Institution: University College London

Unit of Assessment: 10 – Mathematical Sciences

Title of case study: Synthetic weather generation for engineering design and infrastructure development

Period when the underpinning research was undertaken: 2002 - 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Richard Chandler	Professor	1994 - 2020

Period when the claimed impact occurred: 2014 - 2020

Is this case study continued from a case study submitted in 2014? Y

1. Summary of the impact (indicative maximum 100 words)

Research conducted in UCL's Department of Statistical Science developed a state-of-the-art software package for generating synthetic weather sequences. The software has been successfully adapted by engineers and policymakers internationally, in applications such as flood risk and water resource management. It has contributed to increased commerce performance at the UK company, Mott Macdonald, with contracts worth over USD500,000, and on infrastructure development in Jamaica to benefit approximately 150,000 people at a cost of approximately USD35,000,000. Additionally, the close working relationship between UCL and Mott Macdonald contributed to professional development of consultants at Mott Macdonald.

2. Underpinning research (indicative maximum 500 words)

Research led by Richard Chandler at UCL has developed statistical methodology for constructing and simulating from models for daily weather time series. The tools developed can be used at multiple locations, incorporating potential non-stationarities suitable for use in studies of climate impacts and adaptation where a detailed representation of local weather is required. The theory is implemented in a software tool, R-package version of the Generalised Linear Model for daily Climate time series (RGLIMCLIM).

Studies of future climate impacts and adaptation are invariably based around climate projections obtained by running global climate models (GCMs) under specified scenarios of socio-economic development and greenhouse gas emissions. However, GCM outputs are too coarse to represent the local-scale weather features that control some phenomena and must therefore be downscaled to provide application-relevant information. The present research relates to methodology for developing "weather generators": these are statistical models that exploit relationships between large-scale climate and local-scale weather, to enable the generation of local-scale sequences that are consistent with large-scale information from GCMs. Although weather generators have been used since the early 1980s, the demands of modern applications, particularly in data-sparse regions of the world, can be challenging. The RGLIMCLIM methodology aims to: 1) produce daily sequences with realistic spatial, temporal and inter-variable dependence structures over a range of space and time scales; 2) capture realistic levels of unstructured variability associated with phenomena such as extremes; 3) represent systematic variation over space and time, including under scenarios of climate change; 4) generate sequences at locations for which no data are available; and 5) cope with missing values in the historical records used for model calibration. Few other modern weather generators have this range of capability.

The RGLIMCLIM methodology is based around generalised linear models (GLMs). Although GLMs are a cornerstone of modern statistical practice, adapting them to the context of weather

generation poses challenges. The main ones are (a) representing the complex structures in weather sequences (b) handling spatial and temporal dependence when carrying out estimation and inference for large spatiotemporal data sets (c) providing efficient algorithms for simulating dependent sequences at multiple spatial locations, particularly where many of the variables involved (eg precipitation) have highly non-Gaussian distributions at a daily time scale. These challenges have been addressed in a series of papers, for example:

Representing complex structures: early publications demonstrated that common features of daily weather 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 (**R1**). More recent work has tackled the challenges of multivariate space-time modelling when the individual variables potentially have very different distributional forms (**R2**).

Handling spatial and temporal dependence: most of the relevant research on statistical inference for large space-time data sets is described in (**R3**) and (**R4**). The first of these papers shows that temporal dependence can be handled in very general situations by including appropriate lagged terms in the models, while the second shows how to adjust standard "independence" estimation and inference techniques, including likelihood ratio tests, for spatial dependence.

Efficient simulation algorithms: the main challenges here arise in highly non-Gaussian situations, in particular for discrete quantities such as precipitation occurrence (which is binary). Throughout the research programme, efforts have focused on finding algorithms and models for which it is feasible and tractable to sample from the conditional distribution at some sites given observations at others. This provides the opportunity to use imputation to characterise uncertainties associated with missing data (**R5, R6**).

The UCL research programme led by Richard Chandler, has spanned more than 20 years (Research Associate 1994-1997; Lecturer in Statistics 1997-2004; Senior Lecturer in Statistics 2004-2013; Professor of Statistics 2013) working with postdoctoral researchers Zhongwei Yan (2000-2001), Chi Yang (2002-2005) and Chiara Ambrosino (2011-2013).

3. References to the research (indicative maximum of six references)

R1. Yan, Z., Bate, S., **Chandler, R.E.**, Isham, V. and Wheater, H. (2002). An analysis of daily maximum windspeed in northwestern Europe using generalized linear models. *J. Climate* 15(15): 2073-2088. doi:10.1175/1520-0442(2002)015<2073:AAODMW>2.0.CO;2

R2. **Chandler, R.E.** (2020). Multisite, multivariate weather generation based on generalised linear models. *Environmental Modelling and Software* 134, 104867. doi:10.1016/j.envsoft.2020.104867.

R3. **Chandler, R.E.**, Isham, V.S., Bellone, E., Yang, C. and Northrop, P.J. (2007). Space-time modelling of rainfall for continuous simulation. Chapter 5 in Finkenstadt, B., Held, L., Isham, V.S. (ed.) Statistical methods for spatial-temporal systems. Boca Raton: CRC Press. Available on request.

R4. **Chandler, R.E.** and Bate, S. (2007). Inference for clustered data using the independence log-likelihood. *Biometrika* 94: 167-183. doi:10.1093/biomet/asm015.

R5. 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.

R6. Ambrosino, C., **Chandler, R.E.**, and Todd M.C. (2014). Rainfall-derived growing season characteristics for agricultural impact assessments in South Africa. *Theoretical and Applied Climatology*, 115, pp.411-426. doi:10.1007/s00704-013-0896-y.

