PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES

# Advancing national climate change risk assessment to deliver national adaptation plans

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| Journal: | *Philosophical Transactions A* |
| Manuscript ID | RSTA-2017-0295.R1 |
| Article Type: | Research |
| Date Submitted by the Author: | 15-Mar-2018 |
| Complete List of Authors: | Warren, Rachel; Tyndall Centre, School of Environmental Sciences<br>Wilby, Rob; Loughborough University<br>Brown, Kathryn; Committee on Climate Change<br>Watkiss, Paul; Paul Watkiss Associates<br>Betts, Richard; Met Office, Hadley Centre; University of Exeter, Geography<br>Murphy, James; Met Office, Hadley Centre<br>Lowe, Jason; Met Office, Hadley Centre; University of Leeds, Priestley International Centre for Climate |
| Issue Code (this should have already been entered but please contact the Editorial Office if it is not present): | RA-CCAP |
| Subject: | Climatology < EARTH SCIENCES |
| Keywords: | climate change, vulnerability, adaptation, risk assessment |
| | |

PHILOSOPHICAL TRANSACTIONS A
Submitted to Phil. Trans. R. Soc. A - Issue

*Phil. Trans. R. Soc. A.*
doi:10.1098/not yet assigned

# Advancing national climate change risk assessment to deliver national adaptation plans

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**Keywords:** risk assessment, climate change, adaptation, vulnerability

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## 1. Summary

A wide range of climate vulnerability and risk assessments have been implemented using different approaches at different scales, some with a broad multi-sectoral scope and others focused on single risks or sectors. This paper describes the novel approach to vulnerability and risk assessment which was designed and put into practice in the United Kingdom's Second Climate Change Risk Assessment (CCRA2) so as to build upon its earlier assessment (CCRA1). First, we summarise and critique the CCRA1 approach, and second describe the steps taken in the CCRA2 approach in detail, providing examples of how each was applied in practice. Novel elements of the approach include assessment of both present day and future vulnerability, a focus on the urgency of adaptation action, and a structure focused around systems of receptors rather than conventional sectors. Both stakeholders and reviewers generally regarded the approach as successful in providing advice on current risks and future opportunities to the United

Kingdom from climate change, and the fulfilment of statutory duty. The need for a well-supported and open suite of impact indicators going forward is highlighted.

## 2. Introduction

The UK was one of the first countries to advance a national assessment of climate change risks. In 1991 the Climate Change Impacts Review Group published a report on the potential effects of climate change in the UK [1] which was updated five years later [2]. Following the second report, the UK Government set up the UK Climate Impacts Programme (UKCIP) in 1997 to help coordinate scientific research into the impacts of climate change and to help organisations adapt to projected impacts. This programme facilitated a large number of studies (summarised by [3,4]).

The 2008 Climate Change Act established a new statutory framework for adaptation. Within the Act there was a requirement for Government to assess the risks of present and predicted impacts of climate change on the UK via a Climate Change Risk Assessment (CCRA). Following this, the first risk assessment was agreed to be delivered to Parliament by the end of 2011, with a continuing statutory obligation to repeat this process every five years. Moreover, the Act established an independent body, the Committee on Climate Change (CCC), and the Act specified that the CCRA should take into account the advice of the CCC Adaptation Sub-Committee (ASC) before going to Parliament.

The Act also requires the Secretary of State to lay a programme for adaptation before Parliament (a National Adaptation Programme, NAP). This must set out the objectives of the UK Government in relation to adaptation, proposals and policies (and time-scales) for meeting those objectives, and an indication of how the risks identified by the CCRA report would be addressed in policy. The NAP is reviewed every two years by the ASC. This legal context is critical because it meant that the CCRA was political as well as technical.

A scoping study by Watkiss et al. [5] set out options for the CCRA. This included a review of UK and other international climate change risk assessments. The review made recommendations about the preferred methodological approach and governance structure for the CCRA, emphasizing the need to

focus on current climate variability as well as long-term projections (combining a bottom up and top down approach), to adopt a strong policy based approach, and to structure the analysis to provide information primarily for adaptation (as the objective). It also set out options for the governance arrangements for the CCRA, emphasizing the need to include the wide expertise base in the UK.

Since then, two rounds of the Climate Change Risk Assessment have been carried out, using very different methodologies. The first, known as CCRA1, laid before Parliament in January 2012, was performed by a team of contractors (private sector consultants, academics and government scientists) who designed and implemented a comprehensive structure to the assessment, including a large amount of consultation with users of climate risk assessment advice. This involved new analysis, making use of the significant resource of the UK Climate Projections (UKCP09, see ESM) albeit with the impacts analysis and risk assessment undertaken in a short period of time. The second, CCRA2, laid before Parliament in January 2017, was academic-led and consisted of a review of peer-reviewed scientific literature, much of which had applied the UKCP09 projections.

This paper continues with a description of the methodology used in CCRA1 (section 3) to set the context to CCRA2 (section 4). We then evaluate the novelty and value-added by CCRA2 (section 5) before concluding with some reflections on possible directions for future work.

# 3. The UK's first Climate Change Risk Assessment

### 3.1 CCRA 1 Methodology

To produce the first CCRA, the UK Government commissioned a major multi-disciplinary two-year project involving industry, research and stakeholder organisations. The work was procured as an independent analysis (using a private sector provider following a competitive tender process). The CCRA was funded by UK Government and Devolved Administrations with the objective of informing the National Adaptation Programme (published in 2013) by assessing current and future risks (and opportunities) posed by the impacts of climate for the UK to the year 2100. The project compiled findings into the CCRA 2012 Evidence Report [6].

The Evidence report was followed by the CCRA 2012 Government Report [7] which outlined the UK Government's views on the main issues raised in the Evidence Report, and set out the proposals to address these risks and Government priorities for adaptation (subsequently taken forward in the NAP). Both reports were laid before Parliament in January 2012.

The CCRA drew together and interpreted evidence regarding current and future threats (and opportunities) using eleven 'sectors' to report results: Agriculture; Biodiversity & Ecosystem Services; Built Environment; Business, Industry & Services; Energy; Forestry; Floods & Coastal Erosion; Health; Marine & Fisheries; Transport; and Water. Information was also collated for five cross-cutting themes.

The methodological approach used in the CCRA involved a series of steps (or Tiers), intended to prioritise the most important risks or opportunities (henceforth referred to as risks).

An initial review (Figure 1a, '1 Literature Review and other inputs') was undertaken to identify the range of climate risks within each sector (Figure 1a, '2: policy risk mapping'). This yielded a preliminary list of 700 risks. This tier was followed by a selection process that included sector workshops to identify the most important risks, and a multi-criteria analysis (Figure 1a '3: identify main risks). Approximately 20% of the total number of risks across all sectors were selected for more detailed consideration.

These priority risks were then assessed using an impact assessment methodology (Figure 1a, boxes 7-15). The approach may be characterised as a top-down or science-first approach (see [8]), which begins with global and then regional climate model projections, then progresses to quantify bio- and physical impacts using functional relationships (linking climate variables to impact) with either models or response functions (derived from theoretical or empirical analysis). The use of impact assessment was consistent with other national assessments at the time, but a focus solely on this method did not reflect the recommendations of the scoping report nor the emerging evidence on the limitations of this approach (for informing adaptation) that were already known at the time [9,10]. Figure 1a summarises the workflow in CCRA1.

