Spatial Urban Weather Generator for Future Climates

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1 Background and UKCP09 capability

The UK Climate Projections 2009 programme (UKCP09) provides a single-site Weather Generator (WG) capability developed at Newcastle and UEA, see http://ukclimateprojections.defra.gov.uk/. The WG produces daily or hourly time series of weather variables (rainfall, temperature, humidity, sunshine hours/solar radiation and potential evapotranspiration) with realistic extremes for present and future conditions for any location in the UK. Although this has been a major leap in capability for specialist scenario production there are significant shortcomings in terms of what engineers and planners require for studies of future climate impacts on cities as exemplified by ARCADIA.

ARCADIA Task 3 therefore is to develop a method for generating probabilistic scenarios of climate change customised for urban areas. Four major gaps in capability were identified:

(a) **Spatial capability:** Applications to major cities and regions require spatial fields of weather variables capturing persistent spatial patterns such as Urban Heat Islands (UHIs) as well as other forms of correlation affecting collective risk such as spatial dependence of extreme rainfall or extreme temperature. A development of a spatial WG incorporating a space-time rainfall model as well as spatial dependence of temperature fields has therefore been carried out.

(b) **Reproduction of extreme hourly rainfall:** experience with the UKCP09 WG has shown that hourly extreme rainfall amounts were underestimated. This is an acute problem for urban drainage studies where hourly and indeed sub-hourly intense rainfall is of paramount importance. A development of the underlying Neyman-Scott Rectangular Pulses rainfall model (NSRP) has therefore been implemented and tested.

(c) **Reproduction of extreme temperatures:** the UKCP09 WG underestimated daily maximum and hourly extreme temperatures. This is an acute problem for building ventilation studies where cooling degree-day or degree-hour calculations depend non-linearly on only a very few heat-wave events. A development of the WG temperature model with a different distribution has therefore been implemented and tested.

(d) **Reproduction of persistence in heatwaves**: the UKCP09 WG uses a relatively simple form of day to day autocorrelation of weather which is found to underestimate the occurrence of long, persistent heat waves where the daily maximum temperature (Tmax) may progressively build up over time. A development allowing explicitly for longer dry spells with higher Tmax distributions has therefore been implemented and tested.

A spatial weather generator addressing these deficiencies has now been developed which remains statistically consistent with either observations (for baseline scenarios) or changes from the climate models used in UKCP09 (for future scenarios), thus allowing extensions of existing work using UKCP09. These developments will be described in the following section.

2 Improvements to UKCP09 WG

2.1 Rainfall extremes

Urban drainage studies require rainfall time series at hourly resolution or finer. Typically, such studies use design event rainfalls for input to sewer models and standard industry practice is to use extreme events up to 30 year return period. This is beyond the stated aims of the weather generator (WG) of UKCP09. The WG guidance documents clearly state this, with a suggestion that for daily resolution data up to 10 year return period (RP) should be considered reasonably reliable but that for hourly resolution 5 year return periods should be considered the upper limit for reliability. It is apparent that above 5 year RP the UKCP09 WG is systematically under-estimating the extremes because a simplified rainfall model had been specified in the interest of robustness which used an exponential distribution of rainfall intensities.

Improvement of the performance has now been achieved after a number of different and more complex distributions of rainfall intensities was trialled, including gamma, lognormal and generalised Pareto. The gamma distribution version was found to perform the best and is reported here. Rainfall time series have been generated for baseline and future climates for urban drainage studies at a representative site in north-east England and analysed at a range of return periods (2,5,10,30 years) and durations (1, 3, 6, 12 hour and 1 day) and compared with design storm depths taken from the Flood Estimation Handbook Depth Duration Frequency model (FEH DDF) for both validation purposes (baseline) and impact assessment (future projections) using an annual maximum methodology. The return period estimates are validated against the FEH model with the comparisons presented in Figure 1.

