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To cite this article: K.P. Chun , H.S. Wheeler & C. Onof (2013) Comparison of drought projections using two UK weather generators, Hydrological Sciences Journal, 58:2, 295-309, DOI: [10.1080/02626667.2012.754544](https://doi.org/10.1080/02626667.2012.754544)

To link to this article: <https://doi.org/10.1080/02626667.2012.754544>



Published online: 16 Jan 2013.



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Comparison of drought projections using two UK weather generators

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Received 15 February 2012; accepted 16 July 2012; open for discussion until 1 August 2013

Editor D. Koutsoyiannis

Citation Chun, K.P., Wheater, H.S., and Onof, C., 2013. Comparison of drought projections using two UK weather generators. *Hydrological Sciences Journal*, 58 (2), 295–309.

Abstract Possible changes in drought under future climate scenarios may pose unprecedented challenges for water resources, as well as other environmental and societal issues, and need assessment to quantify their associated risk. Two weather generators, based upon (a) the Neyman-Scott Rectangular Pulses (NSRP) model as implemented by the United Kingdom Climate Projections 09 (UKCP09) study, and (b) the generalized linear model (GLM) approach, are used to investigate potential variations in drought conditions for six catchments in the UK under climate projections. The results show that both weather generators provide rainfall simulations having satisfactory monthly statistics. However, the rainfall series from the UKCP09 weather generators lack inter-annual variability, whereas the GLM simulations, which include non-stationary global circulation model (GCM) outputs as driving variables, seem to have a more appropriate representation of the observed drought conditions. For drought projections in the 2080s, the UKCP09 simulations provide repetitive patterns without much temporal variation, similar to the results in the control period. This study suggests that for the drought index considered here (a 3-month drought severity index) the GLM approach appears to be a more appropriate model for drought study on inter-annual scales in comparison with the UKCP09 weather generator.

Key words UKCP09 weather generator; generalized linear models; drought persistence; downscaling; extremes

Comparaison des projections de sécheresse utilisant deux générateurs de données météorologiques du Royaume-Uni

Résumé Les changements possibles d'occurrence des sécheresses dans les scénarios climatiques du futur constituent des défis sans précédent concernant les ressources en eau, ainsi que d'autres questions environnementales et sociétales et d'évaluation des besoins de quantification des risques associés. Deux générateurs de données météorologiques, basés sur (a) le modèle Neyman-Scott Rectangular Pulses (PNRS), mis en œuvre dans l'étude des projections climatiques au Royaume-Uni en 2009 (UKCP09) et (b) le modèle linéaire généralisé (MLG), ont été utilisés pour étudier les variations potentielles des sécheresses, pour six bassins versants du Royaume-Uni, dans des conditions définies par des projections climatiques. Les résultats montrent que les deux générateurs de données météorologiques permettent de fournir des simulations des précipitations ayant des statistiques mensuelles satisfaisantes. Toutefois, les séries de pluie obtenues à partir des générateurs de données météorologiques de UKCP09 manquent de variabilité interannuelle, alors que les simulations MLG, qui sont guidées par des variables de sortie non-stationnaires d'un modèle de circulation générale (MCG), semblent produire une représentation plus adéquate des conditions de sécheresse observées. Pour les projections des sécheresses dans les années 2080, les simulations UKCP09 sont caractérisées par des motifs répétitifs peu variables au cours du temps, semblables aux résultats obtenus pendant la période de contrôle. Cette étude suggère que, pour l'indice de sécheresse considéré ici (un indice de sévérité de sécheresse de 3 mois), l'approche MLG semble être plus appropriée que le générateur UKCP09 pour l'étude des sécheresses sur des échelles interannuelles.

Mots clefs générateur météorologique UKCP09; modèles linéaires généralisés; persistance de sécheresse; descente d'échelle; extrêmes

1 INTRODUCTION

Throughout history, drought has been a recurring hazard that has plagued civilisation (Heim 2002), and under future climate scenarios, increased risk of widespread drought is hypothesized (Bates *et al.* 2008). It is widely recognized that changes of drought pattern will have implications for many different environmental and societal issues, such as water resources (e.g. McIntyre *et al.* 2003), agriculture (e.g. Wang 2005), ecosystems (e.g. Harrison *et al.* 2003) and fire hazard (Hessl *et al.* 2004). Although there is no universal or absolute definition of drought, drought indices have been developed as useful drought indicators (Heim 2002). Using these to quantify future drought characteristics is likely to be important for climate change adaptation and mitigation.

For investigating climatic impacts related to anthropogenic emissions, global circulation models (GCMs) are the main tools in hydrological studies (Wheater 2002). Although there is rapid climate model development, using GCM output directly in hydrological modelling and water resources management is still being questioned (Kundzewicz and Stakhiv 2010). Concerning unrealistic statistical characteristics of climate model outputs, many recent discussions (e.g. Anagnostopoulos *et al.* 2010, Huard 2011, Koutsoyiannis *et al.* 2011) suggest that climate model outputs may not provide good representations of local observations which are important for hydrological applications. Therefore, evaluating and disaggregating the climate model output before hydrological applications (Wheater 2006, Wilby 2010) are still important.

Another challenge in using GCM outputs is that there is no direct information on drought, and drought indices are usually needed to investigate shifts in drought conditions. Since fine spatial and temporal data are generally required for drought index estimation, GCM outputs are still frequently downscaled for drought impact assessments (e.g. Chun *et al.* 2012). Although bias correction is a commonly used linear statistical technique for correcting GCM outputs and there are many other statistical approaches (c.f. Maraun *et al.* 2010), weather generators are the main consideration here. Weather generators are commonly used as a statistical approach for downscaling GCM outputs (e.g. Jones *et al.* 2009). Based on empirical relationships, weather generators aim to simulate rainfall series having the same statistical characteristics as observations (e.g. Richardson 1981). Originally, weather

generators were developed to infill missing data or produce synthetic weather series of unlimited length (Hulme *et al.* 2002). However, by including empirical relationships between regional-scale predictors (e.g. GCM climate variables) and local-scale predictands, weather generators can be used for climate change studies. Dependent on the algorithms used, the weather generators can be parametric (e.g. Chandler and Wheater 2002), semiparametric and nonparametric (e.g. Semenov and Barrow 1997). As many climate variables (e.g. temperature) are shown to have strong correlation to wet and dry states (e.g. Racsko 1991), many weather generators synthesise rainfall series and use them as primary variables to generate other climate variables based on empirical multivariate relationships (e.g. Hutchinson 1995). Therefore, the performance of weather generator rainfall simulations plays an important role in determining the quality of other aspects of climate simulations and their overall performance.

