Tyndall°Centre
for Climate Change Research

The identification and evaluation of suitable scenario development methods for the estimation of future probabilities of extreme weather events

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SECTION 1 – OVERVIEW OF PROJECT WORK AND OUTCOMES

NON-TECHNICAL SUMMARY

Climate change scenarios often describe changes in average conditions, without including estimates of changes in the magnitude and occurrence of extreme weather events (e.g., storms or extremes of temperature and rainfall). This project, funded by the Tyndall Centre as part of Research Theme 3 (Adapting to Climate Change), identified and tested several methods with the potential for including probabilities of extreme events in scenarios, focusing on rainfall. Two approaches for generating realistic simulations at fine scales from coarse-resolution global climate models were compared: statistically-based prediction of local precipitation from larger-scale circulation and moisture fields, and a modelling approach using the output from a fine-resolution regional climate model. By appraising the methods and evaluating the credibility of their results for a case study of UK meteorological drought, an authoritative account of the pros and cons of the scenario development methods was produced. Both methods improve upon the global climate model simulation of present-day climate and its variability. It was shown that scaled relationships between UK precipitation and global-mean temperature could be used to replicate the UK drought event scenarios derived directly from the global or regional climate simulations. These scaling relationships were applied to generate probability-based scenarios of future UK drought frequency, expressed in terms of a benchmark event (summer 1995) whose impacts are known. These scenarios incorporate uncertainties in greenhouse gas emissions and climate sensitivity, though they are conditional upon the assumed relationship between UK precipitation and global temperature derived from a single climate model.

OBJECTIVES

- To identify the range of scenario development methods that are most suitable for extremes of weather and climate, to expertly assess their limitations/problems, and to explore solutions for overcoming these limitations/problems.
- To quantitatively test and compare the most promising scenario development methods using specific UK case studies (such as drought).
- To develop guidelines for the subsequent construction of reliable and consistent scenarios of extremes for the UK, outlining strategies to allow scenarios of extremes to be used in probability-based impact assessments and subsequently in integrated assessment models (IAMs).

WORK UNDERTAKEN AND RESULTS

An initial workshop, with invited stakeholder representatives and scenario/climate model experts, scoped out the key types of weather extremes for which scenarios are required. The importance of 'benchmarking' against real, experienced events was highlighted. The workshop, augmented by an extensive literature review, identified the range of scenario methods that might be used for extremes and this, together with an appraisal of their relative advantages and limitations, forms Tyndall Working Paper 6. The review was extended to consider the representation in IAMs of all forms of climate change (not just weather extremes), and this major review paper has been accepted for publication in the journal *Integrated Assessment*.

The most promising methods were explored in a case study of UK meteorological drought. Characteristics of mean precipitation and its inter-monthly to inter-annual variability as simulated by a relatively coarse resolution global climate model (GCM) were evaluated, and compared with two alternative methods for downscaling the GCM output to produce more realistic simulations at finer resolution. The first was a *statistical* approach, using empirically-defined relationships to predict local precipitation from the GCM's larger-scale circulation and moisture fields; the second was a *dynamical modelling* approach, using directly the output from a fine resolution regional climate model (RCM) embedded within the GCM. [The GCM and RCM were the HadCM3 and HadRM3 models of the Hadley Centre for Climate Prediction and Research, with the model output provided by the Climate Impacts LINK Project; the statistical method used the Statistical DownScaling Model (SDSM) developed by Rob Wilby.]

All three methods produced qualitatively similar results, with wetter winters and notably drier summers over the UK, and enhanced inter-annual variability in summer characterised by an increasingly skewed distribution of summer rainfall amounts (frequent very dry months, with occasional very wet months). Quantitative differences were apparent, however, in terms of the relative magnitude of the summer drying and the length of the period of reduced rainfall. These differences carried over to the occurrence of meteorological drought events, identified by accumulated deficits in precipitation that were benchmarked against the short summer drought of 1995 or the extended drought of 1976. Short summer droughts increased substantially in frequency using all these methods, but to a lesser extent using statistical downscaling than for the GCM or RCM. Multi-season droughts increased slightly in frequency in the RCM and the statistically-downscaled scenarios, but not when using the GCM output directly.

In cases (e.g., an Integrated Assessment Model) for which the climate system does *not* follow a greenhouse gas emissions pathway that has already been simulated with a GCM (thus precluding the use of any of the three methods considered), a common approach is to scale GCM-based patterns of change in average climate by a simulated global-mean temperature change. Analysis of the HadCM3 GCM simulations demonstrated that parameters describing changes in the *variability* – and thus extremes – of UK precipitation also scale quasi-linearly with global-mean temperature change, in a way that is robust over the range of temperature changes and rates of temperature change considered in the study. A method was devised that allowed observed precipitation time series to be perturbed by these changes in variability and mean, to generate scenarios for an arbitrary temperature change. This method reproduced the directly simulated changes in meteorological drought frequency of the GCM and the RCM, and was used to generate probability density functions (PDFs) of future UK drought that account for many of the uncertainties (including emissions and climate sensitivity). The PDFs are, however, still conditional upon the GCM- or RCM-simulated relationship between global temperature and UK precipitation.

The case study results and literature review have been used to develop guidance on the future development of scenarios that include information about extremes. If, as here, the veracity of their simulation of present-day precipitation and its variability is the only indicator of performance, then either statistical or RCM-based downscaling is a clear improvement over the direct use of GCM output. Because more of the GCM-biases remained when using the statistical downscaling approach, we tentatively recommend the use of RCM simulations where these exist.

RELEVANCE TO TYNDALL CENTRE RESEARCH STRATEGY & OVERALL CENTRE OBJECTIVES

This project is directly relevant to one of the key questions of Tyndall Theme 3, i.e., 'what tools and scenario assessment methodologies does an institution seeking to adapt require?' Changes in extreme weather events are likely to impose impacts on many economic activities and natural systems – thus driving adaptive responses – and so the project results are relevant to the Theme 3 flagship project on 'A theory of adaptive capacity'. The results related to scaling of precipitation variability will shape how the Tyndall Centre's Integrated Assessment Model incorporates information about extreme weather events, with relevance to the Theme 1 flagship project on 'A modular multi-purpose integrated assessment system'.

POTENTIAL FOR FURTHER WORK

The most promising scenario development methods for the estimation of future probabilities of extreme weather events which have been identified and evaluated during the course of this project are being further evaluated in ongoing European Commission-funded projects such as STARDEX (STAtistical and Regional dynamical Downscaling of EXtremes for European regions: co-ordinated by Clare Goodess). It is anticipated that these methods will also be further refined and developed as part of other projects in which the investigators are involved (e.g., work by Clare Goodess on the construction of climate scenarios as part of the EPSRC/UKCIP programme on 'The impacts of climate change on the built environment, transport and utilities'). Guidance on the development of scenarios of extremes and for the incorporation of information about low-probability high-impact events such as the abrupt collapse of the thermohaline circulation will be implemented with respect to the Tyndall Centre's Integrated Assessment Model as part of the Round 2 project (T2.11) on 'Interfacing climate and impacts models in integrated assessment systems' co-ordinated by Nigel Arnell and involving Tim Osborn.

SECTION 2 – TECHNICAL REPORT

2.1 Introduction

2.1.1 Background

Many impacts of climate change will be realised as the result of a change in the frequency of occurrence of extreme weather events (such as windstorms, heavy precipitation or extreme temperatures over a few hours to a few days; Mearns *et al*., 1997). Thus the research foci of Tyndall Centre Research Theme 3 include work 'on the construction and application of scenarios which take into account extreme weather, uncertainties and rapid changes'. To date, however, few scenarios consider changes in the magnitude and occurrence of extremes, preferring to focus on changes in mean climate (Hulme and Jenkins, 1998). The reason for this is twofold: first, the lack of suitable tested methods for developing scenarios that include information about climate extremes and variability changes; and second, the limited availability of climate model simulations with reliable output at the necessary spatio-temporal resolution.

An overriding problem – and hence the need for more sophisticated scenario development methods – is that output from climate model simulations cannot, in general, be used to directly quantify future variability and extremes because of bias in simulated means and variability of present-day climate and weather (Zwiers and Kharin, 1998). This bias may originate from systematic model errors (Gregory and Mitchell, 1995), from spatial scale incompatibilities (area-mean grid-box output has different statistical properties to station data; Osborn and Hulme, 1997) and due to the exclusion of sub-grid-scale processes.

In the development of scenarios of mean climate change, the bias in simulated means is the main difficulty and can be "overcome" by assuming that the climate change is independent of these mean biases and, therefore, applying climate change fields to appropriate observed baseline climatologies. The need for this assumption is gradually being reduced as global climate models become more comprehensive and physical parameterisations more accurate, allowing improved reproduction of present-day mean climate. A similar approach can be used for the development of scenarios that focus on climate variability and extremes (Wilks, 1992; Bates *et al*., 1994), i.e., by assuming that changes in higher-order statistical parameters (variance, skewness, persistence, etc.) are reliable, despite differences between observed and simulated present-day values of these parameters. However, for global climate models to become more reliable in their simulation of variability as well as means, requires not only an improvement in the models, but also a solution to the two spatial resolution problems identified above (scale incompatibilities and sub-grid-scale processes). These can only be overcome by an increase in the spatial resolution of climate models together with improvement in their reliability. Higher-resolution global (such as timeslice, Cubasch *et al*., 1996; Voss *et al*., 2002) or regional (nested within a global model, Christensen *et al*., 1997; Jones *et al*., 1997; Durman *et al*., 2000; Christensen *et al*., 2001; Jones and Reid, 2001; Rummukainen *et al*., 2001) models have begun to address this problem, and will become increasingly important as the number of simulations increases (e.g., the suite of simulations performed by the Hadley Centre using the HadCM3, HadAM3H and HadRM3 models).

Statistical, or empirical, downscaling offers an alternative approach to obtaining information about climate variability and extremes (Hewitson and Crane, 1996; Wilby and Wigley, 1997; Wilby *et al*., 1998a; Mearns *et al*., 1999; Murphy, 1999; Wilks and Wilby, 1999; Zorita and von Storch, 1999). Relationships between larger-scale climate variables (such as atmospheric circulation) and local surface climate variables, derived empirically using observed data, can be applied to the generation of climate-change scenarios, under the two assumptions that the larger-scale climate variables are more reliably simulated by climate models, and that the relationships remain valid under a changed climate. Theoretically, the latter assumption (of stationarity) should be valid if all the necessary predictor variables are used. In practice, however, this may be limited by the availability of sufficiently long data series to determine the important predictors on all necessary time scales. Nevertheless, given adequate data, statistical downscaling has sufficient advantages to warrant consideration as a scenario-generation method.

While the need to generate scenarios that successfully reproduce present-day climate variability and extremes and that also give reliable estimates of climate change is paramount, a number of other issues must also be addressed. Ideally, scenarios should have estimates of their associated uncertainty, perhaps by using a range of climate models, and should be able to be scaled to reflect a range of possible greenhouse gas emissions pathways, allowing probabilistic impacts and integrated assessments to be undertaken. These issues are only just beginning to be explored (New and Hulme, 2000). Probabilistic assessments should also, but do not yet, consider scenarios of low probability but high impact events, such as an abrupt reorganisation of the thermohaline circulation or a collapse of the West Antarctic ice sheet, that could arise due to non-linearities in the climate system.

Recent work on scenario development, including that reported in the IPCC Third Assessment Report (WG1, Chapter 13 and WG2, Chapter 3), provided the starting point for a comprehensive assessment of methods that are most suitable for the estimation of future probabilities of extreme weather events in the UK (Section 2.3) – focusing on stakeholder-defined events (Sections 2.2 and 2.5). The completed project was, however, much more than a literature review. All the necessary questions cannot be answered on the basis of past work alone and thus specific applications to test cases (Section 2.4) were undertaken to compare and evaluate the various methods (Sections 2.4 and 2.6).

2.1.2 Objectives

The key research objectives were:

(i) To identify the range of scenario development methods that are most suitable for extremes of weather and climate, to expertly assess their limitations/problems when applied to the range of UK-oriented events and climate variables which are most important for impact assessment studies, and to explore solutions for overcoming these limitations/problems.

(ii) To quantitatively test and intercompare the most promising scenario development methods using a number of specific UK case studies (such as drought) which are relevant to the Tyndall Centre research objectives.

(iii) To develop guidelines for the subsequent construction of reliable and consistent scenarios of extremes for the UK as part of future Tyndall Centre research activities, identifying suitable methods and best practise, and outlining strategies to allow scenarios of extremes to be used in probability-based impact assessments and subsequently in integrated assessment models (IAMs).

2.1.3 Methodology

This Round 1 Tyndall project ran from April 2001 to July 2002. The project methodology entailed the completion of four tasks:

- Task 1: Identification of the weather extremes scenario needs of the UK impacts community (see Sections 2.2 and 2.5)
- Task 2: Identification and evaluation of the suitable scenario development methods (see Sections 2.3 and 2.5)
- Task 3: Quantitative testing of the most promising scenario development methods (identified as part of Task 2) for selected case studies (identified as part of Task 1) (see Section 2.4)
- Task 4: Development of guidelines to underpin the future development of scenarios that include information about climate/weather extremes and variability (see Section 2.6).

2.1.4 Dissemination of project results

The project results have been disseminated *via* various means:

- A Tyndall Centre Working Paper (Goodess *et al*., 2001) has been published; see Section 2.3.2.
- A journal paper (Osborn and Hulme, 2002) has been published by the Royal Society.
- Presentations to the Association of British Climatologists meeting on Climate Change, Variability and Extremes, University of Birmingham, 12 September 2001 by Clare Goodess on 'Scenario development methods for the estimation of future probabilities of extreme weather events (http://www.cru.uea.ac.uk/cru/demos/2001-CMG-birmingham.pdf) and Tim Osborn on 'Observed trends in the occurrence of heavy precipitation in the UK' (see also Osborn and Hulme, 2002).
- Presentation by Clare Goodess at the Evaluation Workshop for the Canadian Climate Action Fund Science Sub-component Climate Scenarios and Climate Extremes, Chateau Bromont, Quebec, Canada, 24-26 October 2001 on 'Scenarios of extremes' (http://www.cru.uea.ac.uk/cru/demos/2001-CMG-montreal-ex.pdf).
- Presentations by Tim Osborn to The Royal Society Discussion Meeting on Flood Risk in a Changing Climate, Royal Society, London, 21-22 November 2001 on 'Evidence for trends in heavy rainfall events' and the European Geophysical Society 27th General Assembly, Nice, 21-26 April 2002 on 'Observed and simulated changes in the distribution and extremes of precipitation over the UK'.
- Preparation of a poster for presentation at the Tyndall Assembly 2002 and future meetings.

In addition to the published paper (Osborn and Hulme, 2002), one journal paper has been accepted for publication and two more are in preparation:

- Goodess, C.M., Hanson, C., Hulme, M. and Osborn, T.J., 2003: 'Representing climate and extreme weather events in integrated assessment models: a review of existing methods and options for development', *Integrated Assessment*, accepted for publication (see Section 2.6.3)

- A paper on the drought case study (see Sections 2.4.2–2.4.9): first author T.J. Osborn

- A paper on the intense rainfall case study (see Sections 2.4.10–2.4.12): first author T.J. Osborn

Case-study results will also be presented at a workshop to be held in 2003 for users of the SDSM Statistical DownScaling Model developed by Rob Wilby.

2.2 IDENTIFICATION OF THE WEATHER EXTREMES SCENARIO NEEDS OF THE UK IMPACTS COMMUNITY

2.2.1 Issues and questions

The investigators had prior experience in this area and were also guided by the indicators of extremes recommended by a recent international meeting (Karl *et al*., 1999) in order to identify a preliminary list of events and variables for which scenarios are required. This list was modified and augmented by stakeholder representatives from the UK Climate Impacts Programme (UKCIP), Environment Agency (EA), Scottish Environment Protection Agency (SEPA) and the insurance industry (ABI/BRE) at the project workshop on 'New dimensions for climate scenarios: a workshop to identify the extreme weather scenario needs of the Tyndall Centre and the wider impacts community' held in Norwich, 4-5 June 2001.

The workshop addressed the following questions:

- What are the important *temperature and precipitation extremes* for particular impact studies?

- On what *temporal scale(s)* are scenarios of extremes required for particular impact studies (e.g., daily, sub-daily)? It is generally assumed that information at the daily time scale is necessary to investigate extreme events. However, are there extreme events which can be usefully defined using monthly data?

- At what *spatial scale(s)* are scenarios of extremes required for particular impact studies?

- What are the important *non-temperature/precipitation extremes* for particular impact studies (e.g., wind, hail, fog, lightning, storm surges)?

- How important are *joint-probability events* (e.g., wind storms with snow/rain, heavy snow followed by rapid thaw, intense rainfall on dry/frozen or already saturated ground, storm surge with river flood)?

- How important is it to know about the *persistence and sequence* of extreme events (e.g., sequences of long dry/hot summers)?

- How important is it to know about *seasonal changes in the timing* of extremes (e.g., changes in the season of maximum frequency of occurrence)?

- For what extremes and impacts is it important to have *self-consistent multi-site and/or multi-variate scenarios*?

- How should scenarios of extremes be *presented* for particular impact studies (e.g., maps, probability distributions)? Is it sufficient to provide information about relative changes or should these be added to an observed base-line climatology? Are daily time series required for input to some impact studies/models?

- *How much data* can realistically be handled in impact assessments (daily, high spatial resolution data sets for a number of different extreme parameters/scenarios/ensembles will be very large)?

- Is it possible to identify a *standard set of extremes* of interest to the widest possible range of impact assessment sectors?

- How should the uncertainties by represented (e.g., should *probabilities* be attached to the scenarios)?

- What *low-probability high-impact events* should be considered (e.g., abrupt reorganisation of the thermohaline circulation, collapse of the West Antarctic ice sheet, large and rapid releases of methane trapped below the seafloor and in permafrost)?

2.2.2 Workshop summary

The workshop agenda is summarised below:

Requirements for extremes and scenarios

- Weather extreme indicators (Clare Goodess)
- Short presentations (5-10 minutes) from UKCIP, EA, SEPA and BRE/ABI outlining requirements/viewpoints.
- Followed by discussion.