For CCRA1, the analysis started with the UKCP09 climate projections [11]. These projections were fed into a large number (140) of individual impact assessment calculations. The full probabilistic projections were

not used – instead, the 10th, 50th and 90th percentile changes from the distributions were used to sample the range in the subsequent physical impact assessment. A peer review process evaluated the overall method for each sector, and the applied impact functions. In some sectors, existing national integrated assessment models were used (e.g. for flooding); this allowed analysis of the combined effects of many variables across different receptors and risk pathways. However, for the majority of risks, impact models were not available (or the evidence base was low) and simple functions were adopted, often using single climate variables (for example temperature). Where possible impacts were quantified in quantitative terms, but where not, qualitative scoring was used based on literature review and expert judgement. The magnitude of the impacts were assessed against the interests of the UK as defined by the three 'pillars' of sustainable development: economy, society (including equity) and environment. Where possible, a distributional analysis of the impacts was undertaken and recorded, with an analysis of whether there was disproportionate impact on vulnerable groups, using for example the index of multiple deprivation. At the end of the process, priority risks were valued in economic terms. By valuing risks from the perspective of social welfare and thereby capturing the wider costs and benefits to society as a whole (rather than considering only the financial aspects) enabled analysis of their relative magnitude using a common metric.

CCRA1 also assessed adaptive capacity by examining sector progress against a set of organisational and structural success factors using detailed questionnaires and interviews [12]. The analysis focused on the capacity of organisations to take effective adaptation actions (such as identifying climate risks and making well-informed, long-term decisions to increase resilience to the impacts of climate change). This found that capacity varied significantly across sectors, but that strengthening capacity was a priority across all areas.

In addition to magnitude scoring, risks were also summarised based on the confidence in the evidence base and the urgency of decisions (to address the risk) to identify the most important and pressing risks for the UK. Information about magnitude and confidence (but not urgency) was reported using consistent scorecards of all priority risks and opportunities. Urgency scores were included in the body of the Evidence Report (though not in the key findings) and summarised those risks where further action was urgently required (i.e. within the next 5 years). These were flood and coastal erosion, natural ecosystems, water resources, overheating of the urban environment (and health service risks from heat waves) and

economic opportunities from adaptation (new products and services). The subsequent analysis in section 4 reflects on the extent to which these priorities were addressed in the period before CCRA2.

The CCRA broke new ground in terms of its very wide sectoral coverage and the exceptionally large number of potential impacts considered, as well as use of a probabilistic format for national climate projections. This breadth led to interesting findings, for example, highlighting impact categories that were not commonly identified in impact assessments at the time, but that could still be important (e.g. potential impacts on businesses and ecosystems). This also highlighted that national assessments, in other countries, may not have reported the full range of risks presented by climate change, although they may still have been capturing the most important risks. However, the breadth required to facilitate comparison between the many disparate risks inevitably led to reduced depth; the process was more time consuming and resource intensive than a more straightforward literature review and synthesis of existing sector-based risk assessments (such as an IPCC type synthesis). As a result, the CCRA did not apply in-depth modelling to all known major risks, notably agriculture [13], and thus the coverage was uneven.

It is also noted that the move from central projections for low, medium and high emission scenarios (based on the Special Report on Emissions Scenarios [SRES]) - as developed with the UKCIP02 projections and their use in previous UK assessment, see West and Gawith [4] - to the probabilistic projections in UKCP09 [11] enhanced the potential consideration of uncertainty, but was extremely challenging to apply analytically and consistently across all areas. It also led to additional challenges with reporting of this uncertainty (due to uncertainty arising from the use of multiple emission scenarios, and from the probabilistic type information for each of these emission scenarios). Thus, CCRA1 results were primarily reported for single central projections only (in the summary). Furthermore, a refresh of UK specific socio-economic scenarios had not been undertaken. This was a major omission, and while socio-economic dimensions (low and high values for different socioeconomic factors such as population) were developed using existing government datasets and assumptions regarding population and economic growth, the application of socio-economic change was applied very unevenly across different impacts. CCRA1 focussed almost exclusively on domestic risks, and did not carry out new analysis of the effects of international risks affecting the UK. This was a deliberate choice, motivated in part by limited time and resources, as a Foresight project, "International Dimensions of Climate Change", commissioned by the

Government Office for Science had been recently published on this issue [14,15]. The findings of that project were, however, summarised in CCRA1.

### 3.2 Review and lessons from CCRA1

Following the completion of the CCRA, a number of reviews were undertaken to learn lessons and recommend priorities for the CCRA2. The first was undertaken by the team that led the CCRA process and the evidence report [16]. The second and third were independent reviews commissioned by the ASC [17,18]. The final document, developed by the Adaptation Sub Committee itself [19], set out the ASC views on the research and actions needed over the subsequent two years to pave the way for an improved risk assessment in 2017.

The self-assessment [16] identified the strengths and weaknesses of the approach. These reflect the earlier discussion, identifying positives (about coverage) and negatives (surrounding challenges of cross sectoral and indirect risks, insufficient consideration of policy, lack of socio-economic scenarios). Furthermore, the availability of data was identified as a project constraint, particularly given the tight timescales, and research gaps and data ownership and licensing issues were identified. The implementation of the approach was also considered to be uneven (good in some sectors, less so in others). Box 1 summarises the most significant achievements and gaps of CCRA1 identified by Wilby [17].

**What was done**

- Synthesis of current state of knowledge on climate risks and opportunities based on evidence drawn from **stakeholder workshops**, Government reports, peer-reviewed literature, and new analysis
- Provision of a baseline assessment for more than **100 climate change risks** disregarding current and future planned action, as well as socio-economic changes
- Analysis of **risks based largely on UKCP09 projections** for three time frames (2020s, 2050s, 2080s) and three emissions scenarios (Low, Medium and High) [but only for the 2080s under Medium emissions for marine environment]
- Comparison of **social, economic and environmental threats and opportunities**
- Used a consistent method for analysing the **magnitude and confidence** in climate risks across sectors and over time (except where population trends alter the numbers of people affected by flooding, water scarcity and summer heatwaves/milder winters)
- Identification of **priorities for action in eleven sectors** (grouped into five themes: natural environment; buildings and infrastructure; health and wellbeing; business and services; agriculture and forestry)
- Published **reports** for individual sectors, themes, UK, devolved administrations (Scotland, Wales, Northern Ireland) and English regional levels

**What was not done**

- Quantification of present and future risks to the **same degree of detail for all sectors and scales**
- Treatment of future socio-economic changes and/or **existing adaptations** in a consistent way
- Analysis of **non-climatic interactions** within the system (such as technological change in agriculture)
- Evaluation of risks of **joint occurrence of multiple extremes** or cascading impacts
- Quantification of climate **risks from abroad** (e.g., changes in global food production)
- Assessment of **risks from major discontinuities and tipping points** (e.g., abrupt climate changes in the North Atlantic sector)
- Monetization of **wider/cross-sectoral impacts** (e.g., some indirect costs of major flooding)
- Assessment of **cost effectiveness** of different adaptation and/or mitigation programmes

Source Wilby, 2012.

