Construction of climate scenarios for the integrating framework: built environment, transport and utilities – Narrative report for GR/S18328/01 (PI Professor P Jones, University of East Anglia) and joint project GR/S18335/01 (PI Mr C Kilsby, University of Newcastle upon Tyne)

Background/Context

This project is one of a portfolio of research projects in the Building Knowledge for a Changing Climate (BKCC) programme looking at how climate change will affect aspects of the built environment. Two research fora were organised by EPSRC and the UK Climate Impacts Programme (UKCIP) when the BKCC programme was first being devised. The requirement to develop high-resolution climate change scenarios tailored to the needs of the programme was identified from these discussions with potential academic partners and stakeholders, together with a group of project partners able to carry out this work: University of East Anglia (UEA), University of Newcastle and the Hadley Centre (subcontracted to UEA). The BKCC community was widely consulted throughout the proposal development stage in order to determine user needs with respect to climate scenario information. The starting point for the work is the UKCIP02 climate change scenarios which have been developed for shorter time periods and point locations, to meet the particular requirements of the built environment, including information about changes in weather extremes.

In order to establish a clear identity for the project and the scenarios, an appropriate acronym was devised at the start of the contract: BETWIXT – Built EnvironmenT: Weather scenarios for investigation of Impacts and eXTremes - http://www.cru.uea.ac.uk/cru/projects/betwixt/.

Although the primary objective of BETWIXT was to act as a service to the other projects in the BKCC programme and to develop best practice in the application of climate change scenarios, this has required considerable advances in weather generator development at UEA and the University of Newcastle (see Key Advances). BETWIXT has also addressed issues of scenario uncertainty (e.g., by analysing the reliability of scenarios of wind speed and direction) and the Hadley Centre has provided new information on potential changes in the 'urban heat island'.

Key Advances and Supporting Methodology

BETWIXT has successfully developed high-resolution climate-change scenarios for key UK locations. These scenarios are based on, and consistent with, the UKCIP02 scenarios, but have been developed for shorter time periods and point locations, to meet the particular needs of the built environment. BETWIXT has developed two types of model to construct these scenarios.

1. The RainClim software package was developed by the University of Newcastle building on previous work on the Neyman-Scott Rectangular Pulses (NSRP) point-process rainfall model applied in hydrological modelling. The software can be used to generate rainfall time series for the present day and future time periods up to 2100 for 18 sites in the UK, with time resolutions of 5 minutes and 1 hour. RainClim consolidates a number of key advances in the area including:

- fitting models to current and projected future rainfall statistics using an approach of applying factors derived from regional climate model (RCM) output;
- fitting using third-order moments to obtain better representation of extremes (Kilsby *et al*., 2004)
- disaggregation of 1-hour series to 5-minute using a second stochastic process model, crucial for urban drainage modelling

A major advance was made in the linkage of the NSRP rainfall model with the CRU weather generator (see below): previous work in this area has used simpler rainfall models (*e.g.* Markov chain) which tend to have inferior performance and more limited ability for modification for future climates, particularly at the sub-daily level. Consistent linkage of the two models provides consistent weather variable series and facilitates more complex impacts modelling such as snow melt estimation. Within BETWIXT, linkage was made with the CRU hourly weather generator (see below). Based on this

experience, linkage has since been made with the CRU daily weather generator in the EARWIG project (see Further Research).

A second major advance was in the development of a graphical user interface for the NRSP model. This allows users to select location and emissions scenario, as well as providing simple graphical display of the output series. This aspect of model use has been rather overlooked previously, with stochastic models remaining in the research domain as "user-unfriendly" code. This principle has been taken further with EARWIG (see Further Research).

2. The weather generator developed by the Climatic Research Unit (CRU) at UEA has been used to construct self-consistent daily time series scenarios for the present day and future time periods for eight variables (maximum and minimum temperature, precipitation, sunshine, vapour pressure, relative humidity, wind speed and potential evapotranspiration) and 10 BKCC case-study locations (including Manchester, Glasgow, Bradford, Birmingham and Heathrow). An hourly version of the weather generator, linked to RainClim, has also been produced.

The CRU daily weather generator was initially developed by Jones and Salmon (1995) and has been extensively modified and further developed in the BETWIXT project. Precipitation is the fundamental, primary variable in the weather generator, from which all the other variables are derived using regression relationships or subsequent direct calculation. A first-order Markov chain model (Richardson, 1981) is used. A major advance in BETWIXT is the use of a continuous distribution for precipitation, making this an infinite state model which is considered superior to the more usual two-state model. Once precipitation has been generated, the secondary variables (minimum and maximum temperature, vapour pressure, wind speed and sunshine duration) are generated. Finally, relative humidity and reference potential evapotranspiration (PET) are calculated from the generated variables.