Requirements of Tyndall Centre RP4 (Extreme Events & Rapid Climate Change)*

** Now Tyndall Research Theme 2: Adapting to Climate Change.*

- Overview of RP4 research programme (Mike Hulme)
- Project IT1.4 "Integrated assessment of the potential for change in storm activity over Europe: Implications for insurance and forestry" (Clair Hanson, UEA)
- Project IT1.8 "Accuracy of modelled extremes of temperature and climate change and its implications for the built environment in the UK" (Geoff Levermore, UMIST)

Requirements of Tyndall Centre RP1 (Integrated Assessment)

- Project IT1.3 "Evaluation of approaches to integrated assessment: A Blueprint approach" (Jean Palutikof, UEA)

Scenario methods

- Presentation on an internal project paper outlining the scenario development methods to be considered, problems, solutions and appropriate inter-comparison methods (circulated prior to the meeting) (Clare Goodess and Tim Osborn)
- Hadley Centre global and regional climate models and simulations (Richard Jones)
- Statistical downscaling methods (Rob Wilby, Kings College London)
- Statistical methods for treating extremes (David Stephenson, Reading University)
- Low-probability high-impact events – thermohaline circulation collapse (Richard Wood, Hadley Centre)
- Structured discussion on scenario methods and extremes

A summary of the requirements for extremes and scenarios identified by the stakeholder representatives is provided in Appendix 1 of this technical report.

A summary of the issues arising in discussion during the project workshop, covering indicators of extremes, methodological issues and case studies, is given in Appendix 1 of Tyndall Working Paper 6 (Goodess *et al*., 2001).

One of the key points arising from the workshop discussion of indicators of extremes was the importance of 'benchmarking' against experienced events (e.g., the 1995 hot summer, the October 2000 floods) for engaging stakeholder attention. This point was followed up as part of the drought case study (see Section 2.4.2).

2.3 IDENTIFICATION AND EVALUATION OF THE SUITABLE SCENARIO DEVELOPMENT METHODS

2.3.1 Introduction

Identification of the appropriate methods and their potential limitations/difficulties was achieved by:

- prior experience of the investigators;
- a literature review carried out during the first three months of the project; and,
- input provided by participants during the project workshop (see Section 2.2.2).

Initially, an internal project position paper was produced. This was circulated to participants prior to the project workshop, and was revised following discussion at the workshop in order to produce a Tyndall Working Paper (Goodess *et al*., 2001). This working paper addresses project Tasks 1 and 2 (see Section 2.1.3).

2.3.2 Summary of the working paper

The introduction (*Section 1*) outlines the project objectives and the structure of the working paper.

The starting point for a comprehensive assessment of methods that are most suitable for the estimation of future probabilities of extreme weather events is recent work on scenario development, including that reported in the IPCC Third Assessment Report, which is outlined in *Section 2*.

In order to assess the most suitable methods, it is first important to identify the range of scenario information that is required by stakeholders and others with requirements for climate change impact assessments. A number of relevant questions and topics debated during the project workshop, including issues which are particularly relevant to the need to develop probabilistic approaches and integrated assessment models, are presented in *Section 3*, together with a list of proposed indicators of temperature and rainfall weather extremes.

The second major focus of the project workshop was the identification of the available scenario development methods and their limitations. A number of potential methods are identified in *Section 4* and the limitations of each evaluated (based, in part, on evidence from the studies identified in Section 2), both generally, and for the specific problems of inter-annual variability, multi-variate correlations, multi-site correlations, spatial-scale dependence and scaling by simple models to obtain a range of scenarios.

In *Section 5*, consideration is given to the evaluation and incorporation into assessment studies of low probability, but high impact events, such as an abrupt reorganisation of the North Atlantic thermohaline circulation. There are two aspects of such events that must be addressed: (i) the possibility of the event occurring, and (ii) the response of the climate system to the event. Both aspects are subject to considerable uncertainty which means that a more preliminary and subjective approach has to be taken compared with the more conventional extremes considered in Section 4.

All the necessary questions concerning scenarios of extreme events cannot be answered on the basis of past work and critical reviews alone. Thus specific applications to test cases have been undertaken in order to rigorously and, where possible, quantitatively, compare and evaluate the various methods, and to further develop methods in order to overcome the problems identified in Section 4. The proposed case-study work is outlined in *Section 6*.

A draft version of this working paper formed the basis of discussion at the project workshop. A number of additional issues which arose in these discussions, relating to indicators of extremes, methodological approaches and case studies, are summarised in *Appendix 1*.

The working paper was published in July 2001. Two tables summarising recent studies which use GCM output directly to construct scenarios of extremes and statistical downscaling studies which include analysis of extreme event indicators were updated in July 2002 in order to incorporate more recent literature and are therefore included in this technical report: see Tables 1 and 2 respectively.

The review of scenario methods from Section 4.2 of the working paper has also been updated and is presented here as a series of tables (Tables 3 to 6). The specific statistical downscaling methods considered (Table 6) have been expanded to include regression-based methods as recommended during the project workshop.

2.4 QUANTITATIVE TESTING OF THE MOST PROMISING SCENARIO DEVELOPMENT METHODS FOR SELECTED CASE STUDIES

2.4.1 Selection of the case studies

The purpose of the case-study work undertaken in Task 3 was to test the most promising scenario development methods identified as part of Task 2 (see Section 2.3) and to investigate ways of overcoming or minimising the problems associated with even the most promising methods. Preliminary suggestions as to the indicators on which the case studies could be based were made at the project workshop. Guidance on the selection of case studies was sought from the participants and a number of additional proposals were made (e.g., see Appendix 1 of this report). While it was not possible to carry out full case studies for all the proposed extremes (which include wind, floods, subsidence, snowmelt and various joint probability events), Section 2.5 includes guidance on approaches for constructing scenarios for a number of these events.

The selected case studies focus on two aspects of the UK rainfall regime because the other relevant Round 1 Tyndall Centre Research Theme 3 projects (IT1.4 on storm activity over Europe and IT1.18 on UK temperature extremes) do not cover extremes of this important variable. The first case study focuses on drought and considers low precipitation extremes at the regional spatial scale (~200-300 km by 200-300 km for the UK) and the monthly to annual time scale. The second case study is on intense rainfall, with a focus on obtaining results that are relevant to the station spatial scale and the daily time scale.

2.4.2 Drought case study: measuring drought

Drought occurrence and severity was measured using an index based on an accumulated precipitation deficit computed from time series of monthly precipitation totals. The index used here was modified from the drought severity index (DSI) used by Phillips and McGregor (1998) by the inclusion of an exponential recovery term (equivalent to a Newtonian relaxation) – hence the index is referred to as NAD (Newtonian Accumulated Deficit). The recovery term has a time scale of either three (NAD_3) or six (NAD_6) months. In order to reflect the stakeholder requirement of 'benchmarking' against experienced events (see Section 2.2.2), the indices are used to define two types of drought event:

- 1995-type "short" droughts: based on NAD_3, length 3-7 months, maximum deficit greater than or equal to 40% of mean rainfall; and,

- 1976-type "long" droughts: based on NAD_6, length greater than 7 months, maximum deficit greater than or equal to 30% of mean rainfall.

The index used here allows us to focus on the performance of different scenario construction methods for estimating precipitation extremes. Changes in other climate variables (especially temperature) would also influence the occurrence and severity of drought, as might non-climatic changes (such as groundwater extractions or irrigation demand). These non-precipitation factors have been neglected and could considerably enhance the changes in drought frequency and severity found here.

2.4.3 Drought case study: climate model data

Results from the Hadley Centre global climate model (GCM) and regional climate model (RCM) available through the Climate Impacts LINK Project (http://www.cru.uea.ac.uk/link/) were used for the case-study work.

Data from eight simulations performed with the HadCM3 coupled atmosphere-ocean GCM (Gordon *et al*., 2000), which has a spatial resolution of 2.5° latitude by 3.75° longitude, were used. One was a 240-year control simulation, with unchanging forcing representative of pre-industrial greenhouse gas concentrations. This run was used here to estimate the magnitude of internally-generated climate variability. The other simulations were driven by estimates of historical anthropogenic forcing from 1860 to 1990, followed by one of four of the IPCC SRES emissions scenarios (A1FI, A2, B2 and B1) out to 2099. Data from the 1950 to 2099 period of each simulation were used. Small ensembles of multiple simulations (three for A2 and two for B2) were available for two of the scenarios; with identical external forcing, but independent realisations of internal variability, multiple ensemble members can enhance the signal-to-noise ratio of the response to anthropogenic forcing. This is especially important for variables such as precipitation at the small spatial scales considered here, because the signal of the response to anthropogenic forcing is relatively weak compared with noise of internal variability. For this reason, the three-member ensemble under the A2 emissions scenario was used for the majority of the analyses undertaken during the case studies. The other simulations were used to provide some information about uncertainties arising from inter-scenario variability. In particular, they were used to test whether the pattern-scaling approach could be extended to changes in variability as well as changes in mean climate.

In order to allow comparison of scenarios based on GCM and RCM output, data from the Hadley Centre's European RCM (HadRM3, Hulme *et al.*, 2002), which has a spatial resolution of 50 km × 50 km, were also used. This output did not become available for use in the project until June 2002, but its inclusion was essential to ensure that the case study comparison was as comprehensive as possible. The comparison of HadCM3 and HadRM3 is not, however, a direct test of the benefits of dynamical downscaling, because the RCM was not embedded within the GCM simulation. Instead, as an intermediate step, a high-resolution (~120 km) global atmospheric model (HadAM3H; Pope *et al*., 2000) was used to provide boundary conditions for the HadRM3 simulations. The only information taken from the HadCM3 simulations was the radiative forcing at any one time and the change in sea surface temperatures (SST). Any biases in the HadCM3 SST simulation were effectively removed by taking only the simulated change and adding that to an observed baseline data set. The reason for including this intermediate step was that the improved physics and finer spatial resolution of HadAM3H, together with the removal of biases in SST, give an improved simulation, particularly with respect to the location of the major North Atlantic storm tracks, and hence improved boundary conditions for the RCM. The drawback for this study is that any improved performance cannot be attributed solely to the use of the RCM, but may partly arise from the intermediate step. Given the additional computing demands of this 'double-nesting' approach, simulations were performed for 1961-1990 and 2070-2100 time slices only. For this study, data were used from the 3-member ensemble performed under the SRES A2 scenario.

2.4.4 Drought case study: observed climate data

Monthly rainfall totals were created from daily rainfall series averaged within the nine coherent UK regions shown in Figure 1 (Jones *et al*., 1997; Alexander and Jones, 2000). Series are available for 1873–1999 for the five regions covering England and Wales, and for 1931–1999 for the others. These time series were analysed in full, although the period 1950–1999 was used to define the observed baseline.

The observed predictor variables, measuring atmospheric circulation, moisture and heat, that were used for developing statistical downscaling models were taken from the National Centers for Environmental Prediction (NCEP) reanalyses. These reanalyses come from an assimilation/forecast model based on a synthesis of all available weather and satellite information (Kalnay *et al*., 1996).

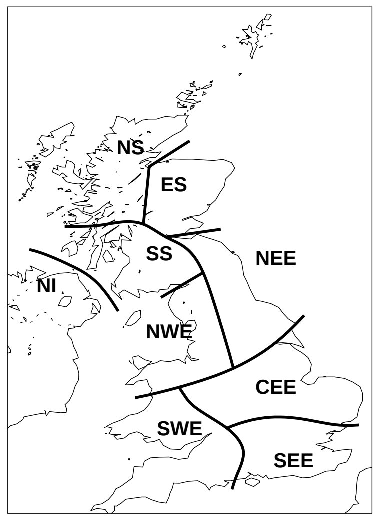

Figure 1: Nine UK regions for which area-averaged precipitation observations were used.

2.4.5 Drought case study: statistical downscaling method

One of the most promising statistical downscaling methods has been evaluated: i.e., a regression-based method (see Table 6). The selected regression-based method is the SDSM Statistical DownScaling Model developed and provided by Rob Wilby (Wilby *et al*., 2002; http://www.sdsm.org.uk). Large-scale daily circulation patterns and atmospheric moisture variables are used as predictor variables to linearly condition the stochastic weather parameters (e.g., precipitation occurrence and intensity) for the predictand series. The predictands were the *daily* regional rainfall observations; thus the model was calibrated and applied at the daily time scale, even though the SDSM output was always accumulated into monthly totals before calculating the drought indices and other statistics. For precipitation, SDSM artificially inflates the variance of the downscaled series using a stochastic component, in order to overcome the problem of underestimated variance (see Table 6).

The predictor variables were derived from NCEP reanalyses (Section 2.4.4) for model calibration, and are replaced by HadCM3 variables from the first member of the A2 ensemble (Section 2.4.3) for scenario construction. A set of 14 potential predictor variables was available for the case-study work including mean sea level pressure, 500 hPa and 850 hPa geopotential height, relative and specific humidity, and zonal and meridional velocity components. No lagged predictors (i.e., from previous days) were used, though SDSM provides this facility. A separate model was built for each region (with different predictors and regression coefficients) and for each of the four standard seasons (no seasonal variation in predictors, but regression coefficients were fitted separately for each season). In each case, five predictors were selected using an ad-hoc stepwise screening procedure. Near-surface specific humidity and 500 hPa geopotential height were selected for all regions. For the western regions (SWE, NWE, NIR, SS and NS – see Figure 1) a second moisture variable was also selected (near-surface relative humidity). The zonal velocity was used in all regions, at the surface for the eastern regions and at 850 hPa height for the western regions. In addition, the meridional velocity was selected for SWE and NS, while this was implicitly included for four other regions by using overall geostrophic flow strength as a predictor. Finally, for the eastern regions, one or more indirect measures of uplift were included (either surface vorticity, surface divergence, or both). The selection of predictors and the fitting of the regression parameters were done using data from the period 1961–1985 only.

The SDSM model for each region and season was run using NCEP (i.e., observed) predictors for 1961–1999, and for 1961–2099 using HadCM3 (A2 scenario) predictors. For each application of an SDSM model, 20 simulations were performed to produce 20 synthetic series of daily precipitation. Differences between these 20 realisations do not reflect the full range of internal variability because only the stochastic component differs between each run. The deterministic component (i.e., controlled by the atmospheric circulation and moisture variables) follows the same evolution in each run because only one realisation of the predictor variables exists in each case (either the NCEP or HadCM3 data). Daily predictors from the other two HadCM3 A2 scenario ensemble members would provide alternative realisations of the deterministic component of the downscaled series, but they were not available within the SDSM framework.

The series downscaled from the NCEP predictors provide an opportunity to evaluate the performance of the SDSM models in comparison with the observed regional precipitation series. Each series is accumulated into monthly totals and averaged over the 20 realisations, and then compared (Figure 2) with the observed rainfall series by correlation and root-mean-squared-error (RMSE) coefficients (the latter are compared with the standard deviation, which is the RMSE obtained when a series is replaced by its long-term mean). The comparison is performed over the period of SDSM calibration (1961–1985) and over an independent verification period (1986–1999). Results indicate that the models replicate observed inter-monthly and inter-annual variability faithfully, achieving correlations of the order 0.8 and leaving residuals whose variance is much less than the variance of the raw data. The performance of the SDSM is almost as good over the verification period as it is over the calibration period, indicating that the empirical model has not been overfit to the data. Regionally, the poorest verification performance is for ES (East Scotland). An evaluation of the performance during individual months indicates that this is due to a small number of very wet months not being predicted by the SDSM (especially March 1992 and September 1995, both of which occur during the verification period).

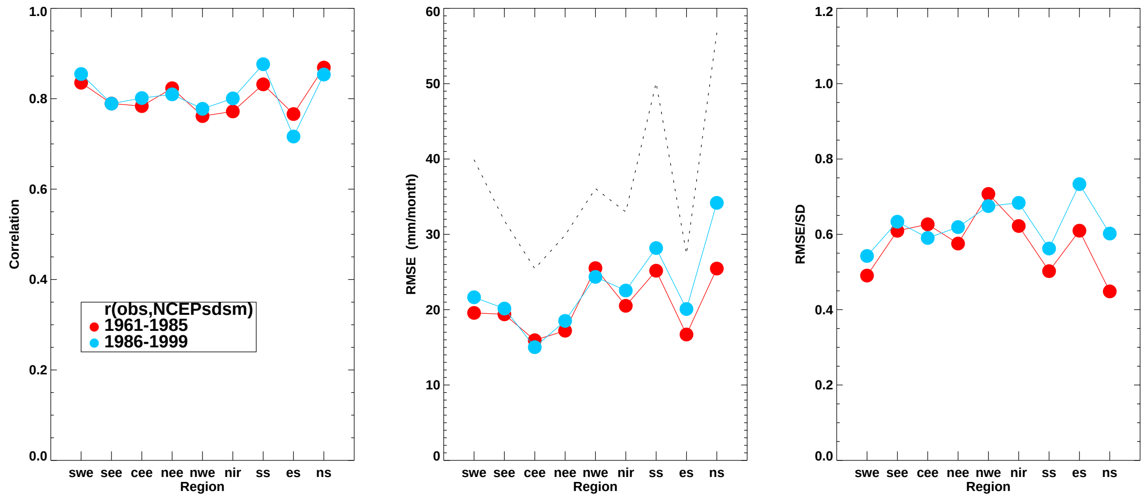

Figure 2: Comparison of monthly regional precipitation predicted by SDSM with that observed, using (a) correlations; (b) root-mean-squared-errors (RMSE); and (c) RMSE divided by climatological standard deviation [the latter is indicated by the dotted line in (b)]. Comparison is over either the calibration period (red) or the verification period (light blue).

2.4.6 Drought case study: evaluation of present-day simulations

The various approaches to generating monthly precipitation time series (i.e., GCM, RCM or statistically-downscaled GCM) were evaluated by comparison with the observed records, focusing on the long-term mean, the shape parameter obtained when fitting a gamma distribution to the data, and the frequency of "short" and "long" droughts (defined in Section 2.4.2).

