Government Office for Science

Review of climate science advice to Government and Met Office Hadley Centre role, governance and resourcing

Summary

For Government and society, the challenge presented to mitigate and adapt to a changing climate is great. In no other area is cutting edge research so closely linked to major policy and investment decisions - decisions that must often be made now. The cost of getting these wrong could be enormous, and impact us over decades.

Critical to getting decisions right will be sourcing the best possible evidence and advice, in a context where the risks but also the uncertainties are often profound.

One example is the estimated £40-£50 billion annual spend on infrastructure (such as energy, water, homes, transport) to 2030, where much of this is still designed for the 20th century climate.

Another is the tens of £bns of investment expected in wind energy, where improved understanding of future wind resources, including storminess and periods of low or no wind, will be critical given implications for site planning, economic viability and security of energy supply.

Looking internationally, DFID provided £5.5bn aid to poorer countries in 08/09 – a figure set to rise to £7.8bn by 10/11. Adaptation support for developing countries is a key part of the global response on climate change. The effectiveness of measures to build resilience and safeguard livelihoods against projected changes could be improved, and costs substantially lowered, with more tailored climate projections and if uncertainties can be reduced.

But all parts of government will be affected, with wide ranging implications across public policy making and spending - some obvious, some less so.

The review has considered the Government's needs for climate science advice over the next 5-10 years, and how these can be met. It has focused in particular on the role, resourcing and governance of the Met Office Hadley Centre, to advise on a sustainable solution where the Centre is seen to have a critical function.

The work has examined the priority advice needs of individual departments, as well as identifying cross-cutting areas and efficiency issues, drawing evidence too from external experts and the private sector.

Hadley Centre

A key conclusion is to confirm the assessment from Sir John Lawton's 2009 report that **the Met Office Hadley Centre provides essential and world-leading climate modelling services to Government, and that it is uniquely placed to do so. It represents a critical national capability, with a central role of meeting the Government's requirements for climate evidence and advice**.

It would not make sense, or be economic, for departments to source core climate modelling services individually. There is positive advantage in a joint approach, and in having policies across government underpinned by consistent, high quality climate projections.

An important facet of the Hadley Centre's role comes from the close link between cutting edge research and major policy developments and investments. A key service provided by Hadley, and at which it is particularly skilled, is delivering not just high performance computing and modelling but also interpretative advice and understanding in a field where fundamental uncertainties remain. This capability is important not only for Government but for a wider customer base, e.g. sectors such as insurance, energy, agriculture and the built environment, a point reinforced by private sector contributors to the review.

Over the longer term there is an opportunity for Hadley to further develop these private sector services, as the market for such services itself evolves. At this stage however the market remains immature, relative to that for weather services.

The role for academia

The Hadley Centre cannot operate in isolation. It has a critical and co-dependent relationship with the UK climate science community, which is similarly world class. Neither could function as they do if the other did not exist. Whilst respective roles differ, there is significant advantage and opportunity to work increasingly closely to maximise the overall value of investments, improve outputs and generate efficiencies. **It will be important for the Met Office and the Research Councils to take forward discussions on how best to pursue opportunities for collaboration**.

More generally, although not a focus of this review, **Research Council investments across a broad field of disciplines, such as via the Living with Environmental Change and other cross-Council programmes, will remain vital to meeting the Government's climate evidence and advice needs** – both through inputs to the Hadley Centre's work and in many other ways. This includes support for a range of wider and inter-disciplinary research.

Similarly, **support for high quality, long term data sets will continue to be critical**.

High performance computing

A key requirement underpinning many of the Government's needs is to better understand, quantify and reduce the uncertainty associated with climate change projections, in particular at regional to local scales and including natural climate variability and hazardous weather.

High performance computing and modelling capability is central to this. The main supercomputing resource currently supporting UK climate science is based at the Met Office. However the review has considered a range of delivery mechanisms, including international initiatives, for accessing computing resource to meet the Government's specific needs.

Supercomputing capacity dominates capital spend because of the requirement for increasing model resolution to improve the accuracy of projections, especially at the regional level - although other computing issues are also important, including software solutions and code development (so models run optimally), and data archiving and sharing.

The review has assessed that **a step-change increase in supercomputing capacity[1], with greater provision e.g. for code development, data sharing and to accelerate the growth of a shared service with UK academia – Option C in this report, would be required to most effectively meet the Government's key evidence and advice needs**, in particular around regional climate change and extreme events, within timescales assessed to be relevant and realistic.

However this would involve a 4-fold increase in supercomputing costs. It is recognised that this is not currently affordable.

A more incremental approach is therefore recommended, building on existing technology upgrade plans[2], with some provision also e.g. for enhanced code development work and to strengthen Met Office/NERC collaboration – Option B+ as described. This would still enable a significant advance in output quality, though answers to a number of key questions required by the Government, such as on regional climate projections and variability, would be delayed compared to when they might otherwise be feasible. Provision for this option is factored in within existing Departmental spending plans (subject to Spending Round outcomes).

In a limited number of instances grid or network computing may offer a viable and cost-effective approach, such as for low resolution ensembles. However, Earth System and high resolution models can only be run on supercomputers.

Where UK and overseas agencies have common scientific interests it has occasionally been possible to collaborate and use overseas supercomputing resources. But overseas National Meteorological Services and research institutes will not provide free supercomputing resources and are mostly unlikely to have material spare capacity to sell to the UK. The availability of such resource cannot be guaranteed, and even if it were available it is not clear how costs would compare with UK provision. Such opportunities are therefore unsuitable for meeting HMG's mainstream need for climate services, including where advice sought may relate to security matters.

In addition, **if HMG is to fully benefit from the UK's world-leading expertise, the UK climate science community will need a stable, dedicated high performance computing service that is developed with climate research needs in mind, requiring effective collaboration between the Met Office and UK academic institutions**.

Collaboration with Europe

Looking ahead, a key need is to extend collaboration with European counterparts. Longer term investments in hardware, at peta/exa-scale level[3], will sensibly be made on a wider European basis. There is indeed likely to be no feasible UK alternative given the costs involved. The Hadley Centre is well placed to

[1] 864Tera Flops from 2011, rising to 8PF in 2016
[2] 324Tera Flops from 2011, rising to 3PF in 2016
[3] 'Peta-scale' supercomputers (ie. 10^{15} Flops, floating point operations per second) are available now. Supercomputer vendors are currently forecasting that 'Exa-scale' supercomputers (10^{18} Flops) will be available around 2018).

be a focus for this wider collaboration, though there is also strong Research Council interest in helping to shape future developments. **It will be important to actively engage with European stakeholders to facilitate and pursue opportunities for the future provision of European climate supercomputing infrastructures**.

However a European supercomputing solution is not currently available, and is judged to be at least 5 years away.

The advantages of a collaborative approach on climate modelling arise not only from the investment realities of supercomputing. **A more immediate opportunity is to further strengthen engagement with European institutes to develop multi-model ensembles to better characterise uncertainties, and to cooperate in other areas such as collective archiving facilities and 'green computing'**.

Future Review

Given the range of evolving issues described above, it is recommended that **the provision of high performance computing, in particular supercomputing capacity, be reviewed again in 2012.** This review should be set in the context e.g. of the Government's developing requirements for climate science advice, the prospects for supercomputing opportunities advancing within Europe and internationally, progress in further strengthening collaborations between the Met Office and UK academia, and affordability issues at that time.

Further recommendations on high performance computing are included in Section 5 of this report.

The Met Office relationship

The case for the Hadley Centre's continued integration with the Met Office is compelling, given the strong synergies with the public weather service and modelling, and the shared infrastructure and common capabilities that link to this. Significant efficiencies arise from this relationship. It will be important to recognise this synergy and how it can be continued in any discussions about business models for the Met Office as a whole.

Governance

The review has considered a number of options for future governance and funding of the Hadley Centre.

A key conclusion, and indeed the prompt for the review, is that the existing arrangements have not provided the stability required, and seem unlikely to do so into the future. There are strong arguments for placing resourcing and governance for what is a key national capability on a more sustainable footing, including to facilitate strategic planning and investments. The risk is of a continued situation in which the Centre lurches from one funding crisis to the next as individual departments, with distributed responsibility, seek to make savings that may not recognise wider Government interests.

In this regard, the nature of the Hadley Centre facility, which requires investment in core capability to be able to meet a wide range of individual departments' needs, provides a cross-cutting challenge.

To address these issues **the option recommended is a governance model in which a single department, perhaps most logically DECC (although there are other options[4]), would hold lead responsibility for sustaining and developing the core capability at the Hadley Centre**. Such a solution would require appropriate budgetary arrangements to be agreed between all key customer departments and with HMT, to take account of the enhanced role and responsibilities of the lead department. The arrangements would need to provide for both sustainable funding and effective governance, including in relation to scientific strategy and to reflect cross-government interests.

Various approaches on funding to achieve this may be possible. What matters is the outcome, to ensure long-term stability and support for core capability, such that Government's future needs can continue to be met.

Future funding

The funding requirement for the Hadley Centre to ensure it can continue to meet the government's needs for climate science advice over the Spending Review period and longer term, including planned computing investments, *is estimated at around £90m (2011/12 – 2014/15)*.

This is less than the ideal level of investment, given the case to further increase computing capability, but will enable delivery of a range of climate services to an adequate level in most cases, and provide the underpinning capability such that additional services can be procured as required. **Further detailed engagement with the Met Office by the contracting department(s) will be needed to finalise these figures**.

