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Simulation of precipitation by weather pattern and frontal analysis

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Abstract

Daily rainfall from two sites in central and southern England was stratified according to the presence or absence of weather fronts and then cross-tabulated with the prevailing Lamb Weather Type (LWT). A semi-Markov chain model was developed for simulating daily sequences of LWTs from matrices of transition probabilities between weather types for the British Isles 1970–1990. Daily and annual rainfall distributions were then simulated from the prevailing LWTs using historic conditional probabilities for precipitation occurrence and frontal frequencies. When compared with a conventional rainfall generator the frontal model produced improved estimates of the overall size distribution of daily rainfall amounts and in particular the incidence of low-frequency high-magnitude totals. Further research is required to establish the contribution of individual frontal sub-classes to daily rainfall totals and of long-term fluctuations in frontal frequencies to conditional probabilities.

1. Introduction

Atmospheric general circulation models (GCMs) were originally developed to investigate the processes and meteorological interrelationships of the present climate; these dynamical and physically based tools have subsequently been used to predict future climate change resulting from rising levels of 'greenhouse' gases. The hydrologic cycle is of growing relevance to these developments because of the acknowledged sensitivity of water resource systems to climate change (Gleick, 1987), because water vapour and cloud feedbacks are inherent to positive amplifications of CO_2-induced warming (Rind et al., 1992), and because changes in water availability affect vegetation and consequently surface energy fluxes through albedo changes (Henderson-Sellers, 1993). However, from a hydrological perspective the present generation of GCMs is limited by coarse spatial (400 km $\times$ 400 km grid-scale) resolution and parameterisation of terrestrial processes (Hulme and

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Jones, 1989), the omission of surface or groundwater routing mechanisms (Kite et al., 1994), and as a result, poor descriptions of seasonal runoff regimes (Kuhl and Miller, 1992).

Within this context, daily weather type models have been growing in stature as a means of disaggregating GCM predictions of regional atmospheric circulation patterns into catchment scale hydrometeorological variables (McCabe et al., 1989; Hay et al., 1992) thus facilitating the application of more realistic hydrological models (Wilby, 1994a). The technique has been described in detail by Yarnal (1993) and involves statistically relating parameters such as station rainfall records to coincident weather patterns at the synoptic scale. Meteorological examples of this approach include precipitation occurrence in Washington State (Hughes and Guttorp, 1994), space–time modelling of daily rainfall in the Ruhr catchment (Bardossy and Plate, 1992) and eastern Nebraska, USA (Matyasovszky et al., 1993), extreme precipitation and drought conditions in the Delaware River basin (Hay et al., 1991) and estimates of daily pan evaporation rates in southern Louisiana, USA (McCabe and Muller, 1987). Secondary hydrological applications of derived precipitation series include low flow analyses of the River Coln, UK (Wilby et al., 1994), episodic soil loss from the English South Downs (Favis-Mortlock et al., 1991) and surface water acidification in the East Midlands, UK (Wilby, 1993).

Although these studies demonstrate the versatility of the approach and the potential benefits of downscaling GCM output, it is apparent that stochastic weather generators are also constrained in several areas. Wilby (1994b) has highlighted a number of limitations; the non-stationary relationship which exists between historic series of circulation patterns and their corresponding, site-specific meteorological variables is regarded as the most serious. This non-stationarity has major implications for model calibration and the extrapolation of future precipitation patterns because at the centre of weather generator design often lies the assumption that the rainfall statistics of a given circulation pattern are constant and hence transferable in time. The observed inter-decadal variations were tentatively attributed to intra-class factors such as the intensity of circulation development, depression tracks or frontal behaviour associated with a given class of weather pattern. The recognition of such sub-class variability is beyond the scope of most conventional weather classification schemes.

Accordingly, Barnsley et al. (1995) have investigated the extent to which internal variations in the rainfall yield of common weather patterns across the UK and Ireland are determined by frontal type and/or frequencies. The inclusion of frontal information in rainfall models was found to improve predictions of gross annual totals significantly at the macro-scale and to a lesser extent at individual stations (Wilby et al., 1995). However, when the total rainfall data set was subdivided into days with or without the presence of weather fronts, a far clearer pattern of precipitation behaviour emerged. This suggests that stochastic weather generators might realistically be calibrated against data sets which have been segregated not only by circulation pattern but also by frontal and non-frontal induced precipitation. The purpose of this paper is to develop a simulation model for daily rainfall occurrence at sites in the UK based on Lamb's (1972) classification of atmospheric circulation patterns and weather front frequencies. This model represents a refinement of earlier versions described by Wilby et al. (1994), and the performance of several model variants is provided for comparison.

2. Lamb Weather Types and frontal precipitation

The Lamb Weather Type (LWT) scheme (Lamb, 1972) is a subjective classification scheme of daily atmospheric flow across the British Isles since 1861 which has been applied to a wide range of climatological and environmental studies (see El-Kadi and

