Institution: University College London (UCL)

Unit of Assessment: 10 – Mathematical Sciences

Title of case study: Synthetic weather sequences informing engineering design and supporting decisions about infrastructure

1. Summary of the impact

Research conducted in UCL's Department of Statistical Science has led to the development of a state-of-the-art software package for generating synthetic weather sequences, which has been widely adopted, both in the UK and abroad. The synthetic sequences are used by engineers and policymakers when assessing the effectiveness of potential mitigation and management strategies for weather-related hazards such as floods. In the UK, the software package is used for engineering design; for example, to inform the design of flood defences. In Australia it is being used to inform climate change adaptation strategies. Another significant impact is that UCL's analysis of rainfall trends in southwest Western Australia directly supported the decision of the state's Department of Water to approve the expansion of a seawater desalination plant at a cost of around AUS$450 million. The capacity of the plant was doubled to 100 billion litres per year in January 2013 and it now produces nearly one third of Perth's water supply.

2. Underpinning research

The underpinning research centred on the use of generalised linear models (GLMs) for simulating daily climate time series at multiple spatial locations. Although GLMs had been widely established in statistics for around two decades by the mid-1990s, their potential for the applications considered here had not been recognised. Barriers to their use included limited interaction between the statistics and climate/engineering communities, difficulties in representing the complex structures in observed weather sequences, and challenges relating to the analysis of large spatiotemporal data sets. A further challenge was to provide efficient algorithms for simulating dependent sequences at multiple spatial locations. Multi-site Gaussian simulation was widely studied; however, at fine timescales (e.g. daily), many weather variables – notably precipitation and wind speed – have distributions that are far from Gaussian and the range of tools for handling such situations was (and remains) much more limited.

Against this background, a programme of research within UCL's Department of Statistical Science sought to build on the limited previous applications of GLMs to climate data, firstly by demonstrating how the complex structures in such data can be represented tractably within the GLM framework using flexible basis functions and, in particular, interactions between covariates representing seasonal and regional variation along with temporal autocorrelation [1, 2]; next by developing simulation algorithms for non-Gaussian situations, motivated in particular by the need to generate synthetic precipitation sequences for hydrological applications [3]; and finally by addressing some of the issues of statistical inference, uncertainty assessment and model intercomparison that arise in the analysis of large space-time data sets [4, 5]. More recent developments have focused on the characterisation of trends in precipitation in particular, with specific and high-impact applications in southwest Western Australia. An initial small-scale study is reported in reference [6]; this identified spatially varying time trends in rainfall over a small part of the region and was subsequently developed further, using nonparametric statistical techniques, to form the basis for the fourth example cited in section 4 below.

The programme has been led by Richard Chandler (Research Associate 1994-1997; Lecturer in Statistics 1997-2004; Senior Lecturer in Statistics 2004-2013; Professor of Statistics 2013) since the mid-1990s, working with postdoctoral researchers Zhongwei Yan (2000-2001), Chi Yang (2002-2005) and Chiara Ambrosino (2011-2013). On-going collaborations with Bryson Bates and Stephen Charles at CSIRO (the Commonwealth Scientific and Industrial Research Organisation) have led to widespread interest in the work in Australia. As the work has evolved, the developments have been incorporated into the GLIMCLIM software package, a tool created by UCL's Chandler for generating synthetic weather sequences.

This research programme has been application-driven throughout, so the most appropriate dissemination outlets have often been outside the traditional statistical literature. Moreover, to encourage uptake of the methods by non-statisticians (particularly those outside academia), the work has focused on the provision of transparent, easily implemented, computationally efficient but nonetheless statistically rigorous ways of doing things.