Professor Sir John Beddington
Government Chief Scientific Adviser
1 September 2010

[4] particularly if part of a wider governance and resourcing solution for climate and weather services combined

Section 1: Assessing future Government needs for climate science evidence and advice

Introduction

The Government requires, and will continue to require over the next decade and beyond, a wide range of climate science evidence and advice, including to inform international negotiations and influencing, mitigation policies, adaptation strategies, and operational decision-making.

This review has worked with relevant Government departments and other public bodies to define these requirements. Each contributor has identified, at a high level, their key needs and priorities for climate science evidence and advice over the next 10 years[5]. Input has also been obtained from the private sector and academia.

Set out below is an overview of these needs, which draws out key priorities, cross-cutting areas and strategic requirements underpinning delivery. The Terms of Reference for the Review are included at Annex A.

Policy context

Mitigation

The 2008 Climate Change Act set a legally binding target for the UK of at least an 80% cut in greenhouse gas emissions on 1990 levels by 2050 and introduced a carbon budgeting system that caps emissions over five-year periods. It also established the independent Committee on Climate Change (CCC) to advise the Government on the level of carbon budgets and on where cost-effective savings can be made, and to scrutinise progress.

Internationally, it is recognised that solutions on climate change mitigation must come from global action and a global deal. The complexity of the international backdrop – for example given political, economic and institutional factors - provides a challenging context.

The new Government has made a number commitments relevant to mitigation, including: to increase the target for energy from renewable sources (subject to Climate Change Committee advice); to introduce measures to encourage marine energy; to deliver an offshore electricity grid to support the development of offshore wind power; to encourage community-owned renewable energy schemes; to work towards an ambitious global climate deal that will limit emissions; and to push for the EU to demonstrate leadership in tackling international climate change, including by supporting an increase in the EU emission reduction target to 30% by 2020.

Adaptation

The Climate Change Act requires government to report at least every five years on the risks to the UK of climate change, and to publish a programme setting out how these will be addressed. The Act also introduces powers for Government to require

[5] The scope was limited to evidence and advice needed to support policy/decision making directly, as opposed to the underpinning climate science and observations. Broader evidence needs related to climate change policy, such as technologies to reduce emissions and behavioural responses to climate change, were also out of scope.

public bodies and statutory undertakers to carry out their own risk assessment and to make plans to address those risks. Adaptation is relevant to all sectors and organisations, from flood protection and infrastructure resilience to preparing for future health risks and changing security threats.

The UK also has interests in helping poor people in developing countries follow resilient and low-carbon development pathways. The new Government is committed to the Millennium Development Goals, which include enhanced access to clean water, and to the Copenhagen Accord, which stipulates Fast Start financial support and the creation of a Green Climate Fund to support activities in developing countries related to mitigation, adaptation, capacity building, and technology development and transfer.

HMG's priorities for climate science evidence and advice

A survey of individual Government departments and other organisations has revealed a broad mix of climate evidence and advice needs. Key priorities are outlined below, based on responses received plus advice from external experts and consideration of the policy context.

Mitigation:

- **Improved understanding of global climate change including climate sensitivity and its impacts under different emission scenarios**. This is needed to determine appropriate global emission targets and to inform (and give momentum to) international climate change negotiations. Information about global targets, in turn, informs UK emission reduction targets (the UK's 2050 target is based on a 'fair share' assessment of reductions needed to prevent dangerous climate change). The information is also needed to understand the consequences of mitigation policies.
- There is an important need to better **understand and quantify emissions from, and the abatement potential of, different sources/sectors** to inform the development and evaluation of domestic and international mitigation policies (e.g. on land use, forestry and agriculture).
- In the longer term, there may be a need for **improved understanding of the risks of abrupt and/or irreversible climate change** (including information to provide an early warning system of such changes), as well as a need to evaluate the **regional consequences of geo-engineering options** (uncertainties in regional projections are currently too large to allow this to be done with confidence).
- **Projections of climate/weather variables are needed to support delivery of marine and land-based renewable energy**. In particular, there is a need for projections of wind, cloud cover and wave heights to support cost-effective deployment of wind, solar and marine energy infrastructure (uncertainties are currently too large to support reliable projections of these variables).

Adaptation

- A key requirement is for **regionally-specific information on changes in both mean weather and its variability (including the frequency, severity and location of extreme events)** on seasonal to decadal timescales. This information is needed to inform planning decisions, including the significant infrastructure investments and engineering challenges, that will be needed to adapt to and mitigate against climate change (e.g. better flood defences, reservoirs, storm sewers, resilient renewable energy infrastructure)[6].

- Related to this, there is a requirement for **improved understanding of single and multi-sector impacts of climate change on the UK** on seasonal to centennial timescales to inform risk assessments and planning decisions. The issues/sectors that appear to be highest priority are: flooding (pluvial, fluvial, coastal), ecosystems, agriculture, health, forestry, transport, the built environment and the marine environment.
- There is also a need for **more information about the nature and impacts of climate change on specific regions and sectors abroad**. This is required both to assess the indirect effects of climate change on the UK (issues may include conflict, resource availability and migration) and to support the UK's international interests, including helping developing countries respond to the challenges of climate change (key areas are likely to include agriculture and water).
- There is a continuing need for **detection and attribution of anthropogenic climate change.** This information is required to distinguish the impacts of climate change from weather, to enable an evidence-based adaptation strategy. Further, to inform impacts and vulnerability assessments in less-developed countries, so adaptation assistance can be targeted at regions and sectors actually affected by climate change; and increase international and domestic engagement on climate change.

Strategic requirements for enabling delivery

A number of strategic requirements underpin many of these needs. In particular, there is a fundamental requirement to **reduce the uncertainties associated with projections**. This is particularly acute at regional to local scales, on seasonal to multi-decadal timescales and for changes in hazardous weather and climate extremes (e.g. drought seasons, hurricanes, floods etc.), because this information is most commonly needed to support decision making, both in the UK and internationally. Current projections of regional and local climate change are characterised by high levels of uncertainty, which make it challenging to develop appropriate policies.

Reducing uncertainty on projections would allow issues such as the likelihood of rapid and dangerous climate change, risks associated with hazardous weather and extreme events, the safety of geo-engineering schemes, the effects of reducing emissions, and the impacts of future climate change to be assessed with greater confidence. This, in turn, could have considerable economic value by enabling society to adopt the most cost-effective adaptation and mitigation strategies.

Uncertainties in projections arise from errors in the initial state, unresolved processes, and incomplete knowledge and partial representation of the climate system in climate models. Significant increases in confidence in projections, particularly at smaller spatial and temporal scales, could be achieved by the following (each of which would be computationally intensive):

- increasing the resolution of models to the point where they can resolve weather systems such as blocking and tropical cyclones (experience from

[6] It is also a critical need for the insurance industry.

weather forecasting shows that the benefits of increased resolution in providing reliable information at the regional and local level are substantial);

- ‘initialising’ predictions with observations of the current state of the climate system to increase their skill at predicting natural inter-decadal climate variability;
- including processes/factors that are omitted (e.g. stratospheric chemistry, improved aerosol microphysics, land-use and different types of vegetation and plankton);
- assessing and improving the model’s skill by evaluating hindcasts and forecasts against observations.

The increases in computing power required to support these developments, considered later in this report, would have the co-benefit of supporting more rapid scientific advance in areas such as dangerous climate change and research into small-scale climate processes that cannot be resolved in lower-resolution models, such as cloud-formation. Resulting advances in understanding would feed back into models/predictive systems and reduce further the uncertainty associated with projections.

A ‘seamless’ prediction system, in which a single model ‘family’ is used to predict both weather and climate on timescales from a few days to hundreds of years[7], would offer some advantage in implementing these changes. Both weather and climate would benefit from the scientific synergy that comes from sharing the same code; optimisation and validation work for weather would benefit climate models and vice versa; and supercomputing resource utilisation would be maximised by running both weather and climate models on the same platform.

As well as reducing uncertainty where this is possible, there is a need to **better understand and quantify uncertainty associated with projections** to facilitate a risk-based approach to decision-making. This requires ensemble-based prediction systems to sample uncertainty in as complete a manner as possible.

Further, **metrics / criteria are required to enable HMG to assess when climate projections are fit for purpose,** and to measure progress in reducing uncertainty.

Finally, there is a strategic need to **ensure that evidence and advice provided to HMG is high quality** (requiring quality assurance). Ultimately, this is dependent on the quality of underpinning observations and climate science, and the strength of the UK climate science community. Also, it is critical **that advice is provided in a timely way** (often this will be ‘on demand’).

Underpinning and supporting requirements for enabling delivery

These strategic requirements critically need to be supported by: (i) **long-term**, **high quality observations** of the climate system, including to initialise and validate climate models, and (ii) advances in the **underpinning science** (e.g. improved

[7] All of the models within a physical model ‘family’ are scientifically traceable to each other, meaning that the key driving mechanisms and feedbacks in these models are consistent and reliable across the whole hierarchy.

understanding of internal variability and climate feedbacks). These requirements, in turn, depend on the quality and availability of scientific expertise and appropriate infrastructure.

Important too will be **ensuring that the benefits of existing and planned climate services are fully realised**. Without a clear strategy for coordinating uptake of new information and products, there is a risk that these will leap beyond the capabilities of HMG and other stakeholder communities to benefit. Attention and resource is therefore needed to translate potentially world-leading evidence and advice into world-leading policy and practice. Requirements include for information to be effectively synthesised, with any uncertainties and risks communicated clearly, and for gaps in the evidence base to be highlighted.

Finally, it should be noted that **evidence and advice in a wide range of other areas** will be needed to support effective adaptation and mitigation strategies. These needs include improved understanding of behavioural responses and adaptation strategies to climate change.