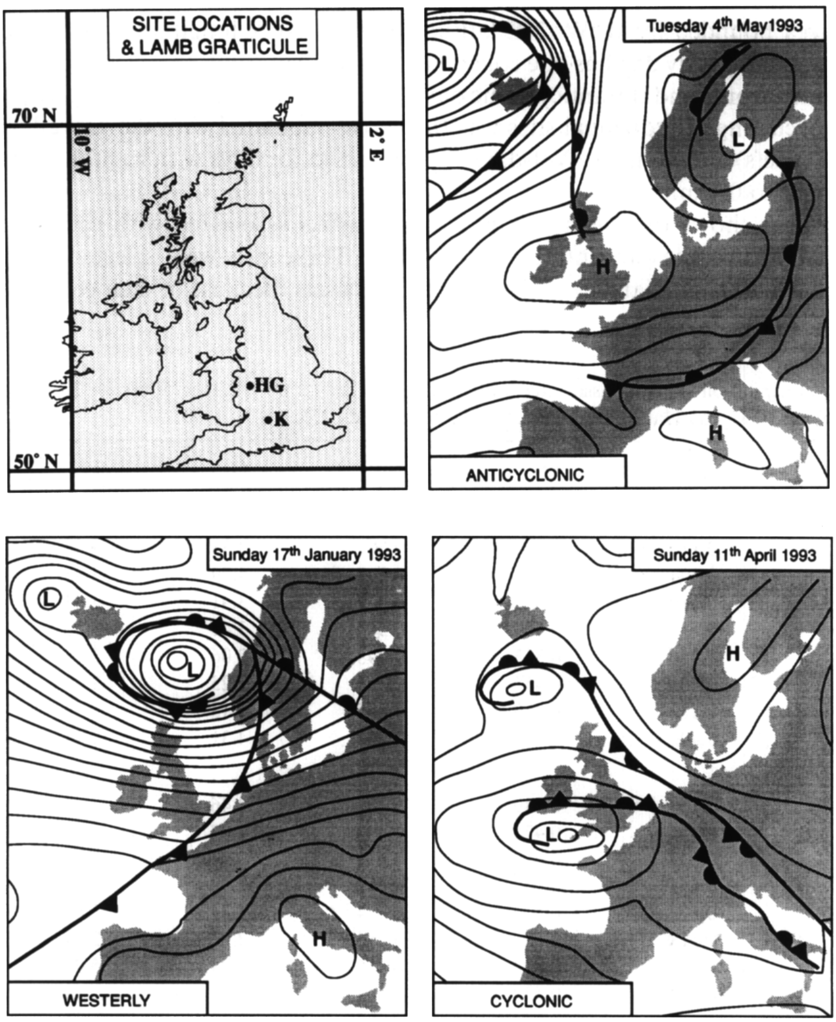


Fig. 1. Site locations (Hatton Grange (HG) and Kempsford (K)) with the area used by the Lamb classification. Example surface pressure patterns associated with the three dominant Lamb Weather Types (anticyclonic, westerly and cyclonic).

Smithson, 1992). Seven main categories of synoptic pattern are recognised: anticyclonic (A), easterly (E), southerly (S), westerly (W), northwesterly (NW), northerly (N) and cyclonic (C). The remaining days (O) are classified into 19 hybrid combinations of the main types. Examples of the three most common LWTs and associated frontal patterns are provided in Fig. 1.

Barnsley et al. (1995) have recorded the number and type (warm, cold and occluded) of fronts occurring by LWT across the British Isles for each day, 1970–1990. Fronts were identified using surface-level weather maps issued by the British Isles Meteorological Office and the German-produced European Meteorological Bulletin. For consistency with the LWT system, only fronts occurring at 12:00 h and within the same graticule as employed by Lamb (1972) were considered (i.e. the area bounded by 10°W–2°E latitude and 50–60°N longitude). For example, in Fig. 1, the westerly day has one cold and one occluded front, the cyclonic day has two occluded fronts and the anticyclonic day has one warm front. Finally, daily precipitation occurring at individual sites was then cross-tabulated with the prevailing LWT, front type(s) and number. Wet-days were assumed for days with rainfall greater than or equal to 0.1 mm.

Table 1 shows the mean precipitation statistics associated with each of the key LWTs for two sites in central–southern UK. These sites were selected on the basis of the length and reliability of their rainfall data sets. Because of their central location

Table 1
Mean precipitation statistics associated with each of the key Lamb Weather Types for Kempsford in the Cotswolds, UK, and Hatton Grange in the West Midlands, UK, 1970–1990

LWT	Gp	Fp	Np	Gr	Fr	Nr
Kempsford						
A	0.110	0.131	0.081	3.33	3.68	2.54
E	0.394	0.468	0.297	4.79	4.85	4.65
S	0.589	0.635	0.377	3.91	3.83	4.51
W	0.555	0.559	0.543	3.41	3.42	3.37
NW	0.356	0.363	0.348	2.06	2.15	1.93
N	0.401	0.455	0.367	2.25	2.73	1.87
C	0.732	0.750	0.667	5.13	5.52	3.57
O	0.405	0.453	0.303	4.31	4.43	3.93
Hatton Grange						
A	0.154	0.189	0.105	2.46	2.58	2.17
E	0.456	0.474	0.432	5.07	6.41	3.13
S	0.639	0.679	0.459	3.94	4.03	3.34
W	0.653	0.650	0.662	2.98	3.09	2.64
NW	0.572	0.570	0.574	1.87	1.80	1.96
N	0.518	0.521	0.516	2.07	2.56	1.75
C	0.809	0.824	0.756	4.74	5.08	3.38
O	0.483	0.539	0.363	3.71	3.94	3.01

Gp, Proportion of days with rainfall; Fp, proportion of days with at least one front and rainfall; Np, proportion of days with no fronts and rainfall; Gr, mean wet-day rainfall (mm); Fr, mean wet-day rainfall (mm) with at least one front; Nr, mean wet-day rainfall (mm) with no fronts.

within the British Isles the sites are also geographically well placed for correlating rainfall with the prevailing LWT, and as such represent 'best case' sites. Regional variations in weather are known to exist in different parts of the British Isles on a single day because of the possibility of several airflow types with any given Lamb circulation pattern (O'Hare and Sweeney, 1992). However, techniques are available for deriving regional airflow patterns associated with the Lamb classes for peripheral localities in the British Isles (e.g. Mayes, 1991).