3. References to the research

[1] An analysis of daily maximum wind speed in northwestern Europe using generalized linear models, Z. Yan, S. Bate, R. E. Chandler, V. Isham and H. Wheater, *J. Climate*, 15(15), 2073-2088 (2002) doi:10/bnp5sf

[2] Analysis of rainfall variability using generalized linear models: A case study from the west of Ireland, R. E. Chandler and H. S. Wheater, *Water Resources Research*, 38(10), 1192 (2002) doi:10/cvfq4q

[3] Spatial-temporal rainfall simulation using generalized linear models, C. Yang, R. E. Chandler, V. Isham and H. S. Wheater, *Water Resources Research*, 41, W11415 (2005) doi:10/dwp476

[4] On the use of generalized linear models for interpreting climate variability, R. E. Chandler, *Environmetrics*, 16(7), 699-715 (2005) doi:10/dpvttx

[5] Inference for clustered data using the independence loglikelihood, R. E. Chandler and S. Bate, *Biometrika*, 94(1), 167-183 (2007) doi:10/fs4b4b

[6] Rainfall trends in southwest Western Australia, R. E. Chandler, B. C. Bates and S. P. Charles, In *Statistical Methods for Trend Detection and Analysis in the Environmental Sciences* (R.E. Chandler and E.M. Scott, eds.), Chapter 5, pp. 283-306. Wiley, Chichester (2011) – *submitted to REF2*

References [4], [3] and [5] best indicate the quality of the underpinning research.

Research grants/contracts: The work was funded by several different bodies including the Irish Office of Public Works (via a consultancy contract), the TSUNAMI consortium (a consortium of UK insurance companies) and Defra. The total value of the grants from which the work was funded was around £1.04 million.

4. Details of the impact

Society and infrastructure are vulnerable to weather-related hazards including floods, droughts and wind storms. To protect against such hazards, engineers and policymakers must assess the effectiveness of potential hazard mitigation and management strategies. To do this, it is becoming increasingly common to build computer simulators of the systems of interest, and to generate synthetic weather sequences to drive these simulators and determine the system response. The research described above has underpinned UCL's development of a software package, GLIMCLIM, for generating such synthetic weather sequences.

The main mechanism by which impact has been achieved is via the increasing use of GLIMCLIM to generate synthetic weather sequences for use in engineering and water resource management applications. Some examples are as follows:

Improved calculations of rainfall and flood mapping: The engineering consultancy Halcrow (now part of CH2M HILL) has used the software as part of three projects (one since 2008) relating to flood mapping and flood defence construction [A]. In each case the software was used alongside other methods, most of which are more standard in the application area, to provide rainfall scenarios that can be used to estimate flood extent and river flows. The rationale for using

GLIMCLIM alongside these other methods is that it is more conceptually defensible but less familiar within the industry; it was therefore seen to provide an "independent verification" of the more standard calculations. Taking into account the use of other methods alongside GLIMCLIM in these projects, Halcrow's Senior Hydrologist estimates that since 2008 the software has provided a value of around £5,000 to the company [A].

Informing Environment Agency recommendations: The software is becoming recognised as a state-of-the-art tool for advanced use in applications that require it. For example, the Environment Agency proposed that Anglian Water make use of GLIMCLIM to model rainfall in a realistic way, for use in the design of their flood defences. This demonstrates that the research has not only informed the Agency's awareness and understanding of available modelling techniques, but has also improved their ability to make informed suggestions about the design of storm overflows at Anglian Water. The Environment Agency, in a letter to Anglian Water dated 10 October 2012 [B], explain that they expect improvements to storm overflows to be designed following the principles set out in the Urban Pollution Management (UPM) manual. These principles are that "simple models and assumed data may be used where they lead to protective (conservative) solutions" but that "more refined techniques [of which GLIMCLIM is an example] are appropriate where they lead to a reduction in the combined cost of the modelling and the solution" [B]. The Environment Agency letter goes on to say that Anglian Water's "designs have generally assumed rain falls uniformly across the catchment varying only in time. This simplified approach conforms to the above UPM principle but clearly leaves scope for improved realism. We therefore support the principle of modelling rainfall in a more true to life way as proposed by James Lau and Christian Onof" [B]. The proposal of these researchers (at Imperial College London) was to use GLIMCLIM to generate realistic rainfall sequences [C].

Development of climate change projections: In Australia, GLIMCLIM is one of the primary tools being used in the development of an agreed set of climate change projections for the state of South Australia, in a project involving collaboration between universities, CSIRO and state government agencies [D]. This work is on-going and will result in the production of hydrological models that will be critical in the planning required to adapt the state's water resource management strategies to future climate conditions.