Cross-cutting areas

Where several organisations have the same need, collaboration would appear to add value and save money. However challenges can also arise in supporting joint research, where no single organisation has a lead. The key cross-cutting areas are:

- Projections of future climate change and its impacts in the UK (particularly of extreme events and variables not included in UKCP09, and on seasonal to decadal timescales) to inform risk assessments and allow cost-effective planning/adaptation strategies.
- Projections of future climate change and its impacts abroad to: inform UK policies/interests abroad (including helping poorer countries adapt); allow the UK to assess the economic risks and opportunities from impacts overseas; and allow the UK to adapt to/plan for changes in the UK resulting from international impacts (particularly threats to national security).
- Information on the climatic effects and economic implications of emissions pathways to inform global and domestic emissions targets and mitigation policies.
- Climate change detection and attribution.
- Synthesis, interpretation and communication of advice.

Section 2: The Economic Value of Climate Evidence and Advice

The market for weather services is much better established, and quantified, than that for climate services.

In the UK, external research[8] on the value of the Met Office's public weather service has shown that the service contributes at least £614m to the economy, based on a sample of the services it provides - many times its budget of £83m. The £614m figure comprised £353m from services to the general public and £261m from services to the Cabinet Office, Environment Agency and Civil Aviation Authority.

The US Department of Commerce's Bureau of Economic Analysis has estimated that at least one-third of U.S. GDP (about $4 trillion in 2005 dollars) is weather and climate sensitive, ranging from finance, insurance and real estate to services, retail and wholesale trade and manufacturing. Industries directly impacted by weather, such as agriculture, construction, energy distribution and outdoor recreation, account for nearly 10% of GDP[9].

Although the above studies did not separately quantify the benefits of climate services, many users are concerned with their exposure to the impacts of weather, in particular extreme weather, taking into account future climate variability and/or changes.

Future climate change is very likely to involve large economic costs. These come from three main sources: the cost of climate damage itself, the cost of adaptation and the cost of reducing emissions (mitigation). The total cost will depend on the balance between, and timing of, mitigation and adaptation.

The Stern Review estimated that without action the overall cost of climate change could be equivalent to losing between 5% and 20% of global GDP each year, now and forever. The damage does not rise linearly, i.e. a doubling of temperature rise will more than double the damage costs. Research in the AVOID programme[10] suggests that the cost of mitigating emissions to limit warming to less than 2ºC may be between 0.5% and 10% of GDP in 2100, and possibly higher. The adaptation costs are more difficult to estimate but are likely to be substantial.

Climate science advice can minimise the cost of climate change by informing adaptation and mitigation policies. The damage cost (and indirectly the adaptation cost) depends on the magnitude and rate of change, and whether any accelerated or irreversible shifts in the large-scale climate are triggered. Advances have been made in better understanding such areas of uncertainty but more reliable information is needed on (e.g.) how hazardous weather will manifest on the local-scale.

The biggest cost of inadequate climate advice is likely to arise from inappropriate or under-adaptation or -mitigation. But costs could also be higher than necessary through if wasteful over-adaptation takes place. For example, bigger flood defences,

[8] PA Consulting Group (2007)
[9] Weiher and Sen, 2006
[10] http://www.avoid.uk.net/

more powerful cooling systems or bigger drought alleviation measures may be constructed than are needed.

Benefits of climate projections and advice come from using forecasts and data to better understand risk, estimate potential damage costs and identify opportunities to mitigate and offset these. Both government and increasingly the private sector can benefit.

For example, the average insured losses from the weather and climate in the UK are currently in the region of £1.5 billion per annum, and are expected to increase in line with the changing climate to £2.25 billion per annum in an average year in the 2040s-2060s, and possibly £28 billion per annum in an extreme year[11]. The cost of the 2007 floods alone has been estimated at £3 billion, with a similar figure put on earlier floods in October 2000. The top 10 natural hazard disasters reported between 1990 and 2009 in the UK were all related to extreme weather – heat-waves, wind storms, snow/cold and floods. The heat-wave in July 2003 caused the death of around 2200 people in the UK, and many more in elsewhere in Europe.

Below are further examples where the value of climate advice has been assessed. In addition, a submission to the Review from the Willis Research Network setting out an insurance industry view of the economic benefits of the Hadley Centre is published alongside this document.

Case study 1: Supporting DFID's Work in Africa

Climate variability and change have huge impacts on food security, water availability, human health and social and economic infrastructures, particularly in Africa where vulnerability to hazardous weather and the natural vagaries of the climate is already high.

More accurate projections of future climates could significantly lower the cost of adaptation measures. This is particularly true for Africa, where knowledge about current and future climate is scant and DFID's development portfolio is significant. In 2008/09, DFID provided £5.5bn of aid to poorer countries (increasing to £7.8bn by 2010/11) - 47% was spent in Africa.

DFID is working with the Hadley Centre to increase understanding of African climate drivers and improve their representation in Hadley's latest global circulation models. Climate model outputs will be adjusted to better meet end-user needs – at both the immediate (seasonal forecasting) and long-term (decadal and beyond) ends of the spectrum. The work will also test an approach to estimate the extent to which particular climate events can be attributed to climate change – a key issue in relation to adaptation financing, and will further develop its dynamic downscaling tool (PRECIS) to provide climate projections at a finer scale.

As a further benefit, the DFID/Hadley Centre partnership is aiming to increase scientific and technical capacity in Africa.

Case Study 2: Wind Power

[11] Surminski, S., Association of British Insurers, http://www.rusi.org/downloads/assets/Surminiski.pdf

Rapid growth in both onshore and offshore wind power is central to the government's targets on carbon emissions and renewables. This will entail investment of several £10s of billions.

To maximise return on this investment, and minimise risks to energy security, it is vital to site developments carefully in regions where winds will be reliable throughout their planned lifetime - typically many decades. The generation of electricity from wind turbines falls off rapidly as wind speeds decrease, with no production in low wind situations such as those found under high pressure systems. The greatest risk to the security of supply of wind energy occurs in 'blocked' situations, where high pressure can persist over much of the country for several weeks, which can result in near total loss of wind power. Many £millions per hour are then lost in energy costs alone. Wind turbines also have upper tolerances for wind speeds beyond which they are shut down, and so changes in storminess need to be considered.

As climate change progresses, weather and wind patterns are likely to alter, possibly quite dramatically, with important consequences for the availability of wind energy. Current projections (such as from UKCP09) provide limited insight into the evolution of wind speeds over the UK as the climate models used were not capable of representing the detailed characteristics of future wind patterns. This includes extreme winds, the likely frequency and duration of low wind (blocking) situations, and the geographical distribution of mean winds, both on- and off-shore. Looking ahead, higher resolution climate models, running on high performance computers, will be needed substantially improve the assessment of changes in meteorological situations like blocking.

More detailed climate projections will enable better planning of wind power networks, and more efficient operation. Estimates of economic benefit are necessarily high level, but with a total wind investment of, say, £50 billion over the next 10-20 years, better climate information to guide the developments, resulting in an increased efficiency of just 1%, would lead to a total saving to the UK economy of around £500 million.

Case Study 3: Thames Barrier

The Thames Estuary 2100 (TE2100) project examined how best to protect London from flooding due to sea-level rise and changes in storm surges over the 21st century. Assets at risk within the tidal Thames floodplain region include £200 billion of property, more than 1000 electricity substations, 8 power stations and key transport infrastructure.

The Environment Agency reviewed the climate science (from the Met Office Hadley Centre and the National Oceanography Centre Liverpool), engineering information on barrier life-time and maintenance, and socio-economic information on how people might live in the Thames area, together with analysing the potential costs of impacts and adaptation. A key issue was the uncertain magnitude of increases in extreme water level under climate change.

Prior to TE2100, the worst case scenario for sea-level rise was taken to be 4.2m over the 21st century. A tidal barrage could deal with this but would come at an estimated capital expenditure of about £20 billion[12] if built in the outer estuary. The

[12] Costs provided by Thames Estuary 2100 project, Environment Agency.

TE2100 project developed new scenarios of projected extreme water level for the Thames Estuary, including a likely range of sea level rise based on current state-of-the-art climate modelling capability and a new worst case "High++" scenario range with increases up to 2.7m (including a storm surge component). The upper part of the High++ range is thought to be highly unlikely but cannot be completely excluded on the basis of either plausible physical limits or proxy measurements of past climates, which bear some relationship to climate projections this future century.

As this new worst case scenario is substantially lower than estimates prior to TE2100, it implies that the more extreme forms of adaptation should not be needed, with an outer barrage now very unlikely to be required in the 21st century.

In addition, information on potential rates of sea-level rise over the 21st century was compared with timescales for implementing adaptation measures. The study was thus able to suggest further cost savings by initially planning for lower sea-level rise and only introducing the highest protection measures needed for High++ if future evidence suggests such higher rates of sea level rise are being realised.

The potential cost saving from this step-wise approach has been estimated at around £2 billion (discounted Net Present engineering costs to 2100). Improvements in climate modelling capability together with ongoing monitoring of sea level should thus allow the most cost effective step-wise adaptation pathway to be followed, so any outer barrage solution is not built prematurely, potentially wasting up to £20 billion of the initial investment if it was partially life-expired by the time it was needed.

Case Study 4: Defence – procurement decision-making

MOD’s Defence Equipment and Support (DE&S) acquires and supports equipment and services, including ships, aircraft, vehicles, weapons, information systems and satellite communications. With a budget of £13 billion, and much of the equipment designed to operate in certain environmental conditions, it is important to assess the implications of a changing change.

The expected lifetime of much of the equipment purchased can be measured in decades. This is particularly true of the largest and most costly items. Decisions made without including robust long term climate information may not be appropriate over the entire lifetime of the equipment. In many cases this could result in the need for expensive retro-fitting, or commissioning of new equipment capable of operating in a changed climate.