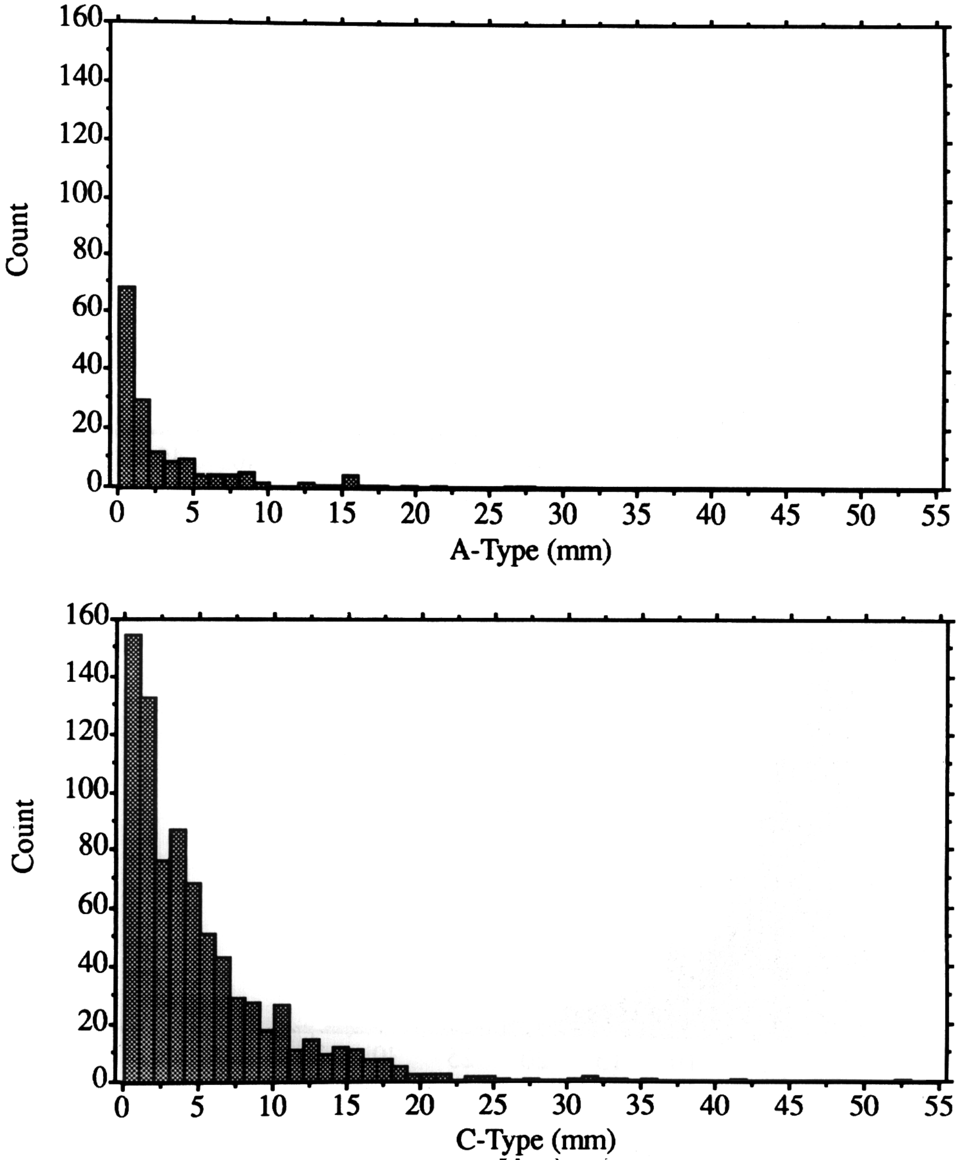


Fig. 2. Comparison of the wet-day rainfall amounts (mm) corresponding to the anticyclonic (A) and cyclonic (C) Lamb Weather Types at Kempsford, Cotswolds, UK, 1970–1990.

It is evident from Table 1 that differences exist both between and within individual LWTs according to whether or not fronts were present. For example, under the E type at Kempsford in the Cotswolds, UK, the overall proportion of days with rainfall was $G_p = 0.394$, but for days with fronts this ratio increased to $F_p = 0.468$ and declined to $N_p = 0.297$ on days with no fronts. Days with fronts also tended to have higher than

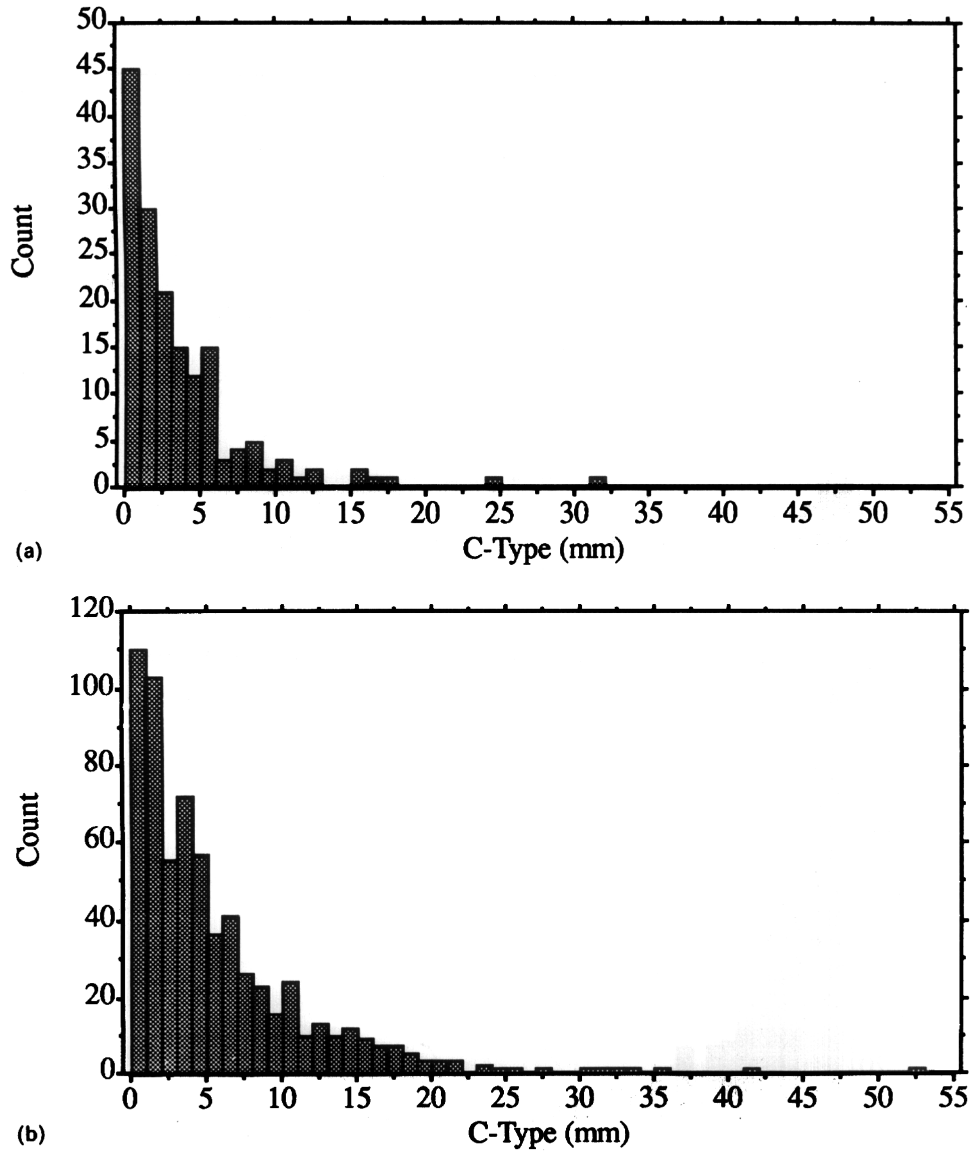


Fig. 3. Comparison of the wet-day rainfall amounts at Kempsford, Cotswolds, UK, 1970–1990, corresponding to the cyclonic Lamb Weather Type on days (a) without fronts, and (b) with at least one front.

average wet-day amounts (G_r). For example, in the case of the C type at Kempsford the mean wet-day amount with no fronts, $N_r = 3.57$ is statistically lower ($p = 0.01$) than on days with fronts $F_r = 5.52$. These trends were also demonstrated by Barnsley et al. (1995) for the British Isles and Ireland, where the A, C, E and S types were all found to be statistically ($p = 0.01$) wetter on days with fronts.