The independent assessment [17] highlighted that a very large body of work had been compiled quickly. It concluded that the first CCRA was successful if measured against the Terms of Reference laid before the

contractors. There was also a widely held view (from consultation) that the CCRA process had been as important as the research outcomes. A key outcome of the CCRA1 was considered to be the inventory of domestic climate risks generated through stakeholder consultation and synthesis of the scientific literature, notably as this had used a consistent set of climate projections and consistent method to look at current and future risks and opportunities.

On the other hand, the review identified a recognised limitation of the response function method used in the CCRA, which limited consideration of risks from multiple climate drivers. Further, the sectoral emphasis meant that inter-dependent risks and those originating from outside the UK were only partially addressed. There are concerns that some response functions were applied when not really appropriate or in simplistic ways. The analysis also reviewed other national level climate risk assessments and concluded that although most had adopted the science first approach (as in CCRA), a policy-first framework (as set out by The Netherlands national assessment [20]) was recommended for the second CCRA.

The review also advised that the second CCRA should take forward a much narrower and deeper analysis of priority risks identified in the first CCRA and by related studies. A series of governance recommendations were also made. Perhaps most important of these was that the UK Government should take steps to improve the wider enabling environment for regular climate risk assessment in the UK, notably with measures for strengthening institutional memory and governance; sustaining long-term monitoring and reporting systems; promoting freedom of access to data and analytical tools; growing technical capacities in public and private sectors; allocating resources for strategic research programmes and bridging organisations; disseminating findings and advice at all levels of governance; and piloting different adaptation measures [17]. This strongly highlights that the lessons from a periodic national climate risk assessment process are institutional as well as technical, and without the necessary steps, the opportunity to act – learn – then act again, are quickly lost.

The third review by Watkiss and Hunt [18] concluded that the CCRA method had focused primarily on direct risks, ignoring indirect risks and international risks which when combined, were likely to be as important (as direct risks) for the UK. It also found that the use of an impact assessment method had led to a more theoretical approach, which excluded current policy (even adaptation). This reflects the challenge of including autonomous and planned adaptation in an impact assessment method, but had the

effect of over-estimating impacts. For example, when quantifying heat related mortality, the assessment ignored the heat alert system in the UK. At the same time, the use of central scenarios when reporting did not capture uncertainty and thus lost important information about the range of outcomes, insufficiently reporting risk (including tail risks). This reflects the challenge of reporting such a large number of risks with uncertainty. As with the Wilby [17], this review identified that choice of methodological approach (impact assessment) had led to an insufficient focus on current risks and not enough focus on adaptation, and had therefore been to the detriment of the key objective of the CCRA, which was to identify key risks for early adaptation.

Finally, the ASC itself considered the lessons from the reviews above, and published its own reflections [19]. The body set out the research needs and early actions that needed to be undertaken to inform the next (2017) CCRA2. This highlighted the need for a policy first approach – indeed, first and foremost, it concluded that the Government should establish clear objectives for the next risk assessment and that these should be set in the context of a set of national adaptation objectives. It also highlighted that the use of a private sector procurement model had been detrimental to the process (in terms of drawing evidence and expertise) and recommended an alternative that was more public orientated and broader based (following an existing national Foresight model). The think-piece documented the research that was needed on scientific information, impacts and adaptation for the next CCRA.

What is interesting is the adaptation-first approach recommended in all these independent reviews had been originally recommended in the 2009 scoping review. A key question is, therefore, why did the CCRA adopt a more classical impact assessment (alone)? One reason for this is that the Government had just published its new set of national climate projections, and wanted these to be at the centre of the risk assessment. In addition, the linear method of impact assessment aligns strongly with the normal policy appraisal development route in UK Government [21]: identify the problem, then assess the response. Unfortunately, this approach does not really work effectively given the unique challenges of adaptation (high uncertainty and the need to make early decisions in the short-term,). For the UK, evidence needs to be relevant to the five year planning period of the statutory national adaptation plan. Another explanation is that organisations (including Government) find it difficult to learn from other assessments and jump to more advanced methods directly (i.e. they may not go through a learning cycle themselves).

A final insight emerges when looking at what happened next, following the publication of the CCRA evidence report. One of the critical factors was that a change in Government occurred towards the end of the CCRA1 process. This led to a major change in policy with respect to climate change, and significantly altered the direction of the subsequent NAP [22] and its use of the CCRA evidence in informing adaptation priorities (somewhat negatively). This was evidenced by the lack of new policy announcements and specified budget within the NAP with which to take forward actions. Meanwhile, other policy initiatives such as the Biodiversity 2020 strategy [23] built upon a dedicated White Paper and contained ambitious, time-bound, quantifiable goals for habitat restoration. This highlights again that the translation of the CCRA into Law had advantages (the requirement for findings to be subsequently considered in policy) but also shifted to a political process and not just a technical assessment.

### 3.3 Parallel developments in other national climate risk assessments

Numerous climate risk assessments have been carried out at global, regional, national, city and local scales. They have been conducted by academic institutions, national or local governments, consultants, or by businesses. They can encompass single (e.g. flood risk, or ecosystems) or multiple sectors (e.g. water-energy-food nexus), via direct, indirect, cascading or physically remote impacts [24]. For example, the Dutch National Climate Adaptation Strategy [25] highlighted nine vulnerable sectors: water and spatial management; agriculture, horticulture and fisheries; nature; health; recreation and tourism; infrastructure; energy; IT and telecommunications; safety and security. The national climate risks requiring most urgent attention included: more heat stress caused by extreme weather conditions; more frequent failure of vital and vulnerable infrastructure due to extreme weather; increased health burden, lost productivity and higher costs due to potential rise in allergies and infectious diseases; and cumulative effects whereby failure or disruptions to one sector contribute to failure or disruptions elsewhere [25].

Although the analysis was top-down (i.e. scenario-led impact assessment), the underpinning climate change scenarios (KNMI'14) were less conventional. Instead of presenting the scenarios on a variable by variable basis, they were grouped by combinations of two global temperature increases ('Moderate' and 'Warm') and two atmospheric circulation pattern changes ('Low' and 'High' westerly airflows). Twenty-two user-relevant indicators were then created for each of the four scenarios (e.g. warmest summer day per year for healthcare). This format followed moves by other climate centres to limit the number of scenarios made available for national climate risk assessment. More generally, smaller sets of plausible

scenarios have been described as Representative Climate Futures (RCFs) [26] that can significantly reduce the effort required to evaluate risks for large numbers of climate models or probabilistic projections. In contrast, the approach adopted by CCRA (and to a lesser extent in CCRA2) was more explicitly tied to climate model experiments than to an RCF description (some say 'boundary object') that need not change between successive releases of climate model results.

The Third US National Climate Assessment (2014) was published between CCRA and CCRA2 (the Fourth US National Climate Assessment is due in 2018). The assessment documents observed and projected impacts for eight regions, rural communities and the coast, plus seven sectors and for 'widespread' impacts [27]. These included transboundary threats arising from multiple system failures (as seen when Hurricane Katrina struck New Orleans), widespread coral reef ecosystem collapse, and cascading effects across linked sectors (such as water supply and energy production/use). Two national scenarios were applied (SRES A2 and B1 emissions), comparing projections for 2071-2099 with the 1970-1999 baseline. The overall emphasis was very much on observed climate trends and vulnerabilities within these sectors and regions as indicative of future risks and opportunities. Other shared features with CCRA2 were the strong reliance on literature review and devolution of evidence to regions. There was also recognition of the benefits of a sustained (rather than quadrennial) assessment process in building national capacities to measure and evaluate climate impacts, including development of a suite of national climate impact indicators. A recent review of 70 indicators used by the ASC found that about 30% could *still* not be updated because relevant information was not identified, or data were not available or accessible to the analysts [28]. Hence, the CCRA2 approach had to strike a careful balance between pragmatism (i.e. working with what *is* available), technical rigour and feasibility, given the dual constraints of insufficient data and limited resources for additional analysis.

