights was applied in the HPC Business Case. This study therefore uses the EUMETSAT weights to maintain consistency with Gray (2015), but undertake in Sensitivity Two, testing of the impact of using the HPC business case approach.

4.2.4 Climate change information benefits

This stream captures the benefits to the UK of climate change information being made available sooner than would otherwise be the case.

There are two major types of benefits which can be accrued:

- **Reducing the sum of impacts of climate change** – Abatement is the taking of decisions to reduce the magnitude of the impact of the change in climate over the long-term. These decisions come with associated costs. The earlier provision of better information permit better decisions to be taken, where better decisions deliver optimal outcomes – the most effective trade-off between costs incurred and future benefits received.
- **Generating net benefits from adaptation** – Adaptation is making informed investment decisions to reduce the impact of any given magnitude of climate change, in terms of ensuring decisions take full account of likely climate outcomes and deliver optimal outcomes. An example of the Met Office's work in this area is given in Annex 7, relating to the work undertaken around the Thames Barrier.

4.2.5 The benefits derived from prevented damage due to flooding

This stream captures the benefits the public and businesses receive through flood warnings providing sufficient warning for property to be moved and damage prevented. This also captures the impacts on health from flooding.

The benefits of flood damage avoidance are calculated using a value chain analysis. The Environment Agency's Flood Incident Management Investment Review (FIM-IR) estimated the average annual flood damage in the UK to be approximately £3.2bn in 2012. Estimates from the PA study (2007) assumed a 25% contribution of the Met Office to the flood warning service, and various sources suggesting effectiveness rates at preventing damage between 6%[36] to 10%[37]. This approach covers river and coastal flooding. Surface water flooding is excluded.

4.2.6 The benefits derived from prevented damage due to storm damage

This stream captures the benefits the public and businesses receive through storm warnings providing sufficient warning for property to be moved and damage prevented.

The benefits of storm damage avoidance from PWS is calculated using a similar approach to flood damage avoidance. Swiss Re (2006) estimated storm damage prevention due to weather forecasts and warnings to be around €2.6bn in Europe. The study assumes weather forecasts reduce losses between 10% and 50%. The study takes a conservative estimate of 20%, which is then apportioned

[36] EUMETSAT (2014)

[37] PA Consulting (2007) quoting earlier Environment Agency research

to the UK based on its contribution to EUMETSAT (13%). In sensitivity testing we use a range between 10% and 50% to try and reflect the uncertainty here.

4.2.7 The benefits derived from prevented costs to winter transport

This stream captures the benefits the public and firms receive from forecasts of winter weather allowing reductions in losses caused by vehicular and pedestrian accidents.

The methodology to estimate the value to land transport from weather services is based on a cost avoidance approach.[38] The Winter Resilience Review (2010) estimated the 'hard' costs of a typical winter in the England were £450m. These were up-weighted to account for Wales and Northern Ireland using respective population ratios, to which Transport Scotland's estimates of £161m in 2010 is up-rated and added. It is also assumed that 14% of the UK public reacted to winter weather information using data from Nurmi et al (2013). Hence, the 'hard' costs avoided due to weather services can be calculated.

'Welfare costs', as calculated by the same source, covered the willingness to pay of individuals to receive information to enable to avoid certain costs. However, for our study there is a concern this double-counts the valuation by the public described in section 4.2, and has been excluded.

4.2.8 Defence and security benefits

The methodology for evaluating the direct benefits to the UK from the Met Office's contribution to national defence and security is a key part of the analysis, as the defence sector is a key customer. In this area it is not possible to rely on existing studies, so the study identified five potential approaches for estimating the benefits accrued by the MoD and wider security services which could be applied, the advantages and disadvantages of each is described in the table below:

1. As a *de minimis* it is possible to estimate this benefit through the implicit 'revealed willingness to pay' revealed by the funding received by the Met Office from MoD for services rendered. This value represents a floor for this service because, were this service not to be worth what is being paid it could be expected MoD would actively challenge this. Because this is not a profit-maximising price, but a regulated price, there is the potential that the consumer would be willing to pay more than this sum.
2. Develop a direct avoided cost by stripping the existing Met Office cost base back to only those services commissioned and required by the security services, at the specified quality level, to identify what the defence sector would have to pay if the Met Office was unavailable to deliver this service. This, however, fails to capture any consumer surplus the MoD or personnel, or personnel's families (from the prevention of lives lost etc) may accrue. As such it is likely to deliver a substantial under-estimate of the true value.
3. Using other comparable countries[39] where the security services direct fund their own capability as a proxy, controlling for defence spend to create an estimate of the avoided cost, based on a real-life comparator.

[38] This approach is similar to previous DfT transport resilience schemes. Because in some instances lost output may be partly recovered on other days, the avoided cost may be lower than estimated. Similarly lost output may double-count with other transport user impacts such as changes in journey time.

[39] We have looked at only top ten countries in the world in terms of defence spend, where the relevant defence ministry or sub-part (i.e. army, air-force or navy) deliver Met services themselves. The key examples are (i) Italy, where Met services for the whole country are provided by the air force; (ii) the US Air Force and (iii) US Navy who each independently deliver services against their requirement.

4. A bottom-up benefits valuation approach involving the construction of detailed value chains, identifying case studies in each of these services multiplied by estimates of the number of uses of each type of service to produce an aggregate valuation. For example, a stream may cover flight-planning, where the number of events is the number of wasted flights prevented through provision of weather information, and the value is the average cost of a flight. Examples are provided in Annex 4.
5. Sourcing a price from an international provider.

Table 11: Advantages and disadvantages of security options

Calculation method	Benefits	Disadvantages
Current pricing as a measure of Willingness to Pay	▪ Computational ease	▪ Fails to capture downstream consumer surplus or social benefits (lives saved and the value of life for family and friends) ▪ As the price is formula driven by Trading Fund rules restricting excess profits, the price may over or under-estimate the true value. Stakeholders considered under-estimation to be significantly more likely as the cost of producing the present menu of requirements is subsidised through the PWS contract
Avoided cost – shrunken Met Office approach	▪ Computationally feasible ▪ Provides a clear estimate of the avoided cost.	▪ Fails to capture downstream consumer surplus or social benefits (lives saved and the value of life for family and friends) ▪ The cost of producing the present menu of requirements is subsidised through the PWS contract. As such, faced with the true cost the security services may discontinue some requirements, or change the quality currently purchased.
Avoided cost – alternative country approach	▪ Provides a clear counter-factual based on full development of a real-world system	▪ Computationally unfeasible because of unavailability of data. ▪ USAF and USN are both not fully 'standalone' agencies, both using information from NOAA. USAF also has a licensing arrangement for the Met office's unified model ▪ Italian met service delivers non-security services, including TV weather forecasts, again not delivering a clean comparator. ▪ Fails to capture downstream consumer surplus or social benefits (lives saved and the value of life for family & friends)
Bottom-up case study approach	▪ Would capture security services consumer surplus	▪ Computationally unfeasible because of large number of benefits streams ▪ Fails to capture downstream consumer surplus or social benefits (lives saved and the value of life for family and friends)

The analysis uses option 2 as this is the only approach feasible in the time available. The analysis uses Met Office data to estimate the value of internal delivery based on the following principles:

- The Defence Met Service (DMS) would remain a trading fund. It is assumed that no economic profits would be made, instead delivering the standard 3.5% required in the Met Office HMT Minute.
- The DMS would not deliver non-security commercial activity, except civil aviation, so would not accrue commercial revenues.
- The DMS would deliver services to

 - o The Defence Science and Technology Laboratory (DSTL)
 - o Qinetiq, a major supplier to MoD, and
 - o US Air Force[40]

- The DMS would deliver strategic climate advice. The analysis costs this at 10% of the current cost of the climate change services.
- The DMS would purchase the HPC, but would not replace it in 2020 with a larger computer. Instead MoD is assumed to buy a replica of the HPC for the period 2020-2024, as the resources freed up by reducing climate science work would permit continued model development to meet defence needs in this period.
- All weather science would continue.

This approach delivers running costs in the region of £130m at steady-state[41], to which must be added HPC capital costs, compared to £225-£230m for the current Met Office similarly excluding capital expenditure.

4.3 Second order benefit streams

4.3.1 Government dividends

As a trading fund, the Met Office pays a dividend to the Department for Business Innovation and Skills, to cover the cost of capital. The Met Office Treasury Minute, agreed in 2009/10, is to achieve a return on capital employed (ROCE) of 3.5% over the five-year period to 31 March 2014.

To calculate this, the Met Office removed retained profit to fund investment, which are treated as a cost, and calculates the total ROCE achieved with the residual. Where the Met Office achieves a total ROCE in excess of the 3.5% set by HMT, this excess return, for the purposes of this analysis, is considered an economic profit, and it is this economic benefit which is the net benefit to Government and the taxpayer. Because this represents a producer surplus, it can be viewed as a benefit to the UK.

The analysis captures total revenues and total costs with the net difference forming the economic profit which flows through into the final net present value.

For clarity, the following items are included in the headings 'Total Revenue' and 'Total Costs' used in the study. Use of these terms may not equate to accounting practice but rather treats the Met Office as an economic actor with a requirement to deliver normal profit as part of its standard operation, where normal profit is taken to mean the 3.5% return on capital set in the HMT Minute.

[40] Because of the nature of the wider relationship, it is assumed that MoD would provide USAF with the Unified Model for free. Because DSTL and QinetiQ are both contractors of MoD, we treat their contract values as ultimately being MoD costs.

[41] This is the operational costs in 2017-18. It excludes any HPC capex investment which would be required. There is a case to be made that having purchased the HPC, if the Met Office close, HMG may pass this to MoD to use, if there was no alternative user available.

Table 12: Total revenue components

Stream	Selected approach
Commercial revenues	Payments received via contracts with 'commercial' clients
PWS contract revenues	Payments received under the Public Weather Service (PWS) contract from BIS
Non-defence Government revenue	Non-PWS payments received via contracts with public sector clients excluding MoD
Defence Government revenues	Non-PWS Payments received via contracts with MoD
HPC Capex funding	See section 2.4.

The study identifies the following costs, aggregating to the Met Office's planned spend in its corporate plans provided by Met Office to the Review.

Table 13: Total cost components

Stream	Selected approach
Observation costs	Capturing the cost of terrestrial and satellite based observation systems, including depreciation. See section 2.4
Scientist/modeller/forecaster costs	Capturing the direct human component of delivering weather and climate outputs
Reach costs	The human and web/app based costs of communicating and archiving services
HPC costs	This captures all capital and operational costs related to the supercomputers
Redundancy costs	In the case where a scenario requires the Met Office to shrink in manpower a cost of £50,000[42] per FTE exited is added to the cost line
Corporate overheads and other costs	All costs falling outside the above, including discretionary international spending and commercial delivery costs.

There are three important factors to note:

- The authors have worked with the Met Office's finance officials to forecast the cost base in future years, but the Corporate Plan only extends five years, so estimates beyond this hold real expenditure and revenue constant at the level in 2019/20. The estimates therefore build on the current cost base, applying any necessary real inflation[43] as necessary.
- The Met Office's costs, especially in relation to capital are lumpy, so to prevent years of 'surplus and famine' in relation to meeting the HMT 3.5% ROCE requirement, the Met Office smoothes certain factors in their costing models. Our estimates match in aggregate with Met Office estimates of the dividend across the period, but individual years can differ because the Met Office does 'smooth' some payments between years. The analysis

[42] Provided by Met Office finance officials.

[43] Inflation over and above CPI inflation. For example, salary inflation is assumed to be 3.68% over the period. In line with Met Office's internal implicit projection. Taking CPI inflation as 2%, the net real inflation rate applied to deliver real prices is 1.68%.

is 'unsmoothed' and therefore will not necessarily match in any individual year with the Met Office's internal or external projections.

- The scenarios tested can cause the costs to move. Because the Met Office has a reactive pricing policy, whereby it calibrates pricing to hit the ROCE target, this means that revenues may change in reaction to this. Because this cost change may affect quality of services, it does not necessarily imply that lower prices will increase consumer surplus if the service quality deteriorates sufficiently to erode consumer's valuation of the service. The study makes the following simplifying assumptions to deliver calibrated results:
  - ***Scenario One: World-class v Standard*** – The analysis assumes in this scenario that if quality was to fall by 20%, then this drop in quality may so decrease the valuation placed on services by relevant consumers that no economic profits are attained.
  - ***Scenario Two: No climate services*** – In this case climate service costs and revenues are deleted. The economic profit is reduced by the sum equivalent to the redundancy costs of the staff no longer working on climate science.

4.3.2 ECMWF benefits

The European Centre of Medium Range Weather Forecasts is an independent European (but not EU body) which operates out of South East England, using funding from NMSs across the continent. This movement of funds into the UK is a benefit to the UK economy, and this stream attempts to capture the element of this which is attributable to the Met Office.

Feedback from the wider General Review revealed that the world-class nature of the Met Office and the impact this has on the UK university sector, were necessary factors to attract the ECMWF to the UK and will be key factors in any decision required for ECMWF to remain in the UK. The analysis assumes, based on stakeholder engagement, that 40% of the benefits to the UK from the ECMWF can be attributed to the Met Office as a cautious but realistic assessment of the Met Offices impact on the decision to base the ECMWF in the UK.

The methodology for evaluating the direct and indirect benefits arising from the Met Office investing in the European Centre for Medium Range Weather Forecasts (ECMWF) are drawn from our updating of the 1995 report by General Technology Systems.

In addition, the ECMWF delivers benefits to the Met Office the analysis does not quantify, which are not location dependent:

- Using ECMWF's model for 7-14 day forecast saves Met Office some HPC capacity but a 'thread' of the overall Met Office model has to run anyway during that 7-14 day period to enable monthly and three month forecasts thereafter.
- As an ECMWF member, Met Office gets use of ECMWF's HPC – up to 25% of HPC capacity is available across its member states and Met Office uses 90-100% of its share of that capacity.
- As an ECMWF member, Met Office staff can attend ECMWF training – there is also regular interchange of staff between the two institutions
- As an ECMWF member, Met Office benefits from ECMWF research, some of which is delivered jointly
- ECMWF generates data which can be sold wholesale by member states.

4.3.3 International leadership benefits

Weather services

To evaluate the direct benefits to the UK from the Met Office's international leadership in this area, the study identified the following streams:

- Any commercial revenue from the sale/sharing of the unified model with Australia, South Korea and the USAF – this is captured through the Met Office revenue, so is not included here to prevent double-counting.
- Payment-in-kind for unified model services - For countries who do not make a cash contribution for the unified model and other services, direct benefits to the UK accrued through the time contribution other countries make to reviewing and developing the UK unified model. The value of this 'payment-in-kind' for free access to and use of the Unified Model is estimated at £15m p.a. by the Met Office's Chief Scientist. This benefit is therefore included in our analysis. Internal Met Office papers itemise this benefit as '*Science partnerships provide the Met Office with significant research gearing, estimated to be worth £15m for 2013/14. This is based on about 90 projects where 60 of these could not have been achieved without collaboration and the rest could not have been done as quickly. This can be broken down as follows:*
  - UM international partnerships: £2m
  - UK Academia through direct involvement with RCUK grants: £5m
  - NERC JWCRP activities through shared directed programmes (e.g. next generation Earth System Model, observational field campaigns): £4.5m
  - EU through engagement with UK and EU partners: £2m
  - Other international bodies: £1.5m
- Increased diplomatic influence because the UK position is based on better information – this study has not been able to quantify this benefit.
- Increased diplomatic influence because Met Office information has made vital improvements to quality of life, or reduced loss of life in partner countries – the study has not been able to quantify this benefit.
- Improved international development outcomes because the Met Office has worked to establish local met services – this study has not been able to quantify this benefit.

Box 6: Fukushima Case study

During the accident at the Fukushima Daichi nuclear power plant, the British Embassy was able to stay in Tokyo because of the quality of the scientific advice provided by the UK from the Chief Scientist, Sir John Beddington, from a number of bodies including the Met Office. This was in marked contrast to other embassies which closed down. The UK's advice, including its public facing website, a live teleconference with Sir John, and the UK government approach in relation to evidence- and science-based policy on issues such as travel, was respected by the Japanese.

Following the accident, the UK has been building its reputation in nuclear decommissioning in Japan, and the UK Government view is that the rational approach taken during the accident has greatly increased the reputation of the UK nuclear industry. UK companies report that the fact the Embassy stayed open during the crisis is often the first thing~~s~~ which is said to them in customer meetings.

Climate services

To evaluate the direct benefits to the UK from its international leadership in this area, the study uses the following streams:

- Increased diplomatic influence because our position is based on better information –this study has not been able to quantify this benefit.
- Increased diplomatic influence because Met Office information has made vital improvements to quality of live, or reduced loss of life – this study has not been able to quantify this benefit.
- Improved international development outcomes because the world-class Met Office has worked to establish local Met Offices – this study has not been able to quantify this benefit.

4.3.4 Health benefits

The analysis captures the following benefits:

- Lives saved in relation to cold weather through providing cold weather warnings. This excludes any impact of winter illnesses (flu etc) and focuses on only deaths caused by unseasonably cold weather.
- Lives saved in relation to heat waves through providing hot weather warnings.
- Lives saved in relation to air quality and respiratory illness through providing air quality forecasts.

The analysis does not capture any benefits arising from avoided treatment or lifestyle adaptation costs.

