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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: FD2113
2. Project title: Spatial Temporal Rainfall Modelling with Climate Change Scenarios
3. Contractor organisation(s): Imperial College; University College London
4. Total Defra project costs (agreed fixed price): £ 153961
5. Project: start date .... 01 October 2003
   end date .... 30 September 2006

6. It is Defra's intention to publish this form.
Please confirm your agreement to do so.. **YES** ☒ **NO** ☐

(a) When preparing SID 5s contractors should bear in mind that Defra intends that they be made public. They should be written in a clear and concise manner and represent a full account of the research project which someone not closely associated with the project can follow.
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(b) If you have answered NO, please explain why the Final report should not be released into public domain

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Background

DEFRA has five strategic priorities. One of these is climate change, for which a target outcome is to manage risk from flooding and coastal erosion in a way that furthers sustainable development (see http://www.defra.gov.uk/corporate/what-do-we-do/climate.htm). This project provided tools to assist in achieving this. The overall aim was to develop methods for the generation of artificial rainfall data incorporating scenarios of future climate change, for any location in England and Wales. Such artificial data can be used to drive simulations of catchment processes over extended time periods. The results can be used to assess, for example, likely changes in flood risk, the effectiveness of potential strategies for risk management, or the impacts of potential changes in land use. This approach to risk assessment and management is called 'continuous simulation'. It is data intensive: most catchments in the UK are small enough to respond to relatively localised rainfall events, and therefore rainfall data are required at high space and time resolution, for example at individual spatial locations and at daily or hourly time scales.

Prior to the present project, continuous simulation methodologies were developed in two other DEFRA-funded projects. Under project FD2106, carried out at CEH Wallingford, continuous simulation rainfall-runoff models were developed to represent catchment flood response to rainfall inputs; and in project FD2105, carried out jointly between Imperial College, UCL and CEH Wallingford, regionally-applicable methods for the continuous simulation of rainfall and evaporation, required as input to the rainfall-runoff models, were developed. The present project built upon the work carried out in FD2105, enhancing the methods there to enable climate change scenarios to be incorporated.

Most of our understanding of the climate system is based on deterministic models of the physical and chemical processes involved. However, despite continuing improvements in these climate models, at present there are questions regarding their ability to represent rainfall adequately at the fine space and time scales required. This project therefore sought to generate rainfall sequences by exploiting statistical relationships between rainfall and other variables that are better represented in climate models. For UK applications, a recommendation is that the most useful variables for this purpose are temperature, sea level pressure and relative humidity.

A further difficulty is that future projections can vary substantially between different climate models. For example, this project found that the Hadley Centre's HadCM3 model projects a much greater decrease in relative humidity over the next century than does the Australian model CSIROMk2; as a result, rainfall simulations driven by HadCM3 tend to be much drier than those based on CSIROMk2. It is increasingly being recognised that more than one climate model should be used to evaluate future climate scenarios, and that climate model uncertainty should be recognised and accounted for in any prudent analysis. In this project, we have proposed and tested a novel strategy for achieving this, in which climate model uncertainty is represented explicitly via probability distributions.

Main achievements and findings

The main achievements of the project are as follows:

1. The daily rainfall simulation methodology from project FD2105 has been used to generate daily rainfall sequences incorporating climate change scenarios. This is done by exploiting relationships between rainfall and large-scale atmospheric conditions. The methodology has been tested extensively. The simulated sequences have realistic properties, and the projected changes in future UK rainfall agree in qualitative terms with those obtained by other means (for example, using climate model rainfall outputs directly). For example, in south-east England, the simulations suggest a tendency for summers to become drier and winters wetter under the SRES A2 greenhouse gas emissions scenario (which underpins many climate change 'headlines'). However, there is considerable year-to-year variability in seasonal rainfall and it would be overly simplistic to conclude that all summers will become drier and all winters wetter. A key feature of the methodology used here is that the changes are represented as shifts in probability distributions. Graphical displays of these distributions provide a clear picture of the magnitude of the projected changes, relative to year-on-year variability.
2. Stable relationships, valid under a wide range of conditions, have been found to exist between properties of rainfall at different time scales. These enable properties of hourly rainfall to be reconstructed surprisingly accurately at any location in England and Wales, given only daily information such as that from (1) above. In turn, the reconstructed properties can be used to deduce the parameters of the hourly rainfall model recommended in FD2105. This provides a means of generating hourly sequences incorporating the effects of climate change. Since the parameters of the hourly model correspond to key features of the rainfall process (e.g. the arrival rate of storms), this work also provides insights into how these features may change in the future. An important conclusion is in England, under the SRES A2 emissions scenario, the changes identified in (1) above are associated with increases in storm frequencies in winter but decreases in summer. However, the intensity of rainfall within storms is likely to increase throughout the year. The combination of these two changes could lead to increased risk of both floods and droughts.
3. It has been demonstrated that multi-site sequences of hourly rainfall, incorporating climate change scenarios, can also be generated, using daily rainfall sequences from (1) above in conjunction with the multi-site disaggregation methodology developed in FD2105.
4. An investigation has been carried out into the sensitivity of results to the choice of climate model used to provide large-scale atmospheric conditions in (1) above. It was found that this choice may affect the results substantially. Climate model uncertainty should therefore be considered in any prudent analysis of future risk.
5. A pilot methodology has been developed for combining the outputs from several climate models in a coherent and interpretable manner, thereby enabling climate model uncertainty to be accounted for in the generation of rainfall sequences. This task was technically challenging, however, and therefore the methodology has not been developed as extensively as other aspects of the project.
6. An investigation has been carried out into the ability of regional climate models (RCMs) to represent properties of daily rainfall sequences directly for risk management purposes. The conclusion was that an individual RCM cannot be relied upon to reproduce rainfall properties particularly well; however, an ensemble of RCMs can be used to obtain a distribution of rainfall properties which is more or less consistent with observations.