Figure 3 shows the annual cycles of mean monthly precipitation, computed over the 1950–1999 baseline period (or whatever subset has data). The observed annual cycles are strongest in those western regions (SWE, NWE, SS and NS) where orographic rainfall is important, due to the annual cycle in prevailing flow strength and direction. These cycles are better replicated by the RCM and the GCM-driven SDSM, though some statistically significant errors remain (significance not shown here), while the GCM data are less realistic (though note that this does not necessarily imply errors in the GCM simulation, but rather that the output it produces is not suitable for the purpose that is required here).

The gamma shape parameter (Figure 4) is a measure of distribution skewness, being lower the more skewed the distribution is. The sampling error for this parameter is greater than for the mean, resulting in "noisier" values that partially hide some systematic errors. Nevertheless, it is possible to see a systematic error in the GCM output, with nearly all shape parameters higher than observed (indicating insufficient skewness, being closer to a Gaussian distribution than an exponential distribution). This is particularly noticeable in the second half of the year in all northern regions (NEE, NWE, SS, ES and NS). The RCM and the GCM-driven SDSM perform better, though the latter produces shape parameters that are too high in some regions during July to October.

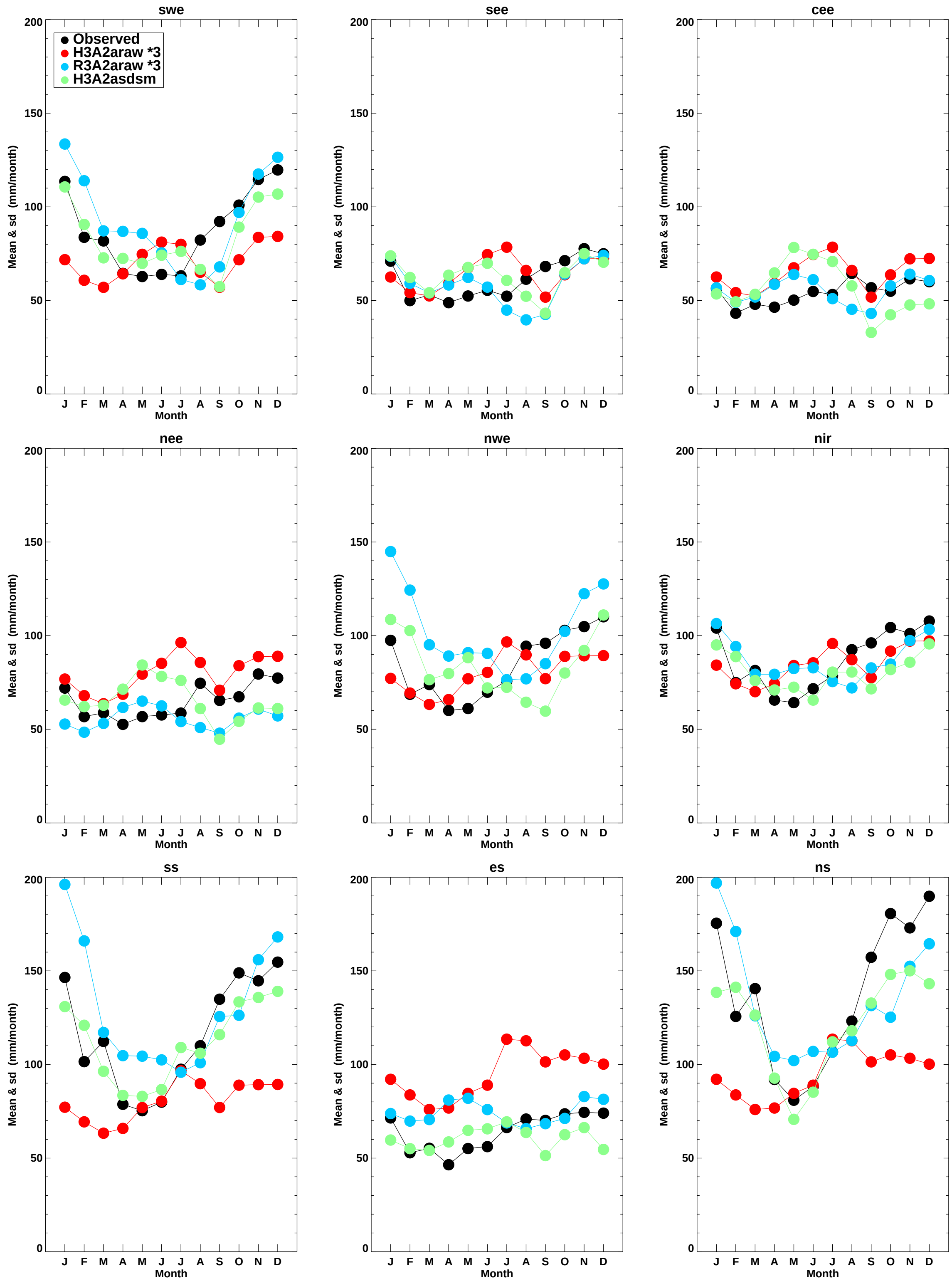

Figure 3: Annual cycle of mean monthly precipitation (mm/month), computed over the period 1950–1999 (or subset for which data were available) from observations (black), HadCM3 GCM (red), HadRM3 RCM (blue) and HadCM3 downscaled using SDSM (green). Each panel shows one of the nine UK regions, according to the label above each panel.

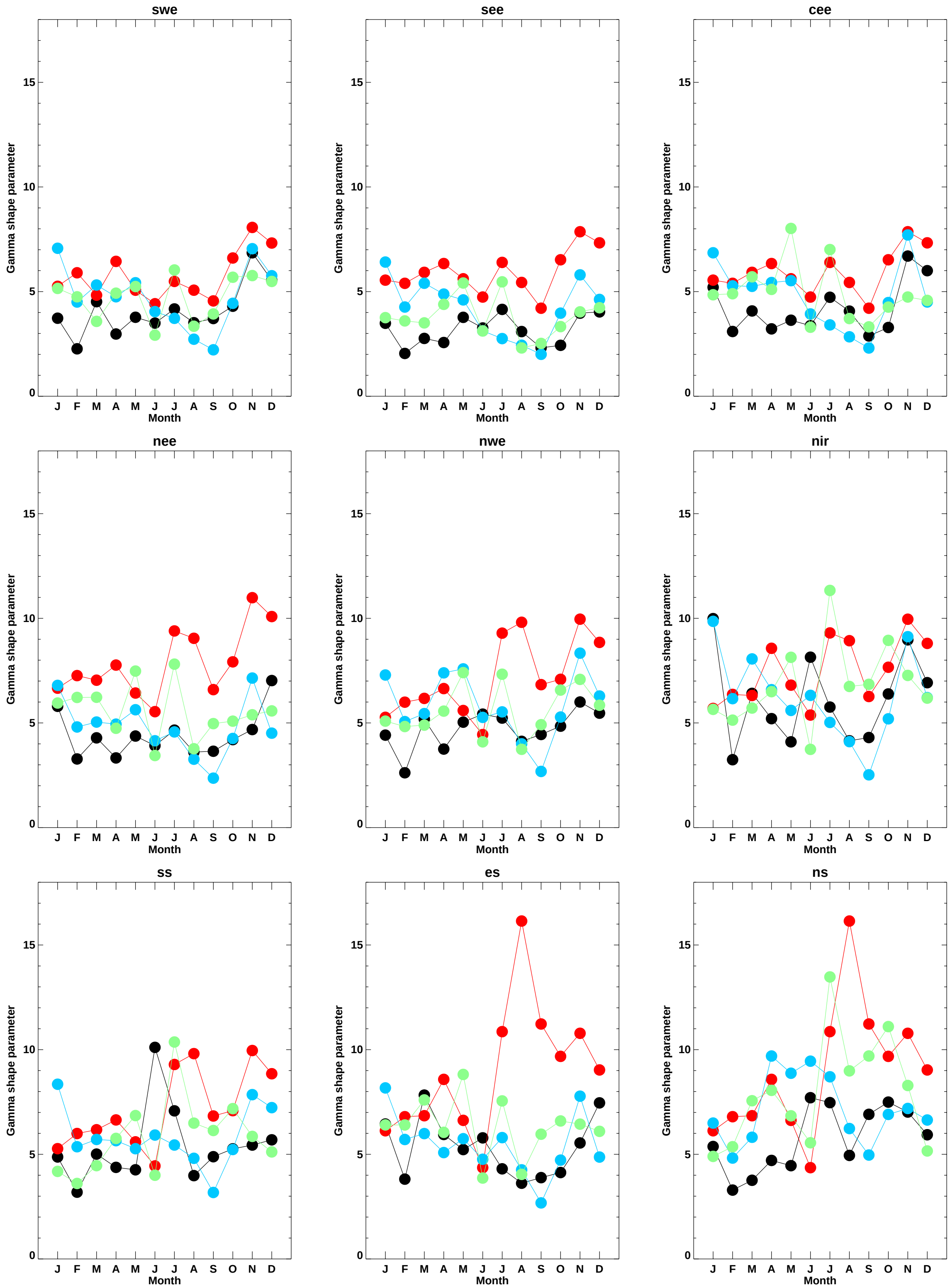

Figure 4: Annual cycle of monthly precipitation gamma shape parameter, computed over the period 1950–1999 (or subset for which data were available) from observations (black), HadCM3 GCM (red), HadRM3 RCM (blue) and HadCM3 downscaled using SDSM (green). Each panel shows one of the nine UK regions, according to the label above each panel.

The top panel of Figure 5 shows the simulated frequency of "short" droughts in comparison to that observed. The drought index is calculated using anomalies from each series' mean, so errors in the long-term mean (Figure 3) will not influence the drought frequency obtained. Errors in the distribution shape (Figure 4) *can* carry over to the drought frequency, however, because the skewed observed distribution is the result of many low precipitation months combined with a fewer number of very wet months, while the more symmetric GCM simulation is the result of a more equal number of low and high precipitation months. This is evident in the simulated frequency of short droughts (Figure 5, top panel), which is fewer than observed in all nine regions. The RCM and GCM-driven SDSM simulate more frequent droughts, though still fewer than observed in some regions. This could partly be because the frequency of extreme events is a statistic with a rather large sampling error; to assess this we have included an uncertainty bar on the observed values, based on an analysis of sampling variability in the 240-year control simulation of HadCM3 (Section 2.4.3). Even taking this into account, there are still fewer simulated droughts than observed – particularly in the SEE region. For this region, the error is partly due to the too strong persistence in the simulated series: there are many more droughts that were not counted in the simulated records because they exceeded the limit of seven months length used to define these short droughts (Section 2.4.2).

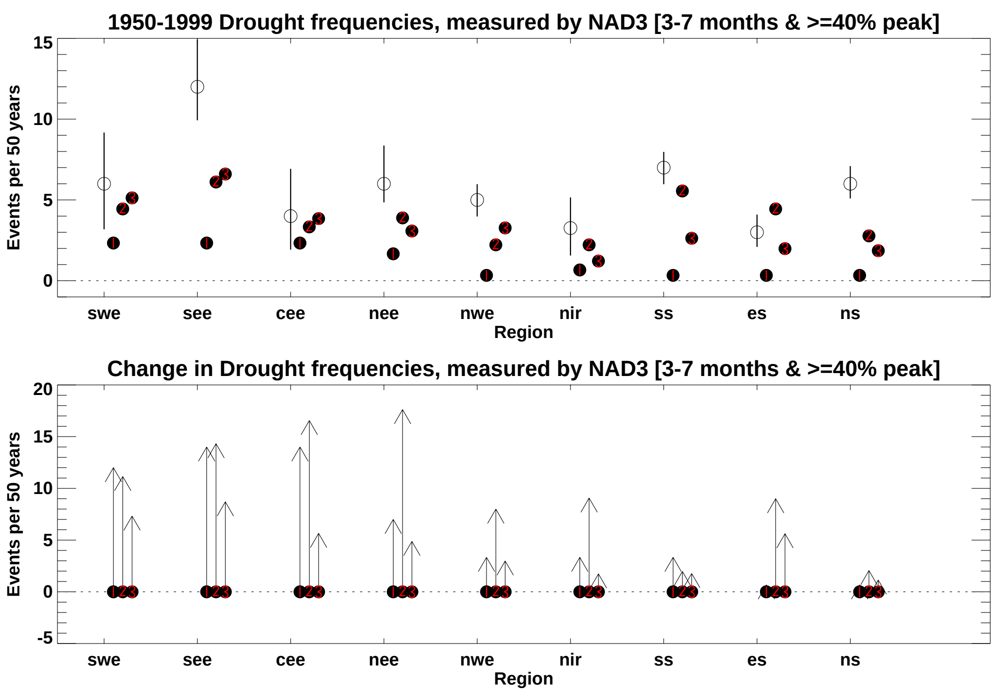

Figure 5: Frequency (expressed as events per 50 years) of short droughts during the late 20th century (top panel) and the change from the late 20th to the late 21st century under SRES A2 scenario (bottom panel). Exact periods differ slightly between cases, being approximately either the last 50 years (observed, GCM and GCM-driven SDSM) or the last 30 years (RCM) of each century. Observed values (top panel only) are indicated by circles, with vertical bars indicating an estimate of the sampling variability. Simulated values are indicated by the dots, with methods identified by red numerals (1=GCM, 2=RCM, 3=GCM-driven SDSM).

The top panel of Figure 6 compares the observed and simulated frequencies of "long" droughts. The observed frequency is lower, the sampling uncertainty is relatively greater (vertical bars), and the overall performance of the simulations is better, than for the short droughts. Only a few simulated values are significantly different (i.e., taking into account the sampling error) from those observed, and the overall spatial structure is captured quite well, with more frequent droughts in the SEE, CEE, NEE and NWE regions.

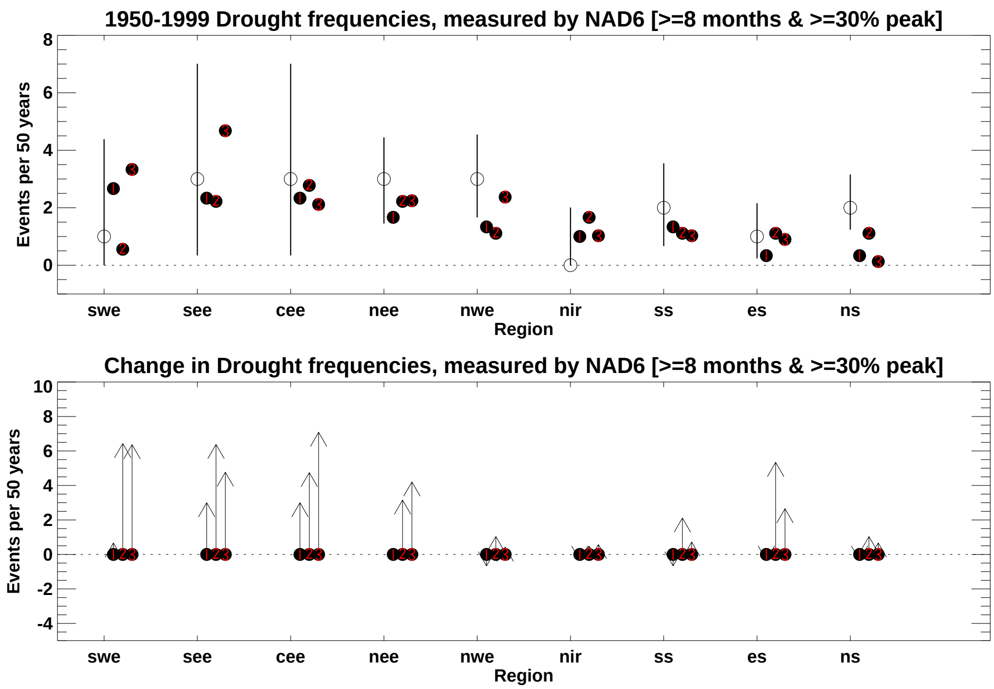

Figure 6: As Figure 5, but for "long" droughts.

2.4.7 Drought case study: comparison of climate change scenarios

Despite the different approaches used (i.e., GCM, RCM and GCM-driven SDSM) and the differences between their simulations of present-day climate, the change in precipitation characteristics under the SRES A2 scenario is remarkably similar in structure and magnitude for all approaches (Figures 7 and 8). The winter wetting and summer drying of the mean precipitation (Figure 7) is of comparable magnitude in all three, though the period of summer drying is typically longer (e.g., April–October) in the RCM than in the GCM (e.g., May-August), with the GCM-driven SDSM producing a drying season that matches the RCM in length but not in magnitude. Winter wetting is typically strongest in the RCM and weakest in the GCM-driven SDSM. The summer drying is accompanied by a decrease in the gamma distribution shape parameter – and hence an increase in the skewness of the distribution (Figure 8). For this parameter, the GCM shows maximum decreases in July, with particularly strong changes in July and August. The GCM-driven SDSM also captures the July maximum decrease, but shows no late spring/early summer decrease and thus the change is skewed towards late summer and autumn. The RCM, on the other hand, shows decreased shape parameters during late spring and early summer, and the seasonal structure of these changes is thus skewed towards that period instead. When interpreting these changes in shape parameter, it is important to consider the initial values (typically higher for the GCM than for the others – Figure 4), because the impact of a parameter change is nonlinear, becoming more influential the lower the value (and also the shape is limited to be > 0 by definition of the gamma distribution, so that starting from a lower value provides a greater constraint on any reductions).

Despite the similar changes in mean precipitation and distribution skewness, when drought indices are calculated, there are some more noticeable differences in the changes in drought event frequencies. This is partly an outcome of using a threshold-based measure of drought events (Section 2.4.2) because the results are sensitive to the choice of minimum and maximum event length and to the choice of the peak deficit required. For the short droughts (Figure 5, bottom panel), there is a strong increase in frequency in the three most southern regions (SWE, SEE, and CEE) in both the GCM and RCM output, but a weaker increase in the GCM-driven SDSM. For NEE, NWE and NIR, the RCM changes are much larger than obtained using the other methods. Despite the large sampling variability (see the vertical bars in the upper panel), some of these differences in frequency change are statistically significant.

Though the summer drying is able to drive large increases in short droughts, the change in long droughts (Figure 6, bottom panel) is limited by the trend towards wetter winters. Nevertheless, there is still an increase simulated by the RCM and by the GCM-driven SDSM in the southern and eastern regions (SWE, SEE, CEE, NEE and ES), which is marginally significant (compared with the sampling uncertainty indicated by the vertical bars in the upper panel). The GCM output does not show any significant changes in the frequency of these long droughts. It is worth noting that the winter wetting does not result in fewer long droughts in any region or with any of the scenario methods tried.