Military equipment is designed to operate in the large range of environmental conditions that exist globally, and changes in climate are likely to be relatively small compared with the range of climates that already exist. But for some regions the change could have particular military significance, and even change the focus of conflict itself. An example would be the melting of Arctic sea ice. This could result in a requirement to operate in this region more frequently. Existing climate conditions in the area are not appropriate to inform investment in future operating capability. Information is required on what the conditions will be like at the time when the requirement to go there may arise.

Just as equipment tested in Germany has not always been suitable for operations in the Middle East, so equipment tested in today’s conditions are unlikely to be entirely suitable in future operating environments, either because the location has changed, or the environment itself has changed. The inclusion of climate change projections in capability testing has the potential to improve operating capability and to reduce costs over the lifetime of procurement decisions.

By incorporating climate information into planning and design stages, opportunities exist to extend platform lifetimes, minimise the need for costly mid-life upgrades, and minimise downtime and operational costs, resulting in large potential savings.

Section 3: Delivery landscape for provision of climate science evidence and advice to HMG

Current delivery landscape

The Met Office Hadley Centre is the main provider of evidence, advice and other services on climate change science to HMG, through the Integrated Climate Programme[13]. Universities and NERC institutes (e.g. the British Antarctic Survey and the National Oceanography Centre), and occasionally think tanks and the private sector, also provide evidence and advice, sometimes in collaboration with the Hadley Centre. International assessments (especially through the IPCC process) and input from individual scientists in the UK and abroad also play a role.

DFID is unique in that it draws on advice from a wide variety of sources, reflecting the global footprint of its work. It is assisted by a number of independent 'resource centres' comprising specialists from universities, consultancies and think tanks, who source primary data and climate predictions from the most relevant sources, including, but not restricted to, those provided by the Hadley Centre. DFID also provides assistance to developing countries to generate and access evidence for their own policy objectives through a range of institutions and initiatives (eg: UNEP and the Climate and Development Knowledge Network (CDKN)).

Key advantages of this delivery landscape to users include: long-term stable investment in climate research and prediction in the Hadley Centre over 20 years has delivered world-class capability that now facilitates world-class research in UK academia; directed climate research is policy-focussed and allows close links between evolving HMG needs and progress in climate science; the Hadley Centre has both world-leading climate modelling / prediction capability and world-class scientific expertise, and is therefore able to provide high quality evidence and advice; Hadley is a known and trusted provider with an established capability and a proven capacity to deliver; it is used to operating within the security constraints that can be required by HMG; departments can obtain specialist advice / services from sources other than Hadley where this is more appropriate.

There are also **'strategic' advantages** to the Hadley Centre being the main provider of evidence and advice, including that climate projections used by HMG are based on similar assumptions, ensuring consistency across different applications. HMG also has a 'traceable' source of high-quality information and advice, and there are economies of scale in using a single-source model across Government.

The main **disadvantages of the current landscape to users** are: uncertainty around future provision of services by the Hadley Centre linked to its future funding and status; difficulties in obtaining high-quality evidence and advice on multi-disciplinary issues (e.g. societal impacts of climate change), where expertise lies in other organisations; and a lack of capacity / capability for integrating, communicating and translating such wider advice to users.

The key **strategic disadvantages to the current landscape** are: it limits the extent to which HMG draws on the breadth of expertise in the academic community; it does

[13] The ICP is a five year directed programme of research delivered by the MOHC and funded by HMG. It delivers directly to policy requirements for both mitigation and adaptation agendas and also funds the climate model development required to support this.

not foster the degree of collaboration between the Hadley Centre and academia that would ensure the fastest possible progress on climate science[14]; it has the potential for insufficient quality assurance of evidence and advice provided to HMG (e.g. through mechanisms for allowing the academic community to challenge advice to HMG – the flipside risk to the single traceable source "advantage").

Meeting future needs

A number of points are relevant in considering how HMG's future needs for evidence / advice can be met most effectively and efficiently:

- there have been significant changes in climate change science over recent years, including an increasingly multidisciplinary nature (which is partly why expertise is now located in many different institutions);
- the policy agenda has evolved rapidly, e.g. with increasing attention on adaptation and consideration of geo-engineering);
- …this has changed HMG's needs for evidence and advice (e.g. greater demand for reliable projections at regional to local scales and on monthly to decadal timescales, and a greater need to interpret the outputs of projections);
- recent changes to the delivery landscape have the potential to play a significant role. In particular, 'Living with Environmental Change' and other similar programmes, e.g. on global food security, aim to strengthen the evidence base and communicate information to policy makers;
- underpinning requirements for meeting HMG's future needs for evidence and advice include increased computing capability and provision and management of high quality observations of the climate system;
- these underpinning requirements are also needed by the academic community to advance the science of climate change (which will, in turn, serve to further improve climate projections, as well as allow the UK to maintain its leadership in climate science);
- access to multi-model ensembles can provide a better assessment of uncertainties than projections made with just one model[15]
- use of a seamless prediction facility, in which a single model 'family' is used to predict both weather and climate on timescales from a few days to hundreds of years, brings important advantages;
- it is highly unlikely that state-of-the-art models would be developed without substantial, sustained investment in modelling capability and observations of the climate system by national governments;
- there is likely to be an increase in the number of providers of climate science services, particularly commercial climate change consultancies, as the sector becomes more 'commoditised' (insurance risk modelling companies are already running global climate models and various universities offer climate consultancy services). This poses challenges in terms of quality assurance of advice to HMG, but also provides an opportunity for UK leadership in a new global market;
- current economic circumstances mean that there are significant pressures on budgets across government, with the emphasis on value for money / efficiency savings exceptionally high.

[14] For example, the MOHC has no specific mandate to support research in the academic community, and the academic community lacks a voice in decisions about the strategic development of the MOHC's climate model – although collaboration is improving, e.g. through the Joint Weather and Climate Research Programme

[15] The importance of using a multi-model-ensemble prediction system was recognised, but not fully implemented, in UKCP09.

Potential role of the Hadley Centre in meeting HMG's future needs

In the near term (the next 5+ years), **there is clearly a need to maintain nationally-funded, world-class computing facilities at the Hadley Centre** in order to ensure that the Government's needs for climate science evidence and advice can continue to be met (as well as to ensure that the UK academic community has access to the modelling capability it requires to advance the underpinning science).

It is also clear that ***within the UK* the Hadley Centre is uniquely placed to maintain the world-class capability for climate modelling and prediction that will be needed to meet the Government's needs in the longer-term (5-10 years)**. One aspect of this arises from the additional benefits and efficiencies that link to weather forecasting and climate prediction being in the same organisation, including the potential to develop a 'seamless' prediction system.

The advantages of maintaining the modelling capabilities needed to meet the Government's needs in the UK on this longer timescale include: rapid response time for providing advice; close links between policy makers and providers; clearance to address issues of national interest/security; facilitating UK excellence in the field of climate change and thereby maintaining UK influence in international science and policy; and providing opportunities for the UK to a play leading international role in the development of commercial climate services (which are likely to be a major growth area).

The Met Office has proposed that maintaining a world-class capability for climate modelling and prediction at its Hadley Centre could have significant added value through the development of a 'UK Climate Service'. The overarching, long-term ambition of this initiative, which would take 5-10 years to develop, would be for the Met Office to be recognised as the world's lead provider of climate information and advice, to both public and private sector organisations, to support mitigation and adaptation.

Potential role for international collaboration in meeting HMG's future needs

For the longer-term (5-10 years), there is potential for international – and particularly European – collaboration to contribute to meeting HMG's needs through the development of new the world-class capability for climate modelling and prediction. A step-change in computing capability will be needed to achieve the step-change in the quality and resolution of climate service information that HMG requires, and funding this increase with EU partners[16] may represent the best value for money for the UK, given the economies of scale that could result. Indeed, it may not be possible for the UK to provide the level of investment required without them. Such collaboration would also reduce the pressure on the human resources needed to develop subcomponents of individual models at different institutions, possibly improving the end-product (although it will be important that the number of models available remains sufficient to allow learning from model inter-comparisons and to provide multiple sources of advice).

Potential disadvantages of this approach include the organisational barriers to

[16] HMG's future needs for climate science evidence and advice will be similar to those of all European nations over the next decade, and the principal models needed to provide this information are global in domain.

implementation and the fact that significant progress may take several years. Dependence on international collaboration could also increase the risk of a long-term erosion of the UK lead in climate science and/or reduced quality of evidence and advice to HMG (through limited access to facilities, loss of control, lack of a policy lead, loss of the link to Met Office weather models and science, and/or dependence on sustained funding from partners). However other European countries will have similar evidence / advice needs to the UK over the next decade, and European cooperation has worked well in the case of European Centre for Medium Term Weather Forecasting (ECMWF). Also, international collaboration may – given the significant scientific and infrastructural challenges ahead – provide the only practical opportunity for the UK to maintain a lead in this area.

There are already some efforts to coordinate supercomputing in Europe (the PRACE: Partnership for Advanced Computing in Europe) but to date there has been little discussion about the specific needs of the climate community. (There is also some activity to try to obtain joint public/private funding for a Climate "CERN" centre[17].) The UK should be in a better position to assess whether the development of a pan-European modelling framework is scientifically sensible within 5 years. **The UK should take an open, proactive and constructive role in these discussions.**

Pursuing longer term international collaboration to improve modelling capability and maintaining capability at the Hadley Centre is not necessarily an 'either/or', but it will be important to determine the appropriate balance of funding and organisational structures between Hadley and European facilities if/where this option is pursued.

