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Perturbing a Weather Generator using change factors derived from Regional Climate Model simulations

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Abstract. The purpose of this paper is to provide a method for perturbing Weather Generators (WGs) for future decades and to assess its effectiveness. Here the procedure is applied to the WG implemented within the UKCP09 package and assessed using data from a Regional Climate Model (RCM) simulation which provides a significant "climate change" between a control run period and a distant future. The WG is normally calibrated on observed data. For this study, data from an RCM control period (1961–1990) was used, then perturbed using the procedure. Because only monthly differences between the RCM control and scenario periods are used to perturb the WG, the direct daily RCM scenario may be considered as unseen data to assess how well the perturbation procedure reproduces the direct RCM simulations for the future.

1 Introduction

Assessments of the influence of climatic variability on an impact sector (e.g. crop yields, flood risk etc.) require observational weather/climatic data and a model that relates this variability to the impact sector (e.g. crop growth, rainfall/runoff models etc.). For the future, researchers in these numerous impact sectors want to use these same types of impact models to assess how a changed future climate might affect their sector. There are three major uncertainties that need to be addressed in these studies: uncertainties in the impacts models, in the future climate projections (from RCMs) and finally in the way the latter are further "downscaled" to the relevant space and time scales for the sector. This paper does not consider the first uncertainty, which will be both sector and regionally specific (Parry et al., 2007). The relative importance of the three uncertainties depends on the researcher's perspective, but from a climatic perspective the second should be considered the most important particularly for more distant futures. This paper addresses the third of these uncertainties but it is necessary to consider this in conjunction with the second and in many respects it is difficult to separate the third from the second due to the differences in spatial scales. The paper is also specific to projections recently developed for the UK (UK Climate Projections, 2009; Jenkins et al., 2009).

Some form of downscaling is necessary for all impact assessments and researchers have employed a number of approaches to provide what is the basic requirement: future sequences of weather for the changed climate. Two basic approaches to downscaling have been recognized: statistical and dynamical (see Schmidli et al., 2007 for a brief review and an intercomparison of both approaches, Christensen et al., 2007 for a focus on dynamic downscaling and Maraun et al., 2010 for downscaling of precipitation). Both approaches make use of climate model simulations (from both RCMs and the driving global scale General Circulation Models, GCMs). There used to be a clear distinction between the two with dynamical downscaling being considered as the direct use of RCM output in an impact model, with statistical downscaling using observational relationships between local and larger spatial scales perturbed by future changes projected from GCMs. This distinction has become blurred in recent years with the recognition that RCM output should generally not be used directly (due to likely biases within the climate models) and that even high-resolution RCM output (at say the 25 km resolution and daily timescale) is not detailed enough for some impact sectors.

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In the UK, there has been a relatively long history of the derivation of specific national scenarios for use in impacts, and more recently adaption, assessments (see discussion in Hulme and Dessai, 2008). The aim of these national scenarios has been to provide a set of future scenarios that all impact sector work in the country should use (i.e. results across sectors can be compared because the basic scenarios are the same). The previous version of these national scenarios UKCIP02 (Hulme et al., 2002) has been extensively used in numerous sectors throughout the UK. The next generation, UKCP09 (Jenkins et al., 2009) has now been released. Although widely used, UKCIP02 and the earlier incarnations have been criticised in the climatological literature in recent years for using a limited number of emission scenarios, integrations based on a single climate model and one set of climate model parameters etc (see extensive discussion in Hulme and Dessai, 2008). Part of the criticism may be considered somewhat unfair as computing power around 2000 did not allow climate model parameters to be varied (to assess uncertainty), running ensembles of simulations with different initial conditions was in its infancy and only a few climate model simulations from other centres were available.

UKCP09 sought to address these criticisms by accounting for uncertainty in the selection of the values of some of the key global and regional climate model parameters by developing a perturbed physics ensemble and through the incorporation of uncertainty from other modelling centres (Murphy et al., 2007, 2009). The latter has been referred to as structural uncertainty and attempts to incorporate additional uncertainties in global climate models resulting from different parameterization schemes (used by other modelling centres) for important processes like convection. The results of this extensive exercise which also involves emulation procedures culminates in future scenarios (at the monthly timescale) being expressed as probability density functions (pdfs) for all 25 km by 25 km grid squares across the UK (Murphy et al., 2009). The pdfs are based on 10 000 equiprobable "possibilities" for each key climate variable (see lists in Murphy et al., 2009) which maintain the correlation structure between the variables. These pdfs can be sampled (see details in Jones et al., 2010 and the UKCP09 website, http://ukclimateprojections.defra.gov.uk/) and we refer to each of the possibilities as a set of change factors (one for each of the key variables).