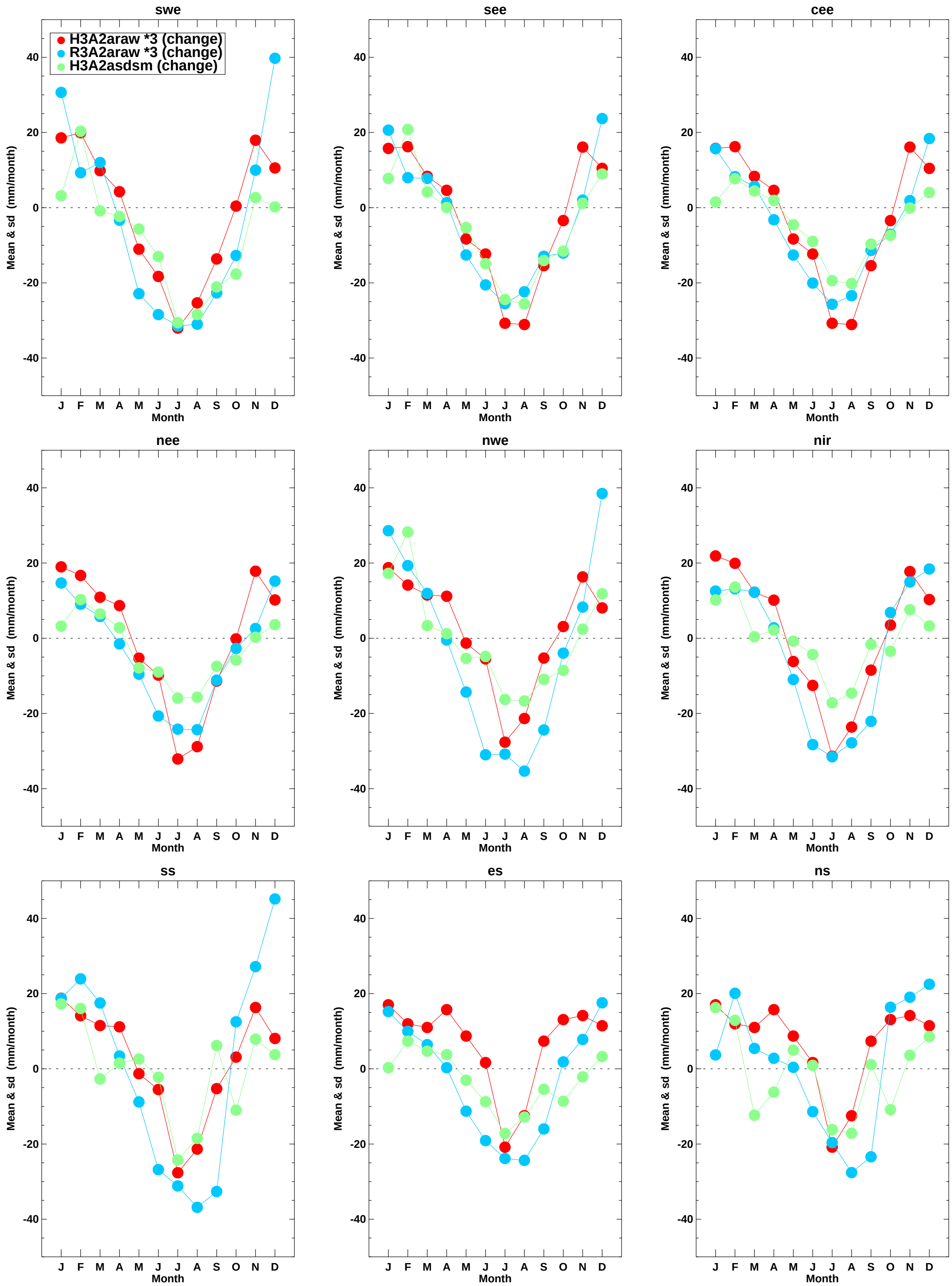

Figure 7: Annual cycle of change in mean monthly precipitation (mm/month), computed as the difference between 2050–2099 and 1950–1999 (or subsets for which data were available) from HadCM3 GCM (red), HadRM3 RCM (blue) and HadCM3 downscaled using SDSM (green). Each panel shows one of the nine UK regions (see the label above each panel).

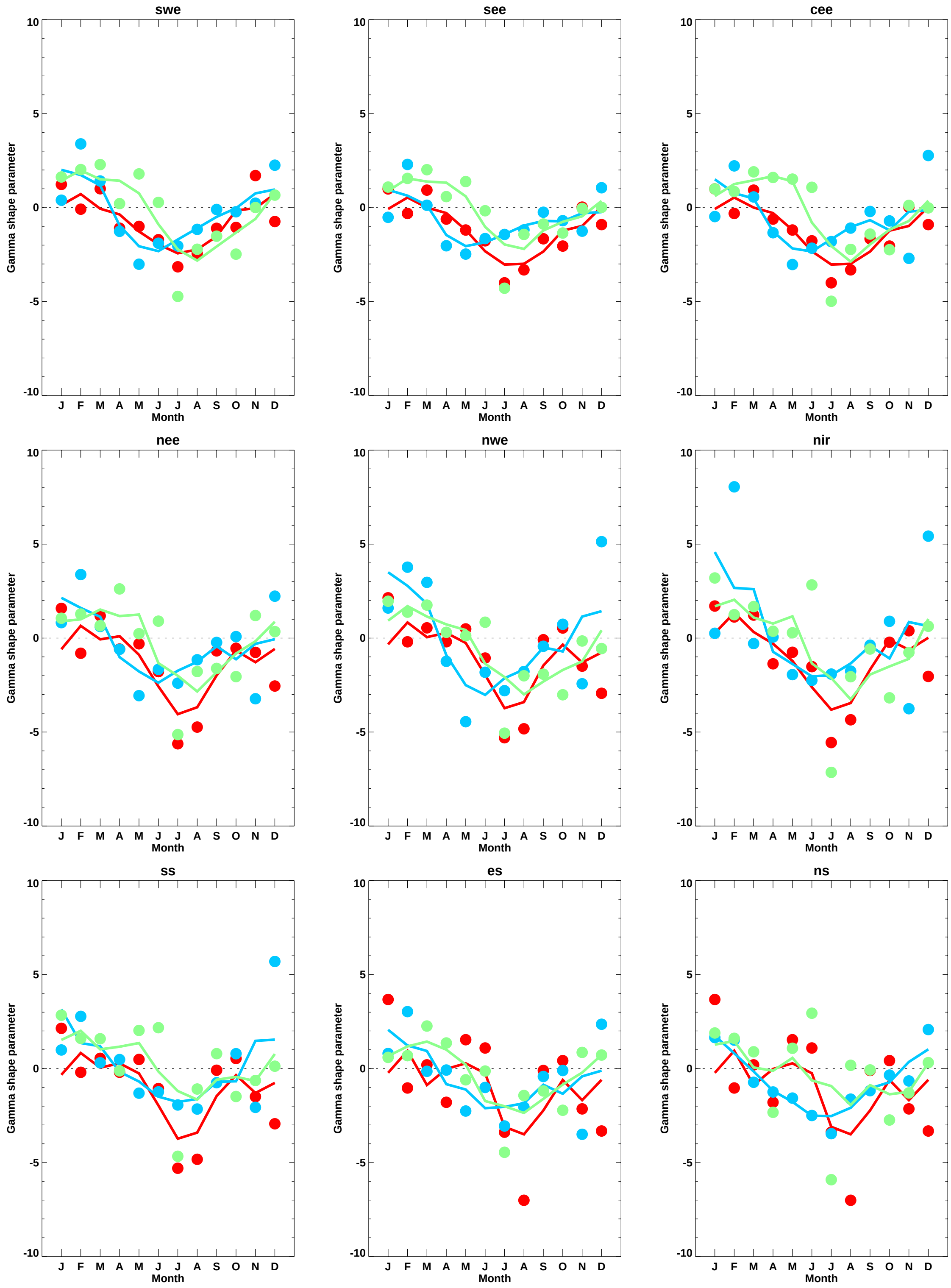

Figure 8: Annual cycle of change in monthly precipitation gamma shape parameter, computed as the difference between parameters obtained from 2050–2099 and 1950–1999 (or subsets for which data were available) from HadCM3 GCM (red), HadRM3 RCM (blue) and HadCM3 downscaled using SDSM (green). To filter out some of the noise, the thick lines connect the average change from groups of three adjacent monthly changes. Each panel shows one of the nine UK regions (see the label above each panel).

2.4.8 Drought case study: investigation of scaling issues

The intercomparison of the GCM, RCM and GCM-driven SDSM (i.e., statistically-downscaled) methods of producing scenarios of low precipitation extremes resulted in some confidence in the seasonal structure and magnitude of the change in mean precipitation, and also some confidence that the warm-season precipitation distribution would become more skewed. None of the methods is, however, directly suitable for use within an Integrated Assessment Model, where the emissions/forcing pathway is not necessarily prescribed and is not constrained to follow a pathway for which GCM and/or RCM simulations have already been undertaken. One method that is suitable is to modify an observed baseline time series by the simulated *changes* in precipitation statistical parameters. The two main difficulties to implementing such an approach have been addressed for the UK drought case study:

(i) the earlier analysis (Section 2.4.7) has identified the need to change the precipitation distribution shape, as well as the mean precipitation; and

(ii) the change in precipitation parameters under any given climate change needs to be computed from the variables simulated by the core climate module of an IAM.

For the first of these issues, a method of changing both the mean and shape of a time series' distribution has been developed, tested and implemented for the case of a time series that is well represented by a gamma distribution. The method takes advantage of the fact that if a gamma-distributed variable, X, is transformed by aX^b (where a and b are constants), the transformed data still closely follow a gamma distribution but with modified shape. This is *not* a general property of the gamma distribution, because the distribution of the transformed data can differ from the gamma distribution, but for the range of parameter values used here the discrepancy is relatively small (relative, e.g., to the uncertainty in fitting a gamma distribution to the original data). The shape parameter of the data is modified in a way that is dependent only on the value of b, while its scale parameter is modified by both a and b. Thus it is possible to iteratively select a pair of constants that will result in a specified change in shape and scale parameters. For given fractional changes in the mean (Δm) and in the gamma shape parameter (Δs), we transform an observed time series X into a scenario time series Y by:

$$Y = \Delta m \cdot \hat{X} \cdot a \left(\frac{X}{\hat{X}} \right)^b \qquad \text{Equation (1)}$$

where the ^ indicates that the series has been smoothed with a 30-year low-pass filter. Thus we modify the low-pass series (which includes information about the mean precipitation) by the fractional change in the mean, and combine it with high-frequency residuals that have been modified to represent the change in distribution shape. The power factor, b, is obtained iteratively, modifying its value until the high-frequency residuals $\left(X / \hat{X}\right)$ have a distribution whose shape parameter is Δs times its initial value; the scaling factor, a, is then selected to ensure that the mean of $\left(X / \hat{X}\right)^b$ remains 1, because all the information about the mean precipitation and how the mean changes is included in $\hat{X}$ and Δm, respectively. This separation into high-frequency and low-frequency series (with information on the mean precipitation included in the latter) works well, with less noise and simpler seasonal structure evident in Δs when it is computed from the fit of a gamma distribution to the high-frequency residuals, compared to the values obtained when using the full data (i.e., Figures 4 and 8). It also enables a simpler controlling of the change in the mean, allowing this to be constrained to match the UKCIP02 (Hulme *et al.*, 2002) mean precipitation changes, for example.

The second of these issues has been addressed (to the extent possible given the available model simulations) by an extensive analysis of monthly precipitation from all of the SRES scenario runs of the HadCM3 GCM that were available (see Section 2.4.3). Neither the analysis nor the results are described in detail here, but the conclusion is that a set of linear relationships between various precipitation parameters (mean, coefficient of variation, gamma distribution shape and scale parameters) and global-mean temperature change produce good fits to the data, with no more outliers than expected by chance (when counted over all UK regions and months of the year). This conclusion was based on two results. First, tests for linearity within the A2 ensemble mean do not fail (i.e., no more outliers than expected by chance), thus indicating that parameter changes can be linearly scaled with respect to global-mean temperature. Second, when the linear relationships derived from the A2 ensemble were applied to the B1, B2 and A1FI simulations, there are again no more outliers (i.e., "failed" predictions) than expected by chance, indicating that parameter changes are also linear with respect to global-mean temperature for the range of *rates of temperature rise* spanned by these scenarios. Despite not rejecting linearity, it is also found that the changes in the gamma distribution shape and scale parameters can be *equally well* fit by an exponential function of global-mean temperature. This exponential approach is used here because the fit to the data is equally good and it prevents the shape parameter from reaching zero (and thus the gamma distribution being undefined) when extrapolating to larger temperature changes.

Scaling relationships (linear for mean, exponential for shape) obtained using both the HadCM3 GCM simulated changes *and* the HadRM3 RCM simulated changes were used in the remainder of the study. Note that the RCM simulations are time slices only and are not sufficient, therefore, to test for linearity in the same way as was done using the GCM simulations; here we assume linearity for the RCM results purely on the basis of the GCM behaviour. We assume that the global-mean temperature change applicable to the RCM simulations is the same as that simulated by the HadCM3 GCM during the years for which the RCM was run (though see the discussion in Section 2.4.3 about the intermediate model used between the GCM and RCM that might weaken this assumption).

By combining the relationships between global-mean temperature changes and precipitation mean and distribution shape with our method of applying these changes to the observed time series (Equation 1), each monthly regional observed time series was transformed under temperature changes from 0 K to 5.5 K (in 0.5 K) steps. The drought index was computed for each transformed (or "scaled") time series and the frequency of short and long droughts was counted, to obtain drought frequency as a function of global-mean temperature change. Figure 9 indicates these relationships for the short droughts, using either the RCM- or the GCM-derived changes in precipitation parameters. Uncertainty ranges are indicated for the RCM-derived results, estimated from the binomial distribution under the assumption that each year represents a single trial whose outcome (drought or no drought) is independent of other years. Comparison with the results of directly counting drought occurrence in the GCM or RCM output (dots in Figure 9) indicates reasonable agreement, including the noticeable differences between RCM and GCM results for east Scotland ("es") that are well captured by the scaling approach. The scaling approach also provides a useful framework for a more faithful comparison of the direct GCM and RCM results with each other: results have been taken from Figure 5, but are now plotted against *different* temperature changes (because the warming during the RCM period, 2070–2100, was greater than during the GCM analysis period, 2050–2099). It is clear that the RCM changes *should* be greater that the GCM changes simply because of this difference, and now the magnitude of this can be estimated.

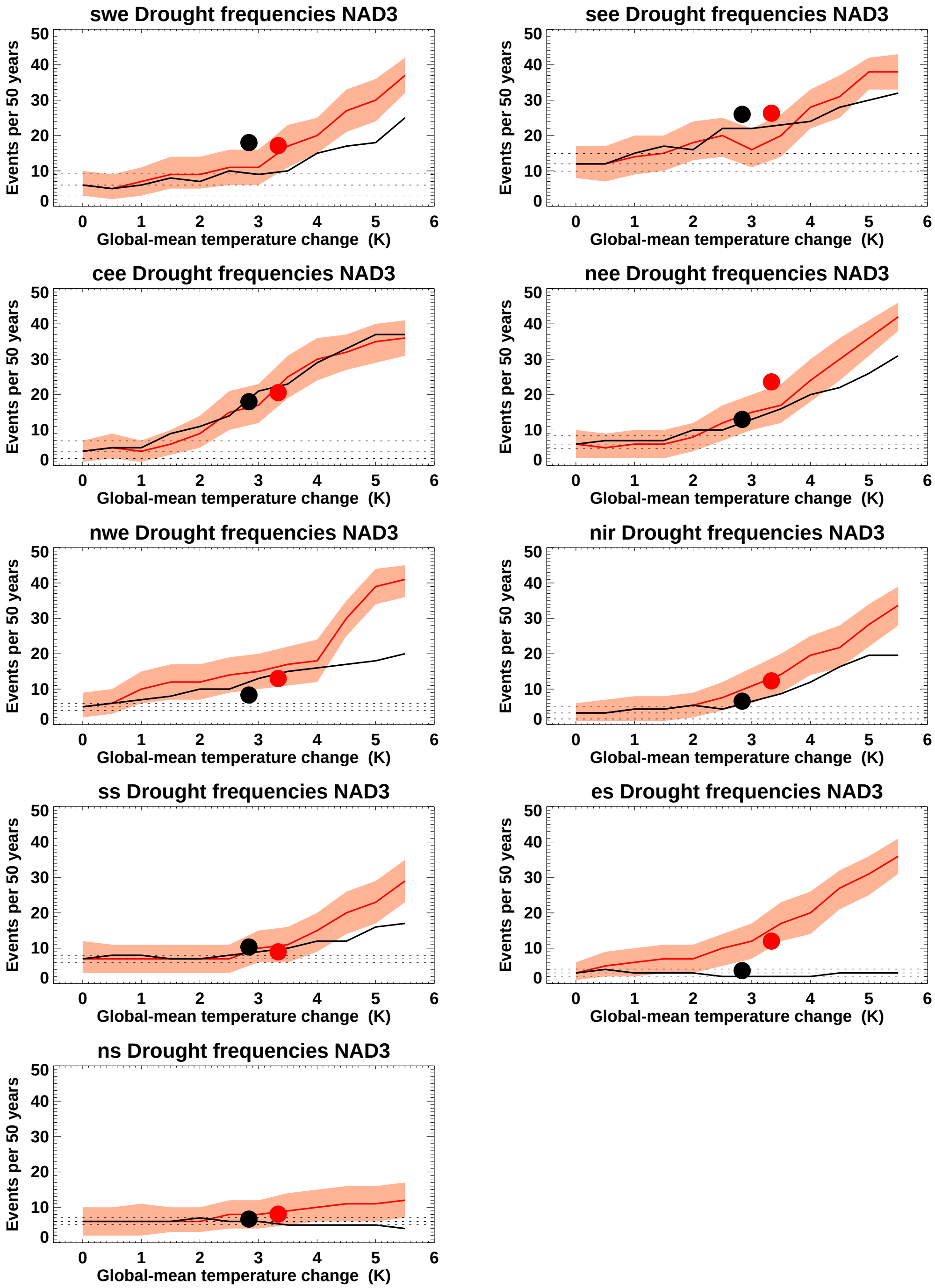

Figure 9: Curves show short drought frequencies (events per 50 years) as a function of global-mean temperature change (K), computed by scaling observed time series means and distribution shapes according to relationships fitted to either HadCM3 GCM (black lines) or HadRM3 RCM (red lines) simulated changes. The drought frequencies are the absolute values, while the temperatures are expressed as changes from the baseline period (1950–1999) mean. Dots show results obtained by *direct* analysis of GCM (black) or RCM (red) output to obtain the change in short drought frequency, added to the observed baseline frequency, and plotted against the simulated global-mean temperature change over the simulation periods used. The observed baseline frequencies are marked by the central dashed lines, with the 95% range of variability quantified from the GCM control run given by the lower and upper dashed lines. Each panel shows one of the nine UK regions, according to the label above each panel.