As well as the mean daily rainfall amounts associated with each LWT it is also necessary to consider the respective size distributions. Fig. 2 compares the frequency histograms for the A and C types at Kempsford, which differ significantly ($p < 0.0001$). The lower frequency of A type wet-days and days with moderate to high rainfall amounts (more than 5 mm) is clearly demonstrated. As Fig. 3 indicates, statistically significant differences also exist between days with or without fronts for individual LWTs such as the C, A, E and S types ($p < 0.01$). Furthermore, the Kruskal–Wallis test suggests that for the C type the frequency of weather fronts also determines the resultant daily rainfall distribution ($p < 0.05$). Although a general relationship between mean daily precipitation and frontal frequency was identified for other key LWTs (Barnsley et al., 1995), the trend was less clear for days with relatively large numbers of fronts owing to the limited sample sizes.

As Table 2 shows, the prevailing LWT also conditions the probability distribution function of the number of fronts per day. For example, the S and C types have the lowest frequency of days with zero fronts (18.1% and 21.9% of days, respectively). In contrast, the N type has no fronts on more than 60% of days, with no more than a maximum of three occurring on a single day. Up to a maximum of six fronts were found to occur on C type days.

These data show that the likelihood of precipitation and the size distributions of wet-day amounts differ not only between key LWTs, such as the C and A types, but also for their respective frontal and non-frontal rainfall populations. The information contained in Tables 1 and 2 forms the basis of the two-tiered stochastic frontal model described below.

Table 2
The proportion of days with 0–6 weather fronts by Lamb Weather Type, 1970–1990

LWT	Number of fronts per day						
	0	1	2	3	4	5	6
A	0.417	0.438	0.121	0.022	0.002	0	0
E	0.431	0.405	0.131	0.029	0.004	0	0
S	0.181	0.426	0.263	0.115	0.015	0	0
W	0.246	0.435	0.205	0.111	0.004	0	0
NW	0.422	0.350	0.177	0.045	0.006	0	0
N	0.608	0.304	0.071	0.016	0	0	0
C	0.219	0.428	0.175	0.146	0.030	0.001	0.001
O	0.318	0.422	0.177	0.071	0.010	0.002	0

3. The models

The generation of daily precipitation from weather pattern and frontal series involves four distinct stages. The model must determine: (1) the prevailing circulation pattern; (2) the number of weather fronts; (3) the corresponding likelihood of rainfall; (4) the aggregate daily rainfall total.

3.1. The daily weather generator

Sequences of daily LWTs were generated using the discrete Markov process described by Wilby et al. (1994). A finite set of states (P) corresponding to the A, E, S, W, NW, N, C and O types is defined. At an initial time, state i_0 is entered and the next state is determined using a transition matrix $\boldsymbol{M}$ consisting of transition probabilities m_{ij} where i and j are in the set of P. The transition probabilities have values such that

$$0 \leqslant m_{ij} \leqslant 1 \qquad (1)$$

Table 3
Lamb Weather Type transformation matrices for (a) 1970–1990 and (b) the total Lamb Catalogue 1861–1992

	Probability (Following Day)							
	A	E	S	W	NW	N	C	O
(a) 1970–1990								
A	0.551	0.015	0.033	0.039	0.017	0.014	0.024	0.308
E	0.014	0.460	0.011	0.000	0.000	0.011	0.079	0.335
S	0.032	0.009	0.342	0.086	0.000	0.000	0.167	0.365
W	0.046	0.000	0.015	0.459	0.072	0.005	0.116	0.288
NW	0.074	0.000	0.000	0.190	0.307	0.119	0.074	0.236
N	0.178	0.003	0.000	0.034	0.113	0.307	0.058	0.307
C	0.038	0.015	0.023	0.094	0.031	0.056	0.453	0.289
O	0.177	0.041	0.051	0.123	0.025	0.035	0.131	0.418
(b) 1861–1992								
A	0.527	0.017	0.032	0.066	0.015	0.014	0.015	0.314
E	0.094	0.426	0.012	0.000	0.000	0.018	0.071	0.379
S	0.028	0.007	0.323	0.086	0.000	0.000	0.139	0.416
W	0.044	0.000	0.016	0.501	0.051	0.012	0.097	0.278
NW	0.091	0.000	0.001	0.208	0.248	0.128	0.055	0.268
N	0.169	0.005	0.000	0.056	0.084	0.302	0.044	0.340
C	0.031	0.023	0.023	0.119	0.027	0.065	0.415	0.295
O	0.169	0.039	0.048	0.147	0.026	0.040	0.126	0.405

A, Anticyclonic; E, easterly; S, southerly; W, westerly; NW, north westerly; N, northerly; C, cyclonic; O other weather types.

for all i and j

$$\sum_{i=1}^{n} m_{ij} = 1 \tag{2}$$

where n is the number of states and $j = 1$. On each successive daily time-step t

$$i_t = j_{t-1} \tag{3}$$

Unlike the models of Bardossy and Plate (1991) and Hay et al. (1992) transitions from a state to itself without a visit to another state is possible. This obviates the need for the calculation and/or estimation of the sojourn time distribution. Only the transition probabilities m_{ij} need be extracted from the Lamb catalogue for the period corresponding to the available precipitation record, in this case, 1970–1990 (Table 3). The transition matrices may be derived on a monthly basis to accommodate seasonal variations in the predominance and persistence of each of the main LWTs. Previous results obtained from this type of weather generator (e.g. Wilby et al., 1994) have shown that the model successfully captures both the frequency and persistence of individual weather patterns.

3.2. Number of weather fronts

Having generated the prevailing LWT the model next determines the number of weather fronts. For each state i_t there exists a cumulative probability function which describes the number of fronts F on any one given day. The actual value for F is determined from a linear random number generator which maps values between zero and +1.0 onto the probability function shown in Table 2.