The analysis calculates these benefits by taking health sector data on the number of excess deaths in the UK, multiplied by the economic value of a life, adjusted for old age[44] and applying three factors:

- The share of the UK covered by the relevant warning (heat and cold warnings are only issued for England[45])
- An effectiveness factor, between 26% and 28%, dependent on service. The analysis applies an assumption of a 5% discount for heat because of noted concerns that there is a potential double-count effect with air quality.
- An intervention effectiveness factor, calculated at 0.12%, in terms of lives saved, drawn from a CBA analysis of the Philadelphia heat-wave system, applied to all three areas in the absence of other data.
- A 20% optimism bias is applied because of the need to apply the Philadelphia impact estimate across all three areas.

[44] Estimates of the impact of these warnings focus on the pensioner population. We therefore take a share of the value of a statistical life by taking the average lifespan (81.5 years), deleting the retirement age of 65 and dividing by 81.5 years to give the share of the value of a life saved by preventing the excess deaths.

[45] Because this additional service is paid for by Public Health England

The value chain approach produces an overall value of the excess deaths avoided through the provision of information by the Met Office.

4.3.5 RIMNET cost savings

The RIMNET service measures the impact of any potential nuclear accidents on the UK. DECC is the nominated lead department, but the service is managed by the Met Office on their behalf. From 2014 the Met Office has played an expanded role as System Integrator and Manager (SIAM), as detailed in the RIMNET business case (2014). There are international legal obligations that mean that this service has to be in place. In our analysis the internal costs in 2014 are £4.982m, these are captured in the baseline costs of the Met Office.

Met Office delivery of this role contributes towards total project cost savings of £4.4m compared to the next best alternative identified in the business case, alongside a number of intangible benefits.

The intangible benefits claimed in the business case relating to this project are listed below:

- *'Monetary benefits from reusing the existing RIMNET system, which already meets the requirement, so there will not be the high capital costs associated with building a new system and DECC will not have to write off the capital costs of the existing system by disposing of it prematurely.*
- *The large and diverse RIMNET user community benefits from a system and user-interface that is familiar, intuitive and well supported, reducing the training burden and maximising uptake.*
- *DECC and HMG benefit by avoiding severe reputational damage if the RIMNET system is terminated due to a failure to put a new contract in place before the existing contract expires.*
- *The UK will benefit from continuity of 24/7 national radiation monitoring beyond the current contract end date. This ensures that the UK remains alert to any potential radiation release from within UK borders or internationally. If this benefit is not realised then the UK will be exposed to a greater risk in the event of a nuclear emergency as it will have lost the ability to monitor and model the dispersing radiation.*
- *DECC and HMG will benefit from continuity of RIMNET support to the national nuclear exercise programme beyond the current contract end date. This allows the national response to a nuclear emergency to be fully tested, including the RIMNET input into the Scientific Advice Group for Emergencies (SAGE).*
- *UK HMG will benefit from being able to meet its domestic and international obligations in terms or radiation monitoring and emergency early warning.*
- *DECC and HMG will benefit from RIMNET becoming aligned with HMG ICT Strategy, resulting in shorter, more flexible contracting arrangements.'*

4.3.6 Commercial catalytic benefits

In the Met Office's commercial sector, investment is undertaken with the purpose of catalysing new market activity, through the development of new techniques or products[46], and enhancing the growth of nascent markets. This does not include the impact of open data or other commercial services provided to businesses. This benefit does not include any catalytic benefits created in public services outside the Met Office commercial sector over the next ten years.

4.4 Unquantified benefit streams

4.4.1 Authoritative voice benefits

'Authoritative voice' (AV) is a descriptor used to capture the perceived benefits which accrue to the public from reduced uncertainty caused by conflicting weather forecasts or high impact event advice. In precise terms, there is a view that in this instance a monopoly on the provision of advice causes a higher take-up of the advice and shifts the Day's Curve upwards through people not experiencing uncertainty and acting both with greater frequency and earlier, allowing them to increase the level of damage prevented. The analysis has treated AV as inherent in the benefits estimates produced and therefore has not quantified this benefit separately. In particular, AV is implicitly included in:

- The value to the public: Our estimate of the benefits of the PWS to the public is based on a willingness to pay survey conducted by GfK NOP on behalf of the Met Office. Given that 87% of the respondents to this particular survey considered it important that the weather forecasts were being 'provided by a trusted supplier', it seems reasonable to assume that the specified willingness to pay of the respondents includes the incremental benefits of AV to the overall value of weather forecasts and warnings to the public.
- Flood and storm damage prevention: The benefits of storm damage prevention were captured in terms of an avoided cost approach. The assumed proportion of maximum possible damage reduction through flood and storm warning systems is based on the current UK Day's curve, already shifted upwards through AV.

Greater detail on the theory relation to AV is provided at Annex 3.

[46] For example, in the renewable sector, The Met Office developed a product known as Virtual Met Mast. This provides modelled history of wind at hub height, replacing (or reducing) the need for a physical met mast to be located at potential wind farm sites. This was perceived as an innovative product on launch and which the wider market sought to mimic. It is now a standard service within the market, with equivalent services offered by both large and niche providers, with the price point reducing considerably over the lifetime of the product. The introduction and gradual commoditisation of this service has encourage innovation amongst providers – including for example provision of site specific wind indices to support Alternative Risk Transfer solutions (effectively 'insurance' for a low wind season).

4.4.2 Wider science benefits

One of the Met Office's key outputs is its pure science publications. Putting a valuation on this analysis and its potential use and impact is extremely difficult. The recent BIS publication (2014) '*Our Plan For Growth: Science And Innovation. Evidence Paper*' which reviewed the impact of public investment in science and research provides an estimate of the social return on public investment in science:

> *Despite the uncertainty and the long lag between investment and payoff, there is a strong body of evidence suggesting that public investment in our science and innovations system delivers average social returns of between 20 per cent and 50 per cent a year, with benefits lasting over decades.*

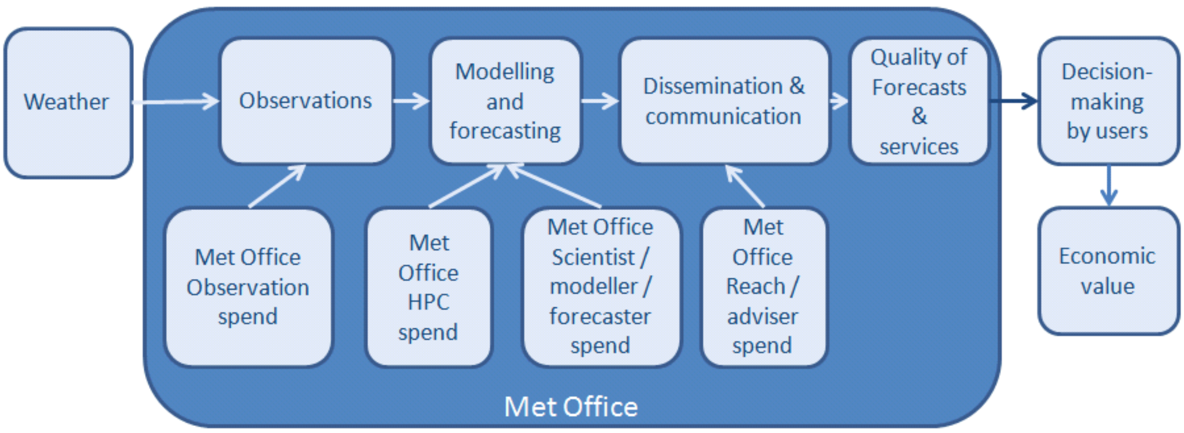
Consideration has been given to modelling this effect through applying a factor in this range to the science spend in the PWS and climate sections of the Met Office. However, this study does not do this because this would duplicate the impact of service quality through time described above.

4.5 The relationship between inputs and benefits

4.5.1 The Met Office and its contribution to delivering benefits,

One of the key requirements of our study has been to identify a methodology to translate changes in inputs into changes in benefits. To do this we have looked to understand how benefits are created through a value chain including the Met Office and its contribution.

Figure 6: The Met Office value chain



The creation of economic value is driven by the decisions people make in response to the weather. If better decisions are taken then fewer costs are incurred, or more production is achieved and value is created.

The key question is therefore how the Met Office enables better decision-making. To do this it supplies forecasts and other services. In many cases these are freely available through the PWS, so everyone can access them. Because of this it is not the availability of the forecast or service, but instead its quality which is the influencing factor. Using Figure 6 we break up the production chain of forecasts into three key stages; gathering observations, undertaking modelling and forecasting and dissemination and communication.

We have then reviewed the major inputs into these, which are:

- Met Office spend on observation data
- Met Office spend on HPC capacity
- Met Office spend on scientists, modellers and forecasters
- Met Office spend on dissemination and communication of forecasts and services.

This section describes how the study has estimated how changes in these inputs ultimately change economic benefits produced by stream.

To deliver this the study uses a strand-by-strand approach to identify:

- Which benefit strands are both substantial enough and sufficiently reactive to changes in the inputs of the Met Office to merit varying.
- How each identified strand will react to changes in inputs. In some cases different techniques were developed for doing this, based on a mix of pre-existing work and developing new approaches. The following table outlines the key benefits streams and methods applied.

Table 14: Benefit streams and reaction to inputs

Stream	Selected approach
Value to the Public	New inputs, quality, and benefits approach
Flood damage prevention	Day's Curve
Storm damage prevention	Flooding Day's Curve applied on basis of similar principles
Aviation industry benefits	New inputs, quality, and benefits approach, assuming a 1:1 relationship between quality and benefits
Other business sectors	New inputs, quality, and benefits approach, assuming a 1:1 relationship between quality and benefits
Winter Transport benefits	New inputs, quality, and benefits approach, assuming a 1:1 relationship between quality and benefits
Climate change information benefits	Values drawn from HPC Business case

4.5.2 Inputs, quality and benefits method

This method is based on the following assumptions:

- Changing inputs into the Met Office changes the quality of the forecasts and services delivered. [47]
- The better the quality of the service the better decisions user make and the more benefit users receive.

[47] Due to the non-excludable nature of much of the core service output, the predominant factor which will cause benefits to vary is the quality of the service.

- Therefore inputs drive service quality and then service quality drives benefits.

This study applies this approach to 'value to the public', 'aviation', 'other business sectors' and 'winter transport' benefits.

Measuring quality

Our discussions with Met Office officials have made clear that there are multiple factors which impact on the overall quality of services delivered by the Met Office:

- **Accuracy** – the percentage of forecasts which are correct
- **Frequency** – the time-step between forecasts (hourly / daily / weekly etc)
- **Timeliness** – the lag (warning time) between forecast and event
- **Resolution** – the geographical coverage of a forecast (the more detailed/ the smaller the geographical granularity the better)
- **Relevance** – whether information is provided in a format, or with sufficient contextual information to allow / enable informed decision-making[48]
- **Reach** – the machinery for transferring the forecast (alert) to relevant citizens, communities and agencies (advisers etc).

However, not all of the performance factors identified above can be easily quantified, and few have consistent data series which the analysis can use. Therefore the analysis has looked to identify any existing metrics which are capable of acting as a proxy for quality, specifically which enable comparisons between countries.

A review of existing data sources identified the internationally recognised performance assessment framework of the World Meteorological Organisation Commission for Basic Systems (WMO CBS) within which the accuracy of numerical weather prediction (NWP) models operated in different countries is assessed[49]. The NWP Index verifies the accuracy of hourly[50] Met Office forecasts of surface temperature, near-surface wind speed and direction, surface visibility, total cloud cover, cloud base height and 6 hour precipitation accumulation against surface observations[51]. The higher the Index, the more accurate the forecasts.

Given the high importance of forecasting accuracy for the Met Office's internal performance evaluations[52], using accuracy as measured by the UK NWP Index as a proxy for quality appears prudent. This is because aligning accuracy and quality appears in line with evidence in relation to

[48] For example a forecast 'there will be high winds, so stay away from trees which may fall down or properties which may have loose tiles or any other material which could be disrupted and fall on you' provides easier to digest messages than 'wind speeds will be higher than normal'.

[49] The ECMWF is also included in the NWP Index, but does not deliver short-range forecasts, which is a key job for NWS's. Therefore ECMWF is normally excluded.

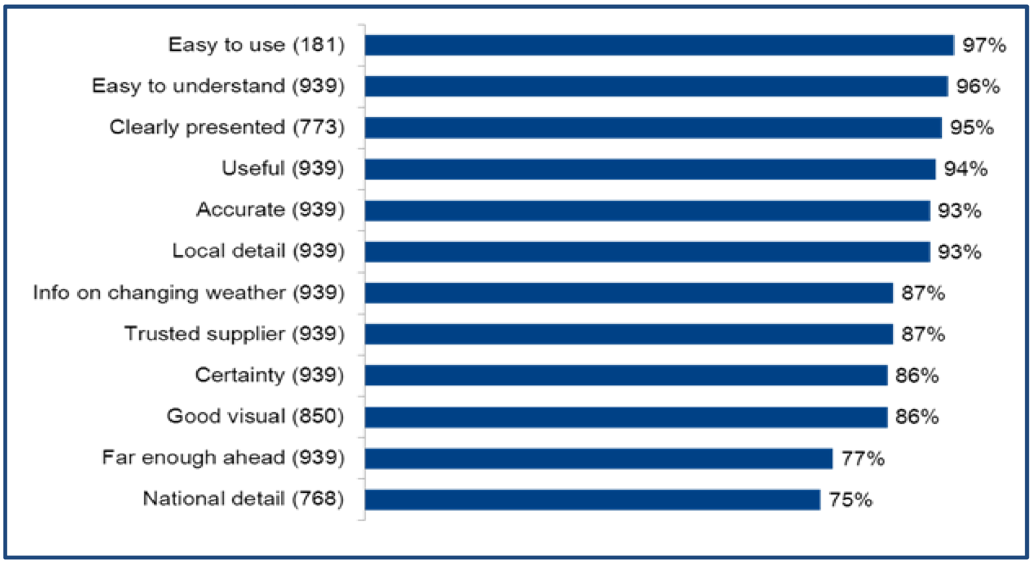
[50] With the exception of precipitation amount, which is measured every six hours.

[51] In the UK's case, from 116 observation points.

[52] Business Performance Measures 1i – 1iv.

the most important aspects of 'quality' according to public surveys, an example of which is shown in the following figure, which shows accuracy is identified as important by 93% of respondents[53].

Figure 7: How important are each of these elements of a weather forecast?'



Source: Met Office (2012b)
Base: All who see or hear a weather forecast and for whom the attribute is relevant (base in brackets after the attribute on the chart)

Having identified the NWP Index the analysis next identifies a relationship between changes in inputs and changes in quality.

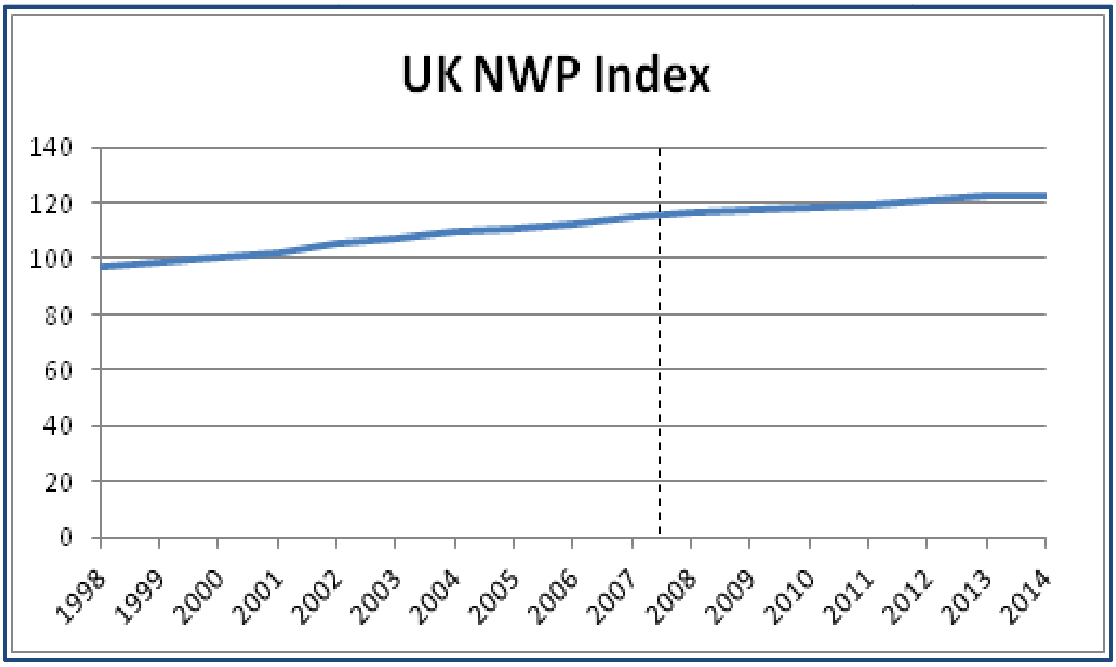
Linking input change to quality change

The UK NWP Index tells us that the measured quality of the services delivered by the Met Office have increased year-on-year, as shown in Figure 8. The annual growth rate for the period 2007-2012 is 1.2%. p.a.[54]

[53] Whilst there are other factors which receive a higher score, these fall in the territory of 'reach' and 'relevance'. We therefore look to address the importance of these later in this section, when we discuss weightings.

[54] We have chosen the growth rate over this period because it matches the consumer surveys described. However, there is a data discontinuity in the NWP series between 2007 and 2008. We have compared the different growth rates for the period 2007-2012 (1.2%p.a.) and 2008-2012 (1.0%p.a.) and these only differ slightly. Therefore the study has used the 2007-2012 estimate because this maintains consistency with the consumer surveys, but also because, due the estimate used being larger this acts through the methodology described to reduce the quality-benefit ratio. This appears the more prudent approach.