In most regions, the RCM-derived short drought increases become greater than the GCM-derived changes when scaling by global-mean temperature changes of 4 K and above. The relationships are nonlinear with respect to temperature change, with steeper increases once temperatures have risen by more than 2 to 3 K. There is evidence of a recurvature (becoming less steep) at high temperature changes in SEE, CEE and NWE; this must of course occur at some stage, given that the drought frequency has an upper limit of one event per year.

2.4.9 Drought case study: applications of the scaling method

Our expression of UK drought frequency as a function of global-mean temperature change (Figure 9) has a number of potential applications. The function could be used directly in an Integrated Assessment Model, if impacts modules were derived that took our particular measures of drought events as input. Alternatively, the scaled (by global-mean temperature change) monthly precipitation series could be used within the IAM to derive specific inputs that other modules may require.

To demonstrate these applications, but without resorting to the use of an IAM, the probability density functions (PDFs) of global-mean temperature change published by Wigley and Raper (2001) have been used. These PDFs (their Figure 4), for the time horizons 2030, 2070 and 2100, incorporate estimates of the uncertainty in future greenhouse gas emissions, climate sensitivity, carbon cycle and ocean heat uptake. Our RCM-derived relationships (Figure 9) have been combined with these temperature PDFs to yield PDFs of short drought frequency (Figure 10). The additional uncertainty due to random sampling variation was also incorporated, using the binomial distribution (see uncertainty ranges in Figure 9). This extra uncertainty can be considered to either represent the "natural" variability from one 50-year period to another, or to represent the uncertainty in the observed baseline frequency. Our PDFs of drought frequency (Figure 10) thus include many of the uncertainties in this quantity, with one major exception: while we have incorporated inter-model uncertainty in global-mean temperature response through Wigley and Raper's climate sensitivity and ocean heat uptake uncertainties, the additional inter-model uncertainty in the relationship between global-mean temperature and UK precipitation change has not been included, because we used only one model (HadRM3 in this example). Thus our PDFs are conditional upon our use of the HadRM3 response, and they are narrower than the (unknown) unconditional PDFs.

The inclusion of random sampling variation changes the baseline values from single spikes at the observed frequencies to binomial distributions expressing natural variability. Under global-mean warming, the PDFs shift towards higher drought frequencies, but uncertainties also increase and the PDFs broaden considerably. A few key points to note are:

- (i) the nonlinear relationship between drought frequency and global temperature (Figure 9) is the cause of the long positive tail in the drought PDFs (Figure 10), most apparent in 2100 in SWE, SEE, NEE, NWE, NIR, SS and ES;
- (ii) the recurvature of the CEE relationship results in the "mesa"-shaped PDF in 2100;
- (iii) even under the warming expected by 2070, there is a non-negligible probability that a 50-year period could have no more short drought events than observed during the 1950–1999 baseline period (though assuming some level of independence between regions, the probability that *no* region would show no increase in drought occurrence is very small); and
- (iv) in seven out of the nine regions there is also a non-negligible probability that event frequency would exceed one event per two years by 2100.

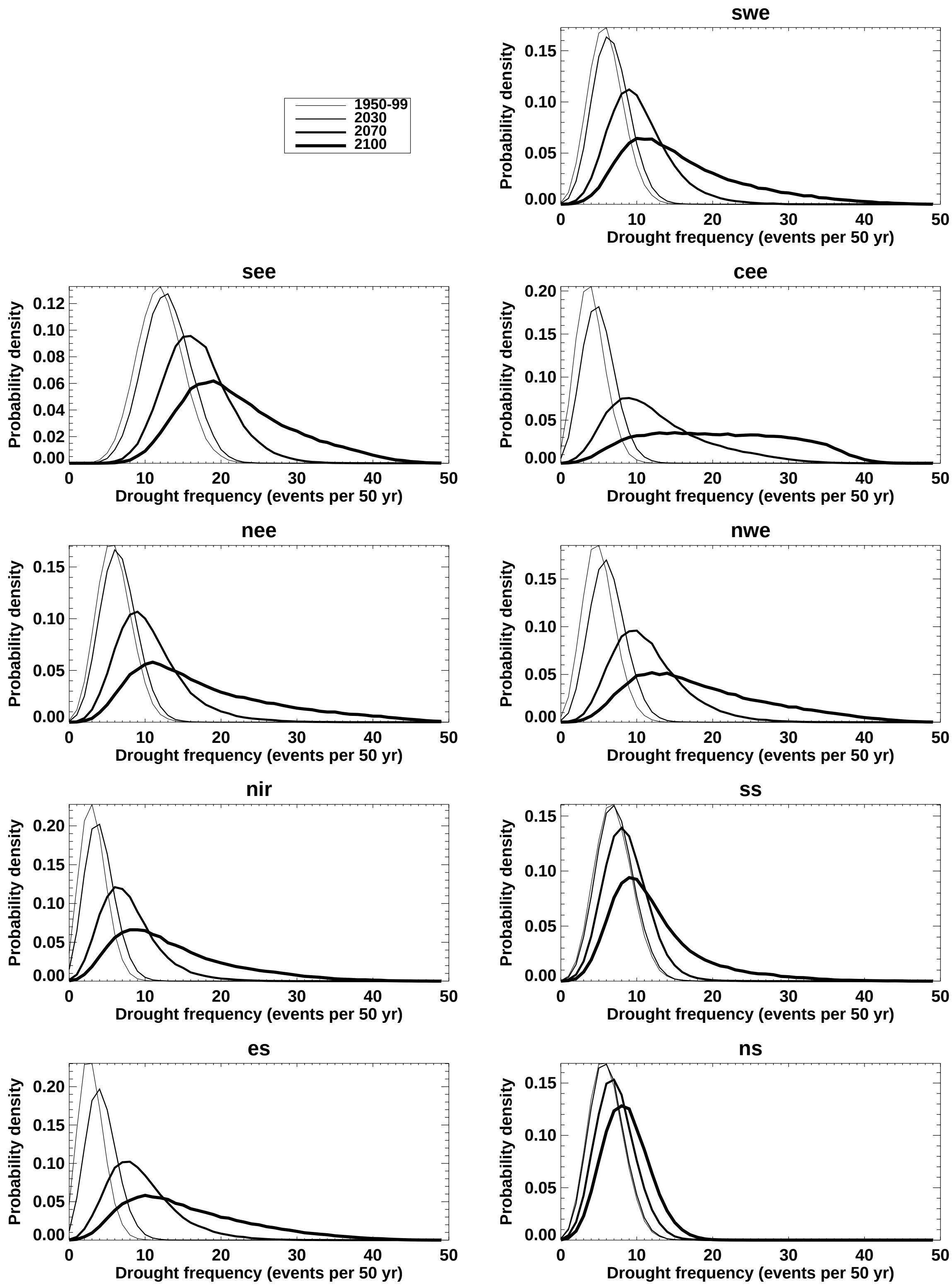

Figure 10: Probability density functions of "short" drought frequency (events per 50 years) for four time horizons in the absence of policies to limit climate change: 1950–1999 (no warming) and with warming in 2030, 2070 and 2100 (thin to thick curves, respectively). Each panel shows one of the nine UK regions, according to the label above each panel.

2.4.10 Intense rainfall case study: measuring intensity

A number of different indicators for intense rainfall have been identified (e.g., Karl *et al.*, 1999). One appropriate indicator is rainfall "total amount quantiles" which have been used to investigate observed trends in intense UK rainfall (Osborn *et al*., 2000; Osborn and Hulme, 2002). In order to calculate the quantiles for each station and month, all wet-day amounts are sorted into ascending order and then grouped into ten classes. The first class (quantile 1) consists of as many of the lightest daily events as necessary to provide 10% of the total rainfall for that month aggregated over the study period. The next class consists of however many of the next lightest events are needed to contribute a further 10% of the total rainfall, and so on. Thus, quantile 1 contains the lightest events and quantile 10 the most intense events. The quantiles are calculated on a monthly basis and the frequency counts aggregated to give seasonal values. On average, the intensity of daily precipitation has increased over the UK in winter, and decreased in summer, over the period 1961-2000 (Osborn and Hulme, 2002). That is, the number of winter days classified in quantile 10 increased during the study period and also the proportion of total winter precipitation contributed by quantile 10 days increased. Observed trends in the fractional contribution of quantile 10 days to seasonal total rainfall are shown in Figure 11.

2.4.11 Intense rainfall case study: intercomparison of simulated and observed changes

The same methodology was applied to output from the HadCM3 GCM and the HadRM2 RCM. HadRM2 was used rather than HadRM3, because output from the latter model simulations did not become available until near to the end of the project period. In each case, the quantiles were defined over the "present-day" simulation period and then held fixed, while the number of days falling in each quantile and the contribution of each quantile to the seasonal totals varied during the model simulations. The RCM simulation (Figure 12) shows stronger trends than have been observed, but this is expected because the change in radiative forcing between the control and perturbed RCM simulations was much greater than that observed over the last few decades. Nevertheless, there is similarity in the seasonal structure of changes over England and Wales: the observed record shows decreases in summer and increases in winter, with a mixture of changes in the other seasons (though a slight increase in this measure of intensity when averaged across the regions), while the simulated changes show little change in summer and strong increases in winter (and almost as strong in the other two seasons). The summer minimum (or decrease) is also apparent in the Scottish regions in the observed record, but not in the HadRM2 simulation.

The HadRM2 changes are similar to those diagnosed from the HadCM3 simulations (not shown), with increased intensity across the UK in winter, spring and autumn, while in summer there was also an increase in Scotland but little change in England and Wales (regional details are, of course, limited by the grid-box resolution of the HadCM3 model). The HadCM3 analysis was extended to most of Europe, and puts these changes into a geographic context (not shown). Intensity increases were simulated in all seasons, but only extending from the north of the domain (65°N) southwards to a seasonally-dependent limit. This limit is around the central Mediterranean in winter and autumn, southern France in spring, and northern England in summer (thus south of Scotland, the summer intensity increase is not strong). This change is combined with another, involving a general decrease in mean precipitation and a weakening intensity, *except* that the very high intensity events increase in importance. This second change is limited to parts of the Mediterranean region in winter, spring and autumn, but is more widespread across Europe in summer. This change is a manifestation of a changing distribution *shape* rather than just a change in the mean; as such, there are clear links with the drought case study (even though that considered monthly precipitation totals).

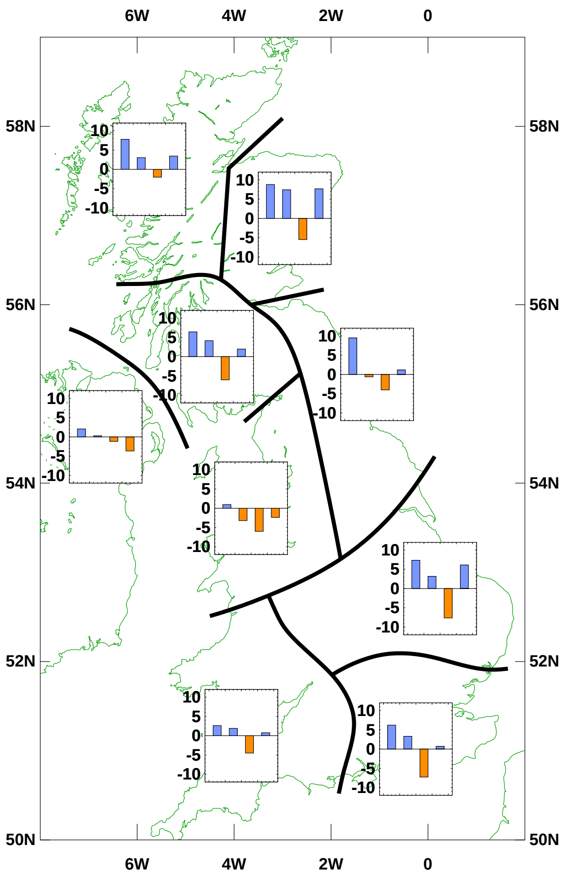

Figure 11: Observed trend (% per 40 years) in percentage of seasonal total precipitation provided by quantile 10 events over 1961–2000. Four bars in each region show trends in winter, spring, summer and autumn, respectively.

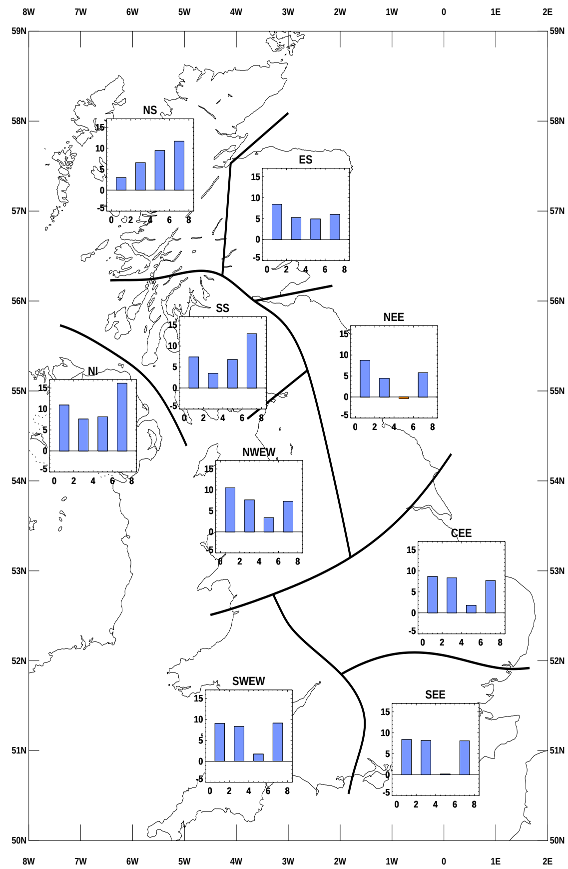

Figure 12: Change (%) in percentage of seasonal total precipitation provided by quantile 10 events between "present-day" and "double-CO_2" simulations of HadRM2 RCM. Four bars in each region show trends in winter, spring, summer and autumn, respectively.

2.4.12 Intense rainfall case study: spatial scale issues

The observed analysis reported above involved the analysis of precipitation at the raingauge spatial scale, before averaging results into regions. The analysis of the HadRM2 RCM output was at the RCM grid box scale (approximately 50 km by 50 km), with averaging of results into regions only undertaken after the analysis was performed. The HadCM3 GCM output was analysed at the GCM grid box scale (approximately 250 km by 250 km). The question arises as to whether changes at one spatial scale are applicable to a different spatial scale? For mean wet-day amount, Osborn (1997) showed that the issue of spatial scale was less relevant if the typical spatial structure of an average rainfall event was constant under climate change *and* if the changes were expressed in relative rather than absolute terms. Booij (2002) showed a similar result for the parameters of the Gumbel extreme value distribution. Durman *et al.* (2001) also found that GCM and RCM results were more comparable when using relative rather than absolute measures of extremes or intensity. The results obtained during this study may also be relatively insensitive to spatial scale because the quantile method uses a relative definition of extremes (i.e., it does not apply the same quantile definitions, in mm/day, to the observations and simulations). The key concern, however, is whether the spatial structure/coherence/scale of a typical rainfall event changes under climate change. If it does, then additional modifications of the results would be required before applying them to, for example, the scale of small river catchments.

A preliminary assessment of this issue was made using daily precipitation from the HadRM3 ensemble of three simulations under the SRES A2 scenario. Within each of the nine UK regions (Figure 1), regional-average precipitation was calculated as the straight average of all RCM grid boxes that fall within each region. During this averaging process, the number of individual grid boxes that had precipitation exceeding various thresholds was counted. Figure 13 shows the change in the average wetted area, in each region, on days when the regional average precipitation is above 0.1 mm during 2070–2100, as a percentage of the 1961–1990 value. There is little change in the wetted area during winter (perhaps a slight increase), while a strong decrease (5 to 10%) in average wetted area is found within all regions during summer, especially during June to September. This diagnostic can used (see Osborn, 1997, for method) to apply changes in wet-day probability or mean wet-day amount diagnosed at regional (e.g., GCM grid box) scales to smaller scales (e.g., small catchments). It is not, however, directly applicable to changes in extremes – though it does indicate that some scale-dependent correction would be necessary even when expressing changes in intensity in relative terms.

2.4.13 Intense rainfall case study: recommendations for further investigation

Further work is clearly necessary to extend the intense rainfall case study, including:

(i) using the HadRM3 RCM output rather than (or in addition to) the HadRM2 RCM output used here;

(ii) extending the comparison to include daily statistically-downscaled data (e.g., using the SDSM driven by the HadCM3 circulation and moisture variables that was used for the drought case study – see Section 2.4.5);

(iii) assessing changes in the spatial coherence of precipitation using measures that are more applicable to extreme values than the measure used here; and

(iv) focussing on catchment-scale extremes to increase the relevance of the results to hydrological extremes.

The progress made during the present study was somewhat limited by the late availability of the HadRM3 RCM data, but nevertheless provides a useful grounding and begins to investigate some of these issues (e.g., whether results are transferable between spatial scales). Some of these issues will be explored within a Round 2 Tyndall project (T2.11) that was developed from the findings of this study.