Precipitation is also the fundamental, primary variable in the hourly version of the weather generator. Thus it is important that a sufficiently reliable method is used to generate hourly precipitation. A major advance in BETWIXT is to use RainClim (see above) to do this. Thus the modelling sequence is as follows:

1. Run RainClim to obtain hourly rainfall
2. Aggregate hourly rainfall to daily
3. Use aggregated daily rainfall to generate daily temperature
4. Run the hourly regressions for temperature and other variables

Extensive validation of both the daily and hourly weather generators has been undertaken, and improvements made where necessary and possible. For example, a problem with underestimation of the strength of the diurnal temperature cycle in winter has been successfully corrected.

The CRU weather generator is perturbed for the future using factors derived from daily RCM output. In BETWIXT, these factors (which are also used by RainClim) are based on output from the Hadley Centre HadRM3 model for consistency with the UKCIP02 scenarios. Climate scenarios have been constructed for four time periods (the 1970s, 2020s, 2050s and 2080s) and four emissions scenarios (Low, Medium-Low, Medium-High and High, as used by UKCIP02).

In addition to this scenario construction work by UEA and Newcastle, the Hadley Centre for Climate Change Research has, for the first time, implemented a parameterisation of urban land surfaces and anthropogenic heat sources in the land-surface scheme of the Hadley Centre Atmospheric General Circulation Model HadAM3.

The following simulations were performed:

i. Current CO_2 with no urban areas
ii. Current CO_2 with current urban areas but no anthropogenic heat sources
iii. Current CO_2 with current urban areas and current anthropogenic heat sources

iv. Doubled CO_2 with no urban areas
v. Doubled CO_2 with current urban areas but no anthropogenic heat sources
vi. Doubled CO_2 with current urban areas and current anthropogenic heat sources
vii. Doubled CO_2 with current urban areas and tripled anthropogenic heat sources.

In these simulations, landscape effects cause urban areas to be simulated to be warmer and less humid than surrounding non-urban areas as a result of landscape effects, both at present-day and doubled CO_2. Estimated present-day anthropogenic heat sources slightly further increase the strength of the heat island and dry island. Tripling of the heat source causes additional urban warming and drying, with large changes in the variance and skew of the heat island distribution. This suggests that the present-day heat island is not a good indication of a future heat island under modified forcings, so heat islands cannot be properly accounted for by simply adding present-day heat island patterns to gridbox-mean projections of climate warming.

These results suggest that state-of-the-art climate change projections, such as those produced using the BETWIXT weather generators, may contain systematic biases in estimates of temperature and relative humidity in urban areas, as a result of urban effects being neglected. Future climate model simulations intended for use in assessments of potential climate change impacts in the built environment should include changes in urban area and anthropogenic heat sources.

Project Plan Review
No major changes to the original work plan were made but where necessary, additional areas of work were added to meet newly identified needs of the BKCC consortium (see Research Impact). For example, UEA undertook an analysis of temperature transects across the Manchester region which provided a valuable input to the work of the ASCCUE project. And in response to user requests, the CRU weather generator was used to construct scenarios for 10 locations, rather than the 3-4 specified in the original project plan.

Obtaining and processing hourly data from the British Atmospheric Data Centre for calibration/validation of the CRU hourly weather generator proved more time consuming and complex than anticipated. Availability of sub-daily (up to 5-minute) data was also an issue for the Newcastle work. Thus it is concluded that there is a need for improved access to long, high-quality sub-daily data for UK locations.

Explanation of Expenditure (GR/S18328/01 only)
There were no significant deviations from the original spending plans. The main item of expenditure was on post-doctoral staff time, together with some technical staff time for web-site development and maintenance. The travel and subsistence budget covered the two BETWIXT workshops, two technical project meetings and attendance at BKCC Integrating Framework and Stakeholder Forum meetings. The subcontract to the Hadley Centre for the urban heat island modelling work is shown in the budget as ‘Consumables’.

Clare Goodess (UEA) attended the EPSRC Infrastructure and Environment Programme Strategy Conference, 22-23 January 2003.