This extensive exercise addresses the criticisms of the earlier national UK scenarios, but doesn't explicitly provide daily time series for all possibilities within the pdfs. RCM output is directly available at the daily timescale, but only for a very limited number of possibilities (11 RCM runs) within the ranges of the pdfs, and also limited to the 25 km by 25 km grid squares across the UK. For many impact sectors, users would like future information at higher spatial resolution (points or small catchments) and higher temporal resolutions (hourly). To address these user needs, the UKCP09 User Interface incorporates a Weather Generator (WG) which provides the spatial and temporal detail required by users as well as allowing sampling across the full range of the pdf. UKCP09 (see the website http://ukclimateprojections.defra.gov.uk/ and also the reports, e.g. Jenkins et al., 2009) gives numerous recommendations about usage of the probabilistic projections and the WG. For example, the latter should be run at least 100 times (sampling from 100 of the change factors) with each run then being used with an appropriate impact model for the sector being addressed.

This paper introduces the WG; with the main emphasis being on the way the WG is perturbed using statistical relationships between the RCM control and scenario periods to provide future weather sequences. The perturbation approach used is then assessed using a single RCM simulation for the control and a future period. Section 2 discusses the daily version of the WG, including the variables calculated from the generated variables (Potential Evapotranspiration, (PET) and Direct and Diffuse Radiation). Section 3 is the main part of the paper and addresses the key issue of perturbing the WG for the future, Sect. 4 discusses the results and Sect. 5 concludes.

2 The UKCP09 WG

WGs have a long history of use in hydrology, climatology and agriculture (e.g. Semenov, 2008; Kilsby et al., 2007). The WG used within UKCP09 is just one of a number of possible WGs that have been proposed (see review by Wilks, 2010). The UKCP09 WG can be considered as a non-conditional WG – since it is not explicitly dependent on the state of the large-scale circulation. The WG is described in detail in Kilsby et al. (2007) and is summarized in the UKCP09 WG report (Jones et al., 2010). To fit this WG requires at least 30 yr of data (for all the variables). The WG generates series at a daily time resolution, using two stochastic models in series: first, for precipitation which produces an output series which is then used for a second model generating the other variables dependent on precipitation. The series are intended to be representative of single sites (as there is no spatial structure incorporated into the WG) defined nationally across the UK at a 5 km grid-box resolution, but can also be generated to be representative across small catchments ($<1000\,\text{km}^2$, see Jones et al., 2010). Table 1 lists the weather variables generated and the order in which this is done.

This WG produces internally consistent series of meteorological variables: precipitation, temperature, vapour pressure, wind[1], sunshine, and a number of variables calculated from the generated variables such as PET (according to the

[1] Within the UKCP09 package it was not considered possible to provide reliable projections of changes to surface wind in the future (see Murphy et al., 2009 for details). Consequently wind is not included in the validation plots in this paper.

Table 1. Weather variables produced by the Daily WG.

Variable	Perturbation statistics ("change factors") and sequence of perturbation
Primary generated variable:	
Precipitation (mm)	Mean wet day amount (ratio) Precipitation daily variance (ratio) Precipitation probability dry (formula) Precipitation skewness (ratio) Precipitation lag-1 autocorrelation (formula)
Secondary generated variables:	
Minimum temperature (degrees C) Maximum temperature (degrees C)	Temperature daily average (difference)* Temperature daily variance (ratio)* Diurnal temperature range (difference)*
Other variables:	
Vapour pressure (hPa)	Vapour pressure daily average (difference)*
Sunshine duration (h)	Sunshine daily average (difference)*
Wind speed ($m\,s^{-1}$)	Not directly perturbed
Calculated variables:	
Relative humidity (%) Diffuse radiation ($kWh\,m^{-2}$); Muneer (2004) Direct radiation ($kWh\,m^{-2}$) (ibid) Reference potential evapotranspiration (mm); Ekström et al. (2007)	

* Adjusted for changes earlier in the perturbation sequence.

formula given in Ekström et al., 2007) and Diffuse and Direct Radiation (according to the formula given in Muneer, 2004). The purpose of computing the variables such as PET and radiation (the latter is particularly important for building simulation, for example) is for the ease of users and consistency across different impact sectors. The WG also maintains the autocorrelation between one variable from one day to the next as well as the cross-correlations between the different variables, producing sequences that look like and statistically resemble measured data. Apart from the daily autocorrelation of precipitation, none of these other relationships (referred to as inter-variable relationships, IVRs) are perturbed for future simulations of the WG as it is not believed that they are well simulated by RCMs.