These examples are included to indicate that the software is being used, and that it is recognised as a state-of-the-art tool. Unfortunately, however, it is not easy to track the use of such tools outside the academic community, so the full extent of its uptake cannot be established.

Informing water resource management strategies: Although GLIMCLIM has been the main vehicle for dissemination of the research, it is not the only one; the results from the precipitation trend analysis for southwest Western Australia (see section 2) are being used to inform water resource management strategies in that state.

The results of the trend analysis were summarised in an animation of statewide rainfall changes from 1940 to 2010, demonstrating clearly a substantial decline in rainfall over the last 30 years except in the most southwesterly corner of the state. The Water Supply Planning Branch of Western Australia's Department of Water (DoW) used this animation at a meeting of the Water Supply Planning senior officers group on 21 July 2011, to "create a sense of urgency that the drying climate and increasing number of dry seasons are impacting on Perth's existing water supplies" and to support the argument that Perth urgently needed a new water source [E]. A Supervising Engineer at Surface Water Assessment, DoW, reported: "The decision at the end of the meeting was that DoW prepares an urgent cabinet submission to government on the need for a new water source for the IWSS [integrated water supply scheme]. The outcome is that cabinet approved the expansion of the Binningup Desalination Plant in July 2011." [E]

The Southern (Binningup) Seawater Desalination Plant was first opened in September 2011, providing 50 billion litres of water to Perth and the surrounding area per year. Seawater desalination is a more expensive means of providing potable water than traditional groundwater or surface water sources, but because it does not depend on rainfall it has become an important

water supply source in the increasingly dry climate of Western Australia. The animation of rainfall changes in the state, produced from UCL research, was instrumental in securing state approval for the expansion of the plant [E] to provide 100 billion litres of water per year, twice the original capacity [F, G]. This expansion, which cost AUS$450 million [F] and was completed in January 2013, enables the plant to now produce almost one third of Perth's water supply [G], benefiting around 600,000 people in the city.

The animation was also used within the REF impact period for informing community groups and the general public about the need to expand the plant and to justify the high costs involved. For example, it was used in a presentation given by the Water Allocation Planning Branch of the DoW to the Jandakot Community Consultative Committee [E], and it was shown on state television as a means of communicating to the public the need to spend such a large amount of money.

5. Sources to corroborate the impact

[A] Supporting statement from Senior Hydrologist at Halcrow – corroborates that Halcrow benefited from their use of GLIMCLIM on a project in 2009 and that this use had a commercial value to the consultancy of around £5,000. Available on request.

[B] Letter from the Environment Agency to Anglian Water (dated 10 October 2012) – corroborates that the Environment Agency has informed Anglian Water that they support the principle of modelling rainfall in a more realistic way, and corroborates that the research has informed awareness about modelling techniques. Available on request.

[C] Proposal from researchers at Imperial College London for the development of a rainfall generator for East Anglia – corroborates that the proposal involves the use of GLIMCLIM to generate rainfall sequences. Available on request.

[D] A summary of the project "Development of an agreed set of climate change projections for South Australia" can be seen online at: http://goyderinstitute.org/index.php?id=31 – corroborates that GLIMCLIM is being used in the project.

[E] Supporting statement from Supervising Engineer, Surface Water Assessment, Department of Water, Western Australia – corroborates that the animation was used at the Water Supply Planning meeting and that it impacted upon the decision to expand the Binningup plant. Also corroborates the use of the animation in a Water Allocation Planning Branch presentation. Available on request.

[F] ABC News article about the expansion of the Binningup plant (1 August 2011): http://www.abc.net.au/news/2011-08-01/desalination-plant-capacity-doubles/2819766
– corroborates the expansion to 100 billion litres per year and the cost of the expansion.

[G] Western Australia Water Corporation desalination website: http://bit.ly/1htGcxE and http://bit.ly/1iu9SZn – corroborates that the Binningup plant produces almost one third of Perth's water supply and corroborates the doubling of the capacity to 100 billion litres per year.