A key methodological development which emerged in the scientific community in relation to climate change risk assessment between CCRA and CCRA2 was arguably the development of the new narrative scenario framework which combines climate change future, quantified in terms of combinations of Representative Concentration Pathways (time series of greenhouse gas concentrations in the atmosphere, [29]) with socioeconomic narratives, quantified as Shared Socioeconomic Pathways [30]. This is a very useful analytical framework, but it was not possible to incorporate this in CCRA2 due to the fact that the latter methodology is based on literature review rather than use of a top-down, harmonized scenario

framework, partly due to budgetary constraints. Another development was an increased focus in the literature on low-emission scenarios, providing additional information about the risks associated with lower levels of global warming of 1.5-2°C above pre-industrial levels. This type of work has led to increasing discussions of the relationship between mitigation and adaptation and how this might affect the level of future risk. Since this work was at a very early stage in CCRA2, much of this literature could not be reflected in the report.

# 4. The CCRA2 Approach

The CCRA2 adopted a new comprehensive 3-step methodology for analysing the priorities for adaptation actions based on climate risks, instead of applying a harmonized, top-down risk analysis as in CCRA1 (Figure 1b). The three steps involved assessing: (1) present climate vulnerability in multiple dimensions (whilst formally including non-climate risk drivers); (2) future vulnerability to both climate and non-climate drivers; and (3) prioritizing intervention options based on transparent criteria such as effectiveness, distribution consequences and the likely feasibility of implementation. In step (3) an 'urgency scoring' framework (Figure 2) was used as a basis for prioritization. Each step is described below and a worked example relating to wildfire risk in the UK is included in the ESM.

**Step 1 Assessing current vulnerability in multiple dimensions**

The CCRA2 approach was designed to gather evidence from the widest possible range of sources, whilst treating the information in a consistent way, regardless of the sector or system affected. The first step in the three-stage methodology for scoring urgency involved literature reviews of: (i) present-day vulnerability, (ii) climate-related risks and opportunities, alongside (iii) existing levels of adaptation.

A glossary of key concepts and terms was developed for CCRA2 to improve consistency of interpretation and use of evidence [31]. Vulnerability was defined as the 'degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes' In step 1, vulnerability depends on both exposure and sensitivity. Exposure was described as the 'presence of people, livelihoods, species or ecosystems, environmental functions, services and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected (by climate variability and change)'. Sensitivity is the 'degree to which a system is affected either adversely or

beneficially by climate-related stimuli'. Risk combines the likelihood of an event with the magnitude of its consequences. Consequences may be defined according to a variety of metrics including economic, social and environmental. Risks can be either adverse costs and damages (true costs including non-monetary costs) or beneficial opportunities. In this way, risks of climate-related impacts were identified where there are existing (or expected) interactions between climate stressors with the vulnerability, exposure and sensitivity of human and natural systems. Hence, there is a risk of impacts due to changes in both the climate system and socio-economic processes. It should be noted that the term vulnerability has been variously defined by different groups and has evolved over time: in this assessment the definition used is similar to that provided in IPCC (2007)[32], because in step 2 it is also affected by the magnitude of climate change (see below).

By international standards, the UK has relatively low vulnerability and high readiness for climate change. According to the Notre Dame Global Adaptation Initiative (ND-GAIN) index[1], out of about 190 countries, the UK was ranked 8th least vulnerable and 14th most ready for climate change in 2016. This reflects the nation's comparative economic strength, quality of governance and education, standards of planning and development control, as well as investments in monitoring networks and research. Hence, a key task of Step 1 was to identify those specific economic, social and environmental systems that are most vulnerable to year-to-year climate variability and extreme weather. This may arise by virtue of their high sensitivity to climate hazards and/or geographic location relative to emerging regional climate change signals.

Assessment of current vulnerability for CCRA2 was supported by new information on recent changes in key indicators, including temperature extremes, heavy rainfall events and peak river flow (e.g. [33–35]). This was augmented by studies of individual high-impact events, providing attribution information not available to CCRA1. For example, climate model experiments suggest that the likelihood of episodes similar to the autumn 2000 floods in England & Wales, the 2003 European heatwave, and the 2014 record Central England Temperature have all increased due to human-induced climate change [36–38]. The importance of internal climate variability drivers was also emphasised, for instance by studies of the 2010-11 cold winter [39], 2013-14 winter storminess [40] and flooding [41]. In the next step of the CCRA2 process, the effects of future changes in climate (as well as other drivers) are taken into account.

[1] http://gain.nd.edu/our-work/country-index/rankings/

**Step 2**

**2.1 Assessing future vulnerability, including non-climate risk drivers as well as climate drivers**

Future vulnerability is a function of exposure to climatic hazards, sensitivity and adaptive capacity, and hence a risk assessment must consider the future socio-economic development pathway alongside the expected climatic change. For example, in the absence of adaptation, further economic and population growth can increase exposure (for example to drought). In CCRA2, the limited resources did not allow for the use of a set of harmonised future projections of climate change and socioeconomic scenarios which could be combined to produce a holistic set of climate change risk projections. Instead, it draws on evidence from the literature that utilises a range of socioeconomic and climatic scenarios and assumptions. In contrast the CCRA1 analysis of future vulnerability was underpinned mainly by changes in multi-decadal averages from the UKCP09 scenarios [11]. However in CCRA2, in addition to the use of literature that used UKCP09, CCRA2 analysts were able to draw on alternative climate modelling results, including future projections from the latest (CMIP5) generation of international climate models [42] as well as new socioeconomic scenarios [30]. The potential for socioeconomic shocks (for example in the wake of extreme weather events) was also considered in relevant parts of CCRA2.

In reviewing the literature, authors of CCRA2 were asked to consider (1) how relevant climatic factors and therefore impacts might change in the future, including an assessment of the uncertainties; (2) which socioeconomic factors could influence the risk/opportunity in the future, and how might changes in these affect the magnitude of the risk; (3) when considering changes involving crossing a threshold, to consider the likelihood of that change occurring; (4) to record evidence for the 2020s (2010-2039), 2050s (2040-2069), and 2080s (2070-2099) separately, where applicable; (5) consider or quantify potential interactions between risks or opportunities and the net effects of risks or opportunities acting together for both incremental change and extreme events; (6) as well as producing a baseline for 'no additional adaptation action' also consider how currently planned adaptation, or future additional adaptation, would affect the overall future risk (see section 2.2).

The CCRA2 assessment also benefited from new evidence on future extreme weather derived from extensions of UKCP09 to provide new advice on daily [43] and seasonal [44] extremes that could be set in

the context of recent events. Moreover, new capability emerged for estimating future changes in sub-daily rainfall extremes, using connective-scale simulations [45].

In CCRA2, greater emphasis was placed on communicating the degree of confidence that can be placed in quantitative risk information available from climate model products such as UKCP09 or CMIP5. These included interpretations of the recent global warming "hiatus" [46], the plausible range for global climate sensitivity, and the potential for climate "surprises" associated with phenomena not yet (or partly) represented by models [42].

