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The problem of "naturally"-occurring drought

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Abstract. Naturally-occurring drought is defined here to be drought arising from the nonlinear interactions which are an inherent part of the dynamics of the climatic system. As such it has no specific excitation mechanism, in contrast to forced drought where sea surface temperature anomalies are frequently cited as an important precursor. The essential difference between these two types of drought is that the former is very local and isolated spatially, whereas the latter is widespread and coherent. Observations for Australia are used to illustrate these points. Results are given for a 10-year general circulation model integration which clearly simulated naturally occurring drought and highlighted its unique characteristics. Multi-annual time series for specific geographical regions in the model show that no differences in monthly mean values of relative humidity or zonal and meridional fluxes of moisture were apparent for years with or without drought. More detailed analysis indicated that rather small differences exist in atmospheric temperatures and absolute humidities between drought and non-drought years which are important factors in determining the onset of precipitation in the model.

Overall the analysis emphasises the subtlety of the processes involved. These processes, however, were able to produce completely different precipitation histories from one year to the next at a given point. The smallness of the changes involved in the atmospheric processes indicates that the nonlinearities were able to modulate conditions at a given point within an existing synoptic system only slightly, rather than initiate a new climatic regime in drought years. The problem of naturally-occurring drought, of course, is that it is intrinsically unpredictable.

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1 Introduction

Despite the widespread nature and frequent occurrence of drought, very few precursors of drought have been positively identified. Undoubtedly, the most commonly nominated precursor is variability in sea surface temperature. For example, drought in northeast Brazil has been shown to be correlated with sea surface temperature changes in the Atlantic Ocean (Markham and McLain 1977), droughts in Australia have been identified with low sea surface temperatures around that continent (Streten 1981), and droughts in the Sahel have been associated with worldwide sea surface temperature anomalies (Folland et al. 1986). Modelling studies of these three situations by Moura and Shukla (1981), Voice and Hunt (1984) and Folland et al. (1986), respectively, confirm, at least in part, the basic cause-and-effect chain. Other instances of the potential precursor role of sea surface temperature anomalies in drought exist, and it would seem that such anomalies are widely associated with many drought situations. In contrast, droughts in the high plains of the U.S.A. have been tentatively linked with both the double sunspot cycle and the lunar nodal period (Currie 1984), although the mechanistic link in both cases remains obscure. The possibility that overgrazing may have accentuated the recent recurring droughts in the Sahel has been suggested by Charney (1975). Undoubtedly other precursors of drought will be identified as future research is undertaken on this important subject.

All of the above droughts can be termed "external" or "forced" in that a change in a driving mechanism of the atmosphere is presumed to be involved. The possibility also exists that another class of droughts, termed here "naturally"-occurring, may constitute part of the atmosphere's basic climatic variability. Such droughts were identified in a 10-year model simulation by Gordon and Hunt (1987) as ones for which no external forcing exists. Specifically, their model had no sea surface temperature anomalies, as the seasonally varying sea surface temperatures were interpolated from climatology at monthly intervals, and were identical for each year of the simulation. Although their model computed its own cloud distribution, sea ice amount and snow cover, which varied seasonally, these were considered to be internally generated model variables. Gordon and Hunt concluded that the nonlinearities of the model atmosphere were sufficient to produce the droughts they identified. Importantly, these droughts differ from forced droughts in that they are spatially rather limited, as might be expected in the absence of a defined forcing mechanism.

Because of the central importance