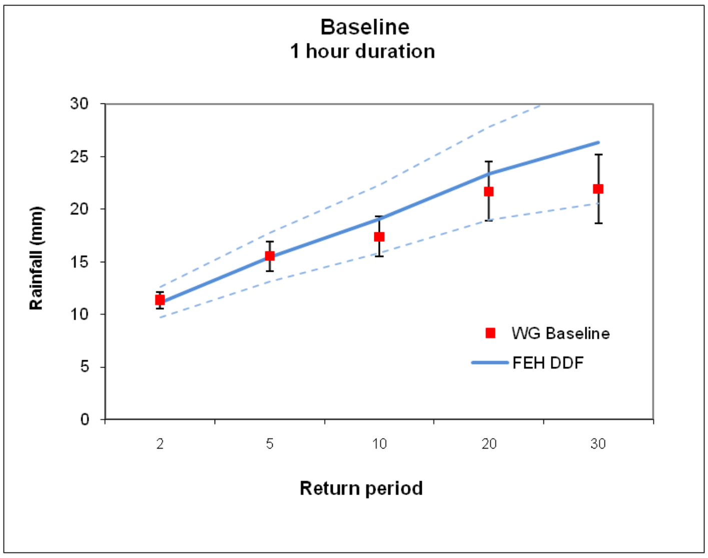

Figure 1 Comparison of new WG rainfall estimates with Flood Estimation Handbook estimates for NE England. 90% confidence limits have been estimated for the FEH values using observed annual maximum rainfall data. 90% confidence limits have been estimated for the WG values using bootstrapping on a generated 100 year series.

The performance of the WG is now more satisfactory and generally within the 90% confidence limits. It should be noted that this approach uses readily available national rainfall statistics rather than site specific data and therefore provides uniform and straightforward application nationwide. Some under-estimation is seen in the highest return periods but this could be allowed for using an “uplift” approach for future impact if necessary. Previously, under-estimation of up to 50% was found in the 30 year return period estimates.

2.2 Future rainfall extremes

A future scenario has been tested in order to assess sensitivity of the new rainfall model in comparison with the old version. The future scenario was chosen to be the 2050s medium emissions scenario (representing 2041-2070) and a similar procedure was carried out as for the baseline, except rather than a single simulation, an ensemble of 100 time series of 100 years length was generated. It can be seen in Figure 2 that little difference is observed in the future regimes at the hourly level with a general modest reduction resulting from reduced summer mean rainfall. However at the daily level, an increase in the annual maxima is seen due to projected increases in winter rainfall amounts.

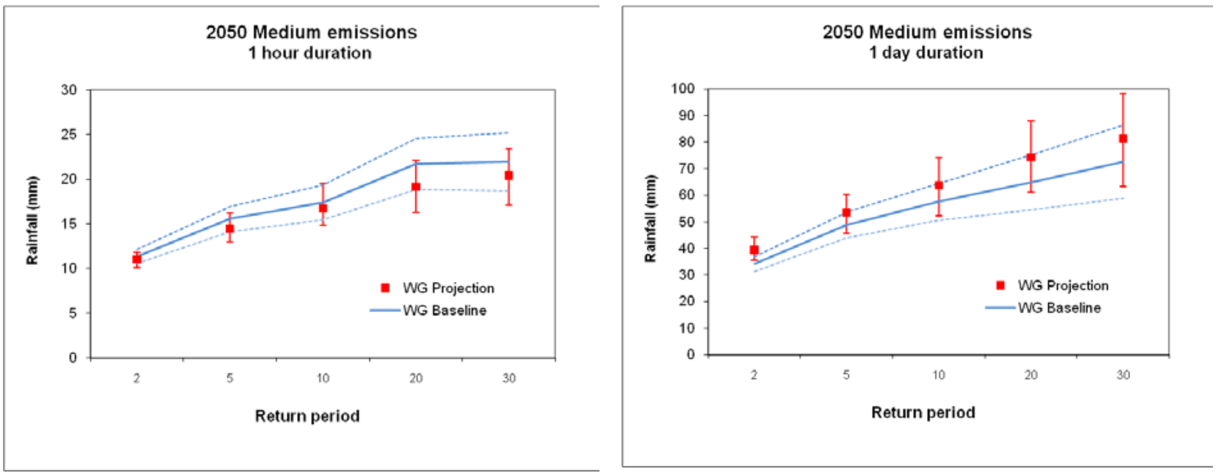

Figure 2 Comparison of WG rainfall estimates for the 2050s medium emission scenario with WG baseline estimates for NE England. Left panel hourly and right panel daily. 10% and 90% probability values are shown as error bars for the future estimates derived from empirical percentiles of the generated ensembles. 10% and 90% probability values for the WG baseline are estimated as before and shown as dashed lines.