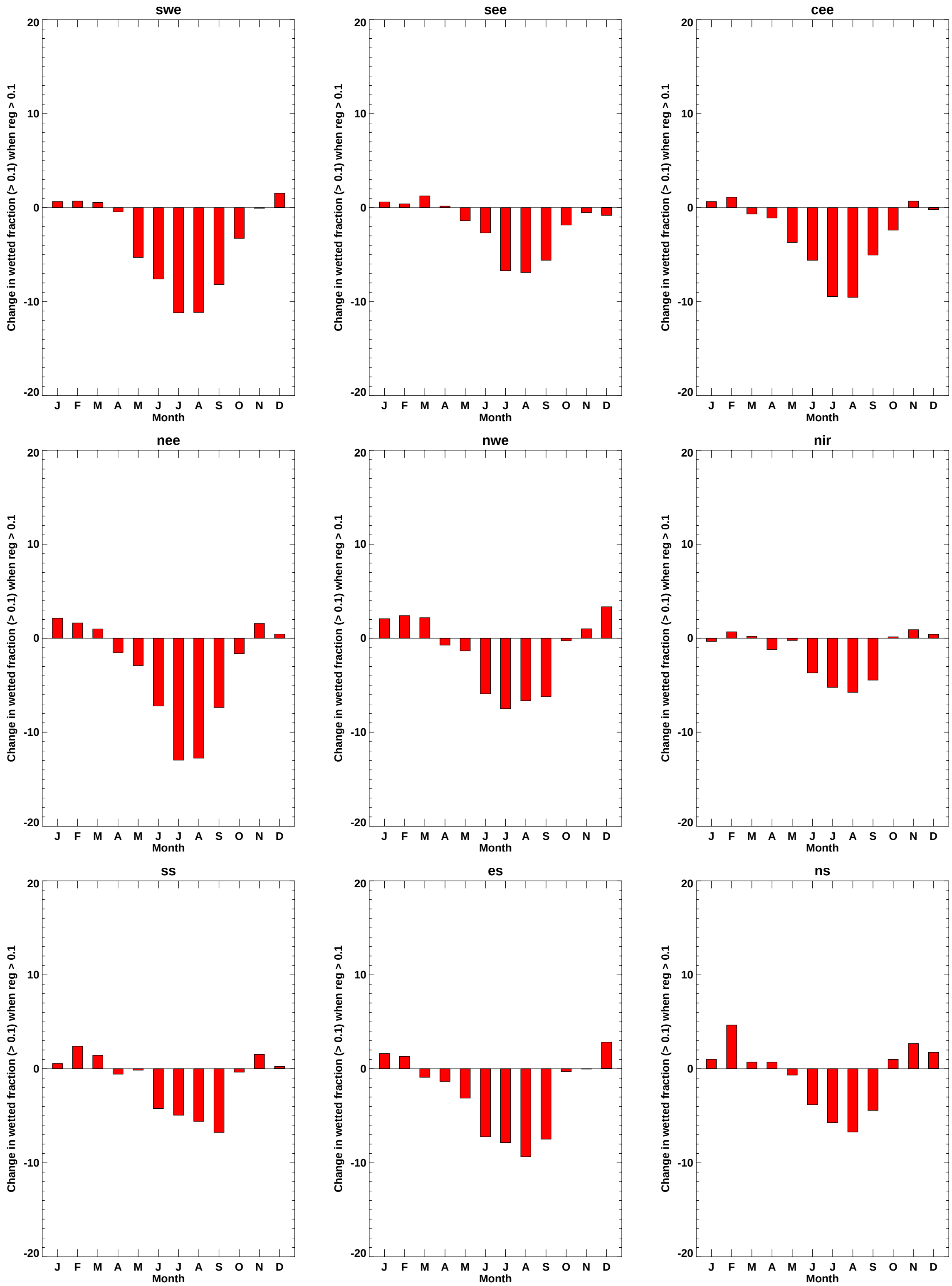

Figure 13: Change in wetted area between 1961–1990 and 2070–2100 periods of the A2 ensemble simulations with HadRM3 RCM, expressed as a percentage of the wetted area simulated during 1961–1990. Wetted area is the average fraction of RCM grid boxes that have > 0.1 mm of precipitation on days when the regional-mean precipitation is > 0.1 mm.

2.4.14 Conclusions and recommendations from the case studies

The main conclusions and recommendations from the drought case study are:

- It is important to use the largest-possible climate model ensemble.
- Results based on a threshold-based drought index are sensitive to the threshold used (thus providing benchmarking against previously experienced events comes at the cost of greater uncertainty in objectively defining those events).
- Some form of downscaling (i.e., HadRM3 or SDSM) is preferred to using HadCM3 output directly.
- Validation against observed data supports the use of HadRM3 rather than SDSM or HadCM3 (which both overestimate persistence, for example).
- However, validation on an independent data period, indicates that the SDSM approach does not suffer from the potential problem of overfitting.
- For time periods for which HadRM3 output is available (i.e., the late 21st century), this is the preferred approach.
- For time periods for which HadRM3 output is not available (e.g., the 2020s, the 2050s) and within the context of an Integrated Assessment Model, observed time series can be scaled by changes in mean and changes in the distribution shape, with scaling factors derived from HadRM3 or HadCM3 simulations.

The main conclusions and recommendations from the intense rainfall case study include some of the above conclusions, but also:

- Changes in extreme events may be less dependent upon the spatial scale used (and therefore more transferable across different spatial scales) when events are measured using a relative definition (rather than, for example, an absolute threshold in mm/day).
- Even when measured using a relative definition, changes in the spatial coherence of precipitation events would necessitate an adjustment to be developed and applied when transferring scenarios from one spatial scale (e.g., GCM grid box) to another (e.g., small catchment). Preliminary results indicate that a change in the spatial coherence of precipitation events may occur in summer in the HadRM3 RCM climate change simulations.

2.5 SCENARIO DEVELOPMENT METHODS FOR OTHER VARIABLES

2.5.1 Non-temperature/precipitation extremes

The methods reviewed in Task 2 (see Section 2.3) and tested in Task 3 (see Section 2.4) provide a range of possible approaches for the construction of scenarios of temperature and precipitation-based extremes. However, scenarios of other types of extreme event may also be required for impact assessments. The IPCC Third Assessment Report, for example, identifies other extreme phenomena (such as cyclonic storms, together with very small-scale phenomena such as thunderstorms, tornadoes, hail and lightning which are not simulated in climate models), many of which may have important impacts on the environment and society, but for which there is currently insufficient information to assess recent trends and for which climate models currently lack the spatial detail to make confident projections. Some of these phenomena, such as hurricanes, are not highly relevant to the UK, while others, such as North Atlantic cyclonic storms, clearly are.

One of the questions addressed by the project workshop was, what are the important non-temperature and precipitation extremes for particular impact studies? The events identified by the stakeholder representatives are listed in Appendix 1.

Storms and extreme windspeeds were identified as important events by all the stakeholder representatives. A number of modelling studies have investigated potential changes in the occurrence of North Atlantic cyclones and storm tracks (Carnell and Senior, 1998; Schubert *et al*., 1998; Ulbrich and Christoph, 1999; Knippertz *et al*., 2000; Carnell and Senior, 2001; Hanson *et al*., 2003). These are, however, subject to some major uncertainties. Most recently, the UKCIP02 scenarios provide information about future changes in the UK wind regime based on the HadRM3 simulations, but the uncertainties are so great that it is not even possible to assign a 'low confidence level' to these scenarios (Hulme *et al*., 2002). Storms and windspeed are the focus of Tyndall Centre project IT1.4 (due to finish in May 2003) which is carrying out an integrated assessment of the potential for change in storm activity over Europe, focusing on the implications for insurance and forestry in the UK. Storm activity has not, therefore, been considered as part of this project.

Lightning, fog and hail were also mentioned by the stakeholder representatives (see Appendix 1). None of these variables are directly simulated by GCMs/RCMs, and so some kind of physical or statistical relationship with larger-scale variables must be used. The UKCIP02 scenarios of lightning and fog were constructed from HadRM3 output in this way, using relationships established in weather forecasting, based on the velocity of updrafts and relative humidity for lightning and fog respectively (Hulme *et al*., 2002). As is the case for all statistical downscaling methods, however, it is necessary to assume that these relationships will remain valid under a changed climate. The relationships used by Hulme *et al.* (2002) were not developed for climate change applications, and without an evaluation of their suitability for this purpose, it is impossible to assign a confidence level to the validity of this assumption. A reliable and continuous lightning data set from 1990-1999 is provided by the UK Meteorological Office's Arrival Time Difference detection and location system. Analysis of this data set may lead to improved techniques for forecasting based on, for example, the relationships observed between lightning and sea surface temperature (Holt *et al*., 2001). The Tornado and Storm Research Organisation (TORRO; Elsom *et al*., 2001; http://www.torro.org.uk) holds a hail data set (Webb *et al*., 2001) which, although not yet fully digitised, could be used to develop a method for statistically downscaling this variable.

2.5.2 Joint probability events

The importance to stakeholders of joint probability events (e.g., wind storms with snow/rain, heavy snow followed by rapid thaw, intense rainfall on dry/frozen or already saturated ground, storm surge with river flood) emerged very strongly from the workshop discussions (see Appendix 1). Three examples of joint probability events are considered here and suitable approaches to scenario construction proposed:

- snowmelt;

- subsidence; and,
- storm surge with river flood.

Snowmelt is an important component of design limits for structures such as dams. The UK Meteorological Office produces snowmelt maps for the present day and the Flood Estimation Handbook provides a methodology for incorporating snowmelt which is extensively used by engineers in the UK. Both of these require review in the context of climate change. The current non-geographically varying 24-hour probable maximum snowmelt of 42 mm recommended by the Flood Estimation Handbook, for example, is considered to be an underestimate for some regions at the present day (Hough and Hollis, 1997). Thus any information about the changing risk of catastrophic snowmelt episodes would be very useful both for flood defence and reservoir design. Snowmelt estimation requires information about temperature, precipitation and, ideally, windspeed, and thus would provide a good test of the ability of climate scenarios to represent joint probability events. Scenarios could be constructed using a simple snowmelt scheme (Harding and Moore, 1988) as implemented in precipitation-runoff models (Arnell and Reynard, 1996) or using the more sophisticated PACK snowmelt module (Moore *et al*., 1999) designed to provide inputs to catchment models.

During the mid 1990s, subsidence of UK domestic properties is estimated to have cost the insurance industry £350 to £450 million annually (CII, 2001). The greatest cost to insurers occurs with properties on shrinkable clay soils. The weather conditions associated with subsidence are complex, involving rainfall, the extent of water absorption into the soil, the run-off away or towards a building, and the drying out due to sunshine, ambient temperature, wind and tree water consumption through evapotranspiration (ABI, 2000). Thus subsidence is another event which requires information about multiple variables and joint probabilities. An additional requirement of climate scenarios is the need for information at very high spatial resolutions (i.e., 10-50 m, see Appendix 1). Some very sophisticated and data-intensive packages for the mapping of susceptibility to clay shrinkage induced subsidence have been developed by the British Geological Survey and other groups for commercial use, however, these cannot currently be used for scenario construction (Brignall *et al*., 1999). A less data-intensive soil water balance model, in which the balance between total monthly precipitation, total monthly potential evapotranspiration and the available water-holding capacity of the soil is calculated, has been developed in a Yorkshire case study and used to construct European-wide scenarios of the meteorological subsidence hazard using output from an earlier, equilibrium version of the Hadley Centre GCM and the GFDL model (Brignall *et al*., 1999). This method could be updated and applied at a higher spatial resolution using output from the current generation of climate models.

GCMs and RCMs have the advantage of providing physically-consistent multi-variate information (Tables 3 and 4), however, this may not be sufficiently reliable, particularly at the high spatial and temporal resolutions required for some joint probability events such as subsidence. Where statistically-downscaled scenarios which are consistent between multiple variables on a day-by-basis are required, a common approach is to first simulate rainfall and then to model the other variables conditional on the rainfall state of each day (Richardson, 1981; Semenov *et al*., 1998; Skiles and Richardson, 1998; Wilby *et al*., 1998b; Goodess, 2000; Hayhoe, 2000; Palutikof *et al*., 2002). In the widely used WGEN weather generator originally developed by Richardson (1981), for example, rainfall is modelled as a first order Markov chain process in the conventional way and then maximum and minimum temperature and solar radiation are modelled as a multivariate first order autoregressive process (Semenov *et al*., 1998; Skiles and Richardson, 1998; Hayhoe, 2000). The Climatic Research Unit has developed an improved version of this weather generator (Jones and Salmon, 1995), in order to provide inputs to crop yield models across the European Union, which provides daily self-consistent scenarios for precipitation, mean temperature, diurnal temperature range, vapour pressure/relative humidity, sunshine duration and windspeed. The same principle has been used by Palutikof *et al*. (2002) to construct self-consistent temperature and rainfall scenarios for the Mediterranean. In this case, temperature was estimated using transfer functions that were constructed separately for wet and dry days, thus maintaining consistency between the two variables. Consistency was also maintained by including sea level pressure, which was used to predict precipitation, as one of the temperature predictor variables. A sampling approach (see Table 6) can also be used to construct self-consistent scenarios for a number of different variables. Brandsma and Buishand (1998), for example, used a nearest-neighbour sampling method to construct daily rainfall and temperature time series for stations in the Rhine basin. Thus statistical downscaling methods can be used to construct self-consistent multi-variate scenarios to investigate changes in extreme events such as snowmelt and subsidence, although care is needed in the development of these methodologies, particularly where stochastic elements are involved.

The risk of tidal/storm surge flooding combined with river flooding was also raised as an issue of concern to stakeholders during the project workshop (see Appendix 1). This is of particular concern to stakeholders in catchments in the southeast of the UK, such as the Thames, which are affected by continuing de-glacial isostatic sinking. The Thames barrier was closed on 23 occasions during the winter season November 2000 to March 2001 due to varying combinations of high spring tides, depressions over the North Sea, wind amplification in the English Channel and high river flows (Bigg, 2001). It is estimated that 50% of the capital value of UK assets potentially at risk from sea, tidal and fluvial flooding lie within the Thames region (Halcrow, 2001). A recent study indicates, however, that the strongest dependence between storm surge and river flow occurs in the area to the north of the Firth of Forth which is not sheltered from south-westerly winds by any major topographical barriers (Svensson and Jones, 2002).

Estimates of storm surge changes can be provided by storm surge models forced with GCM/RCM output, such as that developed by the Proudman Oceanographic Laboratory (Flather and Smith, 1998; Lowe *et al*., 2001), although the uncertainties involved are large (Hulme *et al*., 2002). These models have recently been evaluated as part of the STOWASUS-2100 European Union funded project (http://www.dmi.dk/f+u/klima/english/STOWASUS-2100/). Alternatively, statistical downscaling could be employed, using large-scale predictor variables such as sea level pressure (von Storch and Reichardt, 1997; Holt, 1999). There is a reasonably large literature on statistical techniques for modelling the interaction between the tidal and surge components of sea level (Pugh and Vassie, 1980; Tawn, 1988; Coles and Tawn, 1994; Dixon and Tawn, 1994; Ozer *et al*., 2000) which could be used to combine storm surge scenarios with sea level rise scenarios.

Adding in the risk due to river flooding would first require the construction of scenarios of precipitation (and other variables such as temperature, net radiation, windspeed and humidity which may be required as input variables by hydrological models) which are consistent with the storm surge scenarios. This could be done using GCM or RCM output directly, or by statistical downscaling with the same large-scale predictor variables, such as sea level pressure, used to construct the storm surge scenarios. The precipitation and other scenarios would then be input to a hydrological model (e.g., Arnell and Reynard, 1996) in order to estimate runoff and river flow (it should, however, be noted that such a model does not currently exist for the whole Thames catchment). Joint probabilities could then be estimated, although no general statistical solutions for such problems are available (see Appendix B of IoH, 1999). Even where the input factors are truly independent (which they may not be, if the same synoptic situations are found to give rise to storm surges and intense precipitation, for example), potential solutions are rarely straightforward, although new statistical approaches to multi-variate extreme value problems are being developed (Coles *et al.*, 2000; Coles, 2001).

2.6 DEVELOPMENT OF GUIDELINES TO UNDERPIN THE FUTURE DEVELOPMENT OF SCENARIOS THAT INCLUDE INFORMATION ABOUT CLIMATE/WEATHER EXTREMES AND VARIABILITY

2.6.1 Assessment of the uncertainties

Together with the growing recognition of the need to incorporate information about changes in climate variability and the occurrence of extremes into impact assessments, there is also growing recognition of the need to take into account the full range of uncertainties in scenario construction and, at the same time, to distinguish between climate model deficiencies and the inherent unpredictability of climate (Hulme and Brown, 1998; Hulme and Carter, 1999; Hulme *et al*., 1999; Katz, 1999; Mitchell and Hulme, 1999; Giorgi and Francisco, 2000a,b; Jones, 2000a,b; New and Hulme, 2000; Visser *et al*., 2000; Räisänen and Palmer, 2001). The IPCC Third Assessment Report (TAR) and many of the references cited above, refer to a cascade of uncertainty related to:

- the emissions or radiative forcing scenarios, i.e., inter-scenario variability;
- the use of different climate models, i.e., inter-model variability;
- different realizations under a given emissions scenario with a given climate model, i.e., internal model variability (which is, in part, a reflection of natural climate variability); and,
- sub-grid scale forcings and processes.

Appropriate techniques for handling the first three sources of uncertainty are widely recognised (see references above, also Andronova and Schlesinger, 2001; Wigley and Raper, 2001; Katz, 2002; Stott and Kettleborough, 2002), although they are not yet routinely or comprehensively applied in impacts assessments:

- uncertainties due to inter-scenario variability can be handled by using more than one emissions scenario (possibly necessitating the use of pattern-scaling techniques if climate model simulations are not available for all emissions scenarios);
- uncertainties due to inter-model variability can be handled by using output from more than one climate model; and,
- uncertainties due to internal model variability and thus, in part, natural variability, can be handled by using ensembles of simulations with each model (i.e., simulations performed with the same climate models and forcing, but starting from different initial conditions).