Two of the most widely used families of parametric rainfall models for weather generators are (a) a two-stage approach, consisting of an occurrence and an amounts process (e.g. Chandler and Wheater 2002) and (b) continuous simulation using a Poisson cluster process to model arrivals of storms and raincells within storms (e.g. Jones *et al.* 2009). Many weather generators based on the two-stage rainfall approach (e.g. WGEN; Richardson and Wright 1984) use Markov chain models for the occurrence process. However, these generators are considered to be special cases of the generalized linear model approach (Chandler and Wheater 2002). Regarding amounts models, various probability distributions have been proposed (e.g. Woolhiser and Pegram 1979). However, the gamma distribution is one of the most widely adopted models (e.g. Coe and Stern 1982) and has the added advantage that a single site amounts model can be readily extended to a multi-site model (Yang *et al.* 2005).

For the Poisson cluster process models, the Bartlett-Lewis and Neyman-Scott pulse processes (see Rodriguez-Iturbe *et al.* 1987, 1988) are the two most popular models. The details of their properties and differences can be found in many reviews (e.g. Onof *et al.* 2000). Although some studies (e.g. Jones *et al.* 2009) suggest that the rainfall process is best modelled by clustered point processes, many studies (e.g. Cowpertwait *et al.* 2002) have noted that point rainfall process models break down or reveal lack of fit at certain temporal or spatial scales. Therefore, rainfall model selection for a particular application

should be decided based on available data and the specific requirements of the problem rather than simple rules of thumb.

Although extended analysis and validation has been undertaken for the outputs of many individual generators (e.g. Jones *et al.* 2009), the appropriateness of weather generator output for droughts has not been widely studied. As droughts are related to inter-annual variability and persistence of rainfall (e.g. Mawdsley *et al.* 1994), which are not used by most weather generators as validation criteria, there is a need to assess the appropriateness of simulations. Two parametric weather generators are assessed here based on their relative performance in UK applications. A recent UK national methodology based on Poisson process modelling is compared with a GLM approach. Data and details of the two weather generators are presented in the following sections. Validation and comparison for current climate is based on rainfall and drought indices for six catchments, and

drought projections for the 2080s from the two generators are compared. Important results and further research areas are summarized in the concluding section.

2 DATA AND METHODOLOGY

The meteorological drought characteristics for six catchments (Fig. 1) are studied. The selected catchments from the UK National River Flow Archive (NRFA) are spread across the North West, Midlands and South East of England, and their areas vary from 60 to 250 km². The catchments are located near to a set of areas investigated by Chandler *et al.* (2006), and the GLM structures developed in that study are deemed to be suitable for the six catchments here (Chun *et al.* 2009a, 2009b). Additional NRFA catchment details and previous analyses of changes in rainfall and streamflow series under climate variability can be found in Chun *et al.* (2009a, 2009b).

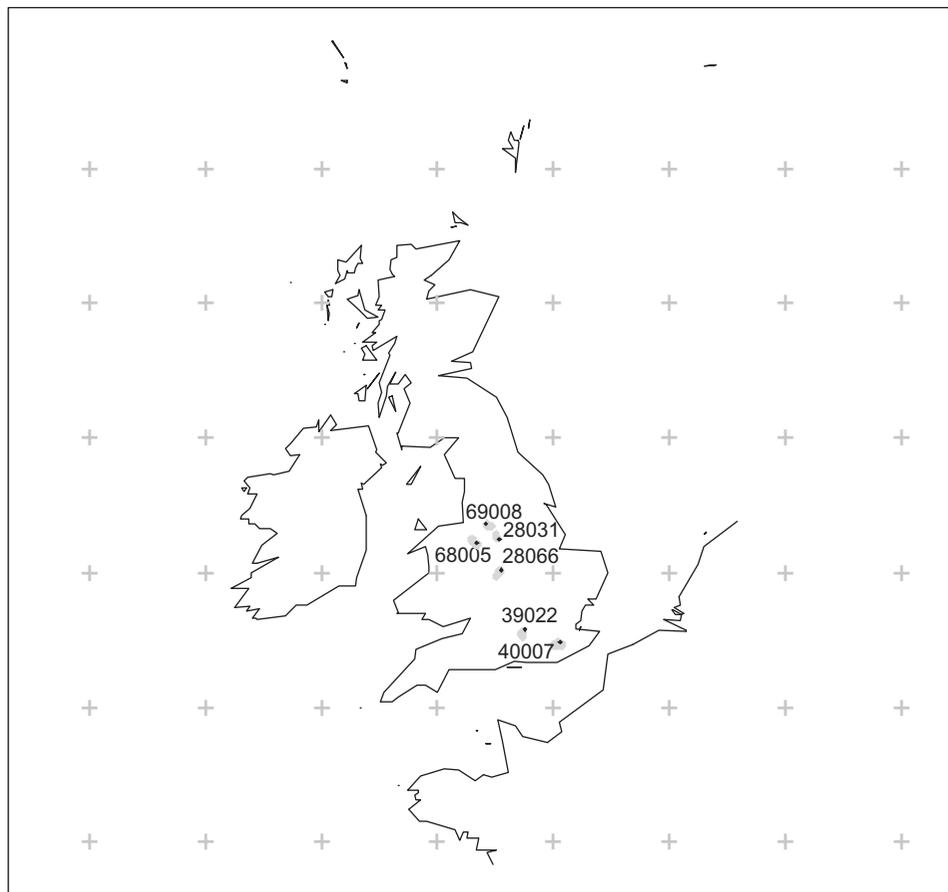


Fig. 1 Location map of the six study catchments. Five-digit numbers are the UK National River Flow Archive (NRFA) references. Grey shaded area: the selected UKCP09 grid cells; black dots: the GLM reference locations, and grey crosses: the Hadley climate model gridded centres.

In the UK, a recent study (the UK climate change projections in the 21st century (UKCP09)) has produced a downscaling methodology based on Poisson cluster modelling for national application at 5-km grid scale (Jones *et al.* 2009). The UKCP09 projections are designed to provide state-of-the-art information on how climate will evolve based upon the best available evidence (Jenkins *et al.* 2009), and they have significant implications for planners and decision makers because a new statutory framework on adaptation will be put in place as a part of a UK government programme (Jenkins *et al.* 2009). Investigation areas are chosen here by selecting multiple 5-km grid squares corresponding to the six catchments in Fig. 1. In the GLM approach, external climate variables are used to modulate long-term variability, and climate variables from the US National Centres for Environmental Prediction (NCEP) reanalysis dataset are used in model fitting as the drivers of the inter-annual variability in the GLM approach. The period from 1961 to 1990 is selected for the study of current climate.

The historical data (used for the development of the Hadley Centre model) of the UKCP09 is based on a 5-km grid observed climate product by Hollis and Perry (2004). The control period is modelled using the Met Office Model HadSM3 which has been extensively examined under a UK national climate change study (Murphy *et al.* 2009). For the future scenarios, the UKCP09 probabilistic projections are given under one of three carbon dioxide emission scenarios defined in the IPCC Special Report on Emission Scenarios (SRES) (Nakicenovic *et al.* 2000). The UKCP09 renamed the emission scenarios as high (A1FI), medium (A1B) and low (B1) emissions (Jenkins *et al.* 2009). As the assumptions for SRES A1B emission scenarios appear to be more robust than those for SRES B1 and A1FI (Murphy *et al.* 2009), they are used here. For the GLM approach, the Hadley Centre HadCM3 GCM A1B climate data (Gordon *et al.* 2000) are used for driving the 2080s GLM rainfall simulations. It should be noted that although both weather generators use the HadCM3 A1B output to drive the weather series generation, they use different climate variables (details are in the following subsections). Moreover, only the A1B scenario is considered in the following sections because the focus of the current paper is the differences between two generators.