As the lead policy Department, DECC has proposed that it will be important for the Hadley Centre to work with international collaborators to develop a platform-independent Earth System Model that could be run anywhere in the world with the required computing capability, and that the UK should invest heavily to help fund the computing capability required.

Other requirements for the delivery landscape

Regardless of how the climate modelling and prediction capability required by HMG is provided, the following changes will also be needed / desirable to ensure that the Government's needs can be met:

- changes to the delivery landscape to foster collaboration between UK academia and the Hadley Centre[18], including joint use of the Hadley model for operational and research needs (this will require resolving current issues relating to the Met Office firewall – the Met Office is already taking steps on this through the MonSOON system);
- changes to the delivery landscape to ensure that HMG can draw effectively on the breadth of expertise in the UK, including social science, to meet its policy needs, particularly in multi-disciplinary areas (the UK Climate Service proposed by the Met Office would be one approach);
- collaboration with European partners to allow outputs from European climate models[19] to be used in multi-model ensemble systems, to provide more

[17] http://cdsweb.cern.ch/record/1241787
[18] NERC and the Met Office are currently drawing together a strategy for Earth System Modelling (ESM) in the UK. This will enable the UK to develop and enhance its world leading brand of ESM and will provide the framework for closer co-operation and collaboration between NERC and the Met Office.
[19] There are a number of global earth-system modelling systems in Europe (the key ones are: the Hadley Centre

comprehensive characterisation of uncertainties in projections[20] (this has already been a focus for the Hadley Centre through its leadership of the EU FP6 ENSEMBLES Project, engagement in the European Seasonal Forecast programme and via an international initiative to produce multi-model decadal forecasts);
- a more strategic and coordinated approach to procuring evidence across government, particularly where several organisations have common needs (e.g. the effect of international impacts on national security);
- improved coordination, communication and interpretation of evidence and advice to stakeholders, including HMG and international partners;
- setting and maintaining standards and success criteria for climate science services, including assessments of the causes of observed climate change and predictions of future change.

It has been proposed that a core 'National Climate Science Programme', bringing together relevant capabilities and expertise at the Hadley Centre and in the academic community, and served HMG needs for both core 'operational' activities and strategic climate research, could help facilitate these changes. **Discussions e.g. between NERC and the Met Office will be important to progress these ideas, including links with the Met Office's proposed UK Climate Service, and to agree how to progressively strengthen collaboration opportunities**.

model, the Max Planck (ECHAM) model, the French Arpège model, and the new EC-Earth model run by a consortium of European countries).

[20] The European Network for Earth-System Modelling will provide the focal point for these types of collaborative European activities

Section 4: Governance Options for the Hadley Centre

The Climate Research and Earth System Modelling carried out by the Met Office is part of an integrated and increasingly interdependent set of broader activities. This includes research to develop Numerical Weather prediction and other underpinning work related to the provision of observations, supercomputing and IT infrastructure for both weather and climate services. As well as enabling the delivery of both science and operational outcomes this integration offers significant efficiencies.

As a consequence, the optimal governance and funding structure for the Hadley Centre needs to be considered in the broader context of national capability embodied more widely in the Met Office.

The trading fund model works well for the development and provision of customer specific services. Arguably it works less well as a mechanism for supporting key underpinning infrastructure and capability. This is particularly the case for climate advice services, where Government is the major customer and the development of a wider market remains embryonic.

In addition, recent experience with funding for the Integrated Climate Programme at the Hadley Centre has demonstrated that funding decisions made separately by individual Departments can lead to consequences that do not recognise wider Government needs, if considered holistically.

"Underpinning capability" includes the measurement, monitoring and prediction of weather and climate supported by leading supercomputer technology, foundation science, weather and climate data handling and modelling, and climate prediction systems.

"Underpinning infrastructure" includes the core physical infrastructure managed and exploited by the Met Office, e.g. supercomputing technology, an observing network including ground based observation sites, radiosonde data sites, radar network and satellite technology. The cost of provision of the radar network is shared in part with the Environment Agency. There are also significant costs for international subscriptions.

This underpinning national infrastructure and capability, which is common across weather and climate, is essential for the delivery of many critical services.

The following governance and funding models for supporting underpinning infrastructure and capabilities have been considered:

- *Option 1: Maintain the current model*

  Under the existing model circa 75% of the underpinning capability is in weather forecasting, purchased as part of the Public Weather Service through the Public Weather Service Customer Group (PWSCG). This includes the provision for international subscriptions and is budgeted, on behalf of several government departments, through the MoD. The majority of the balance comes through the CAA from civil airlines, and from the MCA (Maritime and Coastguard Agency).

Until April 2009, the Integrated Climate Programme Services were purchased by MOD, DECC and Defra, with each bearing a ‘slice’ of the cost of the underpinning infrastructure and capability. MoD’s withdrawal reduced aggregate funding to below critical levels for the “integrated” work contracted. DECC and Defra (with current support for DfID) replaced most of the shortfall for the current year, but there is no confirmed contract beyond March 2011.

The option to continue with this model has been judged not to be viable in the longer term by the PWSCG and MOD, and by Sir John Lawton in his report to DECC in October 2009.

- *Option 2A: Separate Funding for Underpinning Capability in Climate Prediction*

Under this model, core climate prediction capability would be funded separately from direct services provided to government departments. The core capability would be funded by the major departmental users, currently DECC and Defra. The Lawton Report recommended this option and referred to these departments as ‘core customers’.

This option has the vulnerability of requiring multiple departments to fund a core capability, with each needing to maintain consistent, long term funding to ensure viability and support essential strategic investments.

It also does not address the fact that some capabilities, most notably supercomputing and global atmospheric model development, support both weather and climate infrastructure. Given the increasingly integrated nature of building and operating weather and climate prediction capabilities, a more joined up approach to supporting these could arguably achieve greater efficiencies.

- *Option 2B: Centralised Funding for Underpinning Climate Prediction Capability*

This model is the same as Option 2A, except that the underpinning capability in climate prediction would be funded centrally, potentially through a HM Treasury ‘top slice’ budget and via a lead Department (most logically DECC).

Issues around multiple departments managing and planning for a core infrastructure would be addressed with this model, although it would not directly support the combined capability across both weather and climate.

- *Option 3A: Multiple Department Funding for both Weather and Climate Underpinning Capabilities*

This model would involve an integrated approach to supporting the development and operation of both weather and climate core capabilities. It could bring significant scientific, service and cost advantages. Separate contracts would still be let for specific services.

As with option 2A, this option would involve multiple departments funding a core UK capability, with the need for these departments to each maintain a consistent funding position to support long term maintenance and development. The risks might indeed be greater given that the ‘core customer’ group of departments would be larger. Moreover, departments with a specific interest in either weather or climate may find difficulty in endorsing their role in a wider remit.

- *Option 3B: Central Funding for both Weather and Climate Underpinning Capabilities*

Under this model the government would let a single contract for the maintenance and development of the common weather and climate infrastructure and underpinning science. Separate contracts could then be agreed for specific services, related to individual department's needs. This could again be provided for via a single budget held by a lead department (potentially DECC, Defra or MOD).

Arguably this approach could maximise integration and efficiency, encouraging full exploitation of the synergies between climate and weather prediction, infrastructure, IT, research and modelling capabilities.

From this analysis, option 2B is recommended as the most appropriate and viable, whilst recognising that 3B could bring significant additional benefits.

Moreover, it will be important that any solution on governance and funding for core infrastructure and capability recognise the synergies and efficiencies obtained through the integration of climate and weather services.

Section 5: Provision of High Performance Computing Capability

The review has considered in detail the future provision of high performance computing (HPC)[21] capability required to meet the Government's evidence and advice needs over the next 10 years[22], with a key focus on **supercomputing requirements**, in particular to:

- consider the HPC capability required to address specific areas for advice and evidence (including a description of the different levels of capability that can be achieved for different levels of computing power and investment);
- review what supercomputing capability currently exists or is planned in the UK;
- review the options for providing the capability required *(*including Met Office Hadley Centre*,* collaborative projects, mix of different forms of HPC capability, use of other countries' facilities, joint purchase of a dedicated supercomputer facilities through the EU) and the relative merits of these options; and
- develop recommendations for providing the HPC and in particular supercomputing capability required, taking into account factors such as value for money, risks and benefits of collaboration, and potential co- or dis-benefits for other climate science research funders and users, including in academia and the private sector.

The review has assessed the models which will need to be run, and the supercomputing resource needed in each instance, with associated costs. Further background and analysis is included in supporting paper on high performance computing requirements published separately.

A key conclusion is that state-of-the-art climate modelling and prediction cannot be delivered with any HPC platform, but needs access to supercomputers. This is because the nature of the equations to be solved requires large amounts of data to be held in memory and continually transferred between processors. This means that the memory/processor performance has to be high and, more importantly, the interconnect between processors has to be as fast as possible. So climate prediction is not only compute-intensive but also data-intensive and memory-intensive.

Although the current predominant supercomputing resource supporting UK climate science is based at the Met Office, a number of delivery mechanisms, including international initiatives, for accessing computing resource has been considered.

The climate modelling and research required needs to be supported by a range of hardware and software solutions. The supercomputing requirement dominates capital spend because of the need for, and requirements of, increasing model resolution – and is therefore the focus here. However, to satisfy wider computing requirements, particularly the need for ensembles for risk analysis, supercomputing requirements need to be examined in conjunction with other possible HPC solutions

[21] 'High performance computing' (HPC) is a generic term embracing supercomputers and high end servers. High-resolution modeling requires supercomputers but for some work high end servers might be suitable.
[22] Informed by a sub-group chaired by Prof Brian Collins, BIS and DfT Chief Scientific Adviser

and activities. These wider requirements and opportunities are reviewed further in a supporting paper on high performance computing requirements published separately.