The above lines of evidence were synthesised, in particular, in a CCRA2 report on unlikely but plausible "H++" scenarios, considering extreme outcomes for mean sea level rise and changes in storm surges [47,48], heatwaves, cold spells, rainfall, river flows, droughts, windstorms and wildfires [49]. This drew extensively on UKCP09, CMIP5 and other climate model results, but also accounted for information from past observations and physical understanding (e.g. working through the potential consequences of a collapse of the Atlantic overturning circulation).

### 2.2 Treatment of adaptation

In the science-first, impact-assessment method (used in CCRA1), adaptation is the final step in the chain of analysis. Indeed, adaptation was assessed only after the CCRA was completed in the subsequent Economics of Climate Resilience (ECR) [50] and NAP.

For this reason and others (the focus on the medium- and long-term, the omission of existing policy and plans, and insufficient consideration of the objectives and factors determining the adaptation process, see [51,52]), impact assessment (on its own) does not provide the necessary information for early, practical adaptation. Reflecting on these lessons, CCRA2 more explicitly sought to consider adaptation, and support decision-making in the near-term, through two key innovations.

First, the assessment integrated existing policies and potential adaptation within the core CCRA2 process, rather than in an *ex post* stage as in CCRA1. Review teams were asked to consider how risks were/could be affected by three levels of adaptation:

• The current level of adaptation (assuming no additional action). This scenario was applied in step 1 of the urgency scoring framework in step 3 (see below).

• Current objectives (planned or announced policy or actions) and autonomous adaptation. This scenario was applied in step 2 of the urgency scoring framework.

• Current objectives+ (beyond current policy) looking at the potential for planned adaptation.

Second, the framing of adaptation considered the challenge of uncertainty around climate change [53], recognising that this makes it difficult to estimate the benefits (and costs) of adaptation and that a predict-and-optimise approach is not appropriate. In response, an iterative risk management framework (decision making under uncertainty) was adopted in CCRA2. This places a greater emphasis on adapting to current climate variability as well as future climate change uncertainty. It also developed a typology of three early adaptation interventions that were the priority for NAP and which review teams should identify. These were:

• To address existing adaptation deficit in the UK by implementing 'low-regret' actions to reduce risks associated with current climate variability.

• To intervene early to ensure that adaptation is considered in decisions that have long lifetimes, such as major infrastructure developments or land-use change, in order to avoid 'lock-in'.

• To fast-track early adaptation steps for decisions that have long lead times, as well as to initiate early activities that provide information to improve adaptation decisions in the future (e.g. by enabling research, monitoring and piloting to enhance learning).

At the national level in CCRA2, these three types of intervention are complementary.

Finally, there was a focus on the potential barriers to adaptation such as market failures, policy failures, governance failures and behavioural barriers (see [54,55]). These make it harder to plan and implement adaptation actions. In CCRA2, barriers were considered much earlier in the analysis, within the CCRA process itself rather than afterwards in the ECR of CCRA1.

**Step 3 Prioritizing intervention options based on transparent criteria such as effectiveness, distribution consequences and the likely feasibility of implementation**

When designing effective interventions, it is important for policy makers to understand not only how risks and adaptations options may look like in the future, but whether there is a case for additional policy or

other actions. For CCRA1, the Government produced a specification outlining what the CCRA should produce and how. For example, the assessment was required to build on the latest set of UK Climate Projections, UKCP09. Less emphasis was placed on what the intended outcome should be for Government as a result of the CCRA [17]. This was remedied for CCRA2 through the creation of a customer requirement document, produced by the Department for Environment, Food and Rural Affairs in consultation with other Government departments and the Devolved Administrations. This paper asked for analysis to define the policy areas where additional adaptation action would be most likely needed in the five year period following the CCRA, from 2017 to 2022. The requirement paper also set out that such priorities might be where the level of risk was deemed to be high; where there are substantial evidence gaps in understanding the level of risk; and/or where the level of risk was increasing despite any actions already in place [56].

To set priorities for further Government intervention, CCRA2 used a simple conceptual framework based on the idea of 'urgency', using a flow chart method shown in Figure 2. below [57], which fits into the overall CCRA2 framework shown in Figure 1b under the 'Step 3' box.

Each risk or opportunity assessed in the CCRA was assigned one of four urgency categories as shown in Figure 2. 'More action needed' and 'research priority' are defined as those risks or opportunities requiring further work over the next five years, whereas 'sustain current action' and 'watching brief' risks and opportunities were defined as less urgent. The definitions used for each category were as follows:

- **More action needed.** New, stronger or different government policies or implementation activities – over and above those already planned – are needed in the next five years to reduce long-term vulnerability to climate change.
- **Research priority.** Further investigation is needed in the next five years to fill significant evidence gaps or to reduce the uncertainty in the current level of understanding in order to better evaluate the scope for additional adaptation.
- **Sustain current action.** Current or planned levels of activity are appropriate, but continued implementation of these policies or plans is needed to ensure that the risk continues to be managed in the future. This includes any existing plans to increase or change the current level of activity.

- **Watching brief.** Evidence in these areas should be kept under review, with long-term monitoring of risk levels and adaptation activity so that further action can be taken if necessary.

To arrive at one of the four urgency categories, the report authors used the evidence collected on current and future vulnerability and degree of adaptation described above (see section 2.2), to derive a measure of the benefits of additional action in the next five year period. It was important for the urgency scores to be documented transparently, so each step of the framework for every risk was outlined in an accompanying document to the CCRA Synthesis Report. This material was subsequently checked by both a technical peer review panel and a stakeholder review.

A particular analytical challenge arose when justifying 'more action needed' in the next five years. Assessing priorities for additional action on climate change adaptation using an economic framework is challenging for reasons, such as:

- Monetisation of risks is desirable as it allows comparison of impacts across different sectors. However, the costs from the impact of a risk, and the benefits of action to mitigate the risk cannot be fully quantified in most cases due to uncertainties about the future scale and extent of the impact, and imperfect knowledge on the size of impact and effects of adaptation action to reduce the risk. This was found to be particularly true for risks associated with health and the natural environment, in CCRA2.
- In some cases there are limits to adaptation – even in a world where money is no object, it may not be physically possible to reduce the risk to zero or to an acceptable level, particularly in scenarios with higher levels of warming. These limits are not well quantified.
- Risk acceptability criteria could be used as a basis for scoring where this is known, but although many policies may have implicit risk acceptability underpinning them, these judgements are often not clearly articulated.

Following a consultation period, in place of a precise cost-benefit exercise, the following criteria were instead used to justify those risks or opportunities where additional action was needed. 'More action needed' was assigned to the risk or opportunity where any of these statements were applicable:

- Further action retains flexibility, avoiding lock-in to a particular pathway over the next few decades.

- Further action helps to create the right conditions to adapt later (e.g. putting in place measures for changes that have long lead times, or that create the right institutional conditions to adapt later).
- Further action provides the early steps, for example, awareness-raising, capacity-building, research, or monitoring that will enable better decisions in the near future (next five years), especially in relation to longer-term major risks. That is, to build early interventions within an iterative adaptive management framework.
- Further action has benefits for managing a wide range of climate and non-climate related risks.
- Further action is cost-effective to implement now.
- Further action reduces vulnerability now.