The purpose of this paper is not to explore whether this WG fits observational data well, but how the perturbation procedure used within UKCP09 can be assessed (see next section). Examples of the fit of this WG to observational data across the UK are given in Jones et al. (2010) for one location (Heathrow) and also for another nine locations across the UK at http://ukclimateprojections.defra.gov.uk/images/stories/Tech_notes/UKCP09_WGen_validation_V2.pdf.

3 Perturbing the WG

The changes between an RCM control and a future scenario run provide the perturbation (also referred to as a "delta") by which the variables (see Table 1) (precipitation, mean temperature, diurnal temperature range (DTR), vapour pressure and sunshine) could alter in the future. In this section we illustrate the procedure. For some of the variables the perturbation (for each of the twelve months of the year) is applied additively, while for others it is applied using ratios (see Table 1 and Jones et al., 2010). Before applying the perturbation, it must be realized that the variables are not independent of each other. As the WG generates the weather variables in sequence (see Table 1), changes to precipitation influence mean temperature and DTR, and similarly changes to these primary and secondary variables will affect the generation of sunshine and vapour pressure. We need to ensure that future changes (the perturbations or deltas) that occur for all non-precipitation variables will be the same as those prescribed from the differences between the two RCM integrations. To achieve this, we modify the perturbations we apply to the secondary variables to allow for the changes that will have occurred earlier in the generation sequence. This is best illustrated with a simple hypothetical example: one of the selected change factors for a future summer month might be a

Table 2. Indices of extremes used.

Description of indices	Definition
Fraction of total precipitation from intense events	Fraction of total precipitation above the annual 95th percentile value
Maximum number of consecutive dry days	Maximum number of consecutive dry days
% of "Hot days"	% of days when maximum temperature is greater than the 90th percentile value
Heatwave duration	Cumulative count of number of consecutive days when maximum temperature exceeds the 90th percentile value for more than 5 days (NB the first 5 days are not counted in the index)
% of "Warm nights"	% of days when minimum temperature is greater than the 90th percentile value
% of "Cold nights"	% of days when minimum temperature is less than the 10th percentile value

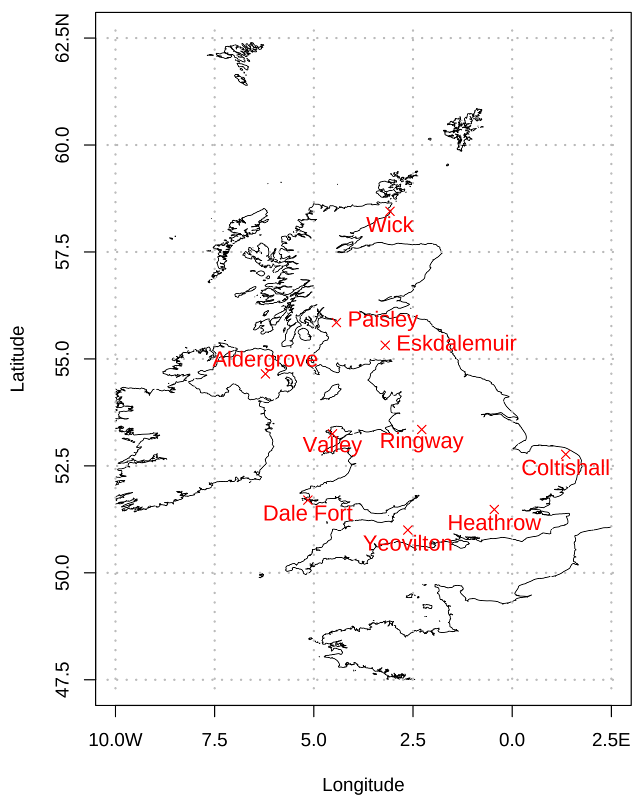

Fig. 1. Distribution of the test locations contained within the ten RCM grid cells used.

50 % reduction in rainfall and a 3 °C increase in mean temperature. From observations, dry summer months are generally warmer, so there will be a precipitation-related change in temperature: linear regression indicates a summer temperature increase of about +0.3 °C for a 50 % reduction in rainfall. Thus in this example, the future change in temperature is adjusted down to ~2.7 °C so that in the generated sequences, the mean change will be equal to the selected perturbation. This procedure becomes more complex for the "other" variables listed in Table 1.