4. Details of the impact (indicative maximum 750 words)

The 13th Sustainable Development Goal of the United Nations is "take urgent action to combat climate change and its impacts". To assess the effects of potential future climate changes, and to evaluate the effectiveness of proposed strategies for alleviating them, 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 underpinning research provided a tool for generating such sequences, in cases where detailed representations of the underlying weather structure are required. This is fundamental in hydrological applications where the response of a system can be sensitive to both the quantity and timing of precipitation as well as other variables that control evapotranspiration rates. The RGLIMCLIM software package addresses these needs, encourages a structured approach to weather generator construction and proves to be efficient and flexible. In Australia, this research has been used to inform climate change adaptation strategies and analyse rainfall trends. The analysis result supported the decision of the Western Australia Department of Water to double the capacity of the Binningup seawater desalination plant to 100,000,000,000 litres per year, at a cost of around AUD450,000,000 (**S1**). The desalination plant continues to operate through this REF period at the increased capacity fulfilling approximately 30% of Perth's water supply requirements (**S2**).

Impact on productivity and performance at Mott Macdonald and population of Jamaica

Mott Macdonald is a global engineering, management and development consultancy focused on guiding its clients through many of the planet's most intricate challenges. During the submission period, the company has won **USD500,000 worth of contracts for three international projects** in which the RGLIMCLIM software played a fundamental role in climate vulnerability assessment and in capturing climate change impacts; and has carried out a **GBP44,000 pilot project** for Anglian Water, successfully demonstrating that RGLIMCLIM can improve on standard industry practice in simulating changes in the frequency, duration and magnitude of droughts (**S3**).

The international contracts are for projects in Jamaica, Barbados and Sierra Leone. These contracts benefit the consultants in terms of earned fees, and also the communities and civil agencies in regions where projects are being executed. The Jamaica project completed in 2019; the others are ongoing, due to delays that are partly due to COVID-19 which has prevented travel for fieldwork and site visits. In Jamaica, the *Essex Valley Climate Change Vulnerability Assessment* was commissioned in 2019 by the Ministry of Industry, Commerce, Agriculture and Fisheries as part of the Essex Valley Agricultural Development Project (EVADP). The EVDAP aims to enhance the production and productivity of farmers in an area of around 1,000 hectares, in a socially inclusive, gender equitable and climate sensitive manner: it **benefits approximately 150,000 people** (**S3, S4**). The Government of Jamaica received an amount equivalent to **GBP35,515,000** from the United Kingdom Caribbean Infrastructure Partnership Fund (UKCIF) towards the cost of this project. Mott Macdonald was commissioned to perform a detailed hydrogeological characterisation of the water supply aquifer, as well a complete climate vulnerability assessment (CVA) of the different assets of the irrigation scheme (renewable power plant, boreholes, mains and secondary pipes, hydrants and roads). **For its work on the CVA Mott Macdonald received USD150,000**. The challenges for this project recognised by Mott Macdonald included:

1) "Standard" climate models were unable to provide direct information at a sufficiently fine scale to assess changes in the region's aquifer recharge or flood risk, both of which are subject to local controls due to shallow soils and limestone geology.

2) The rainfall record in the study area itself (of only three years' duration) was very limited, so a defensible tool was needed for extracting relevant information from longer records in neighbouring catchments.

Based on their knowledge of industry practice in this kind of project, Mott Macdonald identified that most "standard" approaches would not be suitable but that RGLIMCLIM provided the necessary capability. RGLIMCLIM was therefore used as part of the climate change impact

assessment on rainfall, to feed the groundwater recharge model. It allowed a weather generator to be developed quickly, with diagnostic checks to give confidence that the outputs provided a defensible characterisation of future precipitation patterns. **The use of RGLIMCLIM enabled reliable estimation of aquifer recharge, which would not have been possible otherwise**. The results of the CVA, which was completed in 2019, highlighted the need for additional sources of water and informed the selection of crops in the subsequent EVADP (**S3**).

Knowledge exchange and capacity building for commerce

RGLIMCLIM is an open-source software, provided as a library to be run in the R programming environment taking advantage of R's intuitive interface and graphical capabilities. However, the effective use of its sophisticated methodology can be challenging for those without advanced statistical training. This inevitably limits its uptake in industries where there are established industry-wide practices and resistance to investing time in high-level technical training. The partnership with Mott Macdonald has demonstrate the potential added value from such an investment. The strategy for further building impact from this research has been to develop capacity within Mott Macdonald, which they consider gives them a competitive advantage when tendering for contracts (**S3**). The capacity development is being done through short consultancy contributions. Specifically, in the Jamaica project, the weather generator was developed by Professor Chandler, who provided a documented step-by-step approach to the entire process that could be followed in subsequent projects. This has been used as a template by Mott Macdonald staff, with occasional input from Professor Chandler where necessary, when developing weather generators using RGLIMCLIM in other applications.

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. ABC News article about the expansion of the Binningup plant (01/082011) corroborates the expansion to 100,000,000,000 litres per year and the cost of the expansion.
S2. Western Australia Water Corporation desalination website corroborates that the Binningup plant produces almost one third of Perth's water supply.
S3. Supporting letters (dated 22/10/2019 and 18/02/2021) from Principal Hydrologist at Mott Macdonald corroborate the advantages, impact of RGLIMCLIM and a commercial compensation to Mott Macdonald.
S4. The Caribbean Development Bank procurement notice corroborates the financing of the *Essex Valley Agriculture Development Project* in Jamaica.