While grid or cluster computing are valuable and cost effective options for some applications, Earth System Models and high resolution models can only be run on supercomputers. Indeed, all major climate modelling centres (US, Japan, France, Germany) use advanced supercomputing for their top-end research and prediction activities. Also, if HMG is to fully benefit from the UK's world-leading expertise, the UK climate science community needs a stable, dedicated supercomputing service that is designed for climate research needs, including effective collaboration between the Met Office and UK academic institutions.

The review assessed the five high performance computing options outlined in Table 1 for their ability to meet the needs set out in Section 1:

Table1: High Performance Computing Options Reviewed

Option	Computing capacity	Operational capability			Infrastructure			Cost - relative to current
		Collaboration	Code re-design (extra FTEs, capability impact)	Archiving capacity	On-site greening IT measures	Other infrastructure upgrades	Sharing data archive with UK academia	
A	216TF[23] from 2011 No capacity increase beyond that currently contracted	Continue Met Office / NERC collaboration as set out in JWCRP[24]	Nil FTEs; no new scalability requirement	No additional storage beyond that needed to match contracted supercomputing upgrade: when archive full research limited to data produced in last 2.5 years[25] 3.1 TB[26] from 2011, 3.5TB from 2016 onwards.	More energy-efficient plant: cooling (£0.4m), DC power (£0.9m)	None	Existing limited capability continues. No provision for better data sharing	<1
B	216TF from 2011 Increase to 2PF[27] in 2016 and ~16PF in 2020	Continue Met Office / NERC collaboration as set out in JWCRP	Nil FTEs; take advantage of current Met Office / NERC re-design work	Extra storage to match rising data flows. 3.1 TB from 2011, 26TB from 2016, 200TB by 2020	More energy-efficient: cooling (£0.4m), DC power (£0.9m)	None	Existing limited capability continues. No provision for better data sharing	x1
B+	324TF from 2011 Increase to 3PF in 2016	Continue Met Office / NERC collaboration as set out in JWCRP.	Average of +3 FTEs per year; bring forward components of joint Met Office / NERC work to	Extra storage to match rising data flows. 5TB from 2011,	More energy-efficient plant: cooling (£0.4m), DC power (£0.9m)	None	Existing limited capability continues with no provision for better data	x1.5

[23] Teraflops
[24] The Met Office / NERC Joint Weather and Climate Research Programme: http://www.metoffice.gov.uk/research/collaboration/jwcrp and http://www.nerc.ac.uk/research/programmes/jointclimate/.
[25] Arguably an inefficient use of supercomputing capacity, with impacts on services.
[26] Terabytes
[27] Petaflops

	and ~24PF in 2020	Balance between shared (NERC/Met Office) and dedicated (Met Office only) resource review feasible.	radically re-design some elements of climate modelling software	39TB from 2016, 300TB by 2020.			sharing	
C	864TF from 2011 Increase to 8PF in 2016 and ~64PF in 2020	Significantly enhanced data sharing. Additional joint Met Office / NERC supercomputing capacity	Average of +6 FTEs per year, bring forward joint Met Office / NERC work to undertake radical algorithmic changes	Extra storage to match rising data flows. 11TB from 2011, 100TB from 2016, 880TB by 2020.	More energy-efficient plant: cooling (£0.8m), DC power (£3.4m)	Enhanced network connectivity for UK academia (£3m). Upgrade offsite Grid sub-station and cables, and onsite power and cooling (£9m)[28].	Data archive and bandwidth enhanced to facilitate better data sharing within UK climate community	x4
D	3PF from 2011 Increase to 27PF in 2016 and ~200PF in 2020	Significantly enhanced data sharing. Additional joint Met Office / NERC supercomputing capacity	Average of +6 FTEs per year, bring forward joint Met Office / NERC work to undertake radical algorithmic changes	Extra storage to match rising data flows. 38TB from 2011, 350TB from 2016 2.3PB[29] by 2020.	Green measures integrated with new IT facility (see box to the right).	Enhanced network connectivity for UK climate community (£3m). New IT facility with energy-efficient power and cooling plant, new electricity sub-station onsite, upgrade offsite Grid sub-station and cables (total £42m)[30].	Data archive and bandwidth enhanced to facilitate better data sharing within UK climate community	x12.5

Source: Based on information provided by Met Office

[28] Assumes Grid power capacity available in Greater Exeter area.
[29] Petabyte. 1 PB = 1,000TB.
[30] Estimate based on a facility at the Met Office's Exeter site and assumes Grid power capacity available in Greater Exeter area. Non-Exeter sites would also be appraised (ideally close to source of green power) and would be required if capacity not available at Exeter.

Eight key questions

The Review's approach has included an assessment of how each of the five options would help address eight key questions developed, based on the evidence and advice needs identified in Section 1. The questions, with pragmatically estimated dates by which better clarity is needed and is realistic, are:

Q1: What is the risk and impact of changes in regional climate and/or variability?

Answer needed as soon as possible, e.g to inform planning decisions relating to new infrastructure developments such as power stations

- What will happen in the next 20-30 years due to the interaction of natural climate variability and committed climate change?
- What will a warming climate mean for agriculture and will weather pattern changes bring new pests and diseases?
- Are there key thresholds above which crops become increasingly vulnerable and will climate change mean that these are transgressed more frequently?
- Will climate change introduce new health problems (e.g. air pollution, water-borne and vector-borne diseases?
- What parts of the world will become increasingly water insecure?
- How might adverse climate change in Europe, such as Mediterranean desertification, affect demography, lead to immigration pressures on the UK, and alter the make-up of society?

Q2: ***How can we deliver increased accuracy from current climate models to improve mitigation decision making?***

Overall emission results are needed by 2011 to feed into UNFCCC negotiations, mitigation potential from different sectors needed between 2011 and 2016. We need to have the best possible information to make the best possible mitigation decisions.

- Can climate models reproduce past large scale changes in the climate system?
- What are the impacts of different options to mitigate global temperature rise (including geo-engineering options) on the global water cycle?
- What are the feedbacks on climate change through currently poorly understood processes (e.g. methane)?

Q3: What adaptation is required to climate extremes in UK?

Answer needed by 2016, will be used to update UKCP09.

- How will climate change affect the location of renewable energy installations?
- How efficient are they likely to be?
- What design tolerance will be required to withstand potential increases in the frequency/intensity of hazardous weather over the lifetime of the installation?
- What will changing weather patterns and extremes of rainfall, wind and temperature mean for design of transport systems?
- What tolerances will road surfaces need to have? Will bridges and cuttings need to be redesigned need to account for changes in rainfall intensity?
- How will more extreme summertime temperatures affect the railways?
- What will the London Underground be like in 20-30 years time?
- How will future changes in weather and climate affect planning for where and how to build new housing and protect existing housing stock?

- Are there likely to be new environmental stresses (e.g. flooding and landslips, drought and subsidence) that need to be taken account of in building regulations?
- How should houses be designed to optimise energy and water use under climate change? What are the expected tolerances likely to be?

Q4: How can confidence in the most uncertain aspects of large-scale climate projections be improved?
Answer needed perhaps by 2015, although the sooner the better to answer questions such as:
- Are current global climate projections for mitigation decisions accurate?
- What are the sign and magnitude of key cloud feedback processes?
- Is geo-engineering a safe option?
- How can aviation be operated to minimise the impacts of emissions?

Q5: What mitigation pathways can avoid dangerous climate change?
Peak carbon expected sometime around 2015.
- What level of global warming is avoidable and through what means?
- What aspects of climate change are irreversible, and at what point (e.g. in global temperature, CO2 concentration) does the system reach a ‘point of no return’?
- Can we develop early warning systems for low probability/high impact climate events?
- Is accelerated sea level rise possible as a result of rapid loss of ice sheets?
- Do recent changes in the Arctic indicate a rapid loss of the Arctic ice cover over the next few decades?
- What is the current commitment to the loss of major ecosystems (e.g. Amazon, boreal forest), and how much loss can be avoided by mitigation?
- Could the Atlantic Ocean overturning circulation collapse rapidly/irreversibly?

Q6: How will the ocean respond and feed back under climate change?
Answer needed perhaps by 2020, although clearly the sooner the better.
- What are the risks of abrupt or rapid climate change?
- How will the UK’s natural marine and terrestrial environments respond and what will be the effects on biodiversity?
- What sort of sea level rise will coastal communities be exposed to, and on what timescales?
- How will ocean ecosystems respond to acidification and climate change, and how would this feed back on ocean carbon uptake?
- How will ocean sediments respond to, and feed back on, climate change (e.g. through methane release)?

Q7: What are the local effects of climate variability and climate change?
Answer needed by 2020 to allow society to adapt.
- How will the incidence and characteristics of hazardous weather change?
- What sort of sea level rise will coastal communities be exposed to, and on what timescales?
- How will water management and extraction feedback on the local and regional climate?
- What is the likelihood of increasing adverse weather and climate conditions in the coming decades, leading to more infrastructure damage, increased poverty and social unrest?

- How will climate variability in the coming decades affect the ways in which military personnel and equipment operate and are sustained?
- How will climate change shape the global security landscape and how will the structure of armed forces need to be adjusted to meet future threats and contingencies?

Q8: What adaptation is required to local extremes internationally?
Answer needed on the timescale of 2020 to 2025 to inform adaptation. By this time the impacts of climate change will be being felt.