Figure 8: Accuracy index used to proxy for 'Quality' (dashed line indicates methodological change in collection)



Source: WMO

Because inputs into the Met Office changed in the same period, particularly due to the new satellites and new HPC investments, the analysis makes the following assumptions:

- Spend on staffing remained broadly flat in real terms in this period, so this study assumes that the change in quality has not been driven by this factor.
- As described in section 4.1, the EUMETSAT case assumes replacing the existing satellites on a like-for-like benefit basis, therefore the analysis assumes growth in quality has not been driven by the growth in observation data.
- Therefore it could be assumed that the growth has been driven by the regular cycle of five-yearly HPC investments enabling future research and improved operational forecasting.

Given this, the analysis could calibrate a rate of growth in quality driven by HPC investments that HPC investments deliver 1.2 percentage points of improvements in quality per annum. However, this assumption appears to place unreasonable focus on just one input, discounting any influence of labour productivity growth or the importance of observation data. As such, the analysis assumes that the rate in growth of HPC input delivers one percentage point of improvement in quality per annum. Having fixed a relationship between HPC and quality, the analysis then needs to consider how to capture other input factors.

The traditional approach to creating the relationship between a number of inputs and quality is to use a production function with quality as the output. Linear and Cobb-Douglas[55] production

[55] The Cobb-Douglas production function was originally used to estimate agricultural outputs, but has certain characteristics, specifically diminishing marginal returns to each factor of production which make it applicable to many situations. We have not used this form in

functions were considered, but because of the linear nature of the movement in quality, and because our review of the literature could not identify many other examples of using this type of analysis, this study has reverted to a simple linear model including the following factors:

- Capital and recurrent spend on observation data
- Recurrent spend on scientists, modellers, and forecasters
- Supercomputer capital and recurrent costs
- Recurrent spend on reach (advisers, web-site, apps, archiving and library)

The analysis makes some simplifying assumptions about how the production function is configured to allow calculation. The following equation gives the basic logic[56]:

$\sum(\Delta Inputs \text{ x } Weights) = \Delta Quality$

To identify weights to apply to each factor of production[57], the existing literature was reviewed and the following examples were identified:

Table 15: Identified weightings from the literature.

<table>
<tr><th></th><th>Observation</th><th>Scientist, modellers, and forecasters</th><th>Reach capacity</th><th>Supercomputing capacity</th></tr>
<tr><td>UK MO Satellite Business Case</td><td>50%</td><td colspan="3">50%</td></tr>
<tr><td>UK MO HPC Business Case</td><td colspan="3">50%</td><td>50%</td></tr>
<tr><td>US NOAA supercomputer case[58]</td><td>33%</td><td colspan="2">33%</td><td>33%</td></tr>
<tr><td>Input cost shares[59]</td><td>37.9%</td><td>39.7%</td><td>4.7%</td><td>17.8%</td></tr>
</table>

Two points from these examples are clear:

- The reach sector has never been disaggregated before from the other sectoral contributions.
- The other weight-sets are inconsistent with one another, particular the UK satellite and HPC business cases, which both assumed that 50% of the aggregate value of the Met Office was due to their contribution, unless one assumes that Reach and Scientists, modeller and forecaster input have a weight of zero.

As such, it is considered a valid exercise to re-estimate the weights for use, based on qualitative workshops with the Review Team and Met Office staff taking current spend profiles as a starting point. Our approach involves:

- Following Lazo et al (2004) in taking a starting point equally weighting the three major contributor strands.

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this work because of the linear relation between HPC investments and the quality metric, suggesting a simple model is sufficient to capture changes in the time frame analysed.

[56] Triangles represent the change in the relevant metric from one year to the next

[57] On the assumption that a one percentage point increase in science may not have the same impact on quality as a one percentage point increase in reach expenditure

[58] Lazo et al 2003.

[59] LE Analysis of Met Office cost data, excluding fixed overhead costs, including apportioned capital costs.

- Disproportionately weighting the Reach sector relative to current spend to reflect the importance placed on it by the public for the 'value to the public' stream, and to a lesser degree for the other sectors. The rationale behind putting a greater weight on reach is also related to diminishing marginal returns to investments in other factors inherent in quality. In simple terms, once a forecast becomes sufficiently accurate to allow a high level of reliance on its contents, the marginal benefit of further improvements in quality begin to diminish. At this point, which could be argued to have been reached, putting the marginal pound into better modes of communication, ensuring more people can more easily access the information has a greater impact. As such the weights are determined on the basis that the input contributions need to be skewed towards reach.
- Treating the HPC factor differently to keep its weight constant, because of its identified relationship with quality as described above.

As such the analysis uses the following weights:

Table 16: Identified weightings from the literature.

	Observation	Scientist, modellers, and forecasters	Reach capacity	Supercomputing capacity
Reach-intensive sector (value to the public) weights	25%	25%	20%	30%
Non-reach-intensive sector (aviation, winter transport and other business sectors) weights	30%	30%	10%	30%

Linking quality changes to benefit changes

Where we have time series of data on both the growth in forecast quality and benefits received, we can use these to understand the relationship between quality growth and benefit growth. This study refers to this relationship as the ***quality-benefit ratio***.

For 'public value' we are able to identify the quality-benefit ratio using:

- The willingness to pay surveys from 2007 and 2014 to estimate the growth in public valuation of weather services, and
- The NWP index for the same period to assess the growth in forecast quality for the same period.

Table 17: Calculating the Quality-Benefit Ratio

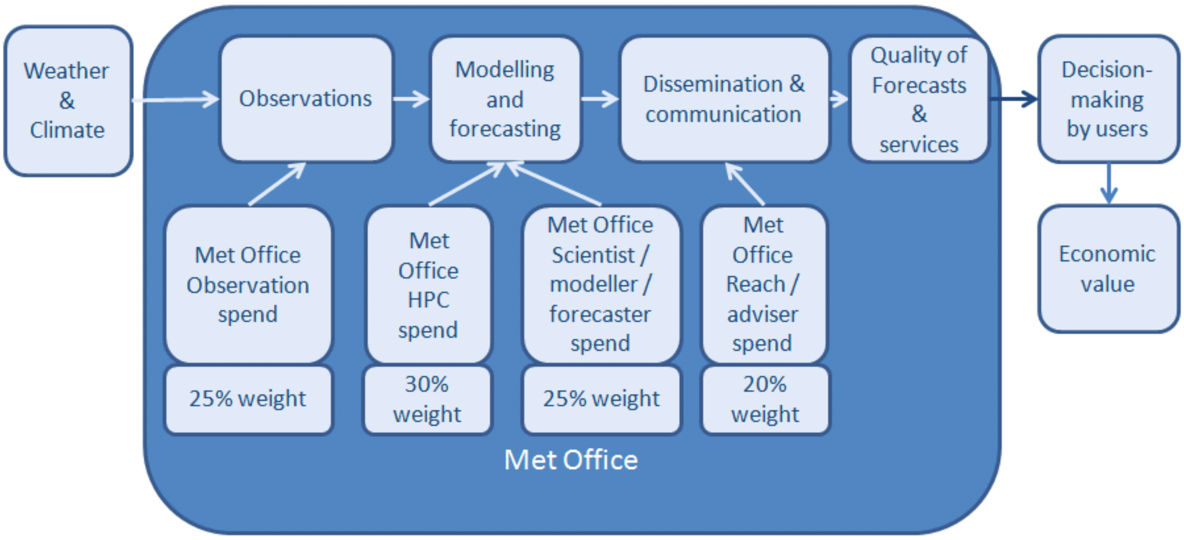
	NWP Index (Quality Metric)	Willingness to Pay (Public value metric)[60]
Growth rates	1.2%	2.2%
Quality-benefit ratio	1.8	

[60] After deflating to consistent real prices

For simplicity it is assumed both that the rate of quality growth will continue into the future in the base-case and that the ***quality-benefit ratio*** will also hold throughout the base-case period.

The following figure describes the links in the chain.

Figure 9: Inputs, Quality and Outcomes for public value[61]



The following worked example draws this section together into two summary equations. Assuming that, only the value to the public sector Reach expenditure increases by 5%, with all other inputs held constant, the net impact is a 1.8% increase in the benefits to the public:

Equation One: $\sum(\Delta\text{Inputs x Weights}) = \Delta\text{Quality}$,

$$(+5\% \times 20\%) = +1\%,$$

Equation Two: $\Delta\text{Quality x } (2.2/1.2) = \Delta\text{Benefits}$

$$+1\% \times 1.8 = +1.8\%$$

Other business sectors

For the following benefit streams the analysis applies the same methodology but assumes a quality-benefit ratio of 1.

- aviation,
- other business sectors and
- winter transport.[62]

[61] Growth rates calculated 2007-12.

[62] The analysis assumes that the winter transport benefit stream is not suitable for application of a Day's Curve, described below because, despite being estimated using an 'avoided cost' approach different type of costs are involved:

We have assumed a quality-benefit ratio of 1 because there is an absence of time series data, similar to that used for public value to be able to deliver any rationale for either benefits growing faster or slower than the growth in forecast quality. This is the key assumption in this analysis which is not supported by an evidence base and where the analysis is forced to use a prudent valuation from the authors. It is clear that across the key benefit streams future analysis would benefit from repeated studies to compare to previous studies to capture the impact of quality change in these areas through time.

Because aviation and non-aviation industries have high levels of benefits attached to them it is worth presenting the case in more detail why this approach has been applied. In the main this is because neither uses an 'avoided cost' approach, for which the Day's Curve (described below) was originally developed. Whilst it is possible to see the validity of the application of the flooding curve to storm damage it is far harder to apply this principle when the valuation approach is not 'avoided cost.'

Therefore, if one repeated the simulation equation above, increasing Reach by 5% in the aviation sector, this results in a 0.5% increase in benefits:

Equation One: ∑(ΔInputs x Weights) = ΔQuality ,

(+5% x 10%) = +0.5%

Equation Two: ΔQuality x (1) = ΔBenefits

+0.5% x 1 = +0.5%

Are factors of production fully flexible?

There is an issue here of whether all these numbers are fully flexible and able to adjust. For example:

- The vast bulk of observation spend is committed through the EUMETSAT satellite programmes and to a smaller extent the joint investment with EA. However, there is sufficient room to permit meaningful sensitivity testing.
- Supercomputer spend through the HPC is already committed for the first half of the period and again, and the analysis assumes this will be fully utilised during its operational life with the Unified Model[63] growing to make full use of the HPC's capability up to the

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- Flooding and storm damage affect fixed and mobile assets. The Day's curve builds this into account by preventing more than 35-40% of any damage from being prevented, due to the large impact and cost of repairs to permanent physical property assets, such as homes and workplaces.
- The avoided costs under winter transport affects mobility and mobile assets – accidents incurred by individuals, cars and other vehicles, and lost time due to lengthened journeys or cancelled routes (trains not running etc). As such, if one could achieve the equivalent of 'putting a roof over the UK' theoretically 100% of the damage could be prevented. As such the Day's curve could be fundamentally differently shaped – it could be s-shaped for example - and with a peak at a fundamentally different level, not necessarily 35-40% of potential damage. With too much uncertainty to be able to develop a better approach the study has retained the simpler approach described above.

[63] The weather and climate model which utilises the HPC.

end of its operational life. Assuming the Unified Model would then migrate to the next supercomputer, there may be risks of trying to shrink the Unified Model to fit on a smaller HPC, unless some fraction of its functionality is being discontinued. The following figure outlines the supercomputing investment under each scenario.

Table 18: HPC investments by scenario

	2015 investment	2020 investment
Base-case	£97m HPC	£125m HPC
Scenario One – 'standard quality'	£97m HPC	£97m HPC
Scenario Two – no climate services	£97m HPC	£97m HPC

This table shows we have built in the 2015 HPC investment into all options, but for scenarios one and two we only replace this with a machine of similar power, rather than the larger HPC assumed in the base-case.

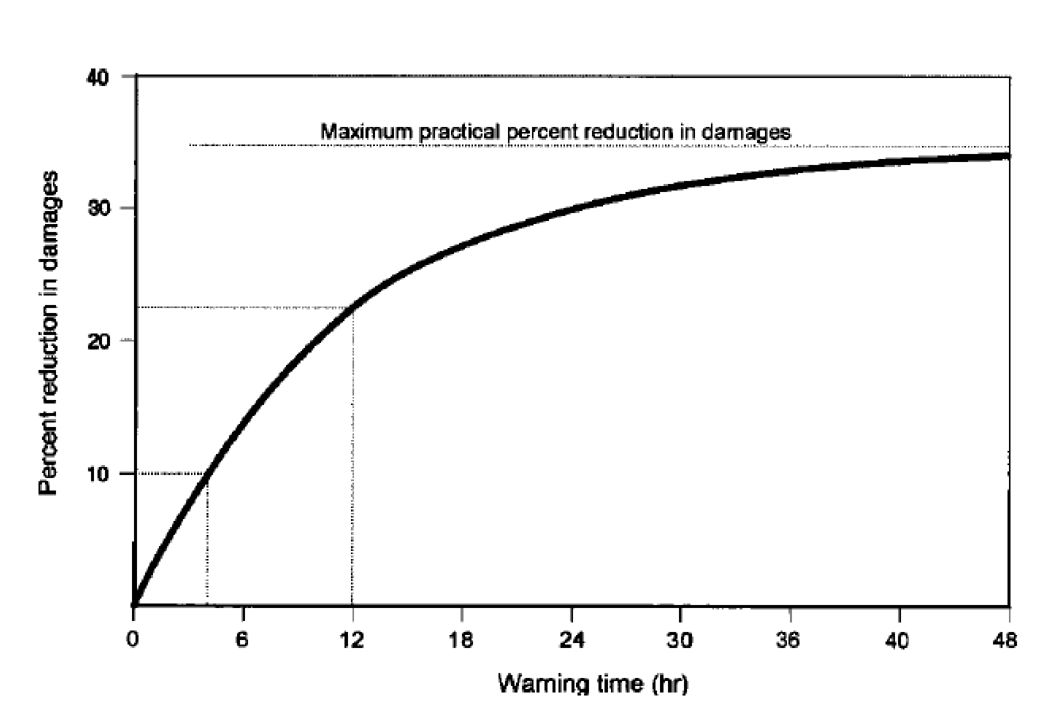
Because of this, specifically in scenario one and sensitivity three where different levels of investment and spend are tested, variable factors and specifically staff salaries account for the bulk of the variation.

4.5.3 Flooding and storm damage

In relation to flooding and storm damage the study has applied the extensively used concept of the Day's Curve, a relationship showing diminishing marginal returns between quality and benefits. Strictly the Day's Curve is only applicable to floods. However, the analysis applies the Day's Curve to storm damage on the assumption this delivers a better approximation of the relationship than a linear model, as both flooding and storm damage impact on both fixed and mobile household and business assets.

Box 7: Day's Curve

Day (1970) proposed that the benefits of a flood warning could be estimated as a function of warning time given by the system, using an example from the Susquehanna River basin in the USA, alongside evidence on how property owners reacted to warnings. The relationship is referred to as Day's curve. In short, the Day's Curve predicts that the more time (warning time) between the warning issuance and the event, the greater the percentage of potential damage which can be prevented, For example, if the warning time is zero hours, there is no benefit. If the warning time is twelve hours, Day's curve predicts that 23% of the total potential damage will be prevented. Day's curve asymptotically approaches around 35% of total potential damage, as '*no matter how great the warning time... some property, including most structures, simply cannot be moved*.'



The study uses an updated version of Day's Curve, taking account of the UK context, as developed by Chris Hope for the HPC business case.

Note: Interpretation of Day's Curve draws heavily on Carsell, Pingell, & Ford (2004). Diagram and quotation also from Carsell, Pingell, & Ford (2004)

5 Detailed definitions and methodology of scenarios and sensitivities

This chapter outlines the three sensitivities and two scenarios included within the analysis:

- Sensitivity One: Testing the impact of variation in weather and climate conditions
- Sensitivity Two: Testing the impact of variation in key assumptions
- Sensitivity Three: Testing the impact of different input and investment decisions
- Scenario One: Testing the impact of delivering a 'standard' rather than 'world-class' service
- Scenario Two: Testing the impact of delivering no climate services.

5.1 Sensitivity and scenario summary

The following table summarises the key elements that change in the sensitivity and scenario analyses.

Table 19: Elements which will undergo change through sensitivities and scenarios

Variable	Whether variable will change under this scenario or sensitivity				
	Sensitivity One	Sensitivity Two	Sensitivity Three	Scenario One	Scenario Two
Value to the Public		✔	✔	✔	
Aviation Industry		✔	✔	✔	
Non-aviation industries		✔	✔	✔	
Flood damage prevention	✔	✔	✔	✔	
Storm damage prevention	✔	✔	✔	✔	
Land Transport benefits		✔	✔	✔	
Defence & Security benefits			✔		
Climate Change Information benefits	✔		✔	✔	✔
Government dividend benefits		✔	✔	✔	✔
ECMWF Direct Benefits			✔		
ECMWF indirect benefits			✔		
International leadership benefits			✔	✔	✔
Commercial catalytic benefits			✔		

5.2 Sensitivity analyses

5.2.1 Sensitivity One

Sensitivity one requires us to estimate how the total value of the Met Office value reacts to variation in the frequency of high impact weather events over the next 10 years and what increase in the number or severity of high impact events would justify an increase in investment in national capability.

In the analysis and the joint-work with Met Office several methods to quantify any potential changes in the frequency or severity of flooding and storms were attempted. None satisfactorily provided a clear basis for modelling, so the analysis takes initial values from other studies and revert to sensitivity to test any impact by varying the flooding and storm damage benefit streams through using a Monte Carlo analysis to test the impact of changing these assumptions. Analysis of the number of high wind and high rain events over the past 11 years by the Met Office indicate ranges of ±48% for flooding[64] and ±56% for storms[65] for inclusion in this Monte Carlo analysis in relation to the variability in frequency of such events.