The WG cannot explicitly perturb variables that are not simulated by the RCM. For example, the shortest temporal resolution typically archived from RCMs is daily, so it is not possible to assess changes for sub-daily resolutions. If output at these timescales is required, relationships at sub-daily scales must be estimated from daily (using observational data) and assumed to be time invariant for the future. Also, for this WG (within UKCP09) we do not alter the IVRs in any way for the future.

Provided that the allowance for the effects of primary on secondary and subsequently on the other variables is made, the approach used guarantees that the change in monthly statistics (see Table 1) will be achieved. Not every WG simulation for the future will have the same mean, but the average over a large number of scenario runs (e.g. the default of 100 WG runs in UKCP09) should differ from the control run average by the perturbation applied. The main purpose of this paper is to show how this procedure (which might also be applied to other WGs) is used to perturb the UKCP09 WG and to illustrate that it produces realistic results. In the next section on results, we will illustrate the agreement between RCM and WG variables using a number of metrics including some independent indices that measure extremes at the daily timescale.

The WG within UKCP09 has been fit to observational data for the 1961–1990 period. We know this works well (see references above) but how can we assess that when applying the perturbation from a set of RCM simulations that it will perform adequately? One possibility might be to use a period of observational data that is markedly cooler or warmer than another period. Within the UK, observational data are not long enough, nor is there enough of a difference between periods

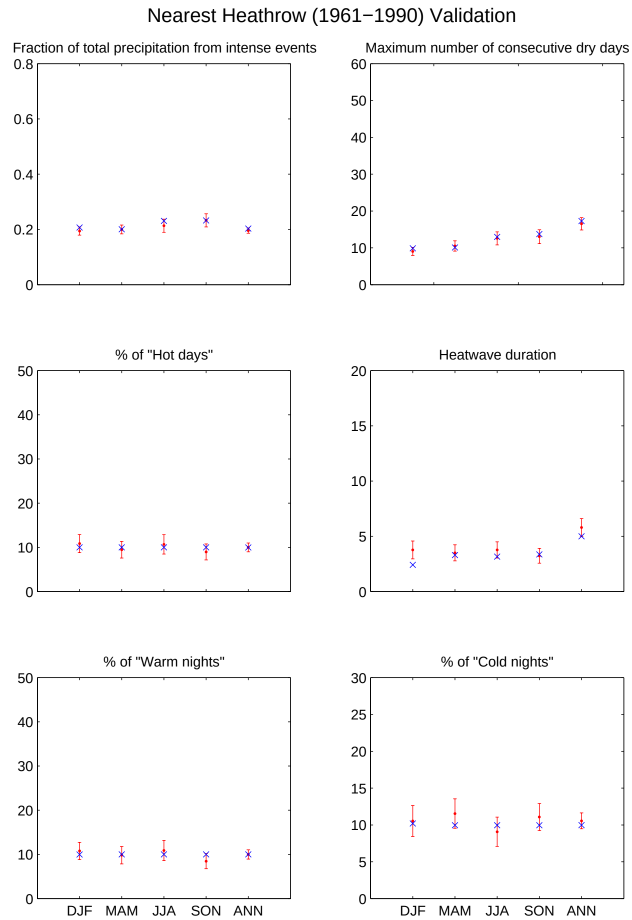

Fig. 2. RCM control (HadRM3Q0 control – blue, shown as crosses) and simulated (red dots and error bars) extremes for each half month mean for the grid cell nearest Heathrow based on a 30 yr period (1961–1990). The simulated values are the means of 100 weather generator runs. The lines and bars show the variability of the 100 runs (plotted as plus/minus two standard deviations around the mean).