Research Impact and Benefits to Society
Major research impacts are evident both within the BKCC portfolio and more widely in the UK and EU climate impacts modelling community. Exciting new developments in ensemble climate modelling at the Hadley Centre and in Europe (ENSEMBLES project) have moved towards a Bayesian framework where probability density functions (pdfs) are generated rather than explicit time series of weather variables for all possible scenarios. The successful demonstration of the stochastic weather generator approach in BETWIXT has lead to the realisation that a major role in downscaling and scenario development can be played by models such as RainClim and the CRU weather generator in providing time series for specific scenarios or quantiles of pdfs derived from ensemble climate projections.

Within BKCC, the final choice of variables, extreme events, temporal and spatial scales, and geographical locations used in the BETWIXT work was strongly guided by the user community. This was an iterative and two-way process. BETWIXT was not able to meet all the initial requests of users, but was able to explain why some requests were impractical due to modelling or data shortcomings, or why some requested outputs would be of limited reliability. Through this consensual process, the BETWIXT programme of work was finalised and, as planned, BETWIXT has had a major impact in feeding data together with advice and guidance on usage into the other BKCC projects. Examples include:

- provision of high time resolution extreme rainfall for the AUDACIOUS project to be used in urban drainage models
- provision of joint precipitation and temperature series for the CRANIUM project case-study at Newcastle on snow melt and hydropower in Scotland
- provision of future climate rainfall series for the BIONICS project at Newcastle, studying wetting and drying impacts on embankments
- provision of CRU daily weather generator output for use in ASCCUE's spatial mapping and risk assessment work for Greater Manchester
- provision of CRU hourly and daily weather generator output to allow projections of future energy demand patterns in the GENESIS project
- provision of CRU hourly and daily weather generator output for Coltishall and Abbotsinch for use in the Engineering Historic Futures case-study work at Blickling Hall and Brodick Castle

Responding to user needs and providing tailored guidance for individual applications was seen as a vital part of the BETWIXT work. In part, this was achieved through two workshops, in May 2003 and May 2004. More specific guidance was provided where needed, e.g., at a joint BETWIXT/ASCCUE workshop held in April 2005.

Particular attention was given to communicating uncertainties to users, focusing on extreme events. The BETWIXT work indicates that there is considerable uncertainty in the nature and magnitude of extremes of rainfall in future climates. This is especially apparent when dealing with hourly and sub-hourly rainfall – in part, because the statistics of extremes in the current climate are not well known for these short time durations. There is greater certainty concerning the nature of changes in temperature extremes: with consistent tendencies towards more hot days and warm nights, longer heatwaves and fewer cold nights. BETWIXT has demonstrated the large differences that exist between observed and simulated values of wind speed and direction – thus wind scenarios should continue to be treated with caution. Through such commentaries, BETWIXT has endeavoured to ensure that its outputs are used appropriately, thus increasing confidence in results across the BKCC portfolio of projects.

Time-series output and summary output from the CRU daily and hourly weather generators can be freely downloaded from the BETWIXT web site (see Dissemination Activities). Users are asked to inform UEA about any applications of the scenarios outside the BKCC programme. These outputs have, for example, been used by Atkins consultants to examine the risks of climate change to London's transport systems for the London Climate Change Partnership, particularly in relation to flooding and hot weather infrastructure problems. They have also been used by the London School of Hygiene and Tropical Medicine to study health impacts in London and the South East, and are currently being used by the Institute of Water and Environment, Cranfield University to explore uncertainties in simulating groundwater recharge in East Anglia.

Dissemination Activities

The BETWIXT work is described in a series of seven technical briefing notes which are suitable for a broad audience, including stakeholders as well as academic users:

1. Description of the CRU daily weather generator

2. Description of the RainClim model
3. Outline of the Hadley Centre urban area simulations
4. Evaluation of the performance of the CRU daily weather generator, i.e., the ability to reproduce present-day mean climate, and temperature and rainfall extremes
5. Evaluation of present-day winds and climate changes from the Hadley Centre RCM
6. Analysis of the Hadley Centre urban area simulations, i.e., analysis of the relative impacts of radiative forcing, landscape effects and local heat sources on simulated climate change in urban areas
7. Description and evaluation of the performance of the CRU hourly weather generator.

These briefing notes are available from the project web site - http://www.cru.uea.ac.uk/cru/projects/betwixt/, together with other information and data resources for BKCC participants and others. The RainClim software package can be downloaded from a password protected section of the web site, once users (research, education and certain industry institutions within the BKCC consortium) have completed a licence form. It is intended to maintain the web site for a period of at least two years after the end of BETWIXT in March 2006.

BETWIXT has also fully contributed to dissemination and communication activities within the BKCC programme including preparation of the BKCC brochure, slide set and briefing pack and participation in Integrating Framework, Stakeholder Forum and Data Management Group meetings. Material has also been regularly provided for the monthly BKCC newsletters.