In relation to the value of climate change information the analysis uses the Monte Carlo technique upon the factors in Dr Hope's value chain, taking the range and distribution of overall values of climate change information, as a factor also. For the relevant modelling the authors thank Dr Chris Hope who has kindly agreed to allow us to use his pre-existing Monte Carlo module from his existing PAGE model and subsequent supporting models tailored to the Met Office's requirement.

Box 8: Monte Carlo analysis

Monte Carlo analysis is a modelling technique which simulates the impact of the expected variance in key variables on the output of interest.

The approach is best described using an example.

Step One: Allocation of ranges: Variables whose impact is of interest are given base-case values (or mean estimates), and a range:

Variable	Lower range estimate	Base-case/mean estimate	Upper range estimate
Example number of excess deaths prevented	1	5	10
Example value per excess death prevented	£1.7m	£1.8m	£1.9m

Step Two: Allocation of a distribution shape

All data has a shape to its distribution. If there is equal likelihood of any value within a range being drawn, then a rectangular distribution can be used (so called because a graph of the probability of any specific value being drawn would appear to be a rectangle). If there is a lower likelihood that a variable at the extreme ends of the range being drawn then a triangular distribution could be used. If there is reason to believe the distribution meets the statistical qualities required to be defined as normal, poisson, etc, then these can be applied. In this study we have applied triangular distributions because this seems to best reflect the fact the ranges we use mainly reflect uncertainty over the value with diminishing probabilities of more extreme values.

Step Three: Random selection of values within the range

The model selects at random a value for each variable from within the range between the upper

[64] No. of days with 10 or more observing sites recorded daily rainfall totals of greater than or equal to 50mm

[65] No. of days with 10 or more observing sites recorded gusts of 50 knots or more

and lower estimate and calculates the outcome from each draw, taking into account the distribution shape selected and therefore the probability of any particular value being drawn.

Step Four: Repetition

Variable	Draw 1	Draw 2	Draw 3	Draw 4	Draw 5
Example number of excess deaths prevented	8	6	6	9	2
Example value per excess death prevented	£1.84m	£1.78m	£1.76m	£1.86m	£1.75m
Benefit (lives saved x value of lives saved)	£14.72m	£10.68m	£10.56m	£16.74m	£3.5m

Five draws are given above, using a rectangular distribution. These deliver estimates lying between £3.5m and £16.74m. The draw is repeated thousands of times. In this study we use 10,000 runs as standard.

Creating 10,000 estimates allows the creation of a distribution of possible outcomes from the draws made. From this distribution we can then compute the range within which we expect 90% of the observations from the draws to fall. This is called the 90% confidence interval. In this case, the 90% confidence interval lies between £2.2m and £18.2m[66].

In the results section below, graphs of these distributions alongside the factors which had the most influence over the benefits estimated are listed.

5.2.2 Sensitivity Two

For Sensitivity Two, the study tests a variety of input assumption values relating to non-weather factors, by allowing the values to change within agreed ranges. Again a Monte Carlo model is used to test these factors. To ensure all factors are treated equally consistent rules are applied across all the factors:

- All distributions are the same shape, in this case triangular
- If a range is available this is used, otherwise all ranges have been set to be ±5% around the core value.
- The ranges which are available and which are used are:
  - Value to the public – individual willingness to pay - ±50%
  - Other business sectors – share of UK economy in ‘high impact’ industries - ±50%
  - Other business sectors – share of sector GVA attributable to Met Office - <-36%, 50%, 100%>[67]
  - Aviation – fuel savings - ±50%
  - Storm damage – share of damage prevented <10%,20,50%>

[66] Limited example, using 556 draws.

[67] For ranges which are not of equal movement on each side of the mid-point, we present these in ‘<>’ brackets, where the first figure presents the lower end of the range, the second number the mid-point used in the base-case, and the third figure the higher end of the range selected.

These factors have been specifically selected because they relate to key uncertainties in the evidence base which may have the greatest impact on the net present value.

5.2.3 Sensitivity Three

This sensitivity attempts to gauge the impact of not re-investing in HPC and the changes in benefits which would accrue, including whether assets would deliver worse performance.

Key to ensuring this work is modelled accurately, the study tests:

- Changes in observation, reach and scientist, modeller and forecaster inputs, and,
- HPC investment levels, using the HPC business case options for the second HPC purchase

In this instance the study includes:

- The cost of a like-for-like successor for the HPC in terms of processing power but lower costs
- Not investing in a replacement for HPC, building in a 'unreliability' factor from year six of its life to account for the increasing risk that the HPC will break down or be off-line for increasing periods for maintenance from this period, resulting in lower benefits as this 'unreliability' impacts on accuracy and ability to predict high impact events, or provide standard forecasts.

Under this sensitivity the study makes the following assumptions:

- Observation costs are cut by 5% in all tests, to reflect that the majority of this cost is fixed, mainly in the form of satellite charges
- Reach and scientist, modeller and forecaster costs cut by 5%

5.3 Scenarios

The scenarios describe significant changes to the base-case in a key dimension to demonstrate the range of potential outcomes, and where value would be potentially increased or destroyed in the process. To recap the scenarios are:

- Scenario One: Moving from a world-class to standard quality of delivery
- Scenario Two: Exiting climate services.

5.3.1 Scenario One

The move from world-class to a standard service delivery requires us to be able to define standard. To define 'standard' the study has compared the Met Office, using WMO data, to other comparable National Weather Services, for major developed nations, which have produced comparable statistics based on global models. Since the analysis requires a measure that is available and comparable between countries, the forecast accuracy of the *global* numerical weather prediction (NWP) models of national meteorological agencies was used.

Therefore for the purpose of this report we are defining world class and standard as it relates to Global NWP ranking.

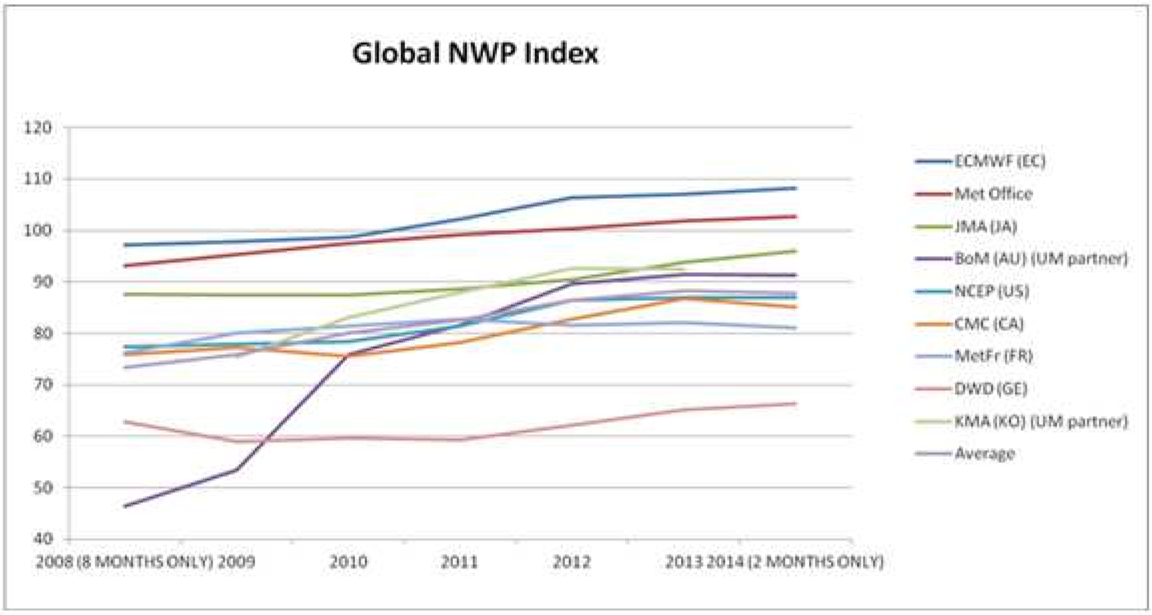
The Global NWP Index is a measure of the forecasting accuracy or skill of the global NWP models over persistence for up to five days ahead worldwide verified against various types of observations as truth in order to maximise the Global coverage, and is based on 36 months of data.

An accuracy score is calculated for each forecast included in the Index by normalising the forecast root mean square (RMS) error against the persistence RMS error. These errors are computed in accordance with the method recommended by WMO's Commission for Basic Systems (CBS).

The scores for each parameter are then combined to form a single value using weights reflecting the importance of each parameter to Met Office customers.

The figure below plots the global NWP Index for different countries. This shows a sustained and consistent gap between the Met Office and its closest comparators, with the exception of ECMWF. We do not consider ECMWF in this analysis as a competitor because it is not an NMS and has no requirement to deliver comparable short-range forecasts. This enables it to run longer models[68] and therefore deliver better quality medium-range forecasts for the same inputs.[69]

Figure 10: International Comparison of National Weather Service Quality



Source: LE analysis of WMO data provided by Met Office

[68] In terms of time and therefore computing power spent analysing data.

[69] Importantly, it should be noted that the study uses two different measures for quality. The UK NWP Index refers to the UK model, which delivers the growth rate used in the analysis as described in section 4.5.2 because it provides sufficient data points to deliver the analysis, whereas this scenario uses the comparable Global NWP Index to gauge the step down from 'world-class' to 'standard.' Importantly we have to assume that the quality of domestic and global models produced by different NMS is heavily correlated. This assumption appears justifiable.

This figure illustrates that Japan, in absolute terms, is delivering at a quality standard the UK achieved in mid 2009. With the majority of national forecasting centres reaching a score between 80 and 95, the study therefore defines 'standard' services as 90.

However, aside from Japan no other NMS competitor has reached the level of performance of the Met Office from 2008. Given the size of the UK's lead it is debatable whether, given the planned HPC investment which has already been committed to that any country will catch up in the ten year period, without significant investment[70]. However, this must be considered in reference to the data presented in Table 25 and Table 26, which shows that the Met Office delivers a benefit-cost ratio at the high end of the international spectrum, suggesting that the extra investment does purchase additional benefits, at a higher rate than other examples.

In short, even with reduced investment there is a strong probability, in terms of the Global NWP index, that the UK will still be world-leading, or at worst one of the top three[71] NMS[72] come 2024, even if active steps are being taken to reduce investment. This suggests there may be merit in future assessments considering longer time periods when estimating the benefits of NMSs.

As such, the study uses a theoretical scenario designed on the basis that the UK made historical decisions to invest at a lower rate, and is now in a position akin to that of close Western European competitors, delivering around 20% lower quality. To do this the following changes have been applied:

- Costs in the scientist, modeller and forecaster group and on Reach drop by 45%, and Observation costs drop by 5%, to account for the higher share of fixed costs in the Observation sector.
    - Replacing the HPC with a supercomputer of at least comparable power in Year 6, because purchasing a smaller supercomputer could result in potentially difficult and risky work to unravel some quantity of pre-existing code from the unified model to fit that model onto a smaller supercomputer. As such, the study presumes a supercomputer of similar operating capability is purchased to replace the HPC, but there will no step-up in quality due to increased computing power, so the engine behind quality growth will stop. Quality will therefore be held constant for 2020-24.
- A £10m p.a. reduction in overhead costs commensurate with this reduction in staffing.
- Removal in expenditure on non-Treaty international commitments (that is all commitments excluding EUMETSAT, ECMWF and WMO[73]
    - EUMETSAT (pan-European, but not EU organisation to procure satellites.) (£35-40m p.a.)

[70] The USA NCEP has already announced a major investment in HPC in relation to its global forecasting system (GFS) model. This will deliver a similar computing capability to the Met Office, although the NCEP focuses on weather forecasting, not climate. The NCEP's five year strategy states a clear ambition to be the global leader, with a focused investment in global weather forecasting. Given this level of investment the Met Office could be overtaken within the ten year period.

[71] Alongside Japan and potentially the USA.

[72] Excluding ECMWF, as discussed above

[73] See Annex One.

    - European Centre for Medium-range Weather Forecasts (ECMWF) – (pan-European, but not EU organisation to deliver medium range forecasts, operating out of Reading) (£6.5m p.a.)
    - World Meteorological Organisation (£3-4m p.a.)
    - Exiting EUMETNET and Copernicus involvement at the earliest opportunity.
- Removal of international leadership benefits (free scientific time)
- Because commercial sales are predominantly domestic, the study does not envisage commercial revenues changing, except it is possible the USAF would source an alternative, world-class provider to maintain its 'battlefield advantage'.[74]
- Loss of climate change information benefits from the purchase of a smaller supercomputer than assumed in the base case in 2020 and commensurate unquantified marginal diplomatic benefits (see Box 7).

5.3.2 Scenario Two

The key issue in relation to scenario two is ensuring that the residual weather function remains fully funded. Because of the activity based funding model of the Met Office and the deep synergies between weather and climate it is clear that removing one element would impact on the delivery of the other unless necessary funding was made available to 'back-fill' the necessary budgets. As such in this scenario the analysis:

- Removes the benefits from climate change information,
- Removes 50% of international leadership benefits, on advice from the Met Office of the expected impact of exiting climate services, meaning 50% is retained for weather services.
- Removing the climate budget from the model
- Removing the staffing costs of climate work from the model, but retains the 'foundation scientist' staff.
- Retaining the HPC and all related staff.
- Amending the ICT investment strategy: In this scenario, the present supercomputer will have some reductions in requirement, allowing the computer to be optimised to deliver enable incremental quality gains of 1.5% p.a. in other services. Therefore the HPC replacement again will be a supercomputer of similar operating capability.
- No assumption is made in relation to changing the relationship between the inputs and the quality of the outputs of the retained weather services, although removing the climate work would potentially have some effect on the weather services produced through the Unified Model.

[74] Equally, one must ask whether MoD would react with counter-active funding in this eventuality to maintain their comparative battlefield advantage. There is a degree to which one can consider that this scenario is hypothetical, if MoD reacted with additional funding as an automatic stabiliser which corrected any shift away from world-class back to a world-class offering again. The avoided cost modelled assumed that the MoD would provide sufficient funding to deliver world-class services themselves. For example, in which instance marginal funding increases necessary to replace the staff and capital investments foregone in this scenario may be cost effective in the MoD's eyes. Alternatively, the MoD may be willing to accept 'standard' quality, either from a reduced Met Office if the 'next-best' alternative was to buy this service from another country's service, probably at a 'standard' quality.

6 Results

All estimates in this section are in 2015 real discounted prices, at the HM Treasury Green Book rate of 3.5%. All estimates are rounded to the nearest £10m, with all estimates presented in billions of pounds unless otherwise stated. This level of rounding is considered appropriate because of the large number of assumptions and estimates included to generate each value[75].

The following scenarios and sensitivities are the result of a desk-based exercise primarily generated from stakeholder interviews and existing primary data sources. It is not a series of estimates for any form of Spending Review process, but presents estimates of the economic value of the Met Office to the UK taxpayer under certain assumptions. Whilst the study has attempted to include redundancy costs for staff in the scenarios at cost of £50,000 per redundancy, as agreed with the Met Office, this exercise has not included any additional reorganisation costs or charges, for example in relation to pension burdens etc and is not suitable for use as a substitute to Met Office financial analysis of the full costs of any and all reforms. The exercise has also needed to make estimates of Met Office income and expenditure for the period beyond the Corporate Plan. These assumptions in no way are estimates or claims by Met Office in relation to funding streams or calls for funding from HM Government, and are used purely for scenario testing and strategic planning purposes.

6.1 Headline results

The following table outlines the headline findings from the base-case, sensitivities, and scenarios.

Table 20: Headline results

Stream	Base-case	Scenario 1 – 'Standard' Met Office	Scenario 2 – No climate Services	Sensitivity 1 – weather effects[76]	Sensitivity 2 – Key factors	Sensitivity 3 – investment options
Total Present Benefits	£31.78bn	£24.70bn	£28.41bn	£29.93bn - £36.45bn	£28.76bn – £39.18bn	£27.82bn-£32.82bn
Total Present Costs	£2.26bn	£1.94bn	£2.13bn	£2.26bn	£2.26bn	£2.00-2.31bn
Net Present Value	£29.53bn	£22.76bn	£26.28bn	£27.67bn - £34.19bn	£26.50bn - £36.92bn	£25.82bn-£30.51bn
Benefit: Cost Ratio	14.1 : 1	12.7 : 1	13.4 : 1	13.2 – 16.1: 1	12.7 - 17.3:1	13.7:1- – 14.2:1

[75] All estimates present the authors' best estimates as of March 2015, under the current financial assumptions in place at that date, and in light of the literature available at that date, and may be subject to being overtaken by further work or publications.

[76] BCR excluding climate calculated by taking the most extreme values from Figure 12, adding the costs back and deleting the base-case climate present benefit (£3.18bn), and then dividing by present costs (£2.26bn).

As this table shows, there are very significant returns to UK from the Met Office, with the base-case delivering a benefit-cost ratio of over 14:1, and even with a smaller Met Office in scenarios 1 and 2 delivering at least 12.7:1. Each scenario is described in greater depth below, with commentary around its particular estimates.

The sensitivities around the base-case provide estimates of the degree of certainty at the 90% level. In the lower range cases the benefit-cost ratio falls to 12.7:1, but in all sensitivities and scenarios the net present value of the Met Office never drops below £22.8bn.

6.2 Base-case valuation

The following table details the value of the base-case scenario, alongside a commentary on the major factor determining the relative size of the benefits, with the largest at the top of the table.