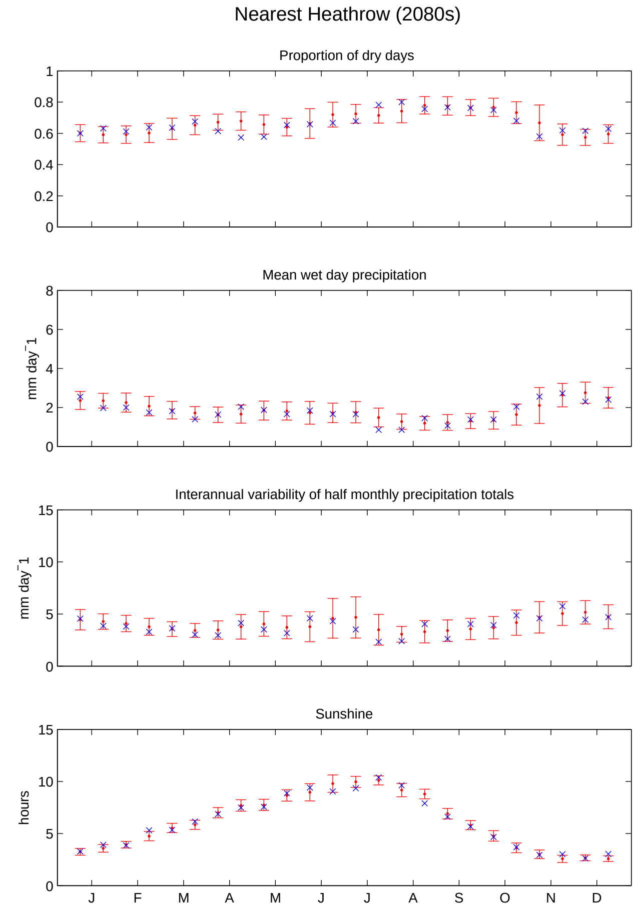

Fig. 3a. RCM 2080s scenario (HadRM3Q0 – blue, shown as crosses) and simulated (dots and error bars) averages for each half month for the grid cell nearest Heathrow based on a 30 yr period (1961–1990). The simulated values are the means of 100 weather generator runs. The lines and bars show the variability of the 100 runs (plotted as plus/minus two standard deviations around the mean).

(compared to the large changes projected for the future by all UKCP09 RCM simulations), to assess whether the proposed way of perturbing the WG will work. An observational possibility is to separate the data into warm and cold years. We have experimented with this approach for Heathrow and Eskdalemuir and while it functions adequately (not shown), the 22 warm and 22 cold years are both a relatively short period with which to fit the WG, but more importantly the difference in climate between the two sets of years is relatively small compared to changes indicated by the future RCM integrations (Murphy et al., 2009).

Instead of using observations, we use the base UKCP09 RCM integration (i.e. the member of the eleven-member RCM perturbed physics ensemble available through UKCIP, with the standard set of RCM parameter values, referred to as HadRM3Q0 – see Murphy et al., 2009) for simulations with a 30-year period of current climate (nominally 1961–1990) and 30 yr of data for the most distant future time (2070–2099, referred to as the 2080s), in order to maximise the amount of climate change (i.e., the perturbation or the delta referred to previously). This is a single RCM simulation. We use this as the WG requires estimation of variances and intervariable relationships at the daily timescale. Thus we cannot use the ensemble mean as that only has any meaning for much longer time averages. Averaging the 11-member ensemble at the daily timescale would completely distort the required daily statistics. The RCM produces most of the variables used by the WG, but it doesn't directly estimate vapour pressure or sunshine duration. These are derived using relative humidity (and hence temperature as well) and cloudiness, respectively.

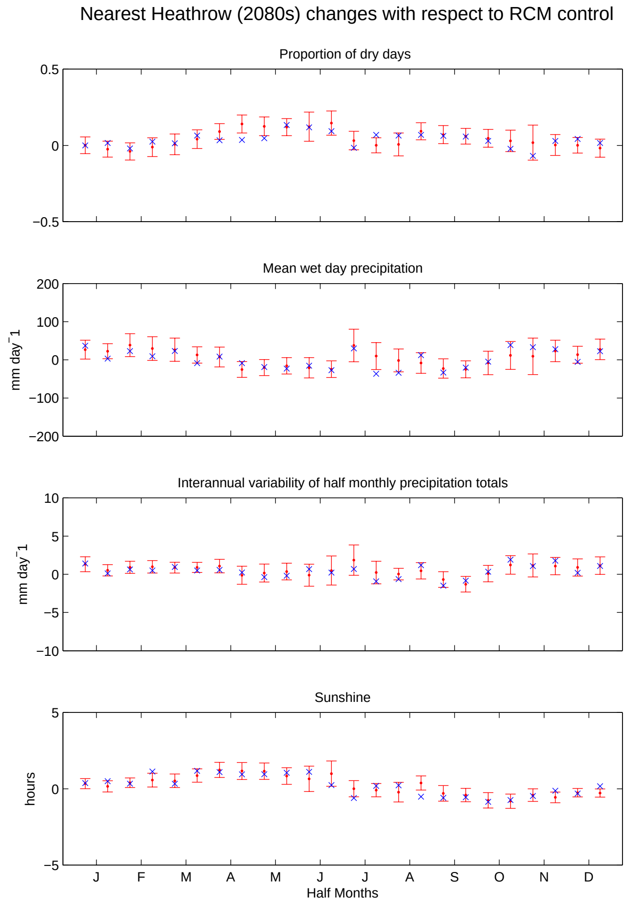

Fig. 3b. RCM 2080s scenario (HadRM3Q0 – blue, shown as crosses) and simulated (red dots and error bars) changes for each half month for the grid cell nearest Heathrow based on a 30 yr period (1961–1990) showing the changes with respect to the RCM control period (Fig. 3a). The simulated values are the means of 100 weather generator runs. The lines and bars show the variability of the changes for the 100 runs (plotted as plus/minus two standard deviations around the mean).