CCRA2 stopped short of then defining what precise actions should be taken. Resource limitations meant that a robust options appraisal exercise was not feasible within the scope of the project. CCRA2 therefore carried the same limitations as CCRA1 on options analysis. Although CCRA1 was followed by an economic asssesment [50], this was not the case for CCRA2 as there was no budget within Government to take this work forward. Such an exercise needs to assess for each risk what options for further action are available; the costs and benefits of each; the distributional consequences of each option and other factors such as political or social acceptability. Separately from the CCRA process, the ASC reports biannually on progress on adaptation in England, which includes supporting analysis on the costs and benefits of different options for managing risks. This analysis is summarised in a series of recommendations to Government on further action, which the Government must publicly respond to (for example, see: [58]).

# 5. Discussion

The CCRA2 advanced the earlier CCRA1 methodology and reflected shifts in emphasis of climate risk and vulnerability assessment that had evolved within and beyond the UK research-practitioner communities. At least five aspects of the CCRA2 approach are regarded as novel:

(1) By auditing both ***present-day and future vulnerability*** to climate risks, existing adaptation deficits are duly acknowledged. This provides a basis for understanding how existing exposures and vulnerabilities might evolve as both the climatic and socio-economic context of the UK changes.

(2) By basing the analysis on ***literature review*** rather than quantitative assessment of response functions, CCRA2 was able to assemble the evidence in a more inclusive and consistent way despite variations in the information available.

(3) By focusing the analysis on ***urgency***, attention was fixed on where action is needed most within the five year timeframe of the NAP (2018-2022). Although specific adaptation options were not identified the CCRA2 framework was inherently 'solution' rather than 'problem' facing.

(4) By structuring the Evidence Report around ***systems of receptors*** (e.g. 'People and Built Environment') rather than conventional sectors (e.g. 'Energy', 'Transport', 'Health'), chapter authors were compelled to think more deeply about the interconnectedness of risks and opportunities (including for those originating from outside the physical footprint of the UK).

(5) By ***benchmarking risks and opportunities*** against the amount of global warming above pre-industrial levels, chapter authors and the CCRA2 Synthesis Report attempted to harmonize information reflecting quite different socio-economic and emissions pathways.

The overall benefit of the above innovations was that CCRA2 cost the UK taxpayer ~£650,000 compared with £3,455,675 for CCRA, whilst also dovetailing better with the information needs of the subsequent NAP. However, the urgency scores are all ultimately based on expert judgement and, like the forerunner, CCRA2 was still hampered by evidence/data gaps in some important domains (e.g. high-resolution data on emerging or projected patterns of non-native species). The literature review was also potentially biased because it relied on information harvested from an open call for evidence, rather than a systematic appraisal process.

A review process for CCRA2 was built in to the project from the outset. Success criteria were defined for the project early on, in consultation with end users, as follows:

1. The CCRA fulfils the ASC's statutory duty to provide independent advice to the Defra Secretary of State on the current and future risks and opportunities to the UK from climate change before July 31st 2016.
2. It is deemed fit for purpose by the CCRA advisory group.
3. It provides an interpretation of the key risks and opportunities to the UK (England, Scotland, Wales and Northern Ireland) from climate change.
4. It is completed on time.
5. It is completed within the specified budget.

6. It is conducted in a transparent way and there is opportunity for anyone to input.
7. It addresses the comments made through peer review.
8. It is considered by the majority of the academic community to be a robust and intelligent piece of analysis.
9. It is proven to be accessible, understandable, and is used by the policy community.
10. It gives new insights (not just a summary of what is already known) to the policy community on the risks and opportunities from climate change.
11. It improves upon the limitations and builds on the positive aspects of CCRA1.

These simple, measurable criteria were reviewed at the end of the project. Criteria 1-7 were evaluated through a simple tick box exercise, based on author, reviewer and stakeholder feedback collated by the Adaptation Sub-Committee. Criteria 8 -11 are more challenging to answer and require further research and feedback over time, once CCRA2 is used to underpin the next NAP and other areas of policy development. This paper provides part of that analysis, and it is expected that other independent reviews of the success or otherwise of CCRA2 will be undertaken, as was the case for CCRA1 (e.g. [17,18,59]).

# 6. Conclusion

The attention given in CCRA2 to vulnerability, taking into account current adaptation deficits, and "urgency" of action, means that the risk-based analysis should be more tangible and readily adopted by the National Adaptation Plan than the analysis provided by CCRA1. The integrating, cross-sectoral approach was a significant advance upon CCRA1, yet the process remains hampered by a lack of (or access to some other) important climate impact indicators. The CCRA2 approach was highly pragmatic and heavily dependent on goodwill so it is unclear whether this would be repeatable in the future. Its findings were synthesized [60] and in particular a summary diagram highlighting how impacts in six key areas accrue with global warming [60, Figure SR1]. These risks are to: (1) flooding and coastal change impacts on communities, businesses and infrastructure; (2) health, well-being and productivity under extreme temperatures; (3) shortages of water supply for the public, agriculture, energy generation and industry; (4) natural capital, including terrestrial, coastal, marine and freshwater ecosystems, soils and biodiversity; (5) domestic and international food production and trade; and (6) new and emerging pests and diseases, and invasive non-native species, affecting people, plants and animals. These risks provide the basis for

development of a small set of UK 'Reasons for Concern' (RFCs) for CCRA3 as a means of improving continuity and intelligibility of successive national scenarios. RFCs have been used at the global scale to provide a synthesis indicating how climate change risks accrue with global mean temperature rise [61]. Looking ahead, a well-supported and open suite of climate impact indicators will also be needed to track emerging risks and outcomes of adaptation interventions.

# 7. Additional Information

**Authors' Contributions** KB led the production of CCRA2 and made a major contribution to the design of the CCRA2 methodology. RFW led the methodology chapter of CCRA2 and the production of this paper. All authors contributed to the design of the CCRA2 methodology. In particular, PW and RLW provided insights from CCRA1 and advice relating to adaptation and vulnerability. RFW, RLW, KB, PW, RAB, JMM and JL all contributed text to the paper.

**Competing Interests** The author(s) declare that they have no competing interests.

**Funding Statement** KH and RFW were funded by the UK Climate Change Committee. RFW and RAB were funded by the European Union Seventh Framework Programme FP7/2007–2013 (grant number: 603864, HELIX). RAB, JMM and JAL were funded by the BEIS/Defra Met Office Hadley Centre Climate Programme GA01101

**Acknowledgements** Glenn Watts and Nicola Ranger were co-authors of Ch 1 of the second UK Climate Change Risk Assessment.

# 8. References

1. CCIRG (United Kingdom Climate Change Impacts Review Group). 1991 *The potential effects of climate change in the United Kingdom*. London: HMSO.

2. CCIRG (United Kingdom Climate Change Impacts Review Group). 1996 *Review of the Potential Effects of Climate Change on the United Kingdom: 2nd Report*. London: Stationery Office Books.

3. McKenzie Hedger M, Gawith M, Brown I, Connell R, Downing TE, editors. 2000 *Highlights of the first three years of the UK Climate Impacts Programme*. Oxford: UKCIP and DETR.

4. West CC, Gawith MJ, editors. 2005 *Measuring progress: Preparing for climate change through the UK Climate Impacts Programme*. Oxford: UKCIP. See http://www.ukcip.org.uk/wp-content/PDFs/MeasuringProgress.pdf.