The UKCP09 and GLM weather generators both provide daily rainfall series, although drought characteristics are generally considered on a monthly

scale. The generated time series can be relatively easily aggregated for assessing monthly drought. It is admitted that simpler methods may be available for downscaling monthly time series. However, the current approaches allow one to assess the performance of the generator at multiple temporal scales (i.e. both daily and monthly). Further details of the two weather generators are provide in the next two subsections.

2.1 UKCP09 weather generators

The UKCP09 weather generator generates daily rainfall, and hence daily mean and range of temperature, vapour pressure and sunshine duration based on inter-variable relationships (Jones *et al.* 2009). Attention in this paper is focused on the daily rainfall simulations from the generators because the other weather variables depend on daily rainfall as a primary variable and, moreover, most droughts originate from lack of precipitation (Wilhite and Glantz 1985). The rainfall model used in the UKCP09 weather generator is the Neyman-Scott Rectangular Pulses (NSRP) approach (Cowpertwait *et al.* 1996) which is one of a family of point process models. The development, general theory and details of point process rainfall models can be found in, for example, Cox and Isham (1980) and Onof *et al.* (2000). Concerning future projections, the UKCP09 weather generator introduces climate variation by refitting the rainfall model parameters using perturbed moments calculated from regional climate models (Jones *et al.* 2009, Murphy *et al.* 2009). The perturbation methodology for changing climate is based on the calculated change field (α) for a general variable P (i.e. half monthly precipitation means) (Jones *et al.* 2009):

$$\alpha = \frac{P^{\text{GCM Future}}}{P^{\text{GCM Control}}} = \frac{P^{\text{Future}}}{P^{\text{Observation}}} \quad (1)$$

Therefore, the change field (α) derived from the climate model half monthly precipitation means can be used to scale the current observations to the future projection as:

$$P^{\text{Future}} = \alpha P^{\text{Observation}} \quad (2)$$

Although Jones *et al.* (2009) asserted that this model has been shown realistically to reproduce extreme values for impact studies, based on Cowpertwait *et al.* (2002) and Kilsby *et al.* (2007), the model performance for those extremes related to low rainfall, i.e. drought, have not been widely examined.

Cowpertwait *et al.* (2002) noted that a space–time Neyman-Scott model of rainfall will break down or reveal lack of fit at certain temporal or spatial scales and Jones *et al.* (2009) found that their NSRP model could not adequately simulate rainfall which is persistently drier than average for individual seasons, hence the GLM approach is also considered here as an alternative model.

2.2 GLM

Generalized linear models (GLMs) have been widely used to project and downscale climate series (e.g. Yang *et al.* 2005, Furrer and Katz 2007, Kenabatho *et al.* 2008).

Using monthly global or regional climate variables (e.g. GCM outputs, North Atlantic Oscillation Index), a GLM approach proposed by Chandler and Wheeler (2002) based on Stern and Coe (1984) is used here to simulate daily rainfall. The rainfall model is comprised of an occurrence and an amounts model. In the occurrence model, the probability of a wet day is in the form a logistic regression:

$$\ln\left(\frac{P_i}{1-P_i}\right) = \mathbf{x}_i^T \boldsymbol{\beta} \quad (3)$$

where the output of the logistic regression is the probability of rain for the i th day (P_i) which is between 0 and 1; \mathbf{x}_i^T is a transposed predictor vector and $\boldsymbol{\beta}$ is a coefficient vector.

In the amounts model, the expected daily amount of a wet day i th (μ_i) is based on a gamma distribution with a log link function:

$$\ln(\mu_i) = \boldsymbol{\xi}_i^T \boldsymbol{\beta} \quad (4)$$

where $\boldsymbol{\xi}_i^T$ is a transposed predictor vector and $\boldsymbol{\beta}$ is a coefficient vector.

The GLM rainfall model structure used here was developed and tested by Leith (2005). Based on the GLM framework (Chandler and Wheeler 2002), Leith (2005) focused on identifying a model capturing the effect of a changing *global* climate on *local* scale rainfall to simulate realistic and consistent rainfall sequences conditional on atmospheric information for hydrological studies. The model was developed using long rain series at Heathrow, Birmingham and Manchester airports, and it is supposed to be robust and applicable to other sites (Leith 2005). The model predictors are surface sea level pressure, relative humidity and temperature (Leith 2005). Some general

drought characteristics of the simulated rainfall from this model have been studied in Chun *et al.* (2012). Details of the model structure can be found in Chun *et al.* (2009a).

2.3 Monthly statistics

Six rainfall statistics (i.e. daily mean, lag-1 autocorrelation, daily variance, monthly variance, skew and probability dry) for each calendar month are used to evaluate the performance of the two generator simulations in comparison with the observed rainfall characteristics. Although Kilsby *et al.* (2007) and Jones *et al.* (2009) only used daily mean, lag-1 autocorrelation, daily variance, skew and probability dry, Burton *et al.* (2010) considered that monthly variance is important for groundwater applications, and as monthly variance provides some insight into accumulated precipitation deficit (Dracup *et al.* 1980), it is also used here for diagnosis of the characteristics and performance of the simulated rainfall series.

The monthly statistics comparison here is considered to be a stricter assessment of performance diagnostics than previous studies (e.g. Jones *et al.* 2009, Burton *et al.* 2010), which used the same monthly statistics for calibration and validation for the Neyman-Scott rectangular process model.

2.4 DSI

In the UK, droughts are related to long-term rainfall deficiencies, commonly computed from the monthly rainfall series (Shaw 1994). A drought severity index (DSI) proposed by Philips and McGregor (1998) was used to quantify the drought conditions of the six catchments based upon monthly rainfall series. This index has been used in several previous climate change studies (e.g. Fowler and Kilsby 2002, 2004). The start and end points are defined by the difference between the cumulative observations and mean rainfall in an n -month period (the rainfall deficit). In a drought, the n -monthly index (DSI_n) is derived from the rainfall deficit and standardized by dividing the absolute value of deficit by the average annual rainfall at the site. The magnitude of DSI value thus represents the accumulated rainfall deficit (volume below average) as a percentage of mean annual precipitation (Philips and McGregor 1998, Fowler and Kilsby 2004). Further details of the severity index can be found in Philips and McGregor (1998).