3.3. Precipitation occurrence

The likelihood of precipitation is a function of the number of weather fronts generated in Section 3.2. For example, if the prevailing LWT is the C type and $F > 0$ then the probability of rainfall at Kempsford is $F_p = 0.750$ and $F_p = 0.824$ at Hatton Grange (Table 1). Conversely, if the prevailing LWT is the A type and $F = 0$ then the respective probabilities of rainfall at the two sites is $N_p = 0.081$ and $N_p = 0.105$. Clearly, these probabilities are site specific and must be obtained from the available rainfall record by matching wet-days (0.1 mm day^{-1} or more) against frontal and non-frontal LWT states.

It should be noted that for days with $F > 0$ the probability of rainfall was defined for the entire day rather than for each weather front. Although the latter option would be a more realistic representation of precipitation processes, it presupposes the existence of high-resolution rainfall and frontal passage data. Although sub-hourly rainfall data are available, the present diurnal recording of fronts across the British Isles is far too coarse to correlate with the contribution of individual storm events.

3.4. Precipitation amount

If a wet-day arises, both frontal and non-frontal rainfall amounts are modelled as an exponential distribution function. When compared with the log-normal and gamma distributions, the exponential function was found to provide a better description of the wet-day amounts for six out of the eight LWTs (Wilby, 1994b).

Three methods of generating the daily rainfall amount are considered, namely, non-frontal, arithmetic and multiplicative. The first does not incorporate frontal series so the likelihood of rainfall (G_p) and wet-day amounts (G_r) are simply generated from the corresponding gross rainfall statistics in Table 1 avoiding Step 2 (above). The arithmetic and multiplicative models utilise frontal frequencies derived from Table 2 in the estimation of the daily rainfall total.

3.4.1. Non-frontal model

Daily precipitation amounts R were modelled using the product of the gross wet-day rainfall amount G_r associated with the prevailing LWT state i_t and the natural logarithm of a uniformly distributed random number r $(0 \leqslant r \leqslant 1)$:

$$R = G_r(i_t)\ln(r) \tag{4}$$

3.4.2. Arithmetic model

Daily precipitation amounts R were simulated using a two-state model. For days with zero weather fronts ($F = 0$), R equals the product of the non-frontal wet-day rainfall amount N_r associated with the prevailing LWT state i_t and the natural logarithm of a uniformly distributed random number r $(0 \leqslant r \leqslant 1)$:

$$\text{if } F = 0 \text{ then } R = N_r(i_t)\ln(r) \tag{5}$$

For days with ($F > 0$) weather fronts the precipitation yield of each front R_f equals the product of the mean frontal rainfall amount F_r associated with the prevailing LWT and the natural logarithm of a uniformly distributed random number r $(0 \leqslant r \leqslant 1)$:

$$\text{if } F > 0 \text{ then} R_f = F_r(i_t)\ln(r) \tag{6}$$

The total wet-day rainfall amount R is the sum of each frontal yield R_f:

$$R = \sum_{f=1}^{F} R_f \tag{7}$$

3.4.3. Multiplicative model

Once again, daily precipitation amounts R were simulated using a two-state model. For days with zero weather fronts ($F = 0$), R is calculated using Eq. (2). For days with ($F > 0$) weather fronts the total wet-day rainfall amount R equals the product of the mean frontal rainfall amount F_r associated with the prevailing LWT state i_t, the natural logarithm of a uniformly distributed random number r $(0 \leqslant r \leqslant 1)$ and the number of fronts F:

$$\text{if } F > 0 \text{ then} R = F_r(i_t)\ln(r)(F) \tag{8}$$

4. Model application

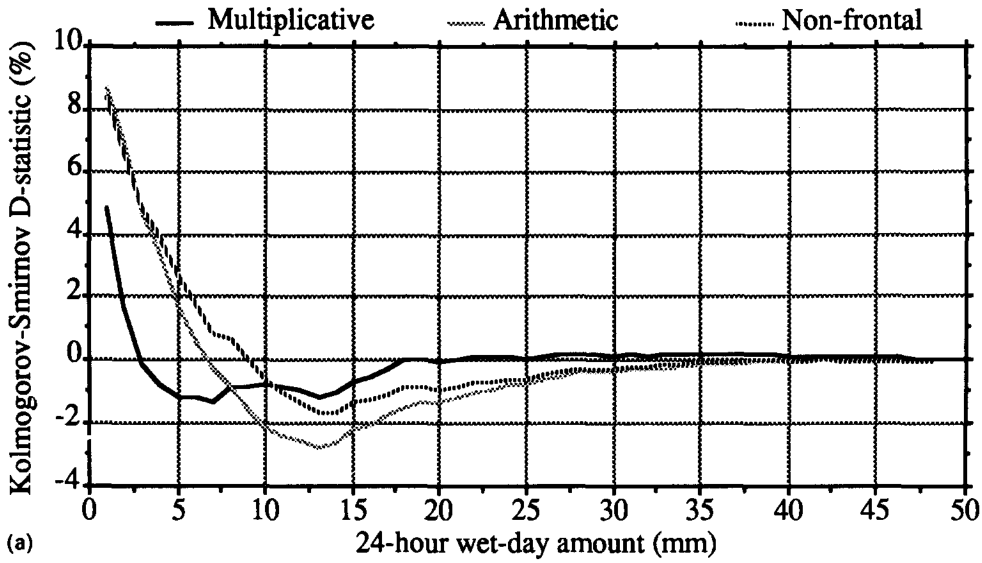
The precipitation models were calibrated using three data sets: (1) daily precipitation data for two sites in central and southern England (Table 1); (2) Barnsley et al. (1995) daily record of fronts across the British Isles, 1970–1990 (Table 2); (3) the Lamb Weather Type daily catalogue, 1970–1990 (Table 3). These data were used to compile the respective Tables 1–3. Each model was used to generate daily sequences of LWTs, frontal frequencies, rainfall occurrences and amounts for a 210 year simulation (i.e. ten times the calibration period). The following statistics were then extracted from the model output: (1) the mean wet-day rainfall amount; (2) the proportion of wet-days; (3) the variance of wet-day rainfall amounts; (4) the size distribution of wet-day amounts; (5) annual rainfall totals. These results were then compared between models and against the observed rainfall data at Kempsford and Hatton Grange, 1970–1990.