5. Watkiss P, Hunt H, Horrocks L. 2009 Final Report for the Scoping Study for a National Climate Change Risk Assessment and Cost-Benefit Analysis.

6. HR Wallingford. 2012 The UK Climate Change Risk Assessment 2012 Evidence Report. Project deliverable number D.4.2.1.

7. HM Government. 2012 *The National Adaptation Programme: Making the country resilient to a changing climate*. London: The Stationary Office.

8. IPCC. 1996 *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analysis: Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

9. Füssel H-M, Klein RJT. 2006 Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking. *Climatic Change* **75**, 301–329. (doi:10.1007/s10584-006-0329-3)

10. Carter TR, Jones RN, Lu X, Bhadwal S, Conde C, Mearns LO, O'Neill BC, Rounsevell MDA, Zurek MB. 2007 New Assessment Methods and the Characterisation of Future Conditions. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson), pp. 133–171. UK: Cambridge University Press.

11. Murphy JM *et al.* 2009 UK Climate Projections Science Report: Climate change projections.

12. Ballard D, Black D, Lonsdale K. 2013 Initial Assessment of the UK's Adaptive Capacity for Responding to the Impacts of Climate Change.

13. Semenov MA, Mitchell RAC, Whitmore AP, Hawkesford MJ, Parry MAJ, Shewry PR. 2012 Shortcomings in wheat yield predictions. *Nature Climate Change* **2**, 380–382. (doi:doi:10.1038/nclimate1511)

14. Foresight International Dimensions of Climate Change. 2011 Final Project Report.

15. Sentance A, Betts R. 2012 International dimensions of climate change. *Climate Policy* **12**, S1–S5. (doi:10.1080/14693062.2012.735804)

16. HR Wallingford. 2012 Climate Change Risk Assessment Recommendations Report.

17. Wilby RL. 2012 Frameworks for delivering regular assessments of the risks and opportunities from climate change: An independent review of the first UK Climate Change Risk Assessment.

18. Watkiss P, Hunt A. 2012 Scoping Study: Reviewing the Coverage of Economic Impacts in the CCRA.

19. ASC (Adaptation Sub Committee). 2012 Climate change – is the UK preparing for flooding and water scarcity?

20. PBL Netherlands Environmental Assessment Agency. 2011 *Climate Adaptation in the Dutch Delta. Strategic options for a climate-proof development of the Netherlands*. The Hague, The Netherlands. See

http://www.pbl.nl/sites/default/files/cms/publicaties/PBL-2012-Climate-Adaptation-in-the-Dutch-Delt-500193002.pdf.

21. HTM (Her Majesty's Treasury). 2007 *The Green Book. Appraisal and Evaluation in Central Government Treasury Guidance*. London: The Stationary Office.

22. HM Government. 2013 *UK Climate Change Risk Assessment: Government Report*. London: The Stationary Office.

23. Defra. 2011 Biodiversity 2020: A strategy for England's wildlife and ecosystem services.

24. Wilby RL, editor. 2017 Who or What Is Most at Risk from Climate Change? In *Climate Change in Practice: Topics for Discussion with Group Exercises*, pp. 141–159. Cambridge: Cambridge University Press. (doi:10.1017/9781316534588.010)

25. NAS (Dutch National Climate Adaptation Strategy). 2016 Adapting with ambition.

26. Whetton P, Hennessy K, Clarke J, McInnes K, Kent D. 2012 Use of Representative Climate Futures in impact and adaptation assessment. *Climatic Change* **115**, 433–442. (doi:10.1007/s10584-012-0471-z)

27. Melillo JM, Richmond T (T. C., Yohe GW. In press. Highlights of Climate Change Impacts in the United States: The Third National Climate Assessment.

28. ADAS. 2017 Research to provide updated indicators of climate change risk and adaptation action in England.

29. van Vuuren DP *et al.* 2011 The representative concentration pathways: an overview. *Climatic Change* **109**, 5. (doi:10.1007/s10584-011-0148-z)

30. O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR, Mathur R, van Vuuren DP. 2014 A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change* **122**, 387–400. (doi:10.1007/s10584-013-0905-2)

31. ASC (Adaptation Sub Committee). 2010 How Well Prepared is the UK for Climate Change?

32. IPCC. 2007 *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

33. Jones MR, Fowler HJ, Kilsby CG, Blenkinsop S. 2013 An assessment of changes in seasonal and annual extreme rainfall in the UK between 1961 and 2009. *Int. J. Climatol.* **33**, 1178–1194. (doi:10.1002/joc.3503)

34. Kendon M. 2014 Has there been a recent increase in UK weather records? *Weather* **69**, 327–332. (doi:10.1002/wea.2439)

35. Watts G *et al.* 2015 Climate change and water in the UK – past changes and future prospects. *Progress in Physical Geography: Earth and Environment* **39**, 6–28. (doi:10.1177/0309133314542957)

36. Pall P, Aina T, Stone DA, Stott PA, Nozawa T, Hilberts AGJ, Lohmann D, Allen MR. 2011 Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature* **470**, 382–385. (doi:doi:10.1038/nature09762)

37. Christidis N, Jones GS, Stott PA. 2014 Dramatically increasing chance of extremely hot summers since the 2003 European heatwave. *Nature Climate Change* **5**, 46.

38. King AD, Oldenborgh GJ van, Karoly DJ, Lewis SC, Cullen H. 2015 Attribution of the record high Central England temperature of 2014 to anthropogenic influences. *Environmental Research Letters* **10**, 054002.

39. Maidens A, Arribas A, Scaife AA, MacLachlan C, Peterson D, Knight J. 2013 The Influence of Surface Forcings on Prediction of the North Atlantic Oscillation Regime of Winter 2010/11. *Mon. Wea. Rev.* **141**, 3801–3813. (doi:10.1175/MWR-D-13-00033.1)

40. Matthews T, Murphy C, Wilby RL, Harrigan S. 2014 Stormiest winter on record for Ireland and UK. *Nature Climate Change* **4**, 738. (doi:doi:10.1038/nclimate2336)

41. Huntingford C *et al.* 2014 Potential influences on the United Kingdom's floods of winter 2013/14. *Nature Climate Change* **4**, 769. (doi:doi:10.1038/nclimate2314)

42. Collins M *et al.* 2013 Long-term Climate Change: Projections, Commitments and Irreversibility. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 1137–1216. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

43. Brown SJ, Murphy JM, Sexton DMH, Harris GR. 2014 Climate projections of future extreme events accounting for modelling uncertainties and historical simulation biases. *Climate Dynamics* **43**, 2681–2705. (doi:10.1007/s00382-014-2080-1)

44. Sexton DMH, Harris GR. 2015 The importance of including variability in climate change projections used for adaptation. *Nature Climate Change* **5**, 931–936. (doi:doi:10.1038/nclimate2705)

45. Kendon EJ, Roberts NM, Fowler HJ, Roberts MJ, Chan SC, Senior CA. 2014 Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change* **4**, 570. (doi:doi:10.1038/nclimate2258)

46. Trenberth KE. 2015 Has there been a hiatus? *Science* **349**, 691–692. (doi:10.1126/science.aac9225)

47. Lowe JA *et al.* 2009 UK Climate Projections science report: Marine and coastal projections.

48. Ranger N, Reeder T, Lowe J. 2013 Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. *EURO Journal on Decision Processes* **1**, 233–262. (doi:10.1007/s40070-013-0014-5)

49. Met Office. 2015 Developing H++ climate change scenarios for heat waves, cold snaps, droughts, floods, windstorms and wildfires.