Comparative studies of the first three sources of uncertainty (the fourth has been less-widely addressed) indicate that, for mean climate, inter-model variability tends to be greater than inter-scenario or internal model variability, particularly over the earlier part of the 21st century (Dutton and Barron, 2000; Giorgi and Francisco, 2000a,b; Bergstrom *et al*., 2001). The uncertainties are, however, likely to depend on the variable being addressed. In an intercomparison of four RCMs, for example, Christensen *et al*. (2001) conclude that inter-scenario uncertainties dominate in the case of mean temperature in Nordic regions.

Uncertainties in extreme event scenarios have rarely been studied. A recent exception is Palmer and Räisãnen (2002) who used an ensemble of 19 GCMs to construct probabilistic scenarios of 'very wet', defined as greater than the mean plus two standard deviations, European winters and Asian monsoon region summers. It is demonstrated that the use of a single deterministic scenario underestimates the risk of making the wrong hypothetical investment decision with respect to flooding, compared with use of the full inter-model ensemble. In a study of 20-year return period precipitation values in the Meuse catchment in Europe using output from a number of GCMs and RCMs, Booij (2002) concludes that the uncertainties due to model errors and inter-model differences amount to 50% of the present-day return values (i.e., they are significantly larger than the projected change of ~18%).

The fourth source of uncertainty identified above, sub-grid-scale forcings and processes, has not yet been adequately addressed in the literature, but may be particularly important for extreme events with small temporal and spatial scales. RCMs provide information at the sub-GCM grid scale, so ensemble RCM output provides one way of exploring this issue (Dutton and Barron, 2000). However, the current resolution of RCMs (e.g., 50 km × 50 km for HadRM3) is still relatively coarse for some extreme event processes, such as convective precipitation. Statistical downscaling methods can provide station or point values and thus may provide another way of exploring this issue, but introduce additional uncertainties due to the methods themselves. Similarly, statistical manipulation methods which attempt to correct for model biases (Table 3 and 4) are also likely to introduce new uncertainties.

Another aspect of uncertainty which needs to be addressed concerns the relationship between the future climate-change uncertainties discussed above and multi-decadal climate variability (Hulme *et al*., 1999), i.e., the issue of signal-to-noise ratios (which is particularly important for determining the significance of projected climate changes and for detection and attribution studies). Changes in extreme events may be non-linear and greater than changes in mean climate (Mearns *et al*., 1997; Wagner, 1999). However, the natural variability of extremes is also greater than that of mean climate, thus the signal-to-noise ratio may be lower for extremes than for mean climate, making it more difficult to identify significant changes in extremes.

The case study on UK drought (see section 2.4) demonstrates how some of the uncertainty sources could be quantified.

(1) Emission scenario uncertainty. Output from GCM simulations under four different scenarios was used to test whether the pattern scaling approach could be extended to consider changes in measures of variability and extremes, as well as changes in mean climate. For monthly precipitation over the UK, such an approach appears to be valid and an appropriate implementation was devised and tested. The scalability of the climate variability and the implementation approach together allow scenarios of precipitation and drought extremes to be generated for multiple emissions scenarios.

(2) Model deficiencies and inter-model uncertainty. Although inter-model uncertainties were not fully addressed, because only one GCM and one RCM were used in the study, the full scope of uncertainty due to model differences should include not only the GCM, but also any methods or models that are used in conjunction with the climate model to yield the final climate change scenario. Thus our intercomparison of the GCM, RCM and statistical downscaling model results provides a partial assessment of the uncertainty in arriving at precipitation and drought extremes.
(3) Internally-generated climate variability. The case study quantified this by using variability simulated during the GCM control run (i.e., due to internal processes rather than any changes in external forcings) to assess variability in parameters of the precipitation distribution and in the occurrence of drought extremes.

Clearly further research is needed to determine which sources of uncertainty dominate for extremes and to quantify the full range of uncertainty. Such work could build on the Monte Carlo approach used by Hulme and Carter (1999) and New and Hulme (2000) by extending it to the treatment of extreme events. Through its adoption of probability density functions (PDFs) based on expert opinion, this approach can be viewed as Bayesian (Hulme and Carter, 1999), although it does not employ the formal Bayesian statistical paradigm (Katz, 2002). The use of PDFs make this approach particularly suitable for risk-based studies of climate change and for use in economic-based integrated assessment models (see Section 2.6.3).

2.6.2 Incorporation of low probability, high impact events

Climate change assessment studies, particularly probabilistic studies and integrated assessments, should, but do not yet (with rare exceptions, e.g., Keller *et al*., 2000; Schneider and Thompson, 2000; Mastrandrea and Schneider, 2001), consider scenarios of low probability but high impact events, such as an abrupt reorganisation of the thermohaline circulation or a collapse of the West Antarctic ice sheet, that could arise due to non-linearities in the climate system (Hulme and Carter, 1999; Lockwood, 2001). It has been suggested that failure to consider such events is likely to result in underestimation of the social and economic impacts of climate change (Higgins *et al*., 2002).

Such events have also been referred to as climate 'surprises' and there has been a tendency to focus on 'surprises' with negative rather than positive impacts (Schneider and Root, 1996; Jones, 2000a; Streets and Glantz, 2000; Visser *et al*., 2000). The concept of climate 'surprise' is somewhat subjective and does not distinguish between events which are truly unpredictable and those which could be anticipated (Streets and Glantz, 2000). Thus the term low-probability high-impact event is preferred (Jones, 2000a).

The IPCC TAR identifies a number of such events:

- abrupt reorganisation of the thermohaline circulation;
- collapse of the West Antarctic ice sheet; and,
- fast changes to the carbon or methane cycle, such as large and rapid releases of methane trapped below the sea floor and in permafrost.

There are two aspects of such events that must be addressed: (i) the probability of the event occurring, and (ii) the response of the climate system to the event. These aspects are somewhat better, but still not well, understood for thermohaline reorganisation and West Antarctic ice sheet collapse than for abrupt carbon or methane cycle changes (see Section 5 of

Goodess *et al*., 2001). For UK impact assessments, collapse of the thermohaline circulation is considered to be the low-probability high-impact event of greatest concern and thus has been the focus of project work in this area.

Many experiments have been performed with the most recent generation of climate models to explore the sensitivity of the thermohaline circulation system to freshening and increased meltwater discharges in the North Atlantic (see references cited in Section 5.2 of Goodess *et al*., 2001, together with the following more recent studies: Gent, 2001; Sun and Bleck, 2001; Thorpe *et al*., 2001; Clark *et al*., 2002; Knutti and Stocker, 2002; Vellinga *et al*., 2002).

The IPCC TAR concludes that most models show weakening of the ocean thermohaline circulation over the 21st century (but see also the discussion and review of Bigg *et al.*, 2002). None of the model projections reviewed in the TAR indicate a complete shut-down of the thermohaline circulation by 2100 but it is acknowledged that the thermohaline circulation could shut-down completely if the change in radiative (and, by implication, freshwater) forcing is large enough and applied for long enough. Thus, there is a necessity to determine how large and persistent the forcing needs to be to cause the thermohaline circulation to collapse. Keller *et al*. (2000), for example, have estimated critical atmospheric CO_2 concentrations (e.g., 776 ppmv for a climate sensitivity of 3.5°C) beyond which the thermohaline circulation is 'supposed' to collapse, based on the model results of Stocker and Schmittner (1997). Other model results, however, are likely to provide different estimates of the critical concentration (Clark *et al*., 2002; Knutti and Stocker, 2002). Further research is also needed on potential recovery mechanisms (Vellinga *et al*., 2002).

The impacts of thermohaline circulation changes on Northwest European climate have not been widely explored. In the climate models reviewed for the IPCC TAR where the thermohaline circulation weakens but does not collapse, there is still a warming over Europe. However, in simulations in which the thermohaline circulation is forced to collapse, cooling and drying occur over Europe (Klein Tank and Können, 1997; Rahmstorf and Ganopolski, 1999; Vellinga and Wood, 2002). While these experiments provide useful guidance as to the climatic changes that might be expected due to the collapse of the thermohaline circulation, the published results do not provide any information about extreme events. Note also, that the recent HadCM3 experiment which indicates a cooling of 1-3° C over Europe in the third decade after collapse (Vellinga and Wood, 2002), does not incorporate greenhouse gas forcing. Even if daily output from all the completed experiments was available for use in scenario construction, the limited number of simulations makes it difficult to investigate uncertainty due to internal and inter-model variability (Section 2.6.1). The probability of thermohaline circulation collapse is dependent on both the magnitude and rate of warming, thus it is considered particularly important to consider multiple forcing scenarios and ensembles (Mitchell and Hulme, 1999).

Within the scope of this project, it has not been possible to obtain improved estimates of either the probability of, or climatic response to, thermohaline collapse. Thermohaline circulation changes are the subject of a current major NERC initiative (http://www.nerc.ac.uk/funding/thematics/rcc/) which may eventually lead to such improved estimates. In the meantime, the project has considered how such information might be incorporated in scenarios and risk assessment studies - work which will require an interface between the basic science and the impact assessment research communities. Recommendations on how this work could be undertaken were incorporated in a proposal for a Round 2 Tyndall Research Theme 1 project on 'Interfacing climate and impacts models in integrated assessment systems' co-ordinated by Nigel Arnell and involving Tim Osborn. The proposal has been accepted and the new project (T2.11) will start in late 2002. The proposed methodology is based on pattern-scaling (see Section 4.1.3 of Goodess *et al*., 2001 for a review of pattern scaling in the context of scenarios of extremes) and is outlined below.

Abrupt thermohaline circulation changes would alter the pattern of climate change. Recent simulations (Thorpe *et al*., 2001; Vellinga and Wood, 2002; Vellinga *et al*., 2002) using the HadCM3 climate model, in which the Atlantic thermohaline circulation is forced to collapse will be used to test the requirements for extending the pattern-scaling approach, viz. the linearity (or linearity following some transformation) of the response pattern to changes in thermohaline circulation strength, and the validity of linear superposition of thermohaline circulation change and transient warming signal patterns. If the linearity assumptions are found to be reasonable, then the climate change pattern due to a given fractional change in thermohaline circulation strength, occurring at a given time during a transient scenario, can be estimated. An integrated assessment model may attempt to estimate the occurrence of abrupt thermohaline circulation changes, rather than respond to prescribed changes, and thus requires an expression giving probability of an abrupt change (or probability density function of thermohaline circulation strength) as a function of predictors such as mean climate change and/or rate of climate change. Current knowledge is insufficient to provide definitive functions, but expert input (from Richard Wood, Thomas Stocker and other collaborators, such as Stefan Rahmstorf) and published model experiments will be used to obtain a defendable formulation and zero order estimates of coefficient values. This function will be applied to the set of SRES scenarios and will be provided for implementation within the Tyndall integrated assessment model.

2.6.3 Requirements of integrated assessment models

One of the major objectives of the Tyndall Centre research strategy is to develop a range of new and existing integrating assessment methodologies, including a Tyndall integrated assessment model (IAM), as part of Research Theme 1. These make new and very specific demands of scenario construction methods, particularly with respect to extreme weather events, which have been assessed as part of this research project.

One of the essential characteristics of integrated assessment is the simultaneous consideration of the multiple dimensions of an environmental problem, in this case climate change. A number of formal IAMs for climate change have been designed over the last decade, IMAGE 1.0 and ESCAPE being perhaps the first two in the early 1990s. The essence of these types of IAMs is that they contain modules that are reduced-form versions of more complex simulation models – whether, for example, of the economy, of the climate system or of ecosystems. Quite often the climate modules, or 'engines', involved generate zero (global; e.g., PAGE) or one (zonal; e.g., IMAGE) dimensional descriptions of future surface climate usually at mean (e.g. 30-year average) seasonal or annual resolution. Some IAMs (e.g., IMAGE and AIM) are then capable of generating spatially explicit descriptions of future climate, usually by accessing stored patterns of climate change extracted from more complex GCM experiments (i.e., by pattern scaling).

These different approaches to generating future climate descriptions in IAMs are versatile, efficient and allow multiple experiments to be easily conducted in an integrated framework. The climate drivers may then be input into an ecosystem, agriculture or health module (e.g., AIM), or used directly to calculate estimates of economic damage due to a look-up climate damage function (e.g., DICE). In either case, the current lack of any information about changes in daily or extreme weather is a major constraint. Agriculture, for example, may well be more sensitive to changes in daily weather sequences than to changes in mean monthly climate (Parry *et al.*, 2002). Climate damage functions that express the economic impact of climate change as a function of global- (or regional-) mean climate alone are likely to underestimate the economic damage associated with extreme events. The lack of information about changes in daily weather and extreme events also limits simulations of adaptive processes in social institutions and environmental systems: an important objective of the emerging third generation of IAMs (Warren, 2002).

Thus it would be desirable to have efficient and robust algorithms that would allow daily weather scenarios to be generated inside an IAM, driven perhaps by one or more large-scale indicators of future climate generated by the climate engine of the IAM. These issues are addressed in a major review paper (Goodess *et al*., 2003), co-authored by project staff and Clair Hanson from Tyndall IT1.3 on 'A blueprint for integrated assessment of climate change'. The generation of future climate descriptions in 13 current IAMs (see Table 7) is assessed, before reviewing recent work on scenario development methods for extremes, focusing on the issues which are most relevant to the needs of IAMs. Finally, options for implementing scenarios of extremes in IAMs are considered. The section headings are given in Appendix 2 of this technical report.

2.6.4 Conclusions and recommendations for future work

The case studies described in Section 2.4 are based on simulations from one GCM (HadCM3) and one RCM (HadRM3) and only one statistical downscaling method (SDSM) has been tested. These limitations should be considered when assessing the case-study results and in planning future work. The most promising scenario development methods for the estimation of future probabilities of extreme weather events which have been identified and evaluated during the course of this project are being further evaluated in ongoing European Commission-funded projects, notably STARDEX (STAtistical and Regional dynamical Downscaling of EXtremes for European regions: http://www.cru.uea.ac.uk/projects/stardex/) which is co-ordinated by Clare Goodess. Amongst the techniques being developed as part of STARDEX is an extension of the SDSM methodology using a re-sampling approach to construct multi-site precipitation scenarios based on a reference series, i.e., a regionally-averaged precipitation series constructed using SDSM (Wilby *et al*., 2003).

It is anticipated that these methods will also be further refined and developed as part of future projects in which the investigators are involved. The Climatic Research Unit weather generator (Jones and Salmon, 1995), for example, is being refined as part of work by Clare Goodess and others on the construction of high-resolution multi-variate climate scenarios during the EPSRC/UKCIP programme on 'The impacts of climate change on the built environment, transport & utilities' (http://www.ukcip.org.uk/built_enviro/built_enviro.html).

Guidance on the development of scenarios of extremes and for the incorporation of information about low-probability high-impact events such as the abrupt collapse of the thermohaline circulation will be implemented with respect to the Tyndall Centre's Integrated Assessment Model as part of the Round 2 project (T2.11) on 'Interfacing climate and impacts models in integrated assessment systems' co-ordinated by Nigel Arnell and involving Tim Osborn (see Section 2.6.2).

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TABLES

Table 1: Summary of recent studies which use GCM output directly to construct scenarios of extremes.

Study	*Extremes*	*Region*	*GCM*
Booij, 2002	Precipitation: 10, 20, 50, 100 year return periods	Meuse, western Europe	CGCM1, HadCM3, CSIRO9 20/30 year time slices
Dai *et al*., 2001	Frequency and persistence of 'hot' days (>80th percentile) Storm activity	Global USA	NCAR CSM Coupled model 2 scenarios 20 year time slices
Delworth *et al*., 1999	Steadman heat index (based on monthly temperature and atmospheric moisture)	Global	GFDL Coupled model 3 simulations 30 year time slices
Huth *et al*., 2000	Heat waves/dry spells	Czech Republic	ECHAM3 Equilibrium model 30 year time slices
Kharin and Zwiers, 2000	Temperature, precipitation, wind: 20 year return periods, thresholds, cooling & heating degree days	Global Canada	CGCM1 Coupled model 3 ensembles 21 year time slices
Kothavala, 1997	Precipitation: return periods, percentiles and Palmer Drought Severity Index (PDSI)	Midwest USA	CCM1-OZ Equilibrium model 10 year time slices
Kothavala, 1999	PDSI (based on monthly temperature and precipitation)	Eastern Australia	CCM0 Coupled model 30 year time slices
Kyselý, 2002	Temperature (max/min): 20 and 50 year return periods	Central Europe	ECHAM/CCCM 30/20 year time slices
McGuffie *et al*., 1999	Temperature and precipitation: Return periods and range of descriptive regional statistics	Global 5 IPCC regions	5 equilibrium GCMs 10 year time slices
Palmer and Räisãnen, 2002	Precipitation: 'Very wet' winters/summers	Europe Asian monsoon region	19 coupled GCMs used in TAR 30 year time slices
Yonetani and Gordon, 2001	Temperature, precipitation: max/min 1xCO_2 seasonal/annual values	Global	CSIRO Coupled model 1x CO_2/2xCO_2 100/30 year time slices
Zwiers and Kharin, 1998	Temperature, precipitation and wind: 20 year return periods and thresholds	Global Canada	CCC GCM2 Equilibrium model 20 year time slices

Table 2: Statistical downscaling studies which include analysis of extreme event indicators.

Indicators studied	***Study***
Studies which include analysis of precipitation-related extreme indicators, e.g. length of (longest) wet/dry spells, return period events, ranked extremes	Bardossy and Plate, 1991; 1992 Bates *et al*., 1998 Beckman and Buishand, 2001 Bogardi *et al*., 1993 Brandsma and Buishand, 1998 Charles *et al*., 1999 Conway and Jones, 1998 Corte-Real *et al*., 1999 Goodess, 2000 Hay *et al*., 1991; 1992 Hughes *et al*., 1999 Semenov *et al*., 1998 Weichert and Burger, 1998 Wilby, 1998 Wilby *et al*., 1994; 1998b Wilks, 1999 Wilson *et al*., 1991; 1992
Studies which include analysis of storm-related indicators, e.g. storm length, inter-storm arrival time	Hughes *et al*., 1993; Hughes and Guttorp, 1994 Schnur and Lettenmaier, 1998
Studies which include analysis of temperature-related extreme indicators, e.g. annual maxima/minima, heat waves and cold spells, frosts, threshold exceedence	Hayhoe, 2000 Huth et al., 2001 Kyselý, 2002 Palutikof *et al*., 2002 Schubert, 1998 Schubert and Henderson-Sellers, 1997 Trigo and Palutikof, 1999 Winkler *et al*., 1997

Table 3: Summary of the advantages and disadvantages of the direct use of General Circulation Model output to construct scenarios of extremes. ✔= advantage, ✘= disadvantage, ? = advantage/disadvantage of the method is uncertain.