5. Results

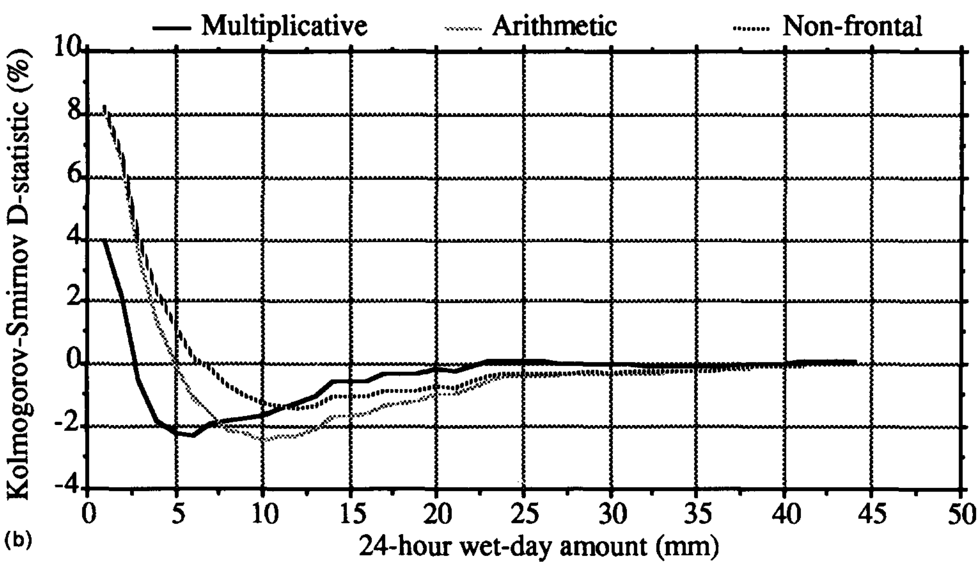
Table 4 compares the model performances against the observed data using criteria (1)–(3) (above). The differences between the observed vs. simulated wet-day rainfall characteristics are statistically insignificant ($p < 0.05$) for both sites, suggesting that all three models adequately describe the mean rainfall regimes of each locality. However, there is a tendency for the multiplicative and arithmetic (i.e. the frontal) models to underestimate the mean wet-day amount. This slight deficiency was attributed to missing data in the frontal record: between 1970 and 1990 approximately 2% of days were unavailable (Barnsley et al., 1995). The majority of these

Table 4
Comparison of model performance with 1970–1990 observed data

Model	Years	Mean wet-day (mm)	Proportion wet-day	Variance (mm^2)
Kempsford				
Non-frontal	210	4.1	0.42	18.6
Multiplicative	210	4.0	0.42	25.7
Arithmetic	210	3.9	0.42	15.1
Observed	21	4.1	0.42	25.3
Hatton Grange				
Non-frontal	210	3.6	0.50	15.1
Multiplicative	210	3.5	0.50	19.7
Arithmetic	210	3.5	0.50	12.7
Observed	21	3.6	0.50	21.3



(a)



(b)

Fig. 4. A comparison of simulated and observed frequencies of wet-day amounts using the Kolmogorov–Smirnov D statistic: (a) Kempsford; (b) Hatton Grange, 1970–1990. (The D statistic shows the percentage difference between the cumulative frequencies of the observed and simulated 24 h wet-day size distributions.)

days were in the winter months, which are known to be wetter on average at both sites.

The principal difference between the models arises in the simulation of the variance of daily rainfall amounts. Both the non-frontal and arithmetic models significantly underestimate the observed statistic. The underestimation of the variance in daily precipitation by the exponential distribution has been documented elsewhere (Wilby, 1994b). Hay et al. (1991) advocated the use of a random 'error term' to increase the variance around the mean. This term was the product of a uniformly distributed random variable between -1 and 1 and an exponential random variable. This term is approximated by the multiplicative frontal model, as the number of fronts in Eq. (8) is effectively drawn from an exponential distribution (see Table 2) by a uniformly distributed random variable.

The improved variance estimate by the multiplicative model is evident in the simulations of the daily rainfall size distributions. Fig. 4 shows the computed Kolmogorov–Smirnov D statistic by site and model type for 1 mm increments in the cumulative percentage of rainfall event frequencies. In all cases, the maximum difference between sets of observed and simulated cumulative percentage frequencies was less than D_{crit} (i.e. the difference that could have occurred by chance). The null hypothesis of 'no difference' cannot in any case be rejected ($p < 0.01$), indicating that all models reproduced the overall size distribution of the observed rainfall at both sites. However, the D statistic revealed that the non-frontal model overestimated the proportion of wet-days less than 6–9 mm at the expense of events more than 10 mm. A similar pattern was present in the size distribution of the arithmetic model. Overall both the non-frontal and arithmetic models yielded greater D statistics than the multiplicative model. At each location the multiplicative model slightly

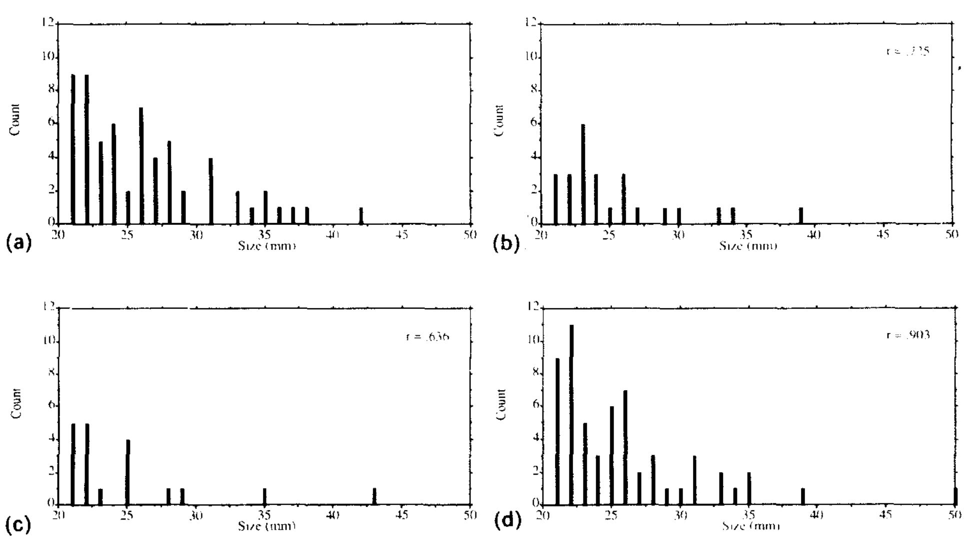


Fig. 5. Comparison of the frequency distributions of large (more than 20 mm) daily rainfall amounts at Kempsford, 1970–1990: (a) observed; (b) non-frontal model; (c) arithmetic model; (d) multiplicative model.

overestimated the frequency of events less than 3 mm but was highly successful at simulating larger events (over 20 mm). The correlation coefficients for the non-frontal, arithmetic and multiplicative models vs. the observed size distribution were respectively $r = 0.967$, $r = 0.958$ and $r = 0.983$ (all correlations were statistically significant at $p = 0.0001$).