This underlines the complexity of analysis of changes in extreme rainfall under climate change and a few general points should be made here about the capabilities of the WG in this regard.

1. Climate model representation of convective extreme rainfall is inadequate in respect of both spatial resolution of convective systems (which are typically of order 1-5 km in Europe) and knowledge of the parameter values themselves.
2. Whilst RCMs operate at 1 hour or better time resolution, the hourly output isn't stored and the smallest resolution that can be accessed is daily. There is also insufficient hourly observed data to validate RCM hourly outputs. UKCP09 is therefore based on data at the daily level only and the WG rainfall model uses fixed relationships between hourly and daily rainfall statistics estimated from the observed climate to generate hourly change information. This is a serious limitation as an increase in convective rainfall (characterised by

hourly intensity) can essentially only be obtained due to an increase in daily rainfall. This situation is projected in many parts of the UK for winter months, but by contrast, the projected decreases in summer rainfall will therefore generate associated decreases in summer intense convective rainfall. This simplification is clearly not consistent with the possibility of an increase in infrequent but intense convective events which do not add up to an increase in mean seasonal rainfall. So, for locations in south east England where summer convection dominates the extreme rainfall regime, low confidence in estimation of future hourly extremes is therefore justified.

2.3 Temperature extremes and heatwave persistence

Improvement to the WG performance for urban heatwaves has been achieved through two measures: the use of an extra dry spell transition and the use of a different temperature distribution.

2.3.1 Extra dry spell transition

The UKCP09 original WG version classified sequences of 2 days using four transitions :

- DD dry today/dry yesterday
- WW wet today/wet yesterday
- DW dry today/wet yesterday
- WD wet today/dry yesterday

Observed weather data were categorized according to these classifications and statistics (such as the mean Tmax for a particular time of year) were estimated for these sets of data. This means that a 2-day dry sequence is treated the same if it is isolated and falls between two wet days (i.e. WDDW) and if it were part of a longer dry spell e.g. DDDDD. Longer dry spells in summer have a tendency to generate higher Tmax values, as in the summer 2006 heatwave, when successive days increased in temperature and little overnight cooling was experienced. The UKCP09 WG therefore tends to under-estimate the occurrence of higher Tmax values during long dry spells in summer as the statistics being sampled are the same as those from shorter dry spells with overall lower Tmax values.

To improve performance of the WG for Tmax and heat wave duration a fifth transition was therefore introduced:

- DDD dry today/dry yesterday/dry day before

Longer dry spells (e.g. DDDDD and longer) could not be used because they occur too infrequently for sufficient sample statistics to be collected. Nonetheless, some improvement is found in WG performance using this extra transition.

2.3.2 Improved temperature distribution

For ease of analysis the UKCP09 WG modelling process assumes that certain weather variables are normally distributed. However, temperature is not always normally distributed and in fact a heavier tail is found in some conditions (*i.e.* heatwaves). This problem has been alleviated by applying a power transform (to normality) to the data prior to regression. This transform is assumed to be the same in the future: again, similarly to the rainfall model, this may not prove to be a justifiable assumption but there is currently insufficient information on extreme temperatures from the climate models to develop a more detailed alternative. This change should also improve cold spell simulation as well as heatwaves.

2.3.3 Validation of improvements to high temperature reproduction

Work on building ventilation and cooling for the GLA and CIBSE proposed the use of the heatwave metric *Weighted Cooling Degree Hours* (WCDH). This metric counts the number of hours the temperature is above a threshold (28°C) and squares the difference between the threshold and the actual temperature. So 38°C adds 100 to the total, but 29°C adds just one. The metric is therefore non-linear in its behavior and a single episode of very high temperatures can generate large values dominating a long period of record. This is a very stringent test of the extremal behavior of the WG.

Using data from Heathrow airport (LHR) it is found that 1976 has the highest value of WCDH in the observations (3987), with an average value for the period 1961-1990 of 651. A number of years have a WCDH value of near zero (i.e. negligible instances of Tmax>28°C). The UKCP09 WG was tested by generating baseline series for LHR and despite reproducing the values of mean temperature and Tmax very well, it was found to severely underestimate the WCDH metric with a maximum value of ~2500 and a mean of up to 336. The improved version produces maximum WCDH values close to 4000 and with a mean of 515 as can be seen in Figure 3.