Advantages/disadvantages of the general approach
✔ Provides physically-consistent multi-variate information ✘ Spatial-scale problems arise, i.e., grid box rather than point values ✘ Even area-averaged extremes (i.e., grid-box values) may not be reliably simulated
1. Diagnosed changes in statistical parameters (mean, plus higher-order parameters, such as variance, scale and shape, etc.) applied to observed baseline time series
✔ Simple method ✔ Suitable for scaling ✘ Non-realistic scenarios, e.g., negative precipitation, may occur when the changes are applied to the baseline climatology ✘ Assumes biases will be unchanged in the future
2. As 1, but changes are applied to weather generator parameters, previously tuned to reproduce observed climate
✔ Long and/or multiple time series can be generated for analysis of extremes/uncertainties ✔ Suitable for scaling ✘ Weather generators tend to underestimate variability and persistence, e.g., length of wet/dry spells ✘ May be difficult to adjust weather generator parameters in a consistent way
3. Direct model time series used, after appropriate statistical manipulation to reproduce present-day climate characteristics
✔ May overcome some model biases ✘ May be more difficult to manipulate extremes than mean values ✘ Assumes model biases will be unchanged in the future ? Either 'un-intelligent' or 'informed' manipulation may be applied, the latter using validation/statistical downscaling approaches to adjust model output for specific physically-identified biases ? Less suitable for scaling
4. Model output used to assess specific extremes (via percentile or extreme value distribution approaches), which are defined in a relative rather than absolute sense
✔ May overcome some systematic model deficiencies and facilitates model inter-comparisons ✔ May overcome some spatial-scale incompatibilities ✘ Assumes model biases will be unchanged in the future (because percentiles or thresholds are defined from the model control period) ? Less suitable for scaling ? Stakeholders may find it harder to relate to 'relative' extremes

Table 4: Summary of the advantages and disadvantages of the direct use of regional climate model output to construct scenarios of extremes. ✔= advantage, ✘= disadvantage, ? = advantage/disadvantage of the method is uncertain.

Advantages/disadvantages of the general approach
✔ Provides physically-consistent multi-variate information ✔ Higher spatial resolution should reduce some biases (e.g., more intense extremes) ✘ Relatively short runs make it difficult to assess multi-decadal natural variability ✘ Runs may not be available for time periods of interest (e.g., 2020s) ✘ Relatively few simulations/ensembles available ✘ Affected by biases in the underlying GCM ? Added value of higher resolution needs to be demonstrated ? Scaling may be more difficult, in part, because of shorter model simulations
1. Diagnosed changes in statistical parameters (mean, plus higher-order parameters, such as variance, scale and shape, etc.) applied to observed baseline time series Advantages/disadvantages same as for GCM output, see Table 3: 1.
2. As 1, but changes are applied to weather generator parameters, previously tuned to reproduce observed climate Advantages/disadvantages same as for GCM output, see Table 3: 2.
3. Direct model time series used, after appropriate statistical manipulation to reproduce present-day climate characteristics Advantages/disadvantages same as for GCM output, see Table 3: 3.
4. Model output used to assess specific extremes (via percentile or extreme value distribution approaches), which are defined in a relative rather than absolute sense Advantages/disadvantages same as for GCM output, see Table 3: 4.

Table 5: Summary of the advantages and disadvantages of statistical downscaling for the construction of scenarios of extremes. ✔= advantage, ✘= disadvantage, ? = advantage/disadvantage of the method is uncertain.

✔	Provides station/point values of extremes
✔	Less computer intensive than dynamical downscaling
✔	Can be applied to GCM and/or RCM output
✘	Assumes that predictor/predictand relationships will be unchanged in the future (the stationarity issue)
✘	Requires long/reliable observed data series
✘	Affected by biases in the underlying GCM
?	May be possible to “correct” predictors for systematic model biases
?	Scenarios may indicate changes which differ substantially in magnitude, and even in direction, from those based directly on model output
?	Ideally, downscaling methods should reflect the underlying physical mechanisms and processes, but statistical downscaling is unlikely, for example, to treat convective rainfall events in a physically realistic way
?	Suitability for scaling needs to be investigated
?	Sensitive to specific methodology, choice of predictor variables, etc.

Table 6: Summary of the advantages and disadvantages of three specific statistical downscaling methods for the construction of scenarios of extremes. ✔= advantage, ✘= disadvantage, ? = advantage/disadvantage of the method is uncertain.

1. *Resampling of observed data conditioned by large-scale climate variables*
✔ Provides self-consistent multi-site, multi-variate scenarios ✔ Multiple time series can be generated ✔ Relatively simple method ✘ Magnitude (but not frequency) of the largest extreme is limited by the observations ✘ Difficult to extend to multiple predictors if sample size is limited ? Requires climate classification
2. *Weather generator (with the option of conditioning the parameters upon large- scale climate variables)*
✔ Long/multiple time series can be generated ✔ Provides self-consistent, multi-variate scenarios ✘ Variability and persistence tend to be underestimated (the overdispersion problem) ✘ May be difficult to perturb the parameters in a consistent way for future climates ? Methods are being developed for the production of self-consistent multi-site scenarios, but tend to be complex and subject to technical/statistical problems ? May require climate classification for conditioning the parameters
3. *Regression-based techniques*
✔ Climate classification is not required ✔ A wide range of potential predictors can be used ✘ Danger of over extrapolation in the future ✘ Danger of overfitting ✘ Difficult to identify best suite of predictors for present-day and future climates ✘ Tends to perform less well for precipitation than temperature ? Stochastic elements can be introduced, e.g., to increase variability

Table 7: Model names, developers and key references for the 13 integrated assessment models reviewed in Goodess *et al.*, 2003

Model	*Developers*	*Key References*
COST-BENEFIT ANALYSIS MODELS		
CETA	EPRI and Teisberg Associates, USA	Peck & Teisberg (1992); Peck & Teisberg (1993); Peck & Teisberg (1995)
DICE Related models: PRICE/RICE	Nordhaus, Yale University, USA	Nordhaus (1994)
FUND	RSJ Tol, University of Hamburg	Tol (1999a); Tol (1999b)
ICAM-3	Carnegie Mellon University, USA	Dowlatabadi & Morgan (1993); Morgan & Dowlatabadi (1996)
MERGE 4.4	Stanford University, USA	http://www.stanford.edu/group/MERGE/ Manne & Richels (2001); Manne *et al,* (1995)
MiniCAM	Global Change Group at Pacific Northwest Laboratory, USA.	http://www.grida.no/climate/ipcc/emission/154.htm http://sedac.ciesin.org/mva/MCPAPER/mcpaper.html Edmonds *et al.* (1994); Richels & Edmonds (1995)
PAGE95	Judge Institute of Management Studies, University of Cambridge, UK	Plambeck & Hope (1996); Plambeck *et al.* (1997)
BIOPHYSICAL IMPACTS MODELS		
AIM	National Institute for Environmental Studies, Japan and Kyoto University	http://www-cger.nies.go.jp/ipcc/aim/ Matsuoka *et al.* (1995)
CLIMPACTS Related models: OzCLIM, BDCLIM, VANDACLIM	International Global Change Institute (IGCI), University of Waikato, New Zealand	http://www.waikato.ac.nz/igci/climpacts_webpage/ Kenny *et al.* (1995)
ESCAPE	Climatic Research Unit, UK and RIVM, The Netherlands	Hulme *et al.* (1995); Rotmans *et al.* (1994)
IMAGE 2.2	RIVM, The Netherlands	http://www.rivm.nl/image/home.html Alcamo (1994); Alcamo *et al.* (1996)
MIT IGSM	Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, USA	http://web.mit.edu/globalchange/www/if.html Prinn *et al.* (1999); Sokolov & Stone (1998)
TOLERABLE WINDOWS APPROACH		
ICLIPS	Potsdam Institute for Climate Impact Research (PIK), Germany	http://www.pik-potsdam.de/cp/iclips Bruckner *et al.*, 2003, Leimbach (2000)

APPENDIX 1: STAKEHOLDER REQUIREMENTS IDENTIFIED AT THE PROJECT WORKSHOP

UKCIP (Iain Brown)

- No standard stakeholder definition of an 'extreme': varies by sector and geographically
- Using recent events (1953, 1995, 2000) leads to better stakeholder engagement with respect to future change

Temperature
- 'air cooling' days (> 25°C)
- frost 'severity'

Precipitation
- amount, intensity, profile

Wind
- max. instantaneous speed
- 'gustiness'
- direction

Hail
- agriculture

Fog
- transport

Multivariate events
- precipitation/temperature
- drought persistence
- 'back-to-back' droughts
- drought followed by intense rain (water quality)

Temporal resolution
- Generally require summary daily data, potentially sub-daily (e.g. urban hydrology, waves) and time series (e.g. water demand, waves)
- Seasonal patterns are very important [e.g., agriculture, biodiversity (migration, nesting, etc.) and tourism]
- Monthly data can be very useful for vulnerability studies (e.g. groundwater, landslides)

Spatial resolution
- 'Local' stakeholders require local (site specific) information, often related to local topography (e.g., rain/snow, wind anomalies)
- Regional/national stake holders require broad areal divisions for policy guidance [e.g., by region (N, S, E, W) or by catchment, water resource unit, coastal cell]
- Maps are very important

Directional component of extremes
- Wind directions during extremes and storm direction across catchment are important for flooding, coastal sediment dynamics, ports, etc.

Probabilities

- UKCIP98 Figures 29 & 30 very popular – 'key information' for stakeholders
- Looking for changes in both magnitude and frequency
- Often used to define risk zones (e.g. 1/100 flood limit)
- Probabilistic analysis obviously very important, but also joint probabilities (e.g. wet ground, rainfall, high winds = many fallen trees; high river flows + high tides + storm surge = severe flooding)

Design limits and extreme events

- Antecedent conditions can be important (e.g. period between storms)
- Event profiles are important as well as individual event maxima/minima [e.g. rainfall profile (in Flood Estimation Handbook – used to design bridges, dams, defences, etc.)]
- How to communicate new information on events – quantiles, percentiles?
- How to use this to revise design limits (UKCIP/NCRAOA Risk and Uncertainty Guidelines)

'Probable maximum' limits for design

- Probable maximum precipitation (Flood Estimation Handbook) – "highest amount physically possible at a location"
- Extreme snow melt – probable maximum snowmelt in Flood Estimation Handbook = 42mm

Uncertainties

- Decision-makers need to have explicit information
- Exactly how event analysis has taken place:
- Assumptions, emissions, etc.
    - RCM/GCM downscaling
    - Length of record/model run
    - Any issues of matching observed/model data (e.g. point vs gridbox)
- If expert judgement is involved, say so!

<u>Environment Agency (Robert Willows)</u>

Water Resources

- Rainfall, dry spell length, multi-season events
- Temperature, evapotranspiration
- River (low) flows and recharge
- Water demand (peak), socio-economic scenarios
- Wetlands, conservation (operational vs policy)

Water quality

- Extreme wet days (following dry period?) – sequencing
- Temperature

Flood/coastal defence

- Catchment/site rainfall
- Daily rainfall
- Individual/runs of extreme wet days
- Storm surge
- Wave climate/heights
- Temperature (affects efficiency of flood warnings)
- Probabilistic scenarios
- Joint probabilities

Air quality
- Persistent anticyclonic conditions (extent, duration, frequency)
- Temperature

Waste
- Intense rainfall
- Temperature

Fisheries
- Flow extremes
- Temperature

Scottish Environment Protection Agency (Peter Singleton)

Rainfall
- Mainly needed in terms of run-off
- Scale: > 100 km^2
- Duration: > 12 hours < 72 hours
- Frequency
- Depth of storm

Snowfall
- Depth of snow falling (as mm of rain?)
- Number of days lying
- Speed of snowmelt
- Increased likelihood of snowmelt
- Contribution to flooding
- Coverage based on altitude
- Ecological impacts

Drought
- Drought periods of > 1 month
- Covering areas of > 1000 km^2
- Relevant to licensing of abstractions and water yield assessments
- Ecological impact

Storms
- Storminess – is there a definition?
- Storm surge – major cause of coastal flooding
- Surge only an issue when it coincides with high tides
- Increased wave action will have serious morphological impact

Thermohaline circulation
- Sea temperatures (impact on fish farming)
- Probability of change?
- Major ecological impact both on land and in marine species

Wind
- Major habitat effect
- Wind frequency diagram for area
- Spatially < 50 km
- Potentially also by altitude

- Extremes and duration important

Cloud cover
- A measure of sunlight
- Number of consecutive 'sunny' days – eutrophication impact
- Sunlight kills bacteria, changes in conditions may alter die-off

Boundary layer stability
- Authorisation for emissions are modelled using past conditions
- Are stability patterns likely to change dramatically?
- The 'extreme' event is generally stable conditions, especially in winter
- Smog events?

<u>Insurance industry (Julian Salt)</u>

- Insurance is involved with short-term effects of the climate ('weather')
- Reinsurance is more concerned with medium-term effects of climate ('cycles'/'trends')
- Neither are thinking about the long-term effects of climate (IPCC)

Temperature and precipitation extremes
- Greater temperature rate than IPCC TAR (0.1°/decade or 1-6°C by 2100)
- Precipitation rate and volume equal to or greater than Oct/Nov 2000 floods

Temporal scale
- Typical time frames for the insurance cycle involve an annual scale
- However, longer timeframes of 2005, 2010, 2020 would be relevant for reinsurers

Spatial scales
- Rainfall events need to be high resolution (km)
- Windstorm events less demanding (10-50 km)
- Subsidence events (10-50 m)

Non-temperature/rainfall extremes
- Storm surges to match 1953 event and more
- Worst-case scenario: heavy rainfall up-river of Thames barrier with storm surge down-river
- Hail matching Canadian ice-storm/Sydney events
- Fog (no. fog-days=double normal for 1961-1990)
- Lightning=2 x average (1 strike km^2 yr^{-1})

Joint-probability events
- Very important as lead to real insurance losses, especially if last more than 72 hours
- Large windstorm (1987/90) with attendant rainfall matching Oct/Nov 2000 floods
- Dry period followed by intense rainfall (large run-off potential)

Persistence and sequence
- Very important for insurance purposes – if several events are separated they are treated as separate claims
- Sequence of floods back to back (e.g., three major floods in a month)
- Run of hot spells (e.g., 1995 summer in three consecutive years)
- Several windstorms in a row (e.g., two or three 1987-type events in a season)

Seasonal changes in the timing of extremes
- Change of onset of wind events (e.g., earlier by a month, i.e. Oct-Sept)
- El Nino onset and duration (frequency and severity more often and intense)
- Winter freeze later (shorter duration)

Presentation of extreme event scenarios
- Maps
- Postcode resolution
- Probability distribution
- Cumulative risk of several events over a given time frame in a given location

How much data?
- Rainfall (daily data)
- Subsidence (weekly PSMD)
- Wind (daily maximum gust)
- Spatial resolution – as high as possible (post code)
- Time series (several years); decade

Standard set of extremes
- Similar to UKCIP scenarios
- Very useful for insurance industry

e.g.,
- wind: increase in wind strength by 10-20% and increase in storminess (10-20% more depressions by 2010-2020)
- flood: 10-20% increase in heavy rainfall events by 2010-2020, actual rainfall 10-20% > 1961-1990 average, storm tracks more south-westerly track
- subsidence: increase in number of hot summers to 1 in 10 by 2010 and one in three by 2050 – increase in PSMD beyond a ‘trigger’ threshold (500 mm by 2010)

Low-probability high-impact events
- nightmare scenarios for insurance (“megacats”)
- hurricane type windstorm hitting SE just as the ground is saturated and trees are still in full leaf
- Entire UK under low pressure (rainfall for weeks on end)

Proposed case study 1: wind
- Increase in 1987/1990 type events in decade
- Increase in max gust strength associated with event
- Change in timing of event (earlier in season – full leaf syndrome)
- Change in storm track – over high-density populations (major cities)

Proposed case study 2: flood
- Repeat of Oct/Nov 2000 floods
- Floods occur over already wet ground (saturated soils/groundwater levels high)
- Floods occur over major cities

Proposed case study 3: subsidence
- Repeat of 1976/1995 hot summer
- Increase in occurrence of events in a decade
- Back-to-back hot summers (three in a row)

Case studies
Should consider impact of these extreme events on insured losses and economic losses (business interruption)

APPENDIX 2: SECTION HEADINGS FROM GOODESS *ET AL*., 2003

1. Integrated assessment and climate change

2. The treatment of climate in IAMs

    2.1 The development of IAMS
    2.2 Representation of climate in the currently-used second generation of IAMs
    2.3 Cost-benefit analysis IAMs for policy optimisation
    2.4 Biophysical-impact based IAMs for policy evaluation
    2.5 Policy guidance IAMs
    2.6 IAMs and adaptation
    2.7 IAMs and uncertainties

3. Evaluation of scenario development methods for extremes and their potential for use in IAMs

    3.1 Recent work on scenario development methods for extremes
    3.2 Suitability of scenario development methods
    3.3 Direct use of climate model output
    3.4 Statistical downscaling
    3.5 Scenarios of weather extremes and associated uncertainties

4. Options for implementing scenarios of extremes in IAMs

Tyndall°Centre
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Research at the Tyndall Centre is organised into four research themes that collectively contribute to all aspects of the climate change issue: Integrating Frameworks; Decarbonising Modern Societies; Adapting to Climate Change; and Sustaining the Coastal Zone. All thematic fields address a clear problem posed to society by climate change, and will generate results to guide the strategic development of climate change mitigation and adaptation policies at local, national and global scales.

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