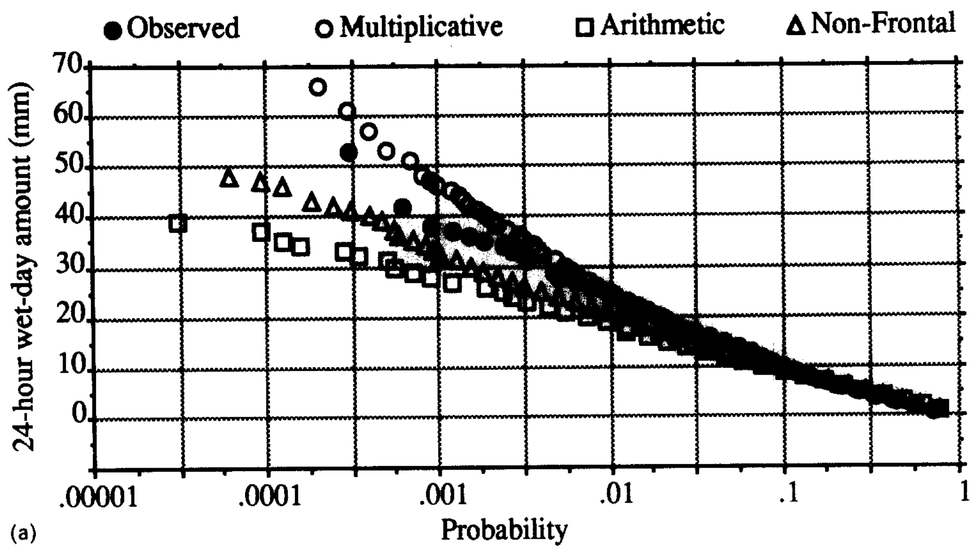
Fig. 5 compares the observed and simulated frequency distributions of daily rainfall amounts exceeding 20 mm day^{-1}. The largest observed amount (not shown) for Kempsford between 1970 and 1990 was 53 mm. The largest amounts simulated by the non-frontal and arithmetic models for the sample-run shown in Fig. 5 were 39 mm and 43 mm, respectively. By contrast, the multiplicative model reproduced the highest magnitude days with two events exceeding 50 mm. The former models also underestimated the observed total number of days with rainfall more than 20 mm. The corresponding figures were: observed (63 days); non-frontal (25); arithmetic (19); multiplicative (60). Thus the multiplicative model provided the best estimate of the largest wet-day amounts, maximum daily totals and, as the correlation coefficients indicate in Fig. 5, the overall size distribution.

The occurrence of extreme rainfall events was further investigated by comparing the observed and simulated probabilities of exceedence. Fig. 6 shows the probability of a given 24 h wet-day amount by location and model type. The probabilities of occurrence are in broad agreement for events less than 10 mm; however, for rarer events there are increasing discrepancies between the observed and simulated series. Both the arithmetic and non-frontal models consistently underestimate extreme events whereas the multiplicative model overestimates the magnitude-frequency of events more than 30 mm at Kempsford and more than 40 mm at Hatton Grange.

The models' ability to reproduce extreme dry periods is equally important, and was evaluated by comparing the maximum observed vs. simulated dry-spell duration at Hatton Grange, where the daily rainfall record is 100% complete. Between 1970 and 1990 this site experienced six spells of zero rainfall exceeding 20 days duration with a maximum 'drought' length of 25 days. None of the models reproduced a dry spell exceeding 20 days duration. The corresponding maximum dry spells were 20 days (multiplicative and arithmetic) and 18 days (non-frontal). These results confirm the difficulty of obtaining dry- or wet-spell persistence from stochastic models, and points to the need for further parameters to simulate this aspect of extreme behaviour (see Wilby, 1994b).

6. Discussion and conclusions

A semi-Markov chain model was developed for simulating daily Lamb Weather Types for the British Isles, 1970–1990. Daily rainfall from two sites in central and southern England were stratified according to the presence or absence of weather fronts and then cross-tabulated with the prevailing LWT. The resultant conditional probabilities were used to simulate daily and annual rainfall distributions at each site. Two methods of rainfall generation from frontal frequencies were presented. The first (arithmetic) aggregated the rainfall contributions of successive fronts to produce a daily rainfall total. The second (multiplicative) calculated the total from the product of the rainfall amount of one front with the number of rain-bearing fronts in any given day. To establish the value of incorporating a frontal sub-model in the rainfall generation process, the results were compared with a standard weather simulator previously described by Wilby et al. (1994).



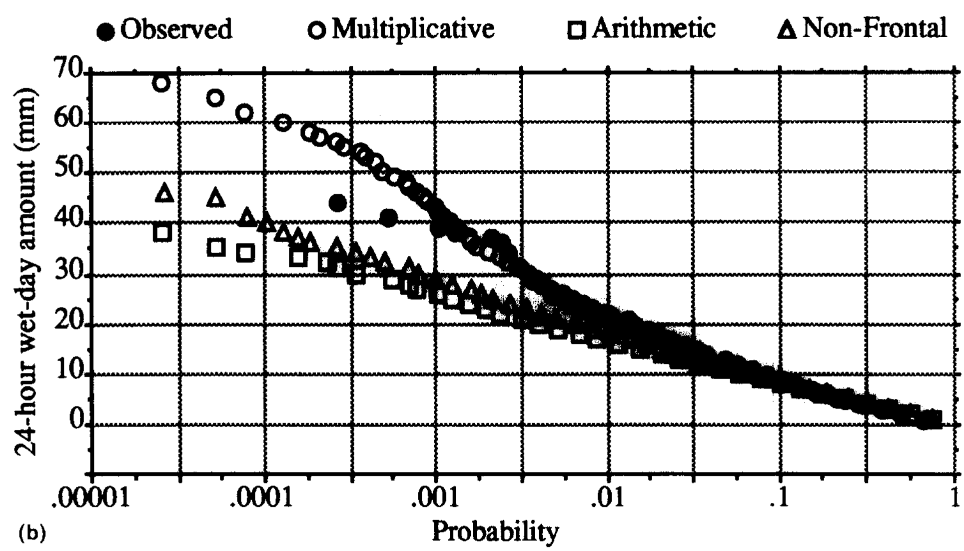


Fig. 6. Comparison of observed and simulated probabilities of 24 h wet-day amount exceedence at (a) Kempsford and (b) Hatton Grange, 1970–1990.