Table 21: Base-case revenue streams

Value stream	Present Benefit	Share of PB	Comments
All other business sectors (market based)	£8.71bn	27.4%	Large market size drives high share
Aviation (market based)	£8.42bn	26.5%	Intense use drives high share
Value to the public (willingness to pay)	£4.73bn	14.9%	Large population = high share. Includes authoritative voice
Climate change information benefits (avoided cost)	£3.18bn	10.0%	Large world impact drives high share
Met Office Revenue (market based)	£2.30bn	7.2%	Majority of revenue cancelled out by costs (only excess dividend / economic profit flows through)
Defence and security (avoided cost)	£1.41bn	4.4%	Does not capture producer surplus and consumer surplus which are included qualitatively
Winter Transport (avoided cost)	£1.16bn	3.7%	Winter impacts only
Flood damage prevention (avoided cost)	£0.67bn	2.1%	High impact, low frequency
Storm damage prevention(avoided cost)	£0.62bn	2.0%	High impact, low frequency
ECMWF (market based)	£0.33bn	1.0%	Relatively small spend
International Leadership (market based)	£0.13bn	0.4%	Relatively small payment in kind. Excludes unquantified benefits
Health(avoided cost)	£0.12bn	0.4%	
Commercial catalytic benefits (market based)	£0.01bn	0.0%	Low market growth
HMG avoided costs from RIMNET (avoided costs)	£0.01bn	0.0%	Avoided cost, not full RIMNET value

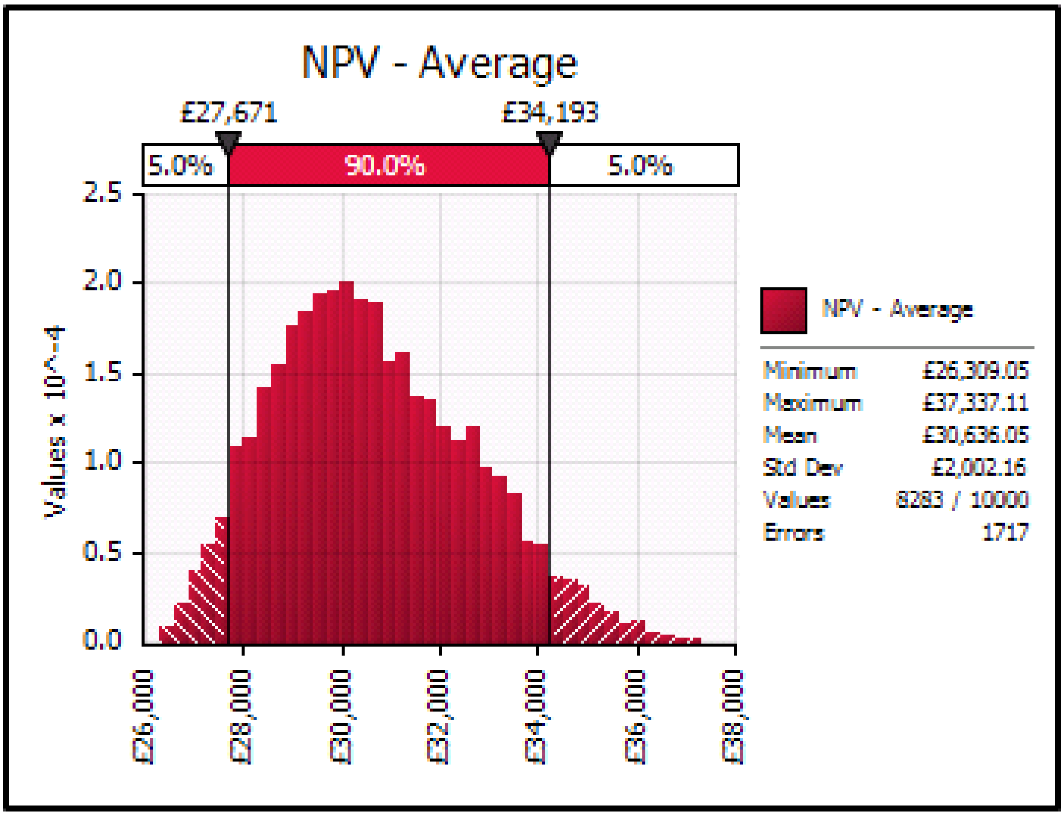
The following sensitivities all take the base-case and vary key assumptions to test three distinct dimensions of the model.

- Sensitivity one tests the impact of varying weather assumptions.
- Sensitivity two tests the impact of varying assumptions key to the generation of benefits by benefit stream.
- Sensitivity three tests the impact of varying investment and disinvestment decisions on the costs and benefit streams of the model.

6.3 Sensitivity One

Figure 11 illustrates the potential variation which could occur in the base-case net present value if key assumptions about the weather and climate factors in the model are allowed to vary within defined ranges. These specifically relate to the variability in the frequency of floods and storms over the next ten years, the proportion of storm damage prevention which is attributable to the Met Office, and the potential variation inherent in estimates of climate change.

Figure 11: Monte Carlo distribution caused by weather and climate factors



The implication of this is that the net present value has a 90% chance of falling between £27.7bn and £34.2bn.[77] This is reflected in the mean from the Monte Carlo analysis (£30.6bn) being broadly £1.0bn larger than the base-case, which uses the core assumption to calculate a value. In the worst case therefore the benefit-cost ratio would fall to around 13.2:1. The following figure outlines which factors have the greatest influence and can cause net present value to shift most substantially. This shows that the value of global benefit from obtaining better climate change information has the single largest impact.

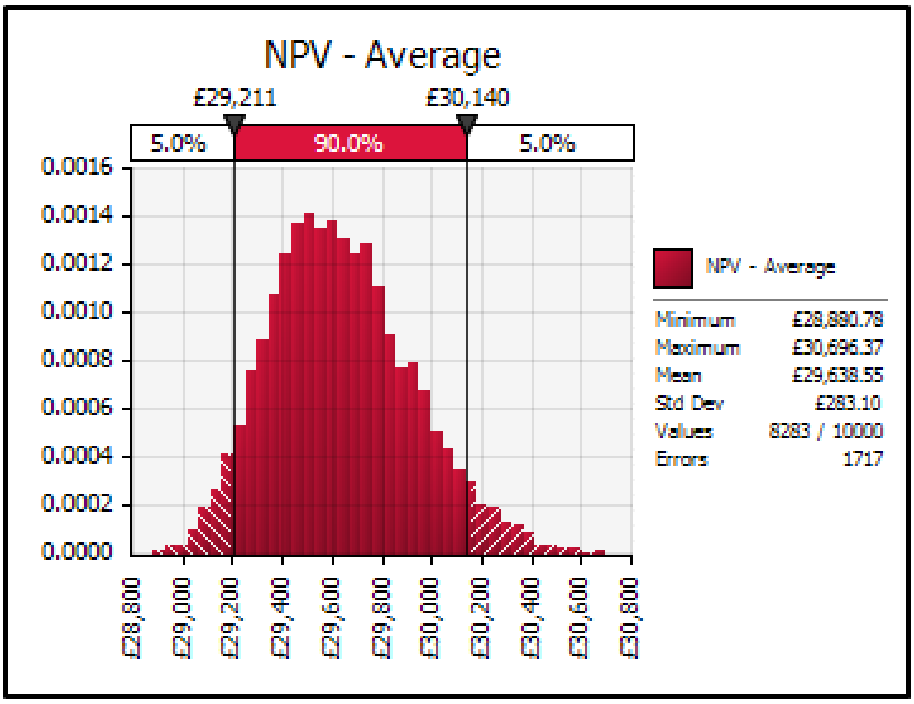
[77] Because the risk that the impact of climate change could be larger than expected is larger than the risk it could be lower, the up-side risk is larger than the down-size risk.

Figure 12: Primary factors determining Monte Carlo distribution (Sensitivity One)

Change in Output Statistic for NPV - Average			
Rank	Name	Lower	Upper
1	Global benefit from obtaining better climate information	£27,628	£34,194
2	Climate - Impact on UK factor	£30,136	£31,225
3	Climate - Equity factor	£30,298	£30,961
4	Proportion of storm damage avoided due to weather forecasts	£30,378	£30,911
5	Climate - Proportion of information used effectively	£30,331	£30,851
6	Average storm damage (Euro millions)	£30,351	£30,862
7	Annual average flood damage (millions)	£30,449	£30,826
8	Proportion of flood damage avoided due to warnings - minimum	£30,519	£30,813
9	Pound to US Dollar exchange rate	£30,534	£30,765
10	Proportion of flood damage avoided due to warnings - average	£30,539	£30,746

The following figure demonstrates presents this sensitivity excluding the climate change elements to provide greater clarity on the impact of the impact of the weather factors selected.

Figure 13: Monte Carlo distribution caused by weather factors only



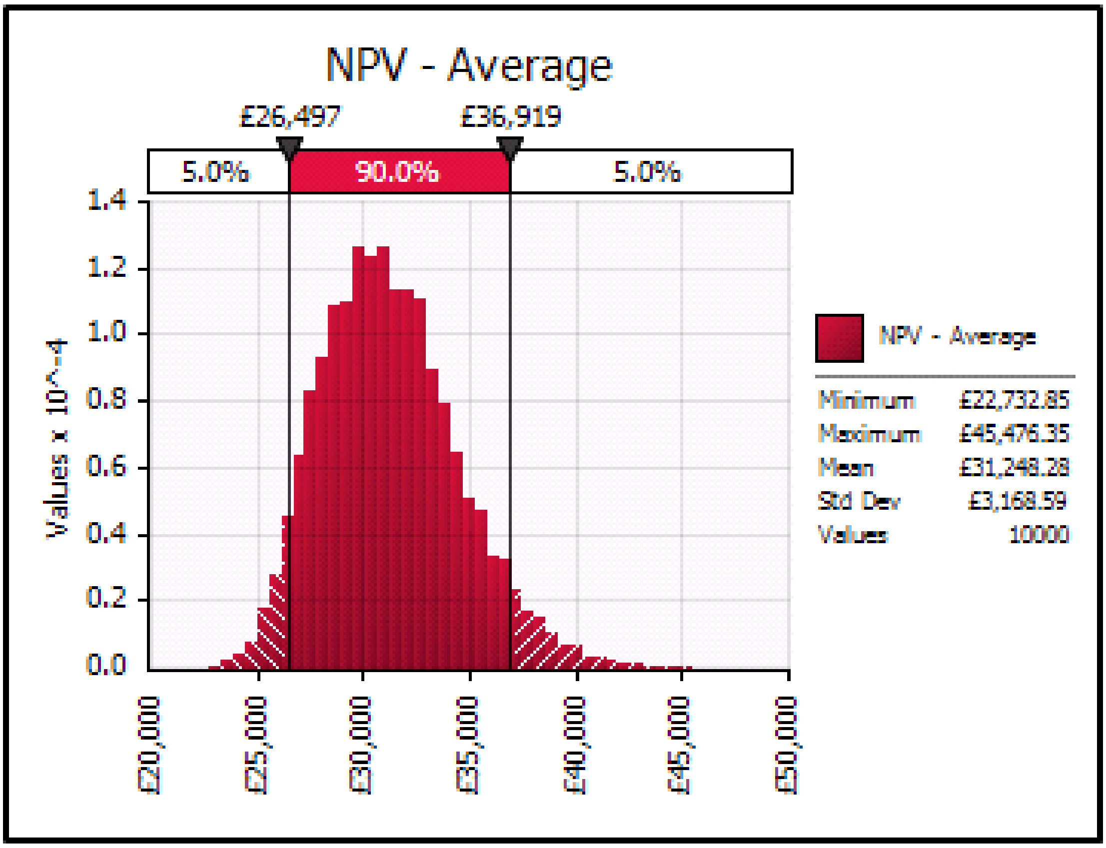
This figure shows that even allowing for significant variation in the frequency of flood and storm events over the ten years, the 90% confidence interval is less than £1bn, whereas including climate widens this to £6.4bn, or in simple terms, only 14.5% of the variation modelled is accounted for from weather variability, as opposed to 85.5% accounted for by climate change variability.

6.4 Sensitivity Two

This sensitivity tested the impact of changing key assumptions in the generation of the different benefit streams. Within these, particular attention is paid to the key elements of the largest benefit streams around which there is the greatest uncertainty. Whilst this has focussed attention onto the largest benefit streams, this is in an attempt to gauge the most influential factors, whilst allowing other less influential factors to vary within a ±5% window.

The following figure illustrates how the base-case net present value varies with the value of these key input assumptions. Figure 15 identifies the assumptions which have the largest impact on this variation.

Figure 14: Monte Carlo distribution caused by non-weather assumptions



This figure demonstrates that variation of key factors would in 90% of case deliver a net present value between £26.5bn and £36.9bn. In the worst case, the benefit-cost ratio would be around 12.7:1 for the bottom-end of the 90% confidence interval.

The following figure outlines which factors have the greatest influence and can cause net present value to shift most substantially.

Figure 15: Primary factors determining Monte Carlo distribution (Sensitivity Two)

Change in Output Statistic for NPV - Average			
Rank	**Name**	**Lower**	**Upper**
1	Value to the economy - Weather dependent industries	£27,571	£34,896
2	Value to economy of weather forecasts - Maximum	£28,334	£35,004
3	Public - WTP 2012	£29,775	£32,410
4	Value to economy of weather forecasts - Minimum	£30,428	£32,119
5	Average operating cost per in-flight minute- 2007	£30,343	£31,743
6	Aviation (National) - Total cost of no Met Office	£30,756	£31,655
7	Public - WTP 2007	£30,833	£31,522
8	Proportion of flights using WAFC data	£30,885	£31,525
9	Aviation (National) - Total cost with current Met Office	£30,985	£31,547
10	Health - Preventable respiratory illness deaths	£30,994	£31,525

6.5 Sensitivity Three

The following table provides a breakdown of benefits, costs and net present values under different investment assumptions, specifically the present supercomputer investment, the supercomputer investment in 2020 and ±5% in relation to other factor inputs, as outlined in section 5.2.

Table 22: Sensitivity Three results (base-case shaded)

Supercomputer 2015[78]	Supercomputer 2020[79]	Other inputs	Total Present Benefits	Total Present Costs	Present Value	Benefit / cost ratio
Current	Current	No change	£28.86bn	£2.06bn	£26.80bn	14.0 : 1
Current	Current	-5%	£27.82bn	£2.00bn	£25.82bn	13.9 : 1
Current	Current	+5%	£29.90bn	£2.11bn	£27.79bn	14.2 : 1
HPC	HPC	No change	£31.11bn	£2.24bn	£28.87bn	13.9: 1
HPC	HPC	-5%	£30.07bn	£2.18bn	£27.89bn	13.8 : 1
HPC	HPC	+5%	£32.15bn	£2.29bn	£29.85bn	14.0: 1
HPC	HPC+	No change	£31.78bn	£2.26bn	£29.53bn	14.1: 1
HPC	HPC+	-5%	£30.74bn	£2.20bn	£28.54bn	14.0 : 1
HPC	HPC+	+5%	£32.82bn	£2.31bn	£30.51bn	14.2: 1
Current	HPC	No change	£29.47bn	£2.13bn	£27.34bn	13.8 : 1
Current	HPC	-5%	£28.43bn	£2.08bn	£26.35bn	13.7 : 1
Current	HPC	+5%	£30.51bn	£2.19bn	£28.32bn	13.9 : 1
Current	HPC+	No change	£30.15bn	£2.15bn	£27.99bn	14.0 : 1
Current	HPC+	-5%	£29.11bn	£2.10bn	£27.01bn	13.9 : 1
Current	HPC+	+5%	£31.18bn	£2.21bn	£28.98bn	14.1 : 1

[78] Current' = a supercomputer of the size utilised in 2010-2014. 'HPC' = a supercomputer of the size being purchased for £97m in 2015.

[79] Current' = a supercomputer of the size utilised in 2010-2014. 'HPC' = a supercomputer of the size being purchased for £97m in 2015. HPC+ = a supercomputer of the size considered for purchase for £125m in 2014 under the HPC Business Case

As can be seen in this figure, the benefit-cost ratio does not substantially vary with changes in investments, varying between 13.7:1 and 14.2:1 around the base-case of 14.1:1.

This analysis covers a ten year period of study. Within this we allow investment and quality to vary and capture the impact of these. However, we do not capture any impacts which fall in subsequent periods. This analysis has identified benefits which accord to the UK because the Met Office is perceived in the scientific community as world-class. Stakeholder discussions indicate this is a function of previous investment made, for example in super-computing capability. This study has only reviewed a ten year window, so therefore we are unable to draw a strong conclusion on how disinvestment may reduce the longer term benefits of the Met Office to the UK.

However, this analysis does apply two assumptions which would be as applicable in the longer term, firstly in cases where the Met Office is no longer world-class it loses the benefits of international scientist payments in kinds, and secondly that increases in quality do deliver higher benefits. Disinvestment in the study period would therefore be expected to have similar negative effects in the subsequent period, but these are not quantified in this study. For a longer period of analysis the key questions would be to determine the impact of supercomputer and other investments and disinvestments, which become harder to predict the further into the future they are.