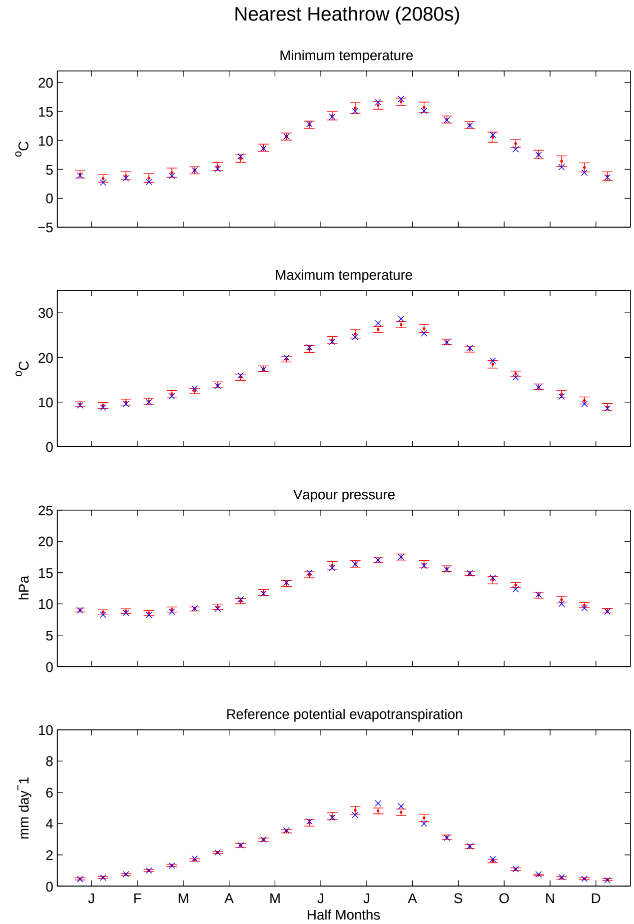

Fig. 3c. RCM 2080s scenario (HadRM3Q0 – blue, shown as crosses) and simulated (red dots and error bars) averages for each half month for the grid cell nearest Heathrow based on a 30 yr period (1961–1990). The simulated values are the means of 100 weather generator runs. The lines and bars show the variability of the 100 runs (plotted as plus/minus two standard deviations around the mean).

For this exercise the WG was fitted to the control run period (nominally 1961–1990) for ten selected 25 km grid-cell squares across the UK each containing a weather station (Fig. 1). Here we examine the one containing Heathrow which is fairly representative in terms of performance (several other cells have better results). The perturbation procedure described above was used for the change between the 2080s future (2070–2099) and the control period. This involved calculation of "changes" in statistical measure(s) for the variables given in Table 1. These were calculated for both the future and the control-run integration, with the "change factors" applied to the WG calculated as either differences or ratios depending on the variable. For mean temperature, changes were assumed to be the same for all five rainfall transitions (i.e. previous day(s) Dry/current day Dry DD and DDD, previous day Wet/current day Wet WW, DW and WD) within the WG (see Jones et al., 2010). To smooth the stochastic variability, 100 sequences were generated of 2080s daily weather with the same "change factors" applied which were then compared with the daily data simulated directly by the 2080s integration of the RCM (HadRM3Q0).

4 Assessment of the perturbation procedure

The WG was fit to the RCM data for the control (nominally 1961–1990) period for the ten locations shown in Fig. 1. We show examples later for Heathrow for the 2080s and use the phrase "nearest Heathrow" to indicate the 25 km by 25 km grid box containing Heathrow. The WG was fit to the RCM (HadRM3Q0) control run and as expected (so not shown) the RCM simulation means (for each variable for each half