Relative to the non-frontal approach, the multiplicative front model was found to improve simulations of the observed variance in daily precipitation amounts and the overall size distribution of 24 h rainfall totals. However, the arithmetic frontal model was shown to be inferior to the standard, non-frontal model, indicating that the way in which the frontal information is used in the model is critical to its performance. This apparent ambiguity was attributed to the actual computational procedure used to generate rainfall amounts in each of the frontal models. For example, the probability of an A type with two fronts at Kempsford producing rainfall $R = 33.9$ mm ($16.95 \times$ number of fronts) is $p = 0.01$, whereas for the arithmetic model, $p = 0.01$ yields 16.95 mm for the first front only. To produce an event $R = 33.9$ mm requires two fronts of this magnitude and hence $p = 0.01 \times 0.01$ or $p = 0.0001$.

Therefore, preliminary analyses have been undertaken using an alternative form of the arithmetic model which uses the LWT to condition the number of fronts (F) on any given day (as before) and thence the the actual probability/amount of rainfall derived from separate distributions of total wet-day amounts obtained from days with F fronts. This model variant does not aggregate the contribution made by individual fronts per se and thereby circumvents the above inconsistency. Initial results obtained for both Kempsford and Hatton Grange suggest that with this modification the arithmetic model surpasses the standard model as a means of simulating the observed variance and extreme (wet-day) events but is still inferior to the multiplicative model. Further research is required to confirm these interim results.

However, it is acknowledged that the frontal model has greater data requirements for model calibration than conventional weather generators. Furthermore, the conditional probabilities for the frontal frequencies presented in Table 2 apply only to the British Isles for the period 1970–1990. Research is currently in progress to develop an objective classification procedure for the identification and description of weather fronts across this region. The present system does not incorporate indicators of the three-dimensional frontal structure, rate of passage, or proximity to the rainfall-recording station, all of which may affect the timing, likelihood and volume of precipitation at any given site. Given the scale of the meteorological patterns involved, area-averaged rainfall would also be expected to yield a clearer signal of the frontal-forcing than the point rainfall statistics used herein.

Thus, the frontal model offers considerable scope for downscaling mesoscale GCM output. Just as daily sub-grid scale rainfall data cannot be adequately represented by the present generation of high-resolution GCMs, neither can the same spatially averaged data represent linear features such as weather fronts. However, it has been demonstrated that daily frontal frequencies, rainfall probabilities and amounts are all conditioned by mesoscale atmospheric circulation patterns. Provided that the control and perturbed simulations of GCMs yield realistic frequencies of daily airflow types (see Hulme et al., 1993) it is possible to determine the number of fronts and subsequently the associated rainfall amounts for the calibration site(s) or region(s). The technique is also able to distinguish between sub-grid scale precipitation that is of stratiform ($F > 0$) and convective ($F = 0$) origin.

Further research is required to establish the extent to which daily circulation patterns condition not only the number of fronts, the probability of a wet-day and daily rainfall amount, but also the relative frequency of frontal sub-classes. For example, Table 5 indicates that for the A type the occluded front occurs only 8.1% of the time compared with 41.3% for the C type. This type of front was shown by Barnsley et al. (1995) to generate the highest mean daily totals across the UK and Ireland. Therefore, inter-annual and inter-decadal fluctuations in the frequency of the frontal categories could have a significant bearing on the conditional rainfall probabilities used to calibrate stochastic weather generators. Such issues can only be truly addressed by relating individual storm events to the passage of specific frontal classes; daily frontal type frequencies and rainfall totals are simply too coarse a resolution to isolate the contribution made by individual fronts.

Future refinements to the existing frontal models should focus on the following issues:

(1) greater attention should be paid to the representation of wet- or dry-spell durations, particularly extreme persistence in either state. The current deficiency is attributed to the fact that wet-days are generated independently of one another when in reality autocorrelation is known to exist between dry- to dry- and wet- to wet-day transitions.

(2) A comprehensive evaluation of alternative probability distribution functions for modelling wet-day amounts should be undertaken. The present models assume an exponential distribution for both frontal and non-frontal rainfall amounts;

Table 5
Frequency of warm, cold and occluded weather fronts by Lamb Weather Type, 1970–1990; the figures in parentheses show the relative proportion of frontal type

LWT	Warm	Cold	Occluded	Total
A	515	511	90	1116
	(46.1)	(45.8)	(8.1)	
E	62	51	98	211
	(29.4)	(24.2)	(46.4)	
S	164	182	113	459
	(35.7)	(39.7)	(24.6)	
W	482	609	203	1294
	(37.2)	(47.1)	(15.7)	
NW	113	138	37	288
	(39.2)	(47.9)	(12.9)	
N	48	80	25	153
	(31.3)	(52.3)	(16.4)	
C	403	487	625	1515
	(26.6)	(32.1)	(41.3)	
O	978	1064	610	2652
	(36.9)	(40.1)	(23.0)	
Total	2765	3122	1801	7688
	(36.0)	(40.6)	(23.4)	

distributions such as gamma or Weibull may be more appropriate for extreme event simulations.

(3) Previous studies (e.g. Wilby et al., 1994) have identified the importance of modelling seasonal variations in rainfall probabilities and amounts for hydrological applications. Therefore, the possibility of developing a frontal model which incorporates seasonality in the conditional rainfall statistics should be explored.

(4) The models described above have been calibrated against rainfall distributions derived for seven non-hybrid LWT classes (plus one miscellaneous category), sub-divided by the presence or absence of fronts. The statistical integrity and distinctiveness of each rainfall set might be increased by collapsing the existing data into fewer, more physically meaningful categories.

(5) The present study has focused on the simulation of daily precipitation in liquid form. For many hydrological uses, such as the estimation of flood magnitude, the occurrence of extreme rainfall in conjunction with or following extreme snowfall may be of greater significance.

Despite the enhanced data requirements, the fact remains that the use of a frontal sub-model to increase the simulated variance in daily precipitation is conceptually more realistic than the use of an 'error' term as in Hay et al. (1991). The ability accurately to downscale extreme precipitation events from GCM output is clearly of benefit to numerous hydrological concerns, including flood generation, river-water quality variations and rates of soil erosion. The modelling of frontal frequencies may also provide a means of simulating the internal variability evident within the long-term rainfall series of individual circulation classes (Wilby, 1994b).

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