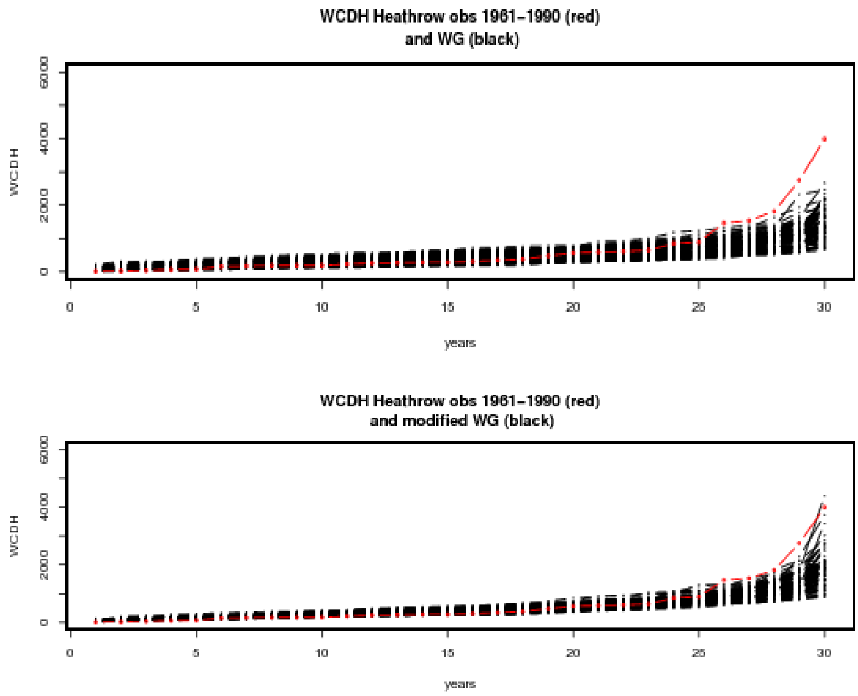

Figure 3 Comparison of WG Weighted Cooling Degree Hours with observations from Heathrow Airport. Top panel shows UKCP09 WG and bottom panel the improved version.

3 Spatial generator implementation and validation

The study of urban layout and the effects of the Urban Heat Island (UHI) require spatial fields of weather variables which represent both the recurrent spatial patterns caused by topography and buildings as well as the statistical and variable aspect of correlations and spatial dependence in "weather" driven by weather systems. A spatial version has therefore been developed incorporating the following aspects.

The domain can be up to the size of a UK region, so the first applications are for the south east of England including London (see Figure 4). Larger domains would require explicit treatment of large weather systems which is not handled by the underlying NSRP rainfall model which is spatially stationary in the mean.

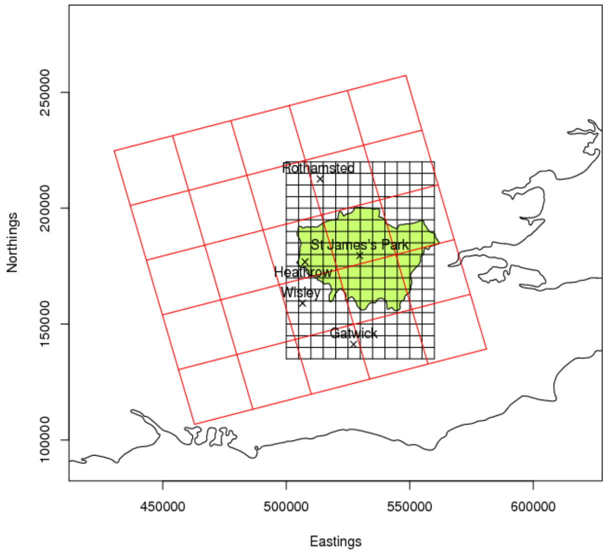

Figure 4 A spatial WG domain for London at 5km (black) overlaid with the 25 km RCM grid (red) for which change factors are available.