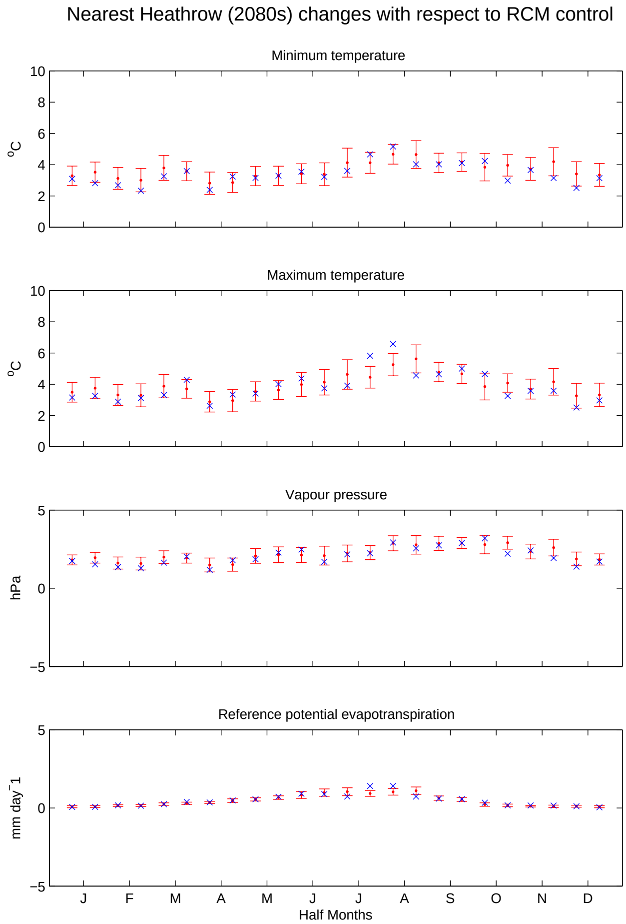

Fig. 3d. RCM 2080s scenario (HadRM3Q0 – blue, shown as crosses) and simulated (red dots and error bars) changes for each half month for the grid cell nearest Heathrow based on a 30 yr period (1961–1990) showing the changes with respect to the RCM control period (Fig. 3b). The simulated values are the means of 100 weather generator runs. The lines and bars show the variability of the changes for the 100 runs (plotted as plus/minus two standard deviations around the mean).

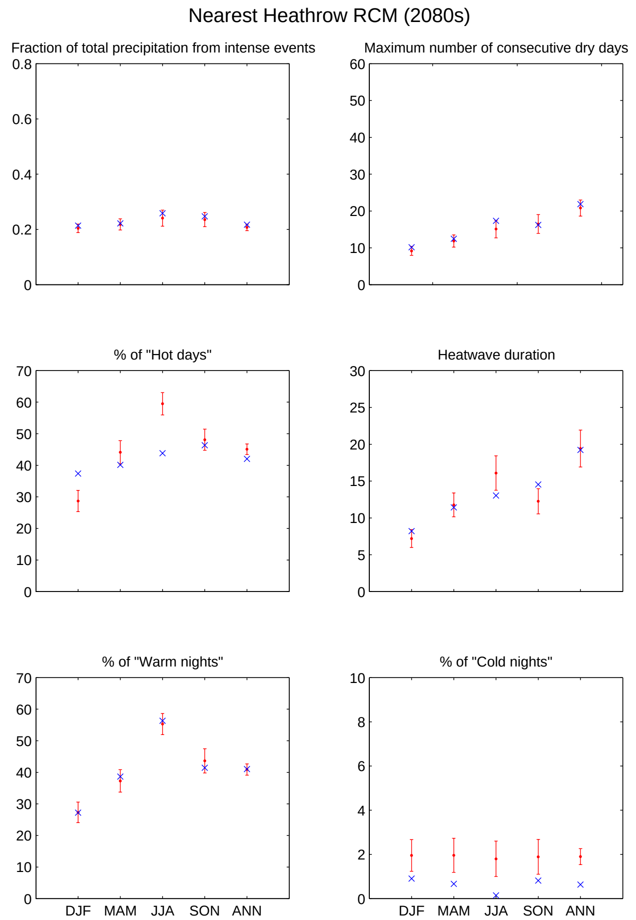

Fig. 4. RCM 2080s scenario (HadRM3Q0 – blue, shown as crosses) and simulated (red dots and error bars) extremes for each half month for the grid cell nearest Heathrow based on a 30 yr period (1961–1990). The simulated values are the means of 100 weather generator runs. The lines and bars show the variability of the 100 runs (plotted as plus/minus two standard deviations around the mean).

month of the year) are within the ranges (±2 standard deviations) of 100 generated sequences. Table 2 introduces six different measures of extremes – based on daily temperature and precipitation data. Some look at the occurrences of warm/cold days/nights and precipitation extremes, while others look at spells (consecutive dry days (CDD) and heatwave duration). These measures may not seem that "extreme" but it is important when undertaking comparisons for the extreme measure to occur in most years. If more extreme extremes are used these extremes may only occur once during the observational sequence. We are comparing counts of extremes above thresholds, so need enough samples to make comparisons meaningful. Figure 2 (nearest Heathrow) shows the generated extremes compared to the original RCM control run series. Apart from heatwave duration for DJF and annually, all the indices are well reproduced by the WG (i.e. the direct simulation is within the WG ranges). Figure 2 can be considered as a partial independent validation of the WG, as these "extremes" are not directly used in the fitting of the WG.