6.6 Scenario One

The following table provides a breakdown of the major benefits under scenario one which tested the impact of a 20% reduction in quality to a 'standard' Western European level of quality

Table 23: Scenario One benefit streams

Value stream	Present Benefit	Share of PB	Change compared to base-case	Percentage change, compared to base-case
All other business sectors (market based)	£6.98bn	28.3%	-£1.72bn	-20%
Aviation (market based)	£6.75bn	27.3%	-£1.70bn	-20%
Value to the public (willingness to pay)	£2.91bn	11.8%	-£1.82bn	-38%
Climate change information benefits (avoided cost)	£2.27bn	9.2%	-£0.91bn	-29%
Met Office Revenue (market based)	£1.94bn	7.9%	-£0.35bn	-15%
Defence and security (avoided cost)	£1.40bn	5.7%	-	-
Winter Transport (avoided cost)	£0.93bn	3.8%	-£0.23bn	-20%
Flood damage prevention (avoided cost)	£0.54bn	2.2%	-£0.13bn	-20%
Storm damage prevention(avoided cost)	£0.50bn	2.0%	-£0.12bn	-19%
Other benefit streams[80]	£0.46bn	1.9%	-	-
International Leadership (market based)	£0	0%	-£0.13bn	-100%

[80] This summary brings together the minor benefit streams for ease.

6.7 Scenario Two

The following table provides a breakdown of the major benefits under scenario two which tested turning off climate analysis.

Table 24: Scenario Two benefit streams

Value stream	Present Benefit	Share of PB	Change compared to base-case
Other business sectors	£8.71bn	30.7%	-
Aviation	£8.42bn	29.6%	-
Value to the public	£4.73bn	16.6%	-
Met Office Revenue	£2.16bn	7.5%	-£0.1bn
Defence and security	£1.41bn	5.0%	-
Winter Transport	£1.16bn	4.1%	-
Flood damage prevention	£0.67bn	2.4%	-
Storm damage prevention	£0.62bn	2.2%	-
Other benefits	£0.53bn	1.9%	-£0.07bn
Climate change information benefits	£0	0%	-£3.17bn

This cost-benefit analysis is compliant with the HM Treasury Green Book methodology, so does not capture non-UK benefits in this scenario or the base-case. **However, benefit estimates, for example by Dr. Chris Hope, of climate change information to the rest of the world from the Met Office's climate work potentially out-weigh the net impact of all the Met Office's work in the UK**.

7 Conclusions

This analysis reveals net benefits of £29.5bn to the UK from the Met Office. This analysis identifies that the Met Office delivers value to the public, businesses, government agencies and bodies internationally. Across the spectrum of weather and climate services this picture of positive benefits is consistent.

Over three quarters of the benefits identified are generated by just four streams of benefits:

- Other Business Sectors – 27.4%
- Aviation sector – 26.5%
- Value to the Public – 14.9%
- Climate Change Information Benefits – 10.0%

Recognising the simplifying assumptions made and the limitations of the data available, the estimated benefits exceed the costs of delivery by a factor of more than 12.7:1[81], after taking account of scenarios and sensitivity tests, and in terms of the base-case more than 14:1, despite being unable to quantify a number of benefits relating to international benefits, defence and security.

Drawing on an unpublished summary of economic assessments of meteorological services around the world, it is possible to put these results into context.

Table 25: International benefit-cost ratios

Study	Geographic Location	Sectors	Benefits Methods/ Measures	Benefit-cost ratio
Contingent Valuation Study of the Public Weather Service in the Sydney Metropolitan Area (Anaman and Lellyett, 1996)	Sydney, Australia	Households	Willingness-to-pay (WTP) survey of households	4:1
Economic Value of Current and Improved Weather Forecasts in the U.S. Household Sector (Lazo and Chestnut, 2002)	United States	Households	Willingness-to-pay (WTP) survey of households	4:1 +
Benefits of Ethiopia's LEAP Drought Early-Warning and Response System (Law, 2012)	Ethiopia	Households	Quantification of avoided livelihood losses and decreased assistance costs	3: 1 to 6:1
Success of the NWS's Heat Watch Warning System in Philadelphia (Ebi et al., 2004) system	Philadelphia, Pennsylvania	Households/ elderly	Regression analysis to determine lives saved; application of the U.S. EPA's Value of a Statistical Life estimate	2,000:1 +
The Benefits to Mexican Agriculture of an El-Nino-southern oscillation (ENSO) Early Warning System (Adams et al., 2003)	5-state region in Mexico	Agriculture	Change in social welfare based on increased crop production with use of improved information	2:1 to 9:1

[81] Using the lower end of the 90% CI in sensitivity one.

The Value of Hurricane Forecasts to Oil and Gas Producers in the Gulf of Mexico (Considine et al., 2004)	Gulf of Mexico	Oil drilling	Value of avoided evacuation costs and reduced foregone drilling time	2:1 to 3:1
Economic Efficiency of NMHS Modernization in Europe and Central Asia (World Bank, 2008)	11 European and Central Asian countries	Weather-dependent sectors	Sector-specific and benchmarking approaches to estimate avoided losses	2:1 to 14:1
Benefits and Costs of Improving Met-Hydro Services in Developing Countries (Hallegatte, 2012)	Developing countries	National level and weather-sensitive sectors	Benefits-transfer approach to quantify avoided asset losses, lives saved, and total value added in weather-sensitive sectors	4:1 to 36:1
Avoided Costs of the FMI's Met-Hydro Services Across Economic Sectors (Leviakangas and Hautala, 2009)	Finland	Key economic sectors	Quantification of avoided costs and productivity gains; Also used impact models and expert elicitation	5:1 to 10:1
Social Economic Benefits of Enhanced Weather Services in Nepal – part of the Finnish Nepalese Project (Perrels, 2011)	Nepal	Agriculture, transport, and hydropower		10:1
Economic and Social Benefits of Meteorology and Climatology (Frei, 2009)	Switzerland	Transport, energy, aviation, agriculture, households	Benefits transfer, expert elicitation, decision modelling	5:1 to 10:1
Socio-Economic Study on Improved Hydro-Meteorological Services in the Kingdom of Bhutan (Pili-Sihvola et al., 2014)	Bhutan	National level	Benefits transfer, expert elicitation, cardinal rating method	3:1

Source: WMO (2015)

Taking the benefit-cost ratio of the base-case, excluding climate change information benefits of 12.4:1, as shown in Table 26 below.

Table 26: Benefit-cost ratios excluding climate benefits

Stream	Base-case[82]	Scenario 1 – 'Standard' Met Office	Scenario 2 – No climate Services	Sensitivity 1 – weather effects[83]	Sensitivity 2 – Key factors	Sensitivity 3 – investment options
Benefit: Cost Ratio excluding climate benefits	12.4 : 1	11.6 : 1	13.4 : 1	12.0-14.3:1	11.3-15.9:1	12.8-12.9:1

[82] Removing climate benefits only, as undertaken to deliver this analysis means that the figure given for the base-case and scenario two do not agree because scenario two also removes relevant Hadley Centre funding and 50% of the benefits from international leadership benefits.

[83] BCR excluding climate calculated by taking the most extreme values from Figure 12, adding the total costs (£2.26bn) back and deleting the base-case climate present benefit (£3.18bn), and then dividing by present costs (£2.26bn).

These estimates lie at the top-end of the studies quoted above[84]. Whilst there are two studies exceeding 30:1, most of the studies identified lie in the range of 2: 1 to 14:1. Therefore, when comparing this study's result it is necessary to consider whether it is reasonable for this estimate to be marginally higher. There appears to be three reasons why this should be the case:

- The Met Office is an established NWS servicing a developed western economy. Comparisons with Bhutan (3:1), Nepal (10:1) Ethiopia (3:1 to 6:1) or the various countries in World Bank (2008) (2:1 – 14:1) or Hallegatte (2012) (4:1-36:1) appear difficult to defend.
- The Met Office provides the full range of services, and this study attempts to be all-inclusive. Studies which relate either to sector-specific reviews (e.g. Considine et al., 2004) (2:1 to 3:1) or to Met Offices which do not deliver the same breadth of services (e.g. Switzerland (5:1 to 10:1) is not a WAFC) can be expected to provide lower benefit-cost ratios.
- The WMO Global NWP Index demonstrates that the UK's Met Office delivers forecasts of higher accuracy than those of other countries. If, as assumed in this study, accuracy is key component of forecast quality and benefits increase with forecast quality, then it should be expected that the Met Office delivers an estimate at the top-end of the range.

The analysis also reveals that alternative estimation approaches in relation to the aviation sector may attribute much larger benefits to the Met Office's contribution. Climate change benefits also, by definition go wider than just the UK, and these are excluded by design from a UK-focussed Cost-benefit analysis.

The scenarios were selected to present pen-pictures of theoretical options along which policy could take the Met Office from its current position; whether or not to remain world-class in relation to quality, and whether or not to focus just on weather, rather than climate services.

- ***Scenario One***, reducing quality by 20% delivers savings of around £0.4bn, but losses in terms of benefits to the UK of £7.1bn.
- ***Scenario Two*** shows the benefits of delivering unified climate and weather services, something stakeholders saw as an overwhelming strength. Due to quantifying benefits strand-by-strand, this synergistic element may not be immediately apparent. However, when reviewing scenario two, the marginal reduction in costs results in disproportionate losses in benefits of £3.4bn, in part driven by this scenario not removing shared elements of the cost base between weather and climate services.

These two scenarios all yield lower net benefits than the base-case, which indicates that in terms of structure[85], the Met Office, at least in terms of these aspects, appears to be delivering more value than the two scenarios considered. This analysis makes no assessment of whether this structure is being efficiently delivered in terms of costs, and it is very difficult to find clear international comparators to allow benchmarking. This study does not make any assessment of the *affordability* of the benefits to the Government as a whole.

[84] Hydrology is not included in Met Office, so when stripping out climate there may be some add backs to deliver full comparability between different benefit-cost ratios

[85] Within the constraints put on it by being a Trading Fund

The sensitivity analysis undertaken reveals that allowing key climate and weather, benefit calculation and investment / disinvestment assumptions to vary causes significant movement in the results, these still never bring the benefit-cost ratio of the Met Office to the UK below the level of 12:1, including climate benefits and never below 11:1 without climate benefits, still securely in the higher range of international studies.

In relation to future analysis, the areas where further work would be beneficial are:

- Gaining a deeper understanding of the defence and security sectors use of meteorological services would reduce uncertainty in relation to this part of the analysis.
- Further research into the impact of weather forecasts and information on health outcomes would provide more reliable estimates than those used in this study
- In some sections of the analysis data has used because it is the only consistent data available other the time period required. In particular the Numerical Weather Prediction (NWP) Index created by the World Meteorological Organisation is relied upon as a proxy for quality when it is strictly a measure of forecast accuracy, which is only one dimension of quality. A wider basket of consistent measures relating to other aspects of quality, such as reach and timeliness would provide benefits to future analysis.
- In common with existing studies (e.g. Hope 2011), the analysis estimates climate change information benefits through estimating savings generated through abatement activity due to climate change information being provided earlier. For a number of reasons outlined in section 4.2.4, we do not include adaptation costs, primarily due to the difficulties in producing an aggregate estimate of adaptation benefits, the consistent treatment of adaptation across both the ‘do-nothing comparator’ as well as the base-case, (so there is no additionality,) and the question of whether the inclusion of both adaptation and abatement benefits may lead to double-counting. However, as evidenced by Annex 7, there is a significant value of the Met Office’s impact on adaptation. Therefore further analysis to identify whether a robust estimate of the value of adaptation efforts in the UK could be produced, and from this the Met Office’s impact on adaptation cost reductions across the economy would be a valuable piece of work to enable this benefit stream to be estimated.
- This study has relied on published and internal Met Office literature, particularly key business cases. These business cases are tailored appropriately to meet their immediate need, but there are some issues relating to consistency of assumptions between cases which introduce some uncertainty into the correct method of estimating some benefit streams. Undertaking research into particularly the impact of Met Services across the sectors captured by ‘other business sectors’ in this study to create standard assumptions which could be used by business cases in the future would provide stronger foundations for the estimation of benefits.
- Possibly the key area of future study, however is new analysis of key benefit streams, to gain a better understanding of how changes in inputs and quality over time have played through into changes in the benefits accrued. This has been the key area where this study has needed to make assumptions because of the lack of evidence. Repeated studies related to how benefits have grown in key business sectors and, potentially in the area of public valuation of services, would allow a greater degree of certainty in future studies. In undertaking such repeat work, consideration should also be given to how to ensure that the public valuation estimations exclude any business use to prevent the risk of double-counting, and potentially splitting out the impact of new services from improving existing services. Annex 6 mentions two areas where new services are being delivered which have

offered the potential to widen the number of areas where Met Office can deliver value, and gaining a better understanding of whether it is improvements in technical quality, improvement in reach or improvement in the number or types of services which drives the change in value of the Met Office would be valuable in informing future strategy.

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ANNEXES

Annex 1 The 'Do Nothing Comparator'

The aspects of the real economy which suggest the 'do nothing baseline', in which there is Met Office, is theoretical are as follows:

- The majority of observation data is accumulated from satellite arrays which have been jointly purchased by European met services. Each met service has the right to sell on this data in their jurisdiction. A world in which there was no Met Office would still be a world in which this data would be available from foreign met services who would have the potential to sell data into the UK to the commercial sector. Because there is already a strong UK commercial market of met service suppliers, ***a world with no Met Office is not a world where we would anticipate no meteorological services.***
- However, a world without the Met Office is one where the quality of services may well diminish. This is because, whilst satellite observation data would be available other data sources would not be available, as Turner, Truscott, Mundy, and Barber (2014) (p21) note *'the operational polar-orbiting meteorological satellites forming the Initial Joint Polar System shared between EUMETSAT and NOAA (USA), are the most valuable source of input data and account for about 45% of the impact of all observations on NWP forecasts, with the current European satellite (Metop) having the highest level of contribution, at around 25%'*

The impact of this is that, without the Met Office, the value of observations would fall by around 36%, at least for global forecast models, taking into account sonde (weather balloons), aircraft, weather buoys (sea surface) and land surface observation points owned or operated by the Met Office.

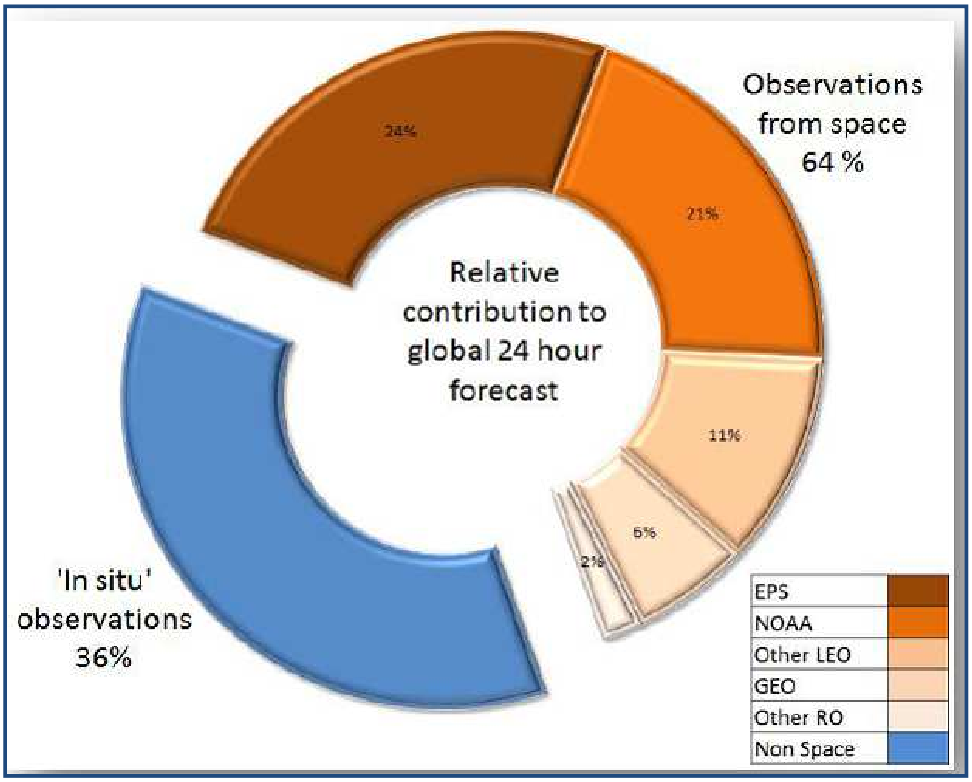
Also, there is a question of how quickly the private sector could move to deliver the full range of services currently offered by the Met Office. Whilst there are a number of markets where the commercial sector is already strong enough to replace the Met Office at short notice, there are others where the available literature suggests this is not the case. For example in Helios (2014 unpulished), in relation to civil aviation '*the role that the data collected and processed by the Met Office plays in enabling other forecasting companies to provide weather forecasts for aviation in the UK...[means] it could be argued that, if the Met Office could not provide this data then eventually another provider would step in. However, it would take time and arguably be outside the 5 to10-year period of our evaluation.'* As such, given the impact this may have on civil aviation, it is possible that the Met Office would never be able to completely withdraw this service.

It is important to note that some costs are fixed, particularly European satellite commitments, which need to be honoured whether the Met Office exists or not. We include these costs in the base-case because to exclude them would give a false impression of the benefit-cost ratio, but this does mean in the sensitivities where the Met Office ceases to function, we assume that MoD take on this cost, as part of the avoided cost basis of the benefit attributed to it. As such the NPV goes to zero. If the MoD did not take on these costs the NPV would go negative (that is worse than the base-case).

The final point to consider is the reaction of key public services to the absence of a UK public sector Met Office, particularly in relation to defence. For countries that do not have a publicly funded weather service delivering a full range of services, or where these are not world-class / sufficient to deliver a battlefield advantage, such as the USA or Italy, we see defence ministries direct funding the creation and continuation of this type of sovereign capability. As such the removal of a public sector Met Office funded by a multitude would likely be replaced, given our stakeholder interviews, by a smaller public sector Met service funded by MoD to meet its own requirements.

Given these issues, whilst we are using a strict 'do nothing' comparator, in reality there is a risk that 'automatic stabilisers' may come into play that would prevent a return to a 'do nothing' world, for example through the need to continue to meet the civil aviation and defence requirements.