- Will climate change lead to greater volatility in seasonal climate and weather patterns (e.g. monsoons) and what are the implications for regional and global food security?
- What are the urban and rural impacts of extreme weather?

Both scientific research and model development will be needed to answer these questions. The latter requires significant computing resource.

To determine the required computing power, the climate models needed to answer each question have been considered. This has taken into account what is needed in terms of the resolutions to adequately represent the important physical processes, the relevant components of the Earth system, and ensuring that the inherent uncertainty is sampled in as complete a manner as possible. Availability of computing capacity and model performance are the main barriers to speed of progress as the science of weather and climate is ahead of the technical constraints.

Whilst the calculations have been based on the performance of the current Met Office supercomputer (which dominates current UK resource for climate science), information on the contracted upgrade from IBM due in 2011, and Moore's Law assumptions thereafter, the results are generic and do not, of themselves, imply that the compute power identified has to be provided at the Met Office.

The Met Office HadGEM3 model can be run at various spatial resolutions, with increasing resolution needing progressively more computing resource. Different resolutions, run length, ensemble size and model complexity are needed to properly answer the questions.

Table 2 shows, for the five HPC options examined, the earliest dates by which better answers to the eight key questions can be obtained.

Cells are coloured green if the question can be answered by the required date, orange if the date is just missed and red if the date is significantly missed. Cells also show the primary limiting factor(s) in brackets, which are:

- *Science* - where the science is only complete by the date shown;
- *Performance* - where the model cannot give an acceptable time to solution to given the answer because further work needs doing, primarily on model scalability;
- *Capacity* - where the option does not provide the necessary computing capacity (or throughput) to complete all the work required.

	HMG question	Date[31] answer required	Date answer available by scenario (limiting factor preventing earlier answer)				
			A	B	B+	C	D
1	What is the risk and impact of changes in regional climate and/or variability?	2012	> 5 years (capacity)	2014 (capacity)	2012 (science)	2012 (science)	2012 (science)
2	How can we deliver increased accuracy from current climate models to improve mitigation decision making?	2016	> 10 years (capacity)	2016 (capacity)	2015 (capacity)	2012 (science and capacity)	2012 (science)
3	What adaptation is required to climate extremes in UK?	2016	> 5 years (capacity)	2014 (capacity)	2013 (science)	2013 (science)	2013 (science)
4	How can confidence in the most uncertain aspects of large-scale climate projections be improved?	2015	> 15 years (capacity)	2018 (capacity)	2016 (performance)	2016 (performance)	2016 (performance)
5	What mitigation pathways can avoid dangerous climate change?	2015	> 10 years (capacity)	2016 (capacity)	2015 (science)	2015 (science)	2015 (science)
6	How will the ocean respond and feed back under climate change?	2020	> 15 years (capacity)	2020 (capacity)	2020 (capacity)	2016 (performance and capacity)	2016 (performance)

[31] Based on pragmatic judgments by the Review Group

7	What are the local effects of climate variability and climate change?	2020	> 15 years (capacity)	2024 (capacity and performance)	2022 (capacity and performance)	2020 (capacity)	2020 (performance)
8	What adaptation is required to local extremes internationally?	2022	> 15 years (capacity)	2026 (capacity)	2025 (capacity)	2022 (performance and capacity)	2020 (performance)

Table 2: Earliest dates feasible for better answers to key HMG questions

Table 2 assumes a two-year upgrade cycle as this is likely to provide access to increased resource more quickly than longer cycles. There is a small risk of not getting value for long enough on the investment, depending on the technology upgrade paths (rip-and-replace, upgrade or add) offered by suppliers.

The analysis does not look at the full range of activities required, such as model development. However, as the baseline for the analysis has been the current, most commonly used model, it is reasonable to assume that the range of current activities can be similarly scaled to fit around these activities.

For simplicity, no account is taken of the time required to synthesise and communicate information, so results are arguably slightly over-optimistic.

Dates in Table 2 have been estimated assuming no increase in code scalability work. If this were increased (e.g. an extra 5 FTEs), the date shown for Scenarios C and D for Q4 could be advanced by one year to 2015.

- Options A and B would fall substantially short in delivering answers to key climate science questions on the timescales in which they are needed and feasible.

- Option B+ would enable greater progress in some but not all key areas.

- Option C would provide the computing capacity to ensure that questions can be addressed as soon as the science and (albeit more difficult) model scalability are ready.

- Option D would require science and model development such that the technology could not be fully utilised in the short-term, although it could be used to provide more ensemble members.

Figure 1 below illustrates how a mix of both model and science development, and increases in compute power, is needed to gain better answers to HMG's key questions:

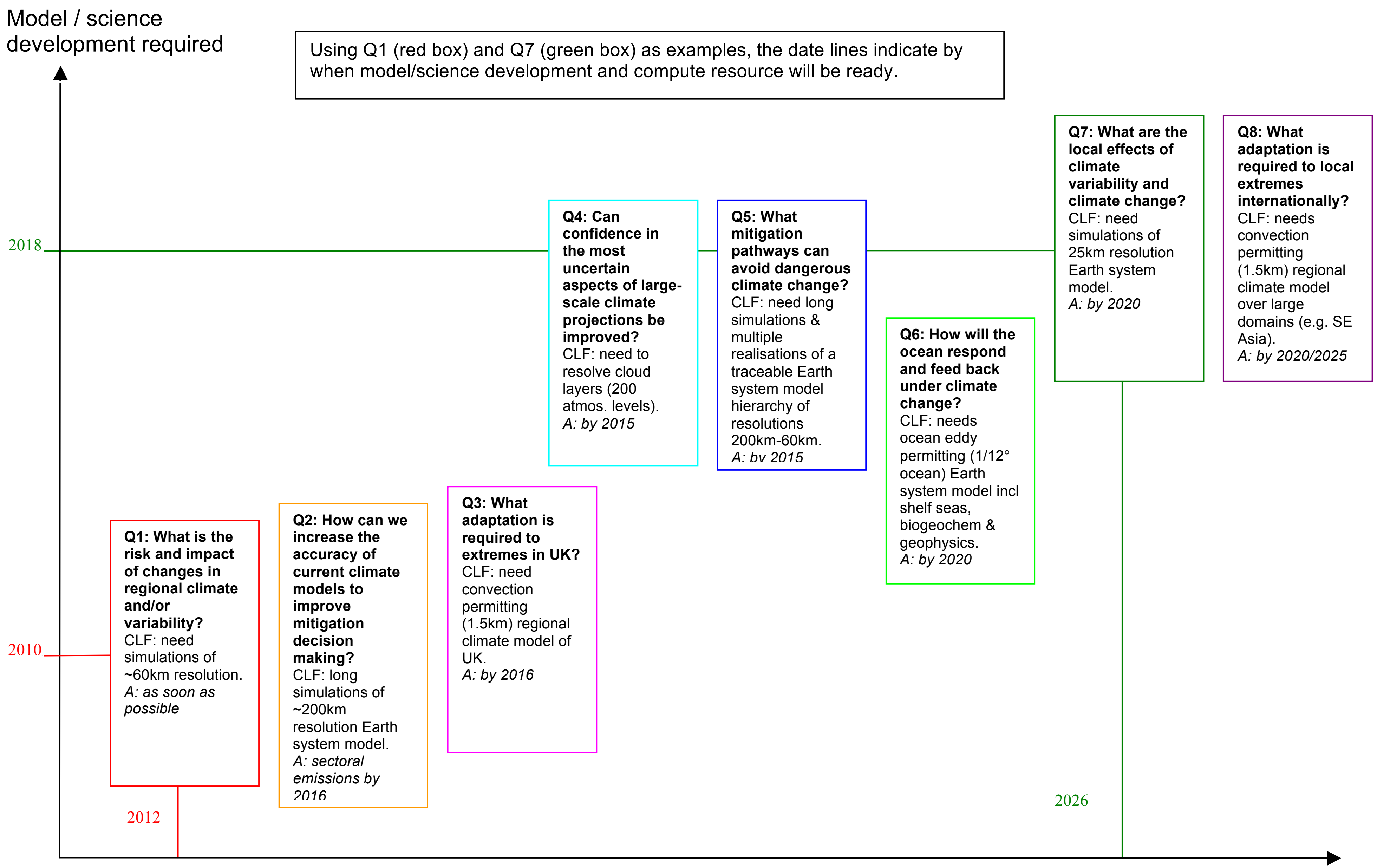

Figure 1: Factors limiting timescale for answers

Where UK and overseas agencies have had common scientific interests it has occasionally been possible to collaborate and use overseas supercomputing resources. However, overseas National Meteorological Services and research institutes will not provide free supercomputing resources to UK scientists, and are mostly unlikely to have material spare capacity to sell to the UK. The availability of such resource cannot be guaranteed and, even if it were available, costs would be broadly equivalent to that of direct UK provision. Such opportunities will therefore be unsuitable for meeting HMG needs for climate services. This includes where security considerations arise in commissioning analyses.

For meeting longer term needs, opportunities to direct some investment to pan-European facilities (there are currently no suitable alternative options in the European arena) should be actively examined. It is not possible to say at this stage how the costs of a European option would compare with Options A-D. Current EU and wider international initiatives are reviewed in the supporting paper on high performance computing requirements.

It will also be important to devote resource to longer-term code development work, so future models will run optimally on next-generation hardware, and to ensure appropriate facilities for data archiving and sharing.

Recommendations

Recommendation 1: The review has assessed that an **optimal solution would be a step-change increase in supercomputing capacity, with significant additional provision e.g. for code development, data sharing and to accelerate Met Office/NERC joint development work - Option C,** to most effectively meet the Government's key evidence and advice needs, in particular around regional climate change and extreme events, within timescales assessed to be feasible. Options A and B could not deliver answers to key climate science questions on the timescales in which they are needed and feasible. Option D would require science and model development which mean the technology could not be fully utilised in the short-term. The cost profiles of options A-D are shown in Table 4.