3 RESULTS

3.1 Monthly statistics

As there are likely to be some biases between site-specific observations and the UKCP09 baseline output (1961–1990), Jones *et al.* (2009) recommended that users validate the UKCP09 weather generator series before subsequent climate change assessments. Here, the UKCP09 baseline output (1961–1990) is validated using observed data with different record length from the baseline but at least 22 years of data for the six catchments. Figure 2 shows the monthly statistics (i.e. daily mean, lag-1 autocorrelation, daily variance, monthly variance and skew) computed from the UKCP09 and a GLM ensemble of 100 synthetic 30-year time series based on the 1980s climate for the NRFA station 28031 (Manifold at Ilam). Even though the monthly statistics were not used to calibrate the model directly, both generators generally provide simulations with satisfactory monthly statistics which are comparable to the observations and each other.

The results for the monthly statistics are similar across the six catchments, but the degree of stochastic variability and biases vary between catchments. Over the six catchments, the UKCP09 simulated mean daily rainfall is lower than the GLM simulations (Table 1), but they are not significantly different. Although the UKCP09 simulations provide a more precise seasonal pattern (i.e. less stochastic variability) than the GLM simulations for mean daily rainfall, it does not mean that the UKCP09 generators provide more accurate mean rainfall series. For the autocorrelation and skewness, both generators provide similar results, except that, again, the GLM simulations exhibit more stochastic variability. The disparities in skewness between each realization are higher than that of the other rainfall statistics. This reflects the fact that the sampling variability of the moments of a distribution increases with the order of the moment. In practice, this is observed in the sensitivity of the skewness to the occurrence of extreme events (Jones *et al.* 2009). Turning to variance, the difference between the UKCP09 and GLM simulations is more apparent. Both the daily and monthly variances in the GLM simulations are generally higher than the UKCP09 simulations, and the difference increases from daily to monthly time scales.

Figure 3 shows the proportion of dry days defined using different rainfall thresholds. For a threshold of 1 mm, the UKCP09 simulations have a higher proportion of dry days than the GLM simulations, although both ensembles of simulations can represent

the observed values fairly well. This result seems consistent with the fact that the UKCP09 simulations have lower mean rainfall than the GLM. When the threshold decreases from 0.2 to 0 mm, the skill for the UKCP09 simulations in capturing the proportion of dry days seem to decrease, but this threshold variation does not greatly affect the GLM simulations. Although a 1-mm threshold is recommended by the World Meteorological Organization (Tank *et al.* 2009), higher rainfall thresholds may be useful to overcome data inconsistencies, but are also associated with a loss of information about the rainfall process (Yang *et al.* 2005). The UKCP09 simulations seem to provide less information than the GLM simulations when the threshold for defining rainfall events is below 1 mm. The definition and threshold of a dry day need further study.

The simulated monthly-average daily rainfall distributions from two generators, along with observations, are shown in Fig. 4. As the UKCP09 weather generators can only provide stationary series, the particular subset of UKCP09 simulations does not correspond to the observed values. Nevertheless, the UKCP09 simulated distributions provide an indication of how the natural variation of the observed rainfall compares with the UKCP09 distributions. The UKCP09 simulations appear to provide a fair representation of seasonal variations, matching observations. For the GLM approach, the simulated distributions in Fig. 4 can be considered in comparison with the observed values. The reason why the GLM approach can provide non-stationary simulations is that the GLM rainfall model contains global climate variables which modulate the inter-annual variability. As a result, the GLM simulated distribution has more inter-annual variation than that of the UKCP09. The regular pattern of year-to-year variability of the UKCP09 poses an important question concerning the justifiability of the UKCP09 generators in the context of inter-annual variability and persistence.

The frequency (return period) plots for the annual maxima are derived using the generalized extreme value (GEV) distribution, and the flood frequency is estimated using the Weibull plotting-position formula (Shaw 1994). As noted above, the shortest observation record for any of the six catchments is 22 years. As the daily rainfall extremes are not the main focus here, frequency (return period) plots (Fig. 5) are only provided to illustrate that the realizations from two generators can represent daily rainfall extremes quite well. In general, the stochastic variability increases when the return period increases.