Implementation of the methodology

In this project, the overall task of using climate model outputs to generate subdaily rainfall sequences has been split into several distinct sub-tasks. These are as follows:

1. Use the pilot methodology for combining climate model outputs, to generate a large number of alternative sequences of large-scale atmospheric variables over the time period of interest.
2. For each atmospheric variable sequence:
    - Generate a large number of daily rainfall sequences using the daily rainfall simulation methodology.
    - For each month of the simulation period, calculate selected statistical properties of the simulated daily rainfalls, and use the relationships between rainfall properties at different timescales to reconstruct the corresponding hourly properties
    - Use the FD2105 single-site methodology and software to fit a separate hourly rainfall simulation model for each month of the simulation period

- Use the fitted hourly models to generate as many hourly sequences as required.

The result of this process will be a large number of subdaily sequences. The variation between these sequences represents uncertainty due to climate models, to the inexact relationship between rainfall and large-scale atmospheric variables and to day-to-day variation in real rainfall sequences.

The division into sub-tasks makes the methodology here suitable for a 'pick-and-choose' approach: for example, in situations where subdaily data are not required, one can stop after the daily sequences have been generated. Furthermore, if a practitioner has their own preferred method for carrying out one of the steps above, they are free to use it.

Further work

Several opportunities for further research arise out of this project. The most important are as follows:

1. To develop further the pilot methodology for combining climate model outputs, and in particular to produce a user-friendly software implementation that is suitable for general use.
2. To verify the scaling relationships between rainfall properties at different time scales using an extended rainfall data set. In this project, the relationships have been tested using data from about a dozen gauges representing a variety of rainfall regimes across England and Wales. A national verification exercise would, however, enhance their credibility.
3. To develop further the daily rainfall simulation model, in order to relax some constraints that currently lead to a slight underestimation of extreme summer rainfalls.
4. To improve the accessibility of some of the techniques that have been developed, by connecting some of the software tools so as to reduce the need for manual intervention when implementing the methodology.

Commercial exploitation

In the SID5A accompanying this form, we have indicated that some of the intellectual property arising from this project may be suitable for commercial exploitation. This relates to the software implementation of some of the methods that have been developed here. Currently, Halcrow are developing a commercial version of the daily rainfall modelling package GLIMCLIM, the development of which was partially funded under DEFRA project FD2105. Depending on the uptake of this product by the applications community, it may be appropriate to consider a similar approach to our other software tools. At present however, this is best regarded as merely a possible development in the medium term.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
   - the scientific objectives as set out in the contract;
   - the extent to which the objectives set out in the contract have been met;
   - details of methods used and the results obtained, including statistical analysis (if appropriate);
   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and
   - any action resulting from the research (e.g. IP, Knowledge Transfer).

Provided separately.

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

Project web site

All of the project reports, along with supporting material and links to other relevant resources, are available from the project web site at http://www.ucl.ac.uk/Stats/research/Rainfall/index.html. Project reports are as follows:

Report no.1: *Review of methods for deriving local scale precipitation from future climate model scenarios* (N. Leith, January 2005).
Report no. 2: *The use of generalized linear models to simulate daily rainfall under scenarios of climate change* (N. Leith, December 2005)
Report no. 3: *Point process models for subdaily rainfall simulation* (N. Leith, September 2006)
Report no. 4: *Multi-site downscaling for the Blackwater catchment* (A.J. Frost, R.E. Chandler and M.-L. Segond, September 2006)
Report no. 5: *Climate model uncertainty* (N. Leith, December 2006)
Technical note no. 1: *Summary of BSc dissertation "Representation of rainfall by regional climate models" by Birgit Schrödle* (R.E. Chandler, October 2005).

Dissemination activities

- March 2006: Royal Statistical Society National Science Week presentation *Floods, Droughts and Fat Cows*, available from http://www.rss.org.uk/waterevent.
- April 2006: poster presentation of FD2113 work at European Geophysical Union conference in Vienna (abstract available from http://www.cosis.net/abstracts/EGU06/01961/EGU06-J-01961.pdf)
- October 2006: presentation on FD2113 work at Royal Statistical Society meeting on downscaling (see http://www.rss.org.uk/main.asp?page=2567).
- January 2007: presentation on FD2113 work at Royal Statistical Society meeting on model uncertainty.

Project-related publications in refereed journals

Wheater, H.S., Chandler, R.E., Onof, C.J., Isham, V.S., Bellone, E., Yang, C., Lekkas, D., Lourmas, G. and Segond, M-L. (2005) Spatial-temporal rainfall modelling for flood risk estimation. *Stochastic Environmental Research and Risk Assessment* **19**, pp. 403-416.
Yang, C., Chandler, R.E., Isham, V. and Wheater, H.S. (2005). Spatial-temporal rainfall simulation using Generalized Linear Models. *Water Resources Research* **41**, doi:10.1029/2004WR003739.