Figure 3a and c (nearest Heathrow) shows plots for the future using the perturbation procedure described above. In these plots we still have the means and ranges of the 100 generated sequences, but the crosses are now for the direct RCM averages for the future period centred on the 2080s (i.e. for the single future simulation of HadRM3Q0). We also show in Fig. 3b and d the differences (in other words the "climate change" component) compared to the fit for the control period (nominally 1961–1990). These difference plots highlight that the range of the generated sequences, in most cases, encompasses the single direct RCM simulation (the cross in all of the Figures) for the 2080s.

The perturbation procedure we are using ensures the reproduction of the changes in all WG variables according to the differences between the future and control simulation of the RCM. Whether these perturbations (i.e. the changes simulated by the RCM) are realistic, is not the subject of this paper. The aim of the exercise is to determine whether or not the WG reproduces the changes over the future 30-yr period given by the RCM.

Figure 4 (nearest Heathrow) shows the corresponding results for the six extreme indices. In calculating the extremes, the required percentile thresholds from the control run sequences (both for the RCM and the WG) have been used for the future period centred on the 2080s. There are a few more instances where the RCM mean falls outside the range of the WG sequences, more so at the Heathrow grid box than other studied grid boxes such as the one containing Manchester Ringway. This contrast between the north and south of the UK is borne out by the other nine selected locations (see http://ukclimateprojections.defra.gov.uk/images/stories/Tech_notes/UKCP09_WGen_validation_V2.pdf).

Much has been written about the large temperature increases in RCM future simulations across Europe, particularly southern parts (see e.g. Räisänen et al., 2004; Rowell and Jones, 2006). This is believed to result from soil moisture in the RCM and GCM drying out, with all the extra heat going into sensible as opposed to latent heat. This is also a problem simulating much of the Mediterranean region with RCMs for the present day (see e.g. Moberg and Jones, 2004), but it also becomes an important issue in the future for UK latitudes (see Räisänen et al., 2004). There are clearly some very dramatic changes in these extremes (Fig. 4) between the two periods (e.g. the number of warm nights in the summer increases from 10 % during the control period (by index definition) to between 40–60 % of the time during the future period), but exploring the causes and reliability of such changes is not the main concern of this paper. Our concern is whether the WG sequences (after perturbation) have the same statistical character as the future RCM sequence. Based on the results shown in Figs. 3 and 4, they clearly do and the direct RCM sequence is within most of the WG ranges for most of the extreme indices. The WG simulations for cold nights overestimate the direct RCM simulations by a factor of two (Fig. 4). It should however be noted that this is an overestimate of two compared to one cold night in the 2080s (using thresholds from the control-run period). This should be contrasted with the ten cold nights (by definition) from the control-run period.

5 Conclusions

The purpose of this paper has been to demonstrate that this WG perturbation method when applied to the WG used within UKCP09 is effective. Establishing that the WG perturbation is consistent with the RCMs is important for any WG. This has been achieved using RCM simulations undertaken by the UK MOHC using the RCM HadRM3Q0. The use of RCMs to assess the procedure is necessary because there isn't enough "climate change" in digitally-available real-world weather data. The method develops "change factors" based on simulations of the control climate (1961–1990) and for the future (2070–2099). Depending on the variable these are based either on differences or ratios of the control and future model simulations. The WG is then fitted to the control-run sequence, perturbed, then compared with the direct simulation of the future by the same RCM. The approach was tested using ten RCM grid cells across the UK nearest to observed stations, one of which, Heathrow, is illustrated within the paper. For the future period, most of the half months of the year have generated data which encompasses the value directly simulated by the RCM for the period 2070–2099. Six indices based on extremes within the precipitation and temperature data were used to assess the perturbation procedure beyond averages and standard deviations. The perturbation method has been evaluated here using a single RCM run whereas in the UKCP09 context the change factors are drawn from pdfs reflecting a wider range of internal and structural model uncertainty (Jenkins et al., 2009; Murphy et al., 2009).

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