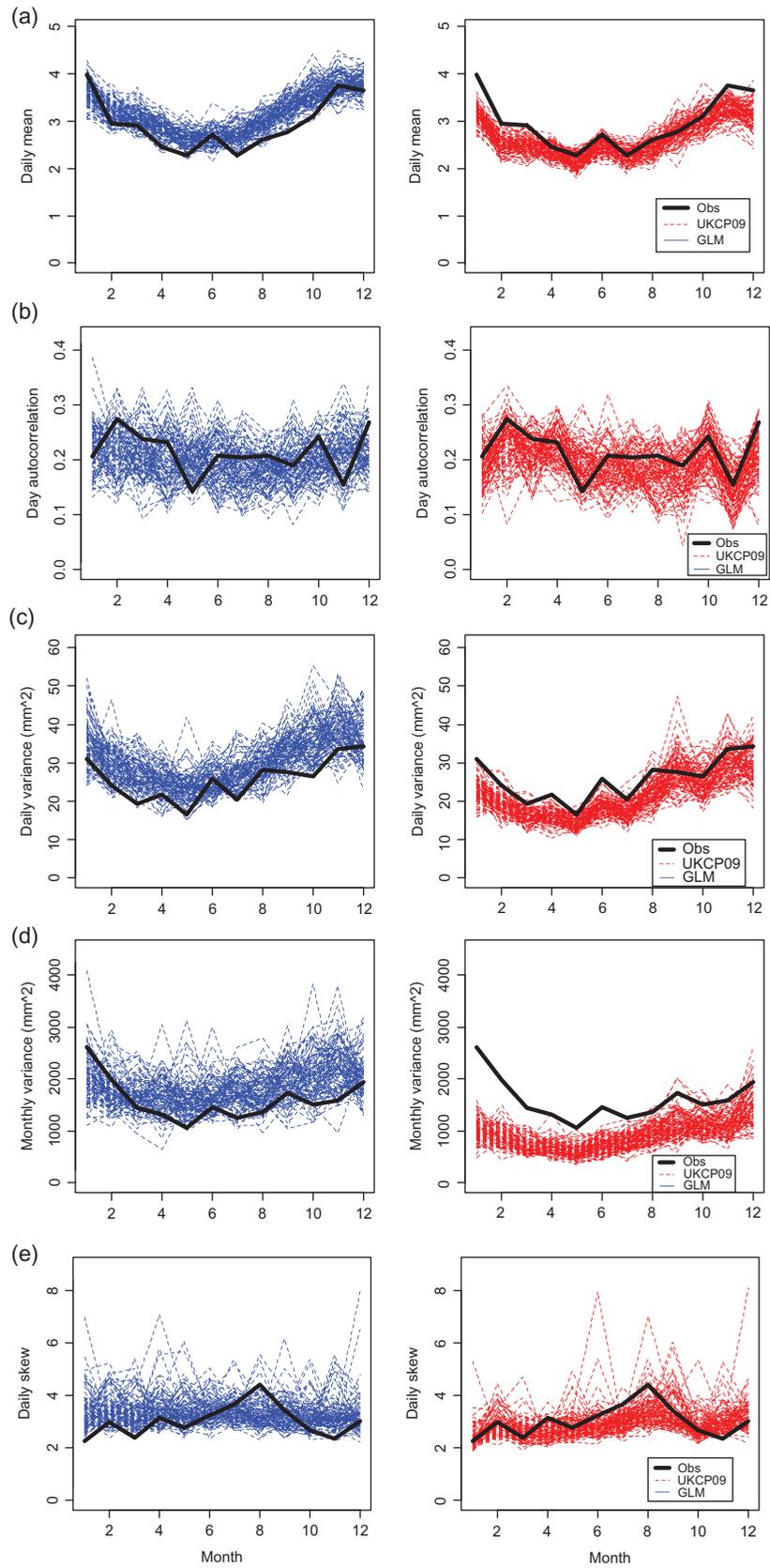


Fig. 2 Monthly statistics for 28031: (a) daily mean; (b) lag-1 autocorrelation; (c) daily variance; (d) monthly variance; and (e) skewness. Left column: GLM results; right column: UKCP09 results.

Table 1 Means of rainfall level for the six study catchments (variances are given in parentheses).

NRFA reference	Observation		UKCP03		GLM	
28031	2.95	(0.57)	2.68	(0.39)	3.18	(0.43)
28066	1.98	(0.20)	2.01	(0.23)	2.13	(0.14)
39022	2.03	(0.36)	2.03	(0.41)	2.20	(0.31)
40007	2.29	(0.49)	2.39	(0.61)	2.43	(0.46)
68005	1.93	(0.24)	1.97	(0.28)	2.07	(0.19)
69008	2.53	(0.47)	2.53	(0.39)	2.72	(0.39)

The UKCP09 weather generators provide simulated extreme distributions having similar stochastic variability to those generated by the GLM approach.

3.2 DSI

Figure 6 shows the observed DSI3 series and simulated DSI3 distributions from the two generators.

The observed DSI3 series of six catchments all indicate that there was a serious drought in the UK during the 1970s. This result is consistent with the dry UK summer in 1976 and, in 1978, the driest autumn since 1752 in South East England (Estrela *et al.* 2001). The DSI series appear to be a good proxy of drought characteristics even though the DSI may be sensitive to mean annual precipitation.

The quality of DSI3 and DSI6 derived from the rainfall simulations of the two generators is assessed by using quantile–quantile (QQ) plots (Fig. 7). The simulated rainfall from both generators corresponds similarly to the observed drought conditions with respect to the cumulative density distribution in the QQ plots, even though the degree and type of bias vary across the catchments and between generators. Comparing the two generated series on the same QQ plots, the relative bias in drought characteristics between two generators can be discerned. Although it is difficult to judge which generator has

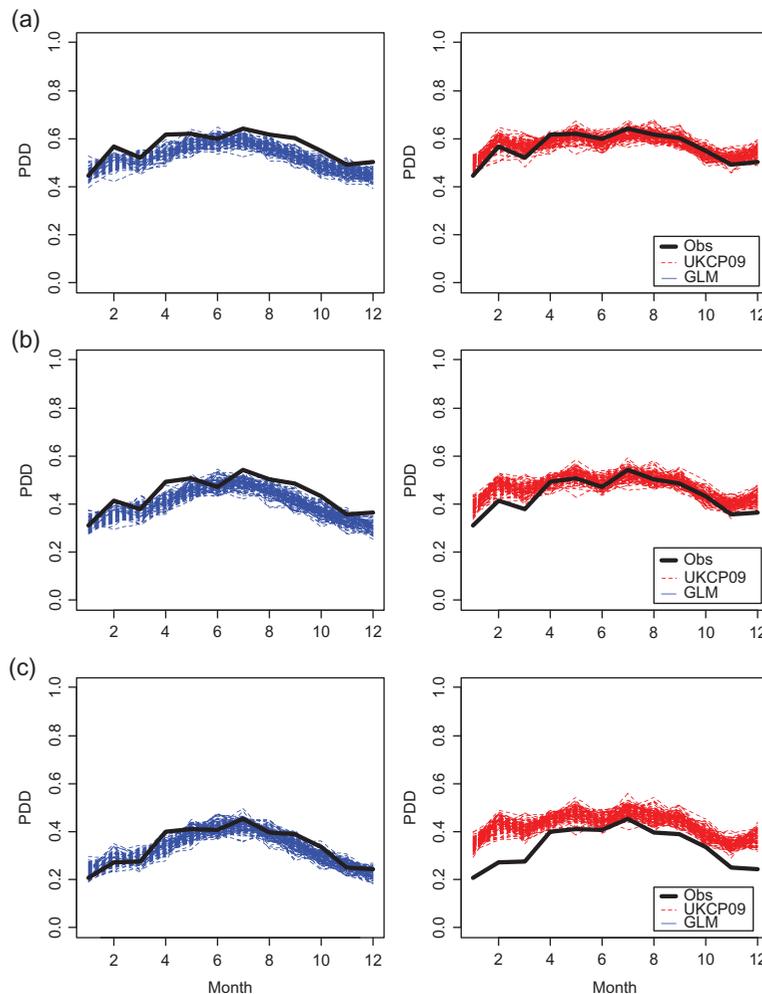


Fig. 3 Proportion of dry days with different threshold for 28031: (a) threshold = 1 mm; (b) threshold = 0.2 mm; and (c) no threshold. Left column: GLM results; right column: UKCP09 results.

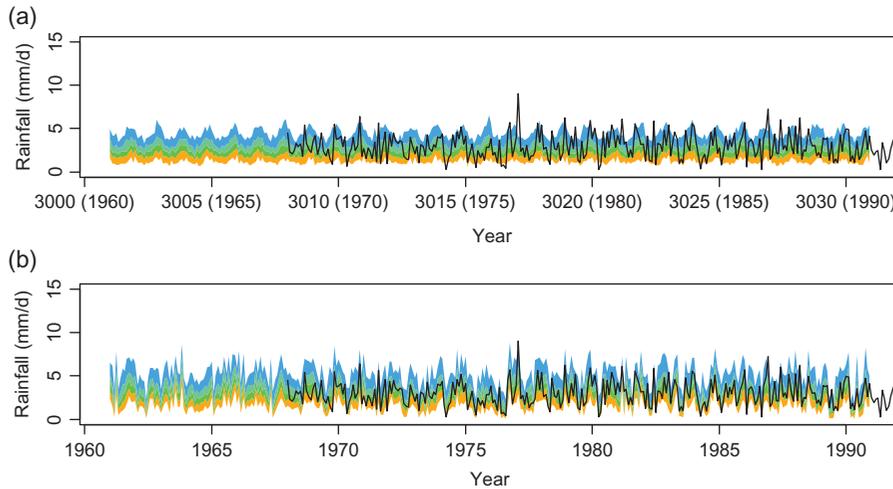


Fig. 4 Rainfall monthly average time series for 28031: (a) UKCP09; and (b) GLM. The bands correspond to the 5th, 10th, 25th, 50th, 75th, 90th and 95th quantiles and the black line shows the observed values.