BETWIXT partners have also taken advantage of a number of other opportunities for dissemination:

1. UKCIP organised a meeting at DEFRA offices in London in March 2005 covering rainfall modelling to support urban drainage studies. The principles and practice of RainClim were demonstrated and there was considerable interest and attendance from the water industry. This has resulted in follow on activities such as:
   - Environment Agency (EA) EARWIG project (see Further Research)
   - a DTi Technology Programme lead by Hydraulics Research Wallingford, SAM - System-based analysis and management of urban flood risks, utilising RainClim technology.
2. Invited presentation by Chris Kilsby at an EPSRC funded RainMap project meeting in June 2006, presenting rainfall modelling methods including RainClim and EARWIG. This meeting addressed rainfall modelling supporting the radio-communications area, and will enable collaboration between two previously separate research communities.
3. Richard Betts attended a workshop on Climate change and Urban Areas in April 2005, held as part of the UK-German Bilateral Action Plan on climate change. The Hadley Centre modelling work undertaken in BETWIXT was presented and discussed.
4. Richard Betts gave a presentation on the Hadley Centre urban heat island modelling work at a meeting on 'Climate change and the urban heat island' convened by UKCIP and hosted by the Greater London Authority in August 2005.
5. 'Cities will swelter on summer nights' is the headline of an article in a June 2004 New Scientist issue reporting Richard Betts presentation on the Hadley Centre BETWIXT work at a conference on Gaia and climate change in Dartington, Devon.
6. The IPCC working group 2 Technical Support Unit and the relevant Fourth Assessment Report chapter lead authors have been provided with information about the series of BETWIXT technical briefing notes.

Further Research and Exploitation

The basis of RainClim and the CRU weather generator have been further developed in an Environment Agency (EA) funded development of a software tool: EARWIG, EA Rainfall and Weather Impacts Generator.

EARWIG (Kilsby *et al.*, 2006) generates consistent daily series of rainfall and other weather variables for 5km grid squares and river catchments across the UK for the same climate scenarios as the

BETWIXT models. EARWIG was developed for strategic projects under the key EA science theme of Climate Change, including implementation of the Water Framework Directive, impact assessments for hydrology, pollution, water resources and flooding. EARWIG has been taken up enthusiastically by consultants, academics and EA projects in the first few months of its availability. Newcastle and CRU are currently in discussion with DEFRA and the Hadley Centre over the development of the UKCIPnext future climate scenarios using the methods developed in BETWIXT. This would allow ensemble outputs of Hadley Centre models to be used in a probabilistic framework, to generate on-demand, specific weather series for given locations, emissions scenarios and quantiles of probability.

The CRU daily weather generator is already being used in the BKCC CRANIUM project to construct probabilistic regional scenarios of extremes and it is anticipated that it will also be used by UEA in the European Union ENSEMBLES integrated project for the same purpose. This work will also feed into a planned workshop on the use of probabilistic scenarios in impacts assessment and adaptation studies as part of the SKCC: Sustaining Knowledge for a Changing Climate project. SKCC will sustain the community developed during BKCC and also reach out to other researchers and practitioners with an interest in the impacts of climate change on the built environment and infrastructure systems and adaptation of these buildings and systems to climate change.

UEA, University of Newcastle and the Hadley Centre are all involved in the SCORCHIO proposal on Sustainable Cities: Options for Responding to Climate cHange Impacts and Outcomes submitted to the EPSRC in April 2006. If successful, this proposal will allow development of a city-scale statistical climate simulator, customised for impacts and adaptation studies, based on the UEA/Newcastle weather generator work and urban heat island simulations performed by the Hadley Centre using a high-resolution RCM rather than the rather coarse scale HadAM3 model used in BETWIXT.

Training

PhD study at Newcastle

The student (Andy Smith) is now in his final year. The aim of the study is to utilise the UKMO 5km grid data made available to BKCC and BETWIXT to develop extreme rainfall models and analyses. The PhD was supported by EPSRC DTA funding. The project has provided training in spatial rainfall data processing, using advanced database techniques and in statistical analysis and modelling of extreme rainfall.

Undergraduate Civil Engineering and MSc projects

RainClim (and later EARWIG) has been used at Newcastle in a MSc module (Hydrological Risks and Climate Change) for future climate assessments, as well as in several MSc and undergraduate industrial projects. These include projects on future water resource assessments and flood risk assessments, particularly for the proposed Thames Gateway development.

The CRU weather generator outputs have been used by UEA students in dissertation projects at both undergraduate and MSc level.

Publications and References

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