The WG is driven by climate model outputs which can be both from UKCP09 for consistency with other studies as well as from new simulations carried out by MOHC reported elsewhere accounting for anthropogenic heat inputs and urban effects on change.

Resolution is hourly on a 5-km grid based on statistics of observed data from the UK Met Office. The relationship between the 5km grid and the 25km RCM grid squares with which change factors are associated can be seen in Figure 4.

The WG is primarily driven by rainfall which is spatially correlated based on the space-time NSRP rainfall model (Burton et al., 2008). The spatial dependence varies across the UK and is based on observed data (1961-1990) – see an example of the form of dependence in Figure 5. The model generates spatial fields of rainfall based on overlapping "disks" or cells of rainfall. Changes to this dependence derived from the UKCP09 11 RCM ensemble are being investigated but are not currently included in the WG.

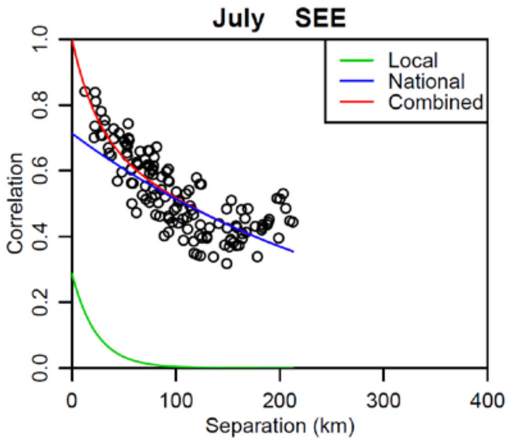

Figure 5 Decay with distance of correlation in daily rainfall for July in SE England and model representation in spatial WG. The dependence model has two components, one applied nationally and the second a local component for each region.

The secondary variable to be generated is temperature. Spatial correlation of temperature (and therefore also subsequent variables to be generated such as humidity, sunshine *etc.*) is maintained by using a single sequence of random numbers across the whole domain which are then used for both "wet" or "dry" squares thus ensuring correlation of the anomaly (i.e. warmer or colder than the mean). A further random "noise" component is added to the temperature sampling to ensure the correct decay with distance.

The spatial WG performance in reproducing observed variables is very good in terms of the individual grid square means since it is essentially sampling from the observed distribution. Performance for extremes has been discussed previously and therefore the most meaningful remaining validation is to show the decay of correlation with distance. This can be seen for temperature and rainfall in Figure 6.