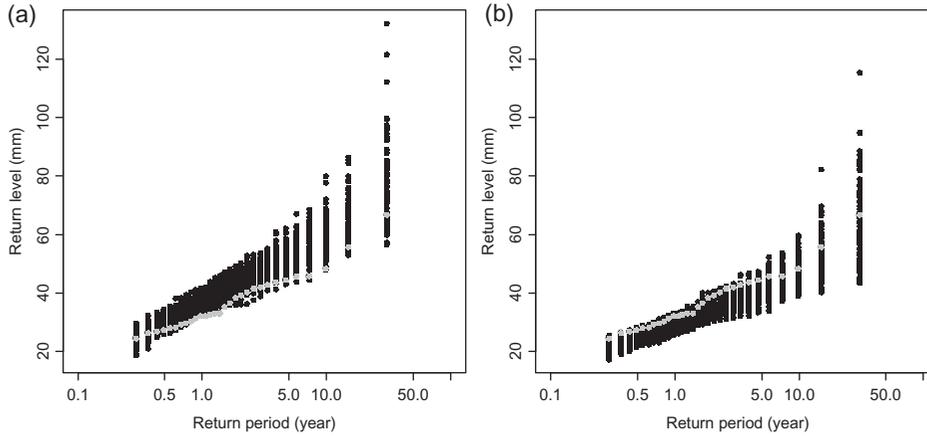


Fig. 5 Rainfall frequency (daily rainfall maxima return level) plots for 28031: (a) GLM; and (b) UKCP09. The grey points are the observation and the black points the ensemble of 100 synthetic 30-year daily rainfall time series.

better performance based on only the QQ plots, the UKCP09 DSI is always lower than the GLM DSI for the corresponding observed DSI3. This result implies that the UKCP09 simulations are more prone to underestimate the DSI3 and the GLM approach is more likely to overestimate the DSI3. Moreover, the result is paradoxical because the GLM simulation has a lower portion of dry days and higher mean daily rainfall than the UKCP simulations but gives higher drought severity. This is because the drought severity does not only depend on the occurrence and amount of rainfall events but also on the event sequence.

As the UKCP09 rainfall does not correspond to particular years in the control period, the simulated DSI3 series from the UKCP09 rainfall (Fig. 6) are also not representative of particular years in the control period. Although most of the

observed DSI3 values lie within the bands of the UKCP09 simulations, the droughts from the middle to the late 1970s are simply not captured by the UKCP09 simulations, regardless of any horizontal translation of the simulated DSI distribution. In contrast, the GLM approach can capture the 1970s DSI peak for all six catchments. Although the stochastic variability of the GLM simulation is higher for some of the period for which the DSI of observations is low, it is not necessarily the case that the GLM simulation overestimates the DSI. For example, Byrant *et al.* (1994) noted that south and east England were subjected to drought conditions in the late 1980s and the early 1990s. Even though the observed DSI3 series in Fig. 6 do not indicate the drought severity was high, the GLM simulated DSI distribution shows that this was indeed likely to have been a drought period. Based on Fig. 6, the GLM

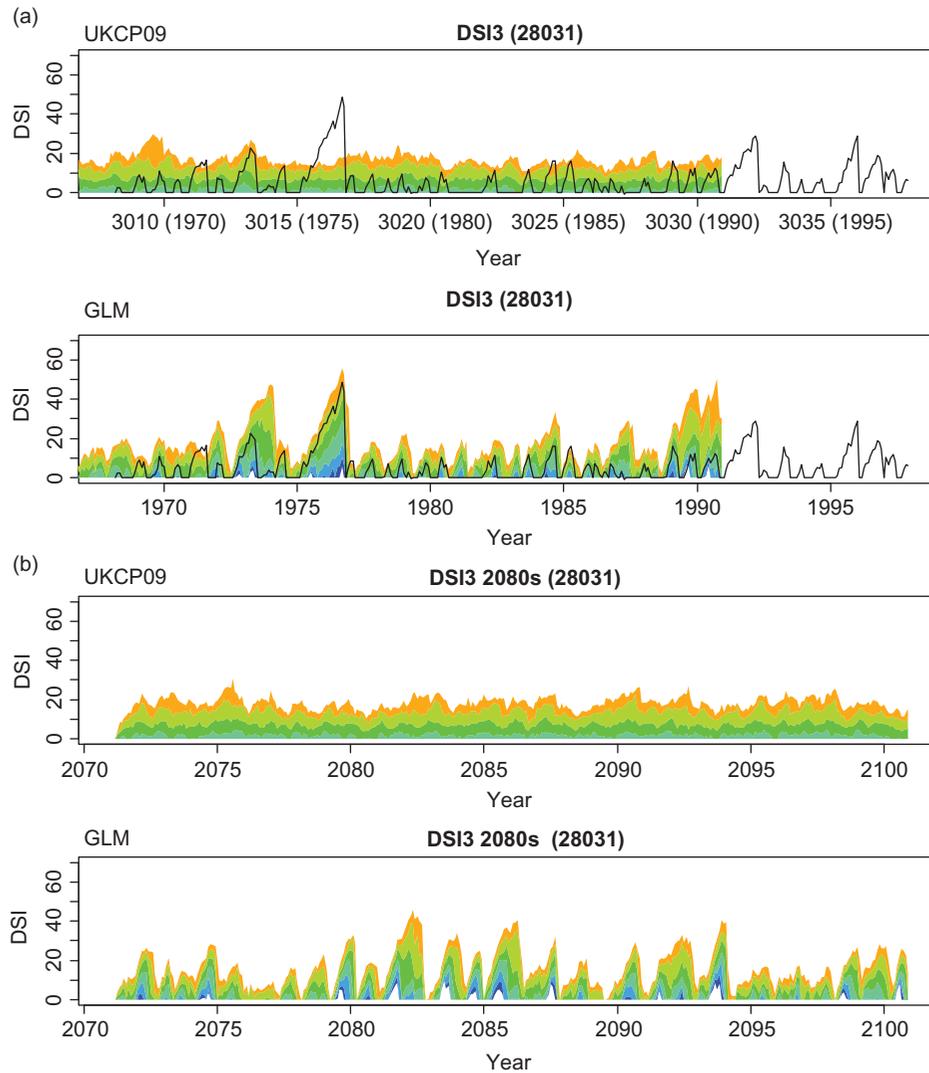


Fig. 6 (a) DSI series control period, and (b) DSI series future period. The bands correspond to the 5th, 10th, 25th, 50th, 75th, 90th and 95th quantiles and the black line shows the observed DSI values for 28031.

approach appears to provide rainfall simulations having adequate persistence characteristics.