Recognising that Option C, involving a 4-fold increase in current supercomputing costs, is not affordable given current economic constraints, **a more limited incremental growth in supercomputing capacity, building on existing upgrading plans and provision, is recommended (Option B+).** This would still enable significant service improvements, though answers to a number of key questions, such as on regional climate projections and variability, would be delayed. This option would entail an increase in computing costs from the current level of £6m per annum to £9m per annum by 2012/13, which is factored in within existing Departmental Spending plans (subject to Spending Round outcomes).

Other recommendations are:

Recommendation 2 – HPC provision should be designed to meet the needs of the relevant academic climate science community – this is essential because (a) the quality of the climate science evidence and advice to HMG depends fundamentally on the strength of the whole UK climate science community, and (b) as climate modelling has become increasingly complex and multi-disciplinary it is no longer possible for the Hadley Centre to maintain world-class facilities by itself. The design of HPC services is a critical issue for enabling the collaborative environment that is necessary for the UK to maintain a world leading position in climate science. Important requirements, in addition to the baseline performance, include stability of service, openness and flexibility of user access, speed of network connectivity between the supercomputer systems and the archive(s), responsiveness to user needs (including at the design stage), availability of third-party software and effective infrastructure for sharing of technical information, for collaborative development of model code, and for archiving, sharing and analysis of data.

Recommendation 3 – The provision of high performance computing, in particular supercomputing capacity, should be reviewed again in 2012. This review should be set in the context e.g. of the Government's developing requirements for climate science advice, the prospects for supercomputing opportunities advancing within Europe and internationally, progress in further strengthening collaborations between the Met Office and UK academia, and affordability issues at that time.

A technology refresh cycle, ideally of about two years, is recommended to maximise the opportunities afforded by new technology and to allow for the lead-times required to develop more-scalable codes and advance the science. Such a cycle would also allow any emerging initiatives (e.g. European) to be reviewed at regular intervals.

Recommendation 4 – To meet the needs of collaboration between the Met Office and the academic community (outlined in recommendation 2) the existing joint Met Office/NERC service should be improved through changes to its security model, provision of systems for sharing information, model code and data, and increased network bandwidth. A review of the balance between shared (NERC/Met Office) and dedicated (Met Office only) resources is possible within Option B+, taking account of the operational constraints of climate prediction. Option C would allow for a more substantial growth of the shared service.

Recommendation 5 – Integrate top-tier supercomputing facilities with next-tier HPC facilities and grid computing infrastructure. If 50+ member ensembles are required for risk analysis, for example, it may be more cost-effective to use a network of 50+ machines rather than running such ensembles on a single facility. This requires that model development and maintenance for the top-tier implementation also takes into account the requirements of lower-tier facilities and that the UK continues to invest in the grid computing capabilities and networks to allow access to distributed compute power.

Recommendation 6 – **Pro-actively engage European stakeholders to take a lead in facilitating the provision of European climate supercomputing infrastructures in the longer-term** – the aim should be to position the UK to host one of the hubs of the proposed EU-funded next-generation supercomputing networks, and in doing so appraise opportunities to switch HMG funding from UK-based to EU-based facilities, if this would offer better value for money without unacceptable loss of control. Also, the UK should continue to engage with European institutes to develop multi-model ensembles, collective archiving facilities, and to continue to explore opportunities for 'green computing' facilities with ECMWF.

Recommendation 7 – **ensure that supercomputing facilities are built and operated in line with best-practice 'green' principles** – this will allow HMG to minimise the cost and emissions impacts of future supercomputers;

Recommendation 8 – provide appropriate resource to allow scalability work to be progressed – whilst existing activities will allow some progress to be made on scalability issues, the work is challenging and additional collaborative work and resource (e.g. at the Hartree Centre, where NERC and the Met Office plan to design and develop a new *dynamical core* suitable for atmospheric modelling on massively parallel computers) would reduce the risk that this work will not be completed on time, and might lead to larger savings in supercomputing costs in later years.

Table 3: Indicative HPC Capital and Running Costs

	Option				
	A	B	B+	C	D
	£m	£m	£m	£m	£m
Capital Costs					
HPC & MASS	0	17	19	58	185
Property Infrastructure	0	0	0	9	30
Greening IT	1.3	1.3	1.3	4	12
Network upgrades	0	0	0	3	3
Total capital cost over 2010-20	**1.3**	**18.3**	**20.3**	**71**	**227**
Operating costs					
Total cost per annum	**2.8**	**6**	**8.5**	**26**	**59**
Memorandum					
Extra staff for climate code re-design included in operating costs above	0	0	0.2	0.4	0.4

Notes:
1- capital costs are totals for period 2010-20
2- additional staff costs included in total running costs
3- total running cost is average pa over period 2010-20
4- capital costs for Options C and D include costs of providing shareable data archive for UK climate science community

Table 4: Indicative analysis of average operating costs per annum

	Option (investment level)				
Operating cost category	**A (<1x)**	**B (1x)**	**B+ (1.5x)**	**C (4x)**	**D (12.5x)**
	£m	£m	£m	£m	£m
HPC, MASS - depreciation and support	2.2	5.3	7.1	21.1	45.7
Property, green IT infrastructure - depreciation etc.	0.1	0.1	0.1	1.3	4.2
Network - depreciation, system charges	0.0	0.0	0.0	0.5	0.5
Power	0.5	0.5	1.0	2.5	8.0
Project costs	0.0	0.1	0.1	0.2	0.2
Staff - for code re-design	0.0	0.0	0.2	0.4	0.4
Total average annual operating cost	2.8	6.0	8.5	26.0	59.0

Notes
1. Indicative estimates only.
2. Power estimates based on current tariffs and current hardware

Table 5: Indicative operating cost profile

Option	2010/11 Year 1	2011/12 Year 2	2012/13 Year 3	2013/14 Year 4	2014/15 Year 5	2015/16 Year 6	2016/17 Year 7	2017/18 Year 8	2018/19 Year 9	2019/20 Year 10	Total
	£m	£m	£m	£m	£m	£m	£m	£m	£m	£m	£m
A	4	4	4	3	3	2	2	2	2	2	28
B	6	6	6	6	6	6	6	6	6	6	60
B +	6	7	9	9	9	10	9	9	9	8	85
C	6	7	30	31	31	32	30	31	30	30	258
D	6	7	72	72	72	73	72	72	71	71	588

For Options B+, C and D only, above figures include extra FTEs for code re-design work (~£70k per FTE)	FTE	FTE	FTE	FTE	FTE	FTE	FTE	FTE	FTE	FTE
Option B +	2.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	2.0	1.0
Options C and D	3.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	3.0	2.0

Notes:
1- Option A shows a decrease over time, as existing supercomputers become life-expired and depreciation charges cease. It might be possible to extend the asset lives, beyond their current life-end thus smoothing the decrease;
2 - For Options B+, C and D, the 'blips' of +£1m in 2015/16 reflect one-off project, open competition and parallel running costs incurred at times of major hardware upgrades. Hardware upgrades not entailing open market procurements would also incur some one-off costs but not to the same extent so these do not show in figures to nearest £1m;
3 - For Options C and D, 2012/13 is the first full year of depreciation on extra hardware installed in late 2011; the depreciation profile assumed is flat from 2012/13 onwards but the exact profile would depend on how hardware was acquired and used;
4 - The figures for Options C and D enshrine the cost of extra staff required to undertake major re-design of the model code. These would be profiled as indicated in the blue-shaded area above, but the differences in cost year by year do not show in figures to nearest £1m - it is the depreciation charges profile which predominates.

31 August 2010

Annex A

Terms of reference

Aims/remit: To consider future provision of and support for climate science services to the UK government. The over-arching aim is to help ensure that the Government's climate change science needs can continue to be met over the next decade, focusing in particular on developing an action plan to ensure that a sustainable solution is agreed for the Met Office Hadley Centre where it has a key role.

Building on the review of the Met Office Hadley Centre (MOHC) by Sir John Lawton and other relevant work, the group will:

1. consider at a high level the UK Government's needs and priorities for scientific evidence, advice and other services to inform and support its policies on climate change over the next 10 years;
2. develop an action plan to ensure a sustainable solution to governance and support for the MOHC where it is considered to provide key evidence, advice and other services, drawing from the conclusions and recommendations of Sir John Lawton's Review.

The group will not start from the assumption that the MOHC should continue to provide any particular service to HMG. Rather, a key element of the group's work will be to assess objectively where the MOHC will be best placed (relative to other options) to meet HMG's future needs, and it will develop an action plan to ensure a sustainable solution for the MOHC in these areas.

Timing: The group will be constituted by early February, meet for the first time by early March and aim to have concluded its work by mid-July/early August.

Secretariat support: DECC, Defra and GO-Science will provide a joint Secretariat for the group.

Membership:

- Sir John Beddington (chair)
- Bob Watson (Defra)
- David MacKay (DECC)
- Chris Whitty (DfID)
- David Clary (FCO)
- Brian Collins (BIS/DfT) - also chair of high performance computing sub-group
- Jeremy Watson (CLG)
- Terence Jagger (MoD)
- Nafees Meah (DECC)
- Rupert Lewis (Defra)
- Adrian Smith (BIS)
- Alan Thorpe (NERC)
- Julia Slingo (Met Office)
- Peter Shortt (Shareholder Executive)

NB on occasions the Committee may meet without the Met Office present where there may be conflicts of interest.

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