50. Frontier Economics, Irbaris and Ecofys. 2013 The Economics of Climate Resilience.

51. Watkiss P, Hunt A. 2011 Method for the UK Adaptation Economic Assessment (Economics of Climate Resilience).

52. Downing TE. 2012 Views of the frontiers in climate change adaptation economics. *WIREs Clim Change* **3**, 161–170. (doi:10.1002/wcc.157)

53. Wilby RL, Dessai S. 2010 Robust adaptation to climate change. *Weather* **65**, 180–185. (doi:10.1002/wea.543)

54. Cimato F, Mullan M. 2010 Adapting to Climate Change: Analysing the Role of Government.

55. Klein RJT, Midgley GF, Preston BL, Alam M, Berkhout FGH, Dow K, Shaw MR. 2014 Adaptation opportunities, constraints, and limits. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds CB Field, VR Barros, DJ Dokken, KJ Mach, MD Mastrandrea, TE Bilir, M Chatterjee, KL Ebi, YO Estrada, RC Genova, et al.), pp. 899–943. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

56. Humphrey KA. 2015 UK Climate Change Risk Assessment Evidence Report – Method.

57. Warren R, Watkiss P, Wilby RL, Humphrey K, Ranger N, Betts R, Lowe J, Watts G. 2016 UK Climate Change Risk Assessment Evidence Report: Chapter 2, Approach and Context.

58. ASC (Adaptation Sub Committee). 2017 Progress in preparing for climate change.

59. Brown I. 2015 Comparative Risk Assessment to Inform Adaptation Priorities for the Natural Environment: Observations from the First UK Climate Change Risk Assessment. *Climate* **3**. (doi:10.3390/cli3040937)

60. CCC (Committee on Climate Change). 2016 UK Climate Change Risk Assessment 2017 Synthesis Report: priorities for the next five years.

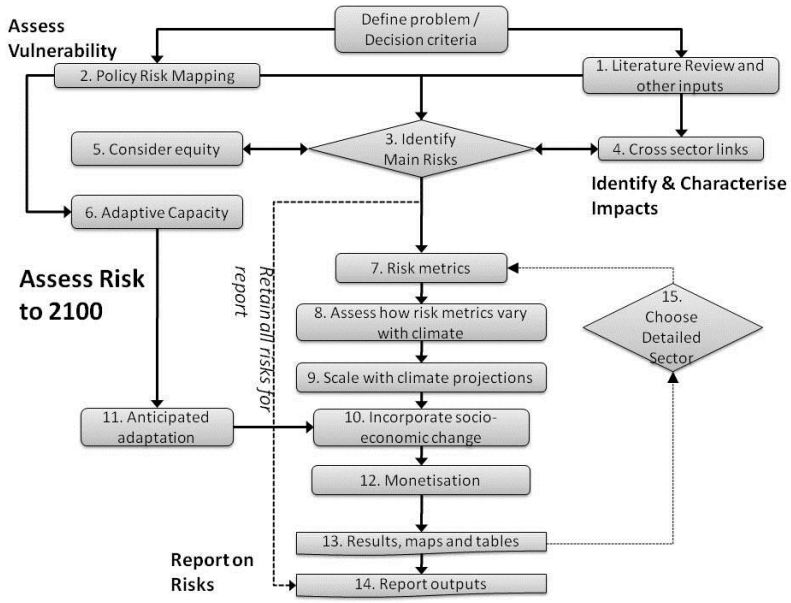
61. O'Neill BC *et al.* 2017 IPCC reasons for concern regarding climate change risks. *Nature Climate Change* **7**, 28. (doi:doi:10.1038/nclimate3179)

**Figure 1a CCRA1 methodology**

**Figure 1b CCRA2 methodology**

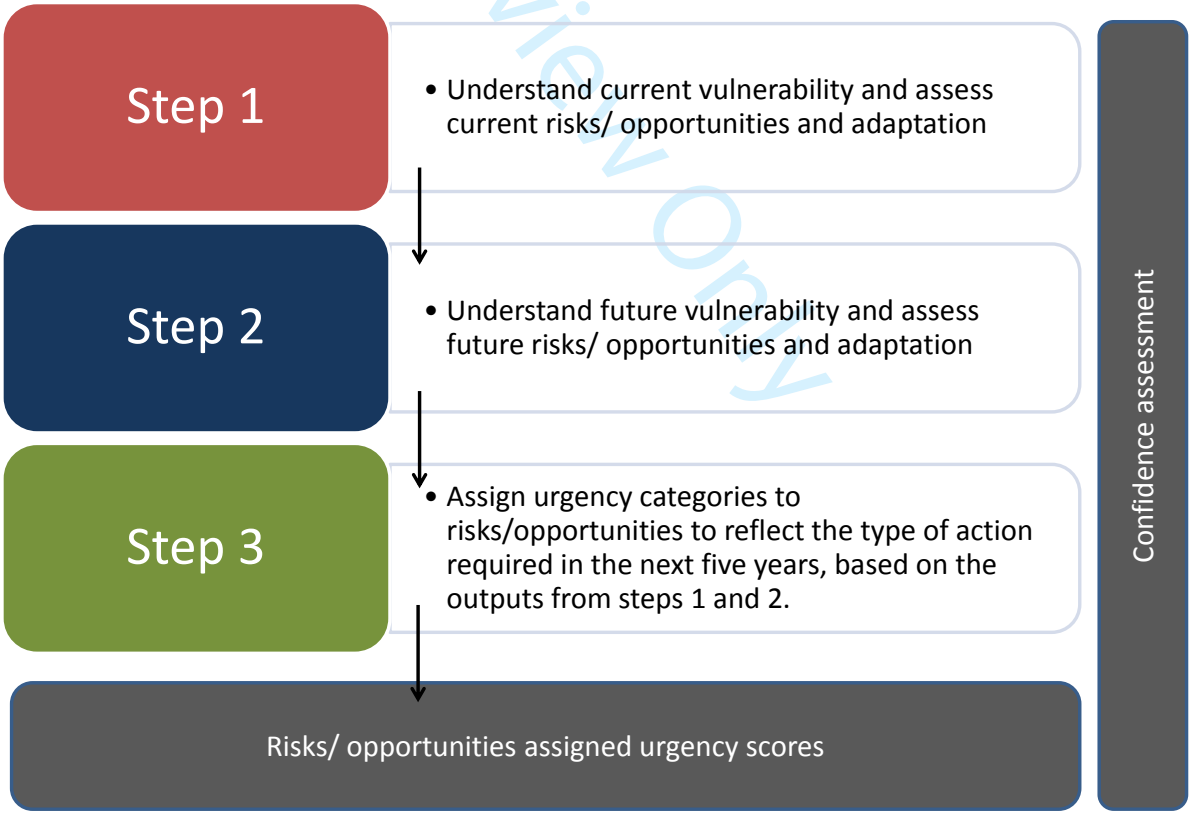
**Figure 2 CCRA2 Urgency Scoring Framework**

a)




b)

**Figure 1b:** The CCRA three-step methodology




**Source:** ASC (2014)