The reason for the distinct difference in the simulated DSI3 distributions between the two generators is the difference in the skill of modelling inter-annual variability between two generators. As the UKCP09 simulations are generated from a stationary NSRP model based on moments, the UKCP09 rainfall models can provide adequate results of statistical moments but the stochastic variability of the model is plainly based on the randomness of the simulation of point process. The randomness in the UKCP09 simulations resulting from the internal rainfall process cannot provide realistic representation of the persistence of the observed rainfall series. Conversely, the GLM approach gives adequate results because of external driving climate variables

providing non-stationary climate signals to the rainfall simulations. The above results provide support for the view that the GLM approach is a more adequate model for drought study and cast doubts on the suitability of using the UKCP09 simulations for assessing drought risks in the UK.

Assuming that the rainfall model and the Hadley Centre projections are adequate for the 2080s, the DSI3 series for the 2080s are simulated. For a simulation ensemble (100 30-year simulations), the probability of having a drought more severe than the 1976-drought for the NRFA station 28031 can be estimated by the ratio of the number of realizations larger than the DSI of the 1976-drought to the total number of realizations. In the control period, the 1976-drought is a one in 25-year event. For the 2080s simulation, the 1976-drought would be a one in 66-year event.

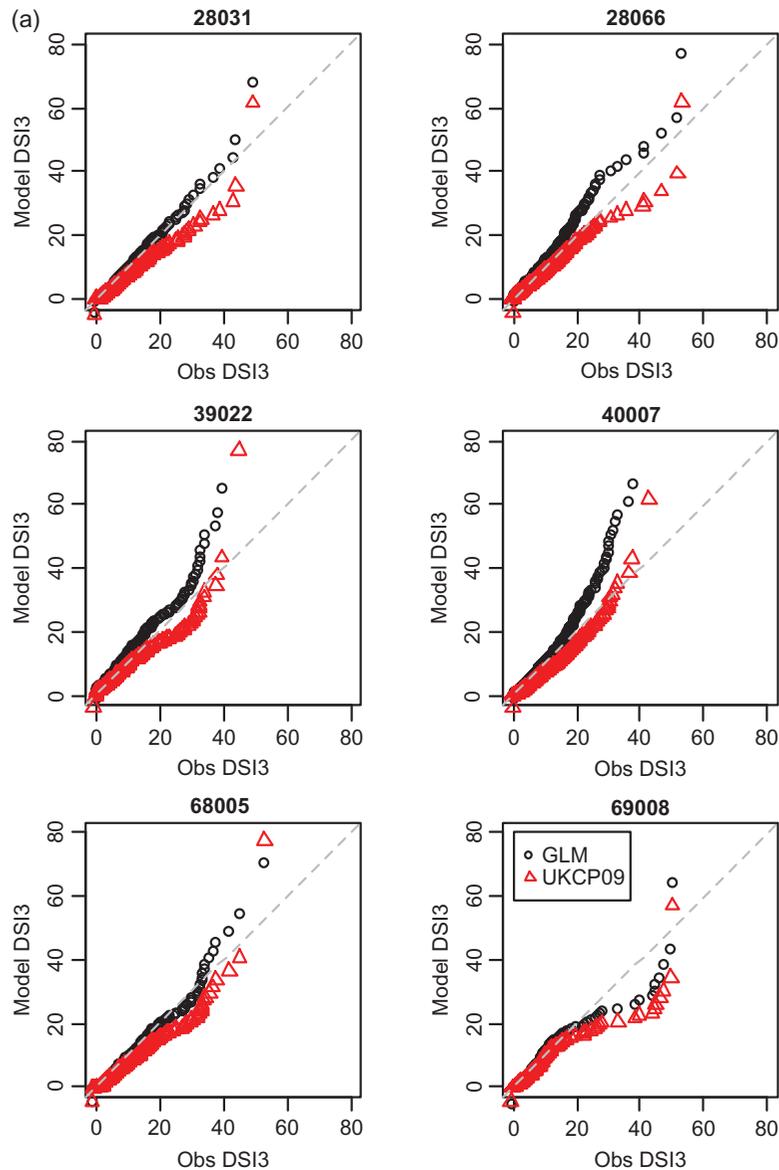


Fig. 7(a) Quantile–quantile (QQ) plots of the drought severity index derived from 3-month rainfall mean (DSI3). Δ : UKCP09 results; \circ : GLM results; grey dashed lines: the 1:1 lines which indicate the observation and model distribution are consistent with each other.

Similar to the control period, the UKCP09 simulations in the 2080s are regular. In information theory, the uniformly distributed quantity (i.e. most regular pattern here) has the highest entropy (Shannon 2001) and the location of the quantity is less certain in the distribution because its mode location is unclear. For the GLM simulations, the simulated DSI3 in the 2080s has higher entropy on average over a 30-year period across the six catchments, which indicates that the 2080s DSI3 generally follows a more regular pattern compared to that of the control period. Despite the fact that the more regular drought pattern may be a simple result of increased uncertainty of the GCM projections, it appears that less inter-decadal

but shorter and less severe drought are anticipated for the 2080s under the assumed scenario, based on the GLM results.

4 DISCUSSION

4.1 Performance comparison

The relative performance of the UKCP09 weather generator and the GLM approach in studying drought is presented. Based on monthly statistics, both generators provide satisfactory rainfall simulations. It is noteworthy that the UKCP09 weather generator can provide adequate rainfall statistics even though