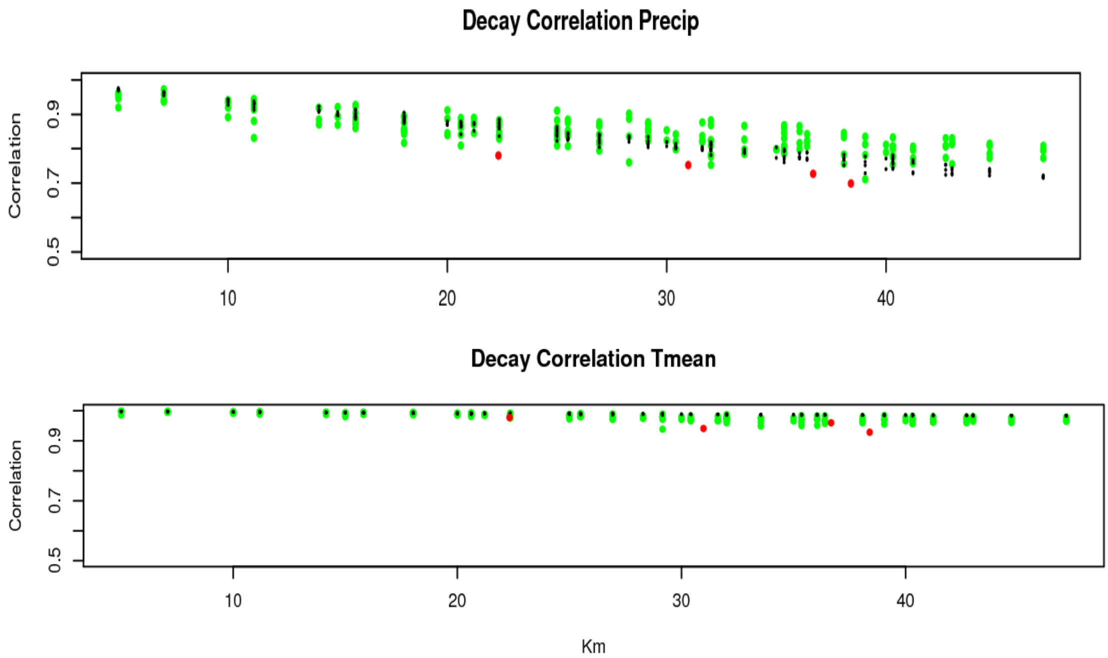

Figure 6 Decay of correlation with distance for SE England in summer for precipitation (top) and temperature (bottom). Black is spatial WG, green is gridded observations at 5km resolution and red are station observations

The spatial WG has been run for sets of baseline and future scenarios to investigate the impacts of the UHI and anthropogenic future change. Some outputs are shown in Figure 7 for Tmax and Tmin in summer. The baseline maps show the UHI, more clearly in Tmin than Tmax. The future scenarios show the impacts of the urban anthropogenic component estimated by MOHC in ARCADIA generated by McCarthy *et al* (2011). These runs take account of land use (urban/rural) in the spatial WG whereas standard outputs driven by UKCP09 are based on “natural” baseline values and change factors taking no account of urbanisation or anthropogenic direct heat input.

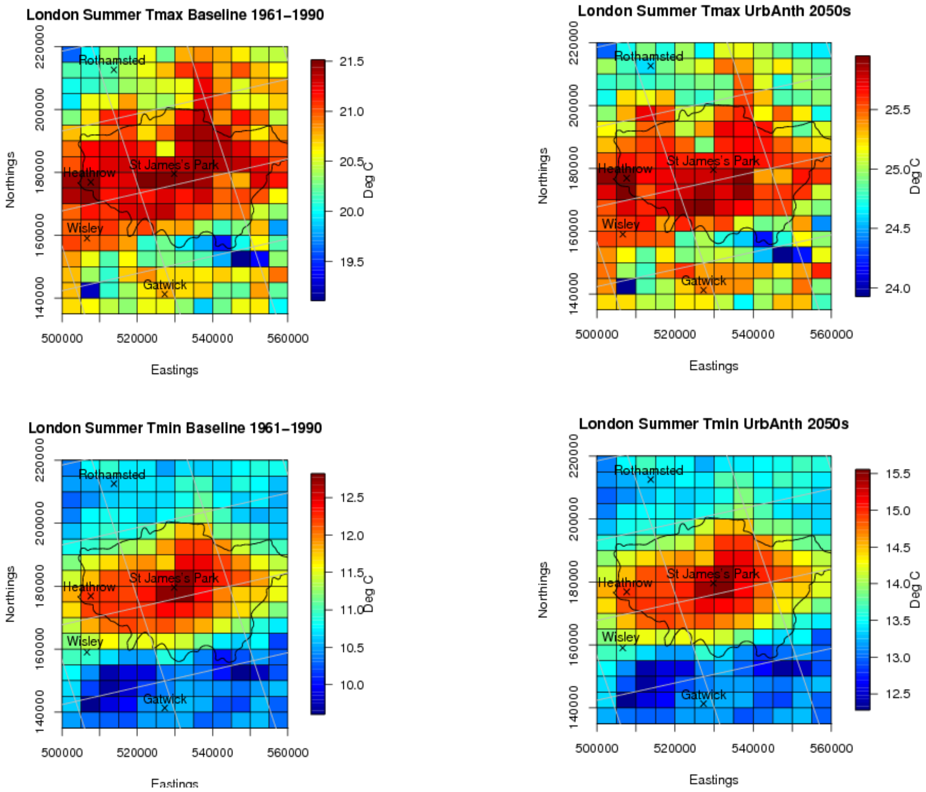

Figure 7 Spatial WG outputs at 5km for baseline (left panel) and future scenarios (right panel). Tmax is shown in the top row and Tmin on the bottom.

4 Further developments

The spatial WG is now undergoing further testing which will concentrate on joint occurrences of extremes in firstly rainfall and secondly temperature.   Further assessment of the reproduction and effects of the urban heat island are required for London and other UK cities.

5 References

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