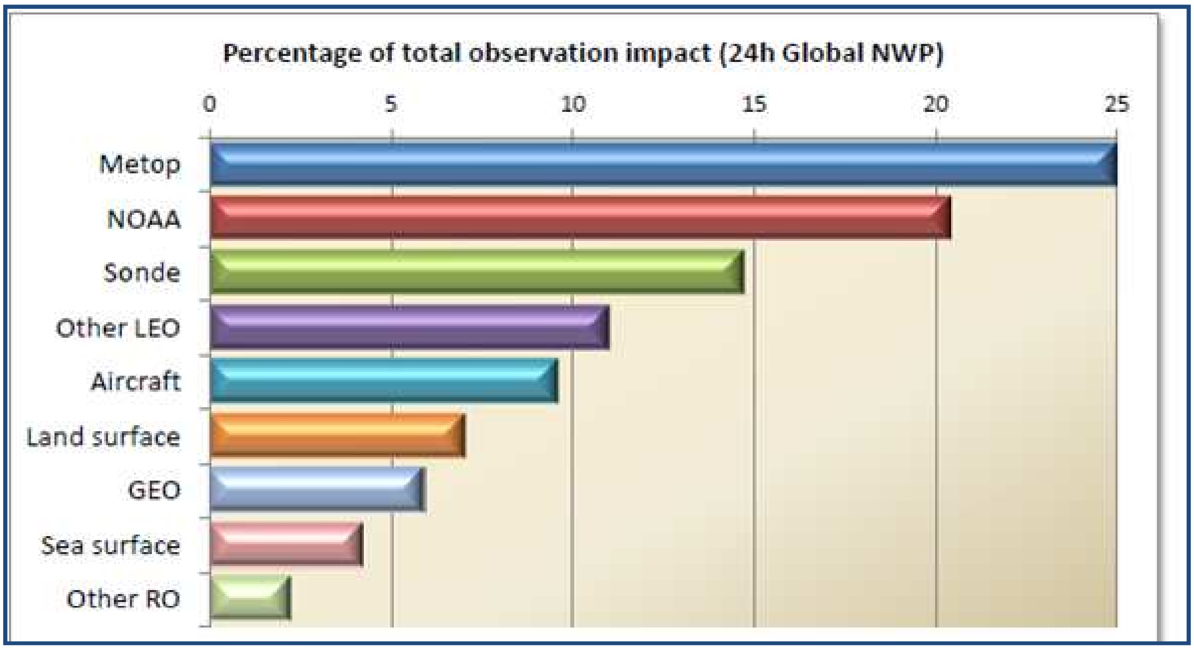
Figure 16: Observation value shares[86]



Source: Turner, Truscott, Mundy, and Barber (2014)

[86] EPS –European Polar Satellite, NOAA – National Oceanic and Atmospheric Administration (US Met Office satellites), Other LEO – Other Low Earth Orbit satellites, GEO – Geo-stationary (and therefore normally equatorial) Earth Orbit satellites, Other RO – Other GPS radio occultation, non-space - other collection mechanisms

Figure 17: Observation value shares



Source: Turner, Truscott, Mundy, and Barber (2014)

Annex 2 Natural Hazards Partnership

The NHP is a partnership between 12 non-governmental and 5 governmental agencies that was set up by the Met Office in 2011. It provides information, research and analysis on natural hazards for the development of more effective policies, communications and services for civil contingencies, government and the responder community across the UK.

As part of the 'Deep dives' carried out by the Met Office General Review team, stakeholders highlighted the Natural Hazard Partnership (NHP) as an opportunity where the Met Office, working with others, could deliver more value for the UK and business.

While the potential benefits of the NHP to the UK economy are out of the scope of this report[87], to examine whether the government can leverage the collective expertise and data of the NHP to better deliver on its national resilience objectives, the General Review team asked London Economics to assist in the provision of a simple economic analysis of the value of the NHP under a small number of scenarios, ranging from the situation before the NHP was established, to the potential further development. This is to test whether further analysis may be merited.

London Economics provided ad-hoc analysis of the potential value-add of the NHP under three scenarios:

- Scenario 1: 'Do Nothing' – i.e. No NHP, but continued delivery by 17 participating bodies.
    - Under this scenario, the Civil Contingencies Secretariat and category 1 and 2 responders would have to go out to all the organisations in the NHP separately to gather the appropriate, assured data and advice needed to forecast and plan for individual natural hazards (including combined hazards)
- Scenario 2: Current 'steady-state' - i.e. the NHP operates as at present excluding any current spend on R&D
    - In its current form, the NHP provides Daily Hazard Assessments (DHAs), a single PDF containing the daily hazard forecast and a 5 day outlook, including standardised formats and terminology for all natural hazard warnings, to approximately 14,000 recipients, and
    - provides one-stop-shop advice for the annual risk assessment
- Scenario 3: Enhanced NHP provision – i.e. building on the R&D underway
    - This scenario considers the potential value of additional hazard impact services that are currently not provided on a national level in the UK and that could be developed by the NHP, in particular

[87] In part because especially since any attribution of NHP benefits to the Met Office would be difficult to undertake given the relatively large numbers of partners involved,

- a Landslide Hazard Model, bringing together rainfall, surface water and landslip risk to provide a forecast and hazard impact model relating to landslips
- Co-ordinated and standardized health warnings and hazard impact modelling for extreme temperatures and short-term air pollution

Assessing the value-add of a partnership of this kind is challenging, because it is difficult to disentangle the incremental benefits of the partnership from the benefits that would accrue if the partners would provide their services individually, in a non-co-ordinated way. This study therefore used the (FFC, 2010) benefit appraisal of a similar institution: the Flood Forecasting Centre (FFC) as a basis for the analysis. The FFC is a partnership between the Met Office and the Environment Agency that was established in response to the extensive summer floods of 2007 in order to improve the partners' ability to forecast and warn against flooding. Since the NHP was established building on the learning and success of the FFC, and given the focus of both the FFC and NHP on a more co-ordinated natural hazard forecasting and warning system, we identified three potential benefit streams for the NHP in analogy to the FFC business case (FFC, 2010): operational savings on the producer side, time savings[88], and hazard damage avoidance.

The first benefit stream, **operational savings**, relates to the efficiency gains of producing all hazard warnings in one centre (synergies and economies of scale). The study assumes that the NHP would achieve operational savings of the same magnitude as the FFC (£1m per year). This seems to be a conservative estimate given that the NHP co-ordinates the efforts of 17 partners, whereas the FFC is made up of two partners only.

The second benefit stream identifies the benefits of an integrated hazard warning provision that accrue on the 'consumption side'. It is assumed that half of the 14,000 recipients of the **Daily Hazard Assessments** (DHAs) saves an average of five minutes a day because they get all the relevant hazard warnings in a condensed form and do not have to search for the relevant information online or in their email systems across the six delivery services (BGS, Defra, PHE, Met Office, SEPA and Environment Agency). Aggregating the five minutes time savings over 7,000 users and half of the number of working days per year (222), and assuming an average hourly salary plus on-costs of £48 for the DHA users[89], this gives us a benefit of £2.5m p.a. This does not include the qualitative benefits of the scientific advice and the standardised warning systems which are also part of the NHP 'as is' operation.

The third benefit stream identifies **hazards for which currently warning service and hazard impact modelling are sub-optimal**. The final selection of hazards was based on relevance (frequency and impact intensity of the hazard), current capability (hazard warnings that are currently provided by other entities were not considered, e.g. flooding) and feasibility (whether the NHP could provide the hazard warning service in a reasonable time given initial infrastructure/ICT investments). The hazards identified through this selection process, and confirmed as being a top priority by both the NHP and the Met Office, were landslides and health impacts of short-term air quality disruptions and temperature extremes.

[88] Note that in the FFC Business Case, time savings benefits referred to the benefits of extending warning lead times (cost avoidance). Since the mechanisms between lead times and possible cost avoidance are less explored for hazards other than floods, we looked at average daily time savings of emergency respondents.

[89] Assumption provided by the NHP.

For landslides, we combined estimates of the minimal annual financial damage of landslides (£10m), the costs of lives lost (1 life every 4.5 years) and the costs of transport disruptions caused by landslides (assumed to be 0.1% of the total annual average hard costs (£450m) of transport disruption caused by adverse weather as estimated by the DfT in 2010). These benefit strands have been reviewed by the British Geological Society, who noted this approach was acceptable, but that the following caveats needed to be applied:

- The societal benefit of awareness/preparedness for delays and the psychological benefits are not captured by this analysis, but it is extremely difficult to quantify in an economic analysis.
- The assumptions used are based on very limited published information on the economic cost of landslide fatalities and damage in the UK.
- The inherent uncertainties that are part of the landslide hazard warning are not taken into consideration.

For health we carried out three calculations:

- We estimated the value of excess deaths related to cold weather prevented through the provision of forecasts and information by the Met Office in England, and then up-rated this for the current 'value-add' of the NHP for option 2, and then up-rated for expanding coverage to Scotland, Wales and Northern Ireland, and improvements in effectiveness for 30% to 50%[90] in option 3.
- We estimated the value of excess deaths related to heat waves prevented through the provision of forecasts and information by the Met Office in England, and then up-rated this for the current 'value-add' of the NHP for option 2, and then up-rated for expanding coverage to Scotland, Wales and Northern Ireland, and improvements in effectiveness for 30% to 50% in option 3.
- We estimated the value of excess deaths related to poor air quality prevented through the provision of forecasts and information by the Met Office in the UK, and then up-rated this for the current 'value-add' of the NHP for option 2, and then up-rated for improvements in effectiveness for 30% to 50% in option 3.

To estimate the number of lives saved, in the absence of a comparable UK statistic which could be identified, the study uses the outputs from Ebi et al, (2004), who identified that the Heat Watch system in Philadelphia saved 2.6 lives per warning from the population of over-65s in Philadelphia. This delivers an effectiveness rate of 0.12%[91]. In the absence of robust effectiveness estimates for cold and air quality, we have applied this factor consistently, on the basis that people's reaction to extreme events and information about these should be fairly consistent, even if the type of event varies.[92]

[90] The assumptions that effectiveness would increase from 30% to 50% is based on using half the assumed step-change identified in the wider Deep-dive analysis. The study uses half the identified improvement for prudency.

[91] Author's calculation using US Census statistics Philadelphia's over 65 population.

[92] We initially considered whether we should apply lessons from the FFC and its impact to gauge an understanding of these benefits. Because FFC applies to one-off or infrequent events (floods), where those affected can take significant action to prevent damage, if these percentages had been applied to the lives saved calculations, the benefits would have been in the region of £3bn p.a. A non-exhaustive review of the literature provided few examples, which is why Ebi et al (2004) is used. There are significant caveats to be applied to using a US metric in this context. For example, heat and humidity variation can be significant between the UK and USA.

Again, this is likely to be an underestimate of the potential benefits of a multi-hazard approach as it is only including a limited number of additional hazards.

All additional investment costs have a 50% contingency added. All additional operating costs have a 20% contingency added. All benefits have a 20% optimism bias removed.

The results from this analysis are:

Table 27: Headline results

Additional benefits attributable to the NHP	Option 1: Met Office delivering current service, no additional input from NHP	Option 2: Status quo	Option 3: Expanded NHP capability
Total Net Present Benefits	£0.0m	£41.35m	£184.07m
Total Net Present Costs[93]	£0.0m	£3.24m	£16.13m
Net Present Value	£0.0m	£38.11m	£167.93m
Benefit: Cost Ratio	-	12.8 : 1	11.4 : 1

The benefit-cost ratios are within a similar ballpark to those calculated for the wider Met Office study. The status quo also does not reflect any sunk costs already expended by the Met Office which contribute towards this estimate, which may account for the benefit-cost ratio being higher. Option 3 includes higher cost assumptions because of the additional investment needed to carry out the underpinning modelling and science. Calculations have been deliberately cautious, with substantial optimism biases and contingencies added. These estimates present a good case for further analysis, to develop a substantive case for further investigation into increased investment in the NHP.

[93] Additional NHP costs over and above existing cost base in 17 source organisations

Annex 3 The theory of Authoritative Voice

A3.1 Concept

The concept of what is an 'authoritative voice' varies significantly. The study defines two potential schools of thought:

- ***A strong conceptualisation of AV***: the assumption that only through providing a single interpretation of the weather, which is uncontaminated with different interpretations or analyses, can the public and firms be expected to have a single, clear view of the expected weather and how to react to it.
- ***A weak conceptualisation of AV***: the assumption that multiple provider voices can provide the public and firms a single, clear view of the expected weather and how to react to it as long as they source their dataset from a common place which is quality assured by a common high quality arbiter.

The concept of AV is most often discussed around high impact weather events in the USA, where sources suggest that examples can be found where damage was significantly higher because different media sources issued very different forecasts and warnings. This has provoked suggestions that a single 'authoritative voice' providing a clear, high quality steer would have delivered greater benefits.

To review this we have considered what this source literature said and secondly the state of the markets in the US and UK to see if their characteristics mean one would meet a strong conceptualisation and the other not.

Our review of the key papers which make reference to AV, specifically in the US context suggests **these papers do not make a strong case for the importance of AV**, noting that problems emerge because of contradictions in advice / information coming from different parts of the National Weather Service (NWS), and also noting the strong positives which come from a vibrant private sector providing services. **They nowhere identify that there would be additional benefits which could have been delivered from complying with a stronger conceptualisation of AV**, instead describing a system, which due to the absence of the NWS in the down-stream market is definitively weak, and possibly does not even meet the requirement of weak AV to share a common data source. The winter storms in New York in 2015 are quoted as relevant, where the Weather Channel and other media used NOAA/NWS data, whilst some emergency services used ECMWF data[94].

One key issue here is the trade-off between the price advantages of an active commercial market during the periods of time when high-impact weather is not occurring, against the benefits of AV during the occasional instances of high-impact weather events. The existence of AV benefits may not be sufficient for these to outweigh the gains to consumers and private consumers from competitive day-to-day markets.

Lazo et al (2014) also make the very important point that communities or groups who are 'disconnected' or alienated from Government may also be less likely to respond to an

[94] Noting in addition that both the US Air Force and US Navy, if called upon, would each have used their standalone capacity, which draws on the NWS data, which the USAF puts through the Met Office's Unified Model, which it licenses from the Met Office.

authoritative Governmental voice in the event of evacuation warnings, raising the point that an authoritative voice may, in some cases be a weakness not a strength in terms of such events.

Taking this evidence into the UK arena, with competitive markets in the delivery of weather services, including some elements of the public task and downstream services, and the Met Office selling / releasing data to multiple organisations, once again it is clear that in terms of the concepts described, even though it is involved in downstream services t**he UK Met Office does not meet the criteria of a strong conceptualisation of AV**, whilst the US case appears to, at best deliver at the weak end of the weak AV spectrum.

As such, the study reaches the following conclusions:

- It is unclear that authoritative voice benefits have been quantified anywhere in the world, above and beyond the base estimations for different benefit streams currently in existence.
- When one looks closely at the service delivery design and market design of the UK compared to the US, whilst the UK has a stronger AV position which could generate benefits, it is unclear that these would be significant because, even though the UK is relatively stronger, it is still only compliant with the weak conceptualisation.

Box 9: Ad-hoc Severe Weather Warning Surveys

A key service provided by the PWS is the issuance of National Severe Weather Warnings (NSWW) to the public via various channels to warn them of impending severe weather events. To assess whether people in affected areas are aware of and change their behaviour in response to these severe weather alerts, the Met Office regularly commissions ad-hoc surveys in regions were amber NSWW had been issued. These surveys show that:

- Most people know that the Met Office issues severe weather warning
- A majority of the public considers it either essential or very important that the warning is provided by ‘a trusted provider’, as the Met Office is

Similarly, *the Forecast and Warnings Report 2009*, providing a qualitative assessment of the public’s requirement of weather forecasts and warnings, notes that a consistent message across weather forecasts increases trust, and that having several suppliers providing different information can lead to confusion (p. 24, 65). Comparable findings were reported in the Met Office Trust Tracker and online forums. While these sources thus indicate that AV is an important component of the benefits of Met Office weather forecasts to the public, it is not clear there is sufficient evidence to quantitatively disentangle the benefits of AV from the general benefits of the public provision of weather services, because

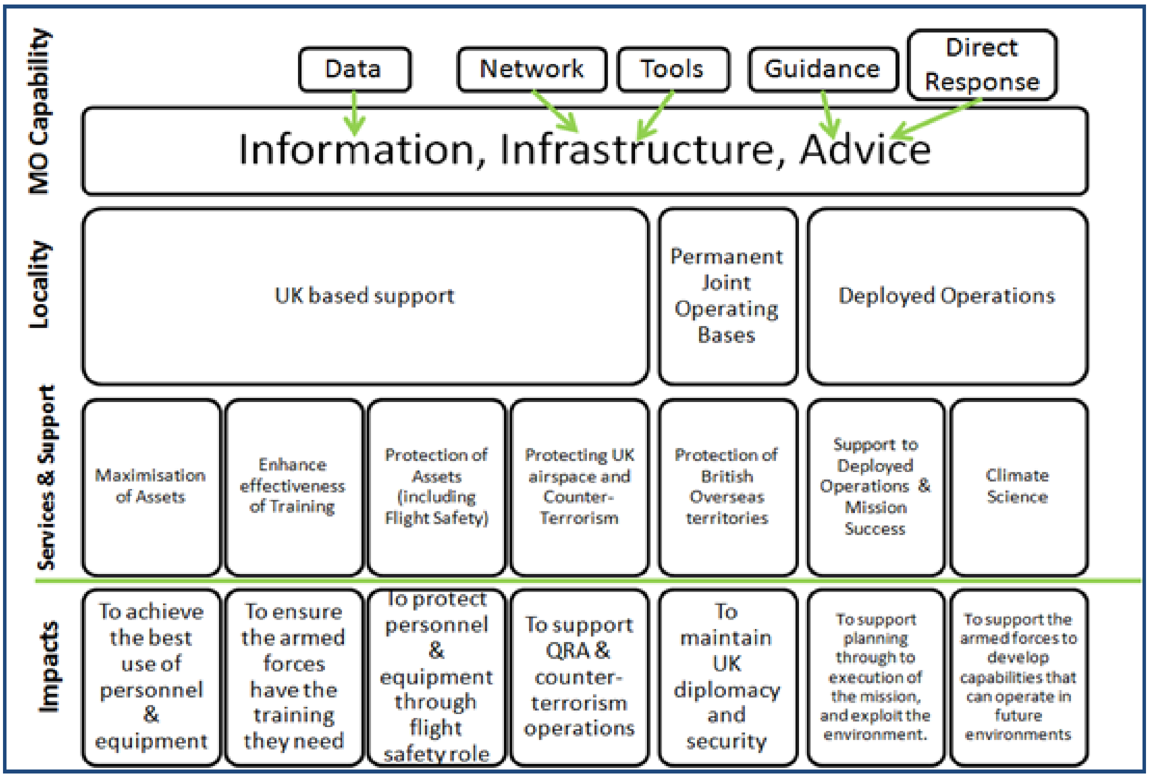
- The term ‘trusted provider’ might transcend the concept of AV if it includes other qualities such as the perceived accuracy of warnings.
- The surveys are limited to the importance of AV, or trust in general, in the context of severe weather warnings. This is confirmed by an internal Met Office analysis of the amount of traffic to their main website, mobile site and apps (Met Office, 2014), which increases by 200%+ during periods of severe weather. We could not find any evidence of the importance of AV for the value of more general weather forecasts.

While some of the surveys listed above offer some quantification of public responsiveness to weather warnings, it was not possible to directly attribute responsiveness parameters to AV, and therefore we could not disentangle the benefits of AV from the benefits by stream.

Annex 4 Defence and Security – relevant sources

The following diagram lays out the main value chains where the Met Office interacts with the security sector:

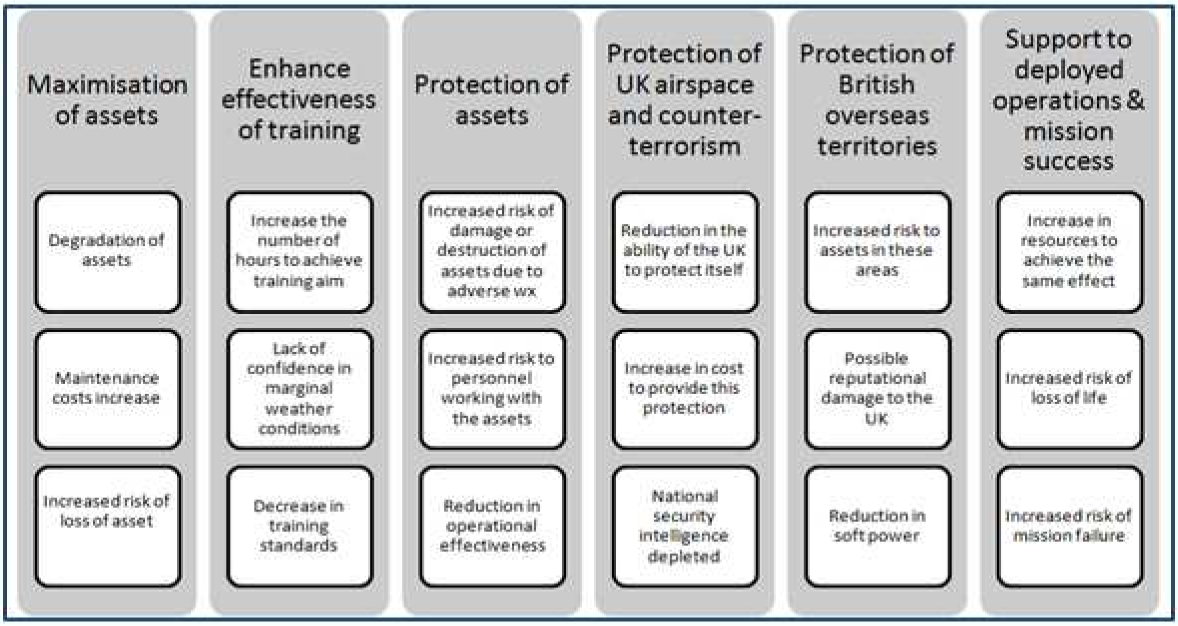
Figure 18: Met Office capability through to services & support for defence and security



Source Met Office internal analysis (2015)

And the following provides some counterfactuals scenarios which we could use to determine how to estimate the value of the service, if we were to pursue a bottom-up valuation:

Figure 19: Illustrative impacts of a reduction in effectiveness of services and support to defence and security



Source Met Office internal analysis (2015)

Box 10: Weather forecast impacts on USAF combat operations

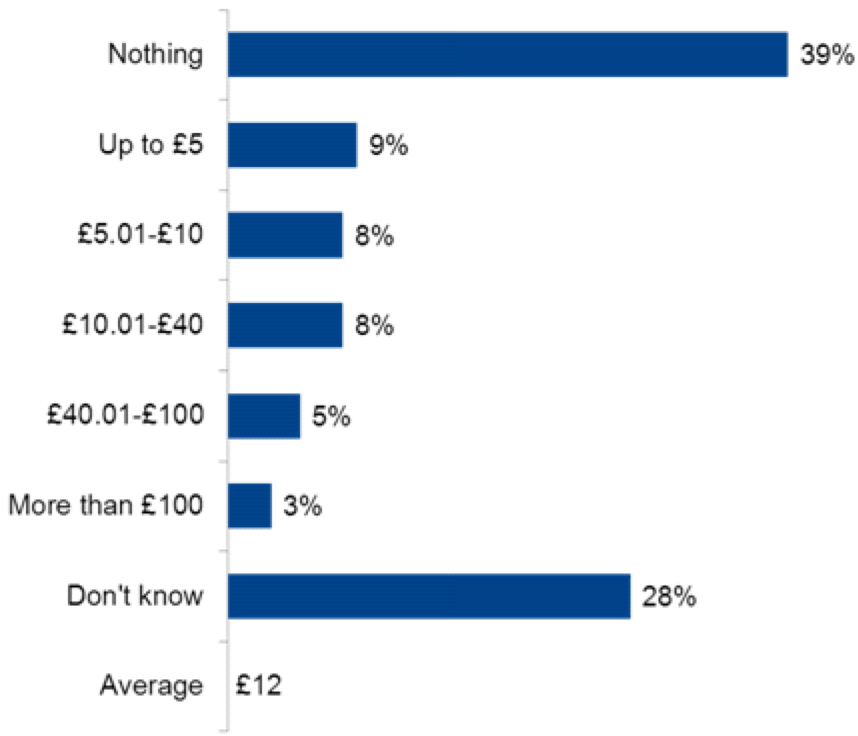
Accurate weather forecasts are vital to air combat operations. Darnell (2006) conducted a survey among aviators to determine the operational impacts of both US Air Force Weather (AFW) forecasts and actual weather encounters. For a sample of 107 missions, she found a *positive mission contribution* of AFW forecasts, defined as the percentage of successful missions which involved a mission plan change in response to a forecast implying a negative mission impact, of 10.2%. The *potential positive mission contribution*, the percentage of unsuccessful missions for which no mission plan change was undertaken despite a correct forecast of meteorological circumstances implying a negative mission impact, was calculated at 4.7% (for planning weather forecasts) and 3.7% (for mission execution forecasts). A majority of unsuccessful missions was attributed to bad weather conditions, with 71% out of all unsuccessful missions, or 5% out of all missions, being attributed to bad surface visibility.

Annex 5 GfK NOP Willingness to Pay Survey (2012) details

GfK NOP interviewed **993 people** between 25th and 30th November 2012[95]. The survey was administered face to face on GfK NOP's random location Omnibus. Interviewers were set a demographic quota to complete. In this case it was 3 age categories (16-34, 35-54 and 55+), with gender and working status quotas interlocked (men working full-time, men not working full-time, women working, women not working). Where the interviewer went was carefully chosen to ensure a representative sample of adults is achieved (Buchanan, 2012 unpublished, p.3).

All candidates who indicated to see or hear weather forecasts were asked about the monetary value they would assign to weather forecasts (956 people) The exact question wording was: **'Thinking about how the weather forecasts may have helped plan your daily routines during the last 12 months, what value would you attach to this service?'** (Buchanan, 2012 unpublished, p. 32).

Figure 20: Estimated willingness to pay



Source Buchanan (2012 unpublished)
Base: All who see or hear a weather forecast (956)

It is important to note that, in line with Gray (2015) this study does not use the average above, but one weighted by 'market segment' which excluded disengaged users who were reporting extremely high values. The survey report does not include this breakdown.

[95] The Executive Summary states October 2012, but this appears to be an error

Whilst this did not exclude employment related benefits, the immediate follow up question was: '**You said earlier that you have a specific interest in the weather due to your job. Thinking specifically about how the weather forecasts may have helped plan your work/business during the last 12 months, how much value would you estimate this service has contributed towards your work/business?**' (p. xii). It does not appear that Gray (2015) excluded this benefit from his analysis. Therefore whilst we have maintained consistency there is a risk of double-counting which we address through sensitivity testing.

Annex 6 Public catalytic case studies

This annex provides two case studies of investment by the Met Office in new services, which are currently nascent but represent growing areas which could drive more significant benefits in the future. Text was provided by the Met Office.

A6.1 Hydrological Outlook

Climate change is driving increased concern about water resources and risk of droughts and as a result there is increasing demand for services to help with water management and flood anticipation. The Hydrological Outlook provides Government and Industry with insights into future hydrological conditions across the UK, such that, for example, Agriculture and the Water Companies can plan water-usage more effectively.

Box 11: Hydrological Outlook Case Study

The Hydrological Outlook[96] provides an insight into future hydrological conditions across the UK. Specifically it describes likely trajectories for river flows and groundwater levels on a monthly basis, with particular focus on the next three months to help improve water management and flood anticipation.

Well established monitoring programmes provide the current status of both river flows and groundwater levels at many sites across the UK, and data from these programmes provide the starting point for the Outlook. A number of techniques are used to project forwards from the current state and results from these are used to produce a summary that includes a highlights map.

Much of the information in the Hydrological Outlook is presented with reference to normal conditions, rather than to specific figures. Normal conditions vary with the time of year and characteristics of the river or groundwater body.

It is produced in a collaboration led by the Natural Environment Research Council's Centre for Ecology & Hydrology (CEH) and involving the Natural Environment Research Council's British Geological Survey (BGS), the Environment Agency (EA), the Met Office (MO), the Scottish Environment Protection Agency (SEPA), Natural Resources Wales (NRW), and the Rivers Agency Northern Ireland (RA).

Data are provided for the Hydrological Outlook by the EA, NRW, SEPA and RA. Meteorological data and modelling expertise are provided by the MO. Hydrological and hydrogeological modelling expertise are provided by CEH, BGS and the EA.

[96] http://www.hydoutuk.net/

A6.2 Space Weather

Innovation on the back of scientific collaboration also leads to new service development. Space Weather is an example of this.

Scientific collaboration between the Met Office and the US enabled both organisations to accelerate the development of space weather modelling and forecasting. As a result of these advances, the Met Office can now provide a space weather forecasting service which enables UK Government to avoid the costs of damaged to telecommunications, GPS and the national grid.

In the future, this capability also has the potential for bespoke services to industry sectors, where it could bring significant benefits to key national industries.

Box 12: Space Weather Case Study

In 2013, the Royal Academy of Engineering undertook the UK's first in-depth study of the impacts of space weather. The report concluded that whilst the space weather risk can be engineered out of many systems, there was a still a need for real-time alerting and forecasting of space weather to help minimise the risks it poses.

The UK Government had already made a small investment in the development of a space weather prediction capability within the Met Office and working alongside experts in the U.S, the ensuing scientific collaboration enabled both organisations to accelerate the development of improved space weather models and prediction systems to make more effective use of space weather data in providing a 24/7 forecasting service that enables government and industry to take steps to improve resilience.

Annex 7 Thames Barrier 2100

The following text was extracted from the Met Office's website[97] to provide an example of the potential impact of adaptation costs.

The Met Office has been doing detailed work in the Thames Estuary on flood risks, looking ahead over the next 80+ years. Work on the finalised TE2100 Plan will ensure that the right investments are made to avoid flooding or other serious water hazards that could result from climate change.

The project examined the potential future climate-driven changes in extreme water levels in the southern North Sea near the Thames Estuary up to the year 2100. The Thames Estuary 2100 Project (TE2100) is tasked with protecting London and the people living in the Thames Estuary from flooding now and into the next century.

The Environment Agency, Met Office Hadley Centre, Proudman Oceanographic Laboratory and the Centre for Ecology and Hydrology have been working together to better understand the uncertainties around future change and to relate them to plausible adaptation options.

The results suggest that future increases in extreme sea levels in the southern North Sea near the Thames estuary are likely to be driven predominately by changes in the regional time average sea level rather than local changes in storminess. However, changes in storms are projected to result in increased river flows in some parts of the Thames river catchment.

Climate scientists at the Met Office Hadley Centre combined ensemble projections, which give a likely range of future extreme water levels, with H++, a new high-end water level scenario based on observations for the basis of the report.

Our scientists have developed ten-year climate forecasts to strengthen UK contingency planning, for use alongside the 50- or 100-year time frame projections currently deployed worldwide.

Such decadal forecasts offer predictions of more direct, practical relevance to organisations where adaptation to global warming is a key operational concern. Decadal models seek to forecast natural variability, such as El Niño and fluctuations in the Gulf Stream, in addition to man-made climate change. This has already been demonstrated to improve the skill of global temperature predictions and climate forecasts on a regional basis are currently being assessed.

Current status

The Thames Barrier offers London unparalleled protection against North Sea tidal surges and holds back high tides when the river is swollen by heavy rainfall upstream. It was designed to withstand a 1 in 1,000 year severe weather event, but research by the Met Office Hadley Centre indicates that the next quarter century could see greater frequency of extreme weather events along with more torrential rain, particularly during winter months.

Key findings from the project include:

[97] http://www.metoffice.gov.uk/services/climate-services/case-studies/barrier

Climate change

- Water levels in the Thames Estuary are likely to rise by between 20 cm and 90 cm over the next century due to thermal expansion of the oceans and additional water from melting glaciers and ice sheets caused by climate change.
- There is still much uncertainty over the contribution of polar-ice melt to increasing sea level rise. At the extreme, sea level may rise by up to 2 metres (including thermal expansion) by 2100 - although this is thought highly unlikely.
- The change in extreme water levels will be driven predominantly by the increase in mean sea-level. Changes in storminess will have less effect.
- Future peak freshwater flows for the Thames, at Kingston for instance, could increase by around 40% by 2080.
- The previous worst-case scenario of increases in maximum water levels has been revised down by approximately 1.5 metres.
- Such a reduction in worst-case scenario for this century means that a costly tide-excluding outer barrage is much less likely to be necessary to manage flood risk this century.

Thames Barrier

- Many of the Thames' defences were built following the 1953 floods and will reach the end of their design lives during the next 50 years. The system includes the Thames Barrier, over 300 km of fixed defences and numerous smaller structures.
- The Thames Barrier is expected to hold fast and continue to provide London and the Estuary communities with a higher standard of protection than anywhere else in the country. When it was built, engineers planned for 8 mm per year sea-level rise, while sea-levels are currently rising by 6 mm per year.
- However, the Thames Barrier must continue to be maintained to ensure its reliability and to reduce major costs in the future.
- Upstream plans also need adapting - to handle increased water run-off from the torrential winter rains expected as our climate continues to change.

Only the beginning...

By understanding the uncertainties around future climate change, plausible adaptation options can be recommended to protect people living in London and the Thames Estuary now and into the next century. The success of TE2100 will depend on monitoring activity in the Thames Estuary - in terms of its changing climate, people numbers and property development - and adapting to changes early as the century progresses.

Annex 8 Glossary

This glossary covers the acronyms used in this report, excluding the references:

BGS – British Geological Survey

BIS – Department for Business Innovation and Skills

CEH – Centre for Ecology & Hydrology

DECC – Department for Energy and Climate Change

DEFRA – Department for Environment, Food and Rural Affairs

EA – Environment Agency

ECMWF – European Centre for Medium Range Weather Forecasting

EPS – European Polar Satellite

EUMETSAT - European Organisation for the Exploitation of Meteorological Satellites

GDP – Gross Domestic Product

GVA – Gross Value Added

HMT – Het Majesty's Treasury

HPC – High Performing Computing

MO – Met Office

MoD – Ministry of Defence

NERC - Natural Environment Research Council

NRW – Natural Resources Wales

NMS – National Meteorological Service

NOAA – National Oceanographic and Atmospheric Administration

NPV – Net Present Value

NWP – Numerical Weather Prediction

NWS – National Weather Service

PWS – Public Weather Service

PWSCG – Public Weather Service Customer Group

RA - The Rivers Agency Northern Ireland

RIMNET – Radioactive Incident Monitoring Network

SEB – Socio-economic benefits

SEPA – The Scottish Environment Protection Agency

WAFC – World Area Forecasting Centre

WMO – World Meteorological Organisation

WMO CBS – World Meteorological Organisation Commission for Basic System

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