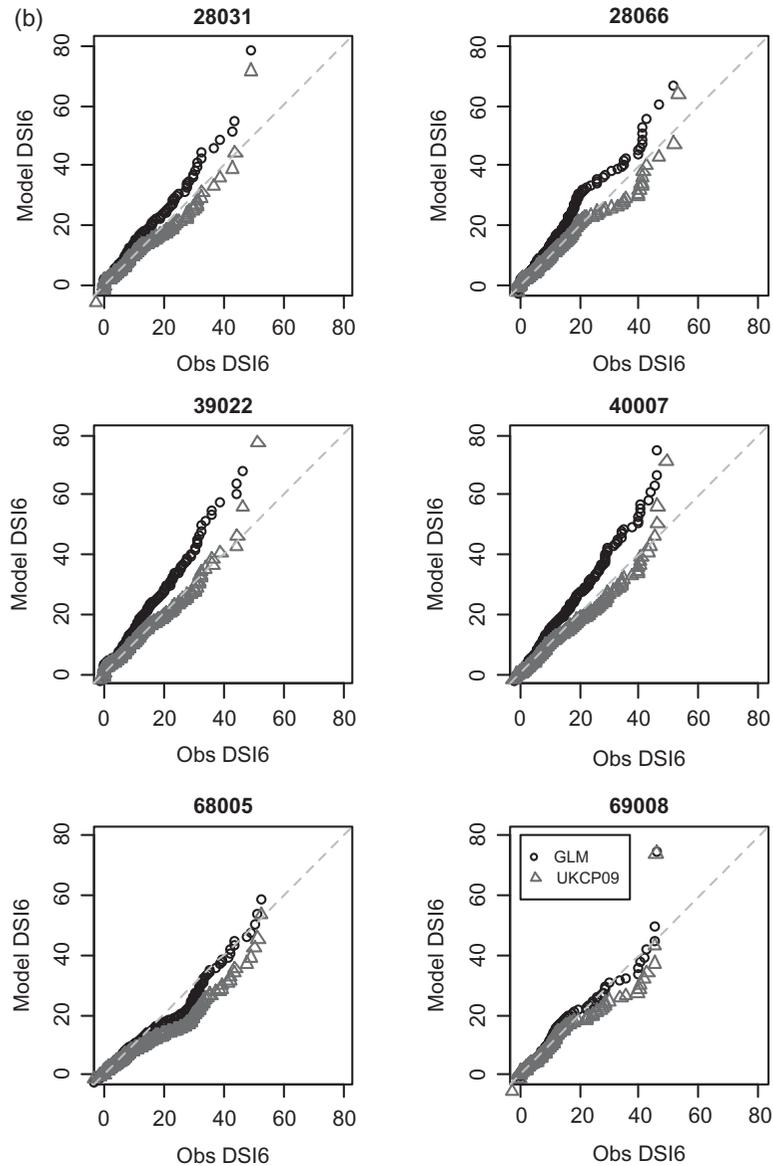


Fig. 7(b) Quantile–quantile (QQ) plots of the drought severity index derived from 6-month rainfall mean (DSI6). See Fig. 7(a) for explanation.

the observed data used here were not used directly for the model fitting. Overall, the UKCP09 simulations provide lower rainfall average and variance than the GLM simulations. Although the UKCP09 simulations give more precise seasonal representation of the autocorrelation and skewness of the rainfall, the inter-annual variance appears to be under-represented as a result. Concerning the proportion of dry days, both generators give satisfactory results when the threshold of dry days is equal to 1 mm. However, when the threshold is set lower than 1 mm, the GLM approach appears to provide a more reasonable representation for low rainfall. As the UKCP09 outputs are grid average values (a raster representation) whereas the

GLM outputs are for particular points, the difference between the two sets of simulations may in part be the result of the different schemes of the two models with respect to spatial and temporal aggregation.

Although the UKCP09 simulations do not correspond to any particular observations in the control period, Fig. 4 shows that UKCP09 simulated rainfall series repeat the seasonal variability routinely whereas the GLM simulations have more inter-annual variation. This difference in inter-annual variation is probably a consequence of the different approaches in including external climate variables. The driving of the external climate variables for the UKCP09 weather generator is through the calibration

of the model parameters using statistical moments (Jones *et al.* 2009). As statistical moments are overall representations of stationary distributions, the NSRP model in the UKCP09 is inherently stationary for a particular period with a set of invariable parameters. On the contrary, the external climate variables are covariates in the GLM approach, and the inter-annual variations of the GLM simulations are driven by the signals of climate covariates. As a result, the GLM simulated rainfall can represent observations in a particular period and have more inter-annual variability than the UKCP09 simulations.

Turning to the simulated drought index, QQ plots (Fig. 7) show that the performance based on the quantiles of the simulated distribution against those of the observations for the two models varies between the catchments. The difference between the two models generally increases along with DSI values on the QQ plots. For the DSI time series plot (Fig. 6), the UKCP09 methodology seems to be unable to provide drought extremes. This result is consistent with the lack of long-term variability in the UKCP09 simulations (Jones *et al.* 2009) as drought not only depends on the average or particular rainfall statistical moments but also on long-term variability. For the GLM approaches, the simulated DSI series correspond with observed values. Overall, the UKCP09 weather generator gives lower averages of simulations and a more precise seasonal pattern, but it does not give better drought prediction. The GLM approach appears to be more suitable for drought assessment, for which long variability is crucial.

For the future projections, the simulated DSI from the UKCP09 weather generator provide limited information for the 2080s drought pattern. The simulations of the GLM approach show that the drought pattern may change (Fig. 6). However, drought change needs to be further quantified. Moreover, the performance of the projected drought pattern depends on the skill of the Hadley Centre projections and the robustness of adopted model structure under climate scenarios. Further comparisons between models which have similar skills in reproducing drought characteristics are needed to provide a better indication of performance based on the consistency of their predictions.

4.2 Limitations of the current generators

Although both the UKCP09 weather generator and the GLM approach can produce rainfall with adequate

monthly statistics, and the GLM simulated rainfall series appear to be adequate for drought assessment using DSI, the current results are only for the single raingauge or lumped catchment rainfall, but not for simultaneous multi-site sequences. Even though spatially correlated time series are not produced from the UKCP09 weather generator (Jones *et al.* 2009), the GLM approach can be used to generate multi-site rainfall (see Yang *et al.* 2005). A further investigation of spatial droughts, similar to that of Lloyd-Hughes (2002), on a catchment scale, would shed much light on the potential of the GLM to provide useful insights into the impact of climate change upon spatially extended droughts.

Regarding the drought projections, only one future period and climate scenarios from a single climate model was considered. In addition, no transient climate changes were investigated. Further studies such as those of Burton *et al.* (2010) are needed for the UKCP09 simulations. For the GLM approach, climate covariates are included to modulate the long-term properties of the series. Therefore, transient climate change from different climate models can easily be included in the GLM approach despite requiring additional work.

As inter-annual variability is identified to be a very crucial driver for the drought pattern, the skills of the GLM approach may improve if external climate variables can provide better inter-annual variability signals. Chandler and Wheeler (2002) found that the North Atlantic Oscillation (NAO) is important for inter-annual variability of the GLM rainfall series. The inclusion of the NAO may improve the skills of the GLM approach to model drought persistence. However, the realism of the simulated NAO from GCMs has always been questioned. For example, Osborn *et al.* (1999) noticed the Hadley Centre climate model overestimates the correspondence between the NAO and sea level pressure over the North Pacific Ocean. Keenlyside *et al.* (2008) noted that North Atlantic Oscillation (NAO) does not correspond well with observations based on ECHAM5/MPI-OM coupled general circulation model (IPCC version). van Oldenborgh *et al.* (2005) comments that some global climate models from the IPCC Fourth Assessment Report do not have adequate inter-annual variability in the tropical Pacific Ocean. As the GLM approach is driven by the GCM external variables, the skills of GLM generated series is limited by the ability of the GCM to provide adequate inter-annual variation.

5 CONCLUSION

Overall, the performance of the two UK weather generators is comparable in terms of monthly statistics. However, for the applications related to inter-annual variability such as drought assessments, the GLM approach may be considered to be better and preferred based on the current result. Despite the fact that some literature (e.g. Jones *et al.* 2009) advocates a consistent set of downscaled information from a particular model, the presented comparison shows that the relative performance of different approaches is a useful alternative for model evaluation. The presented work also shows how the hydrological phenomena of interest determine which particular temporal and spatial scales are important in model selection. Further multi-model comparisons similar to the present study should be embraced.

Acknowledgements The first author was supported by the Grantham Institute for Climate Change Research at Imperial College. Access to the catchment data was provided by A. Young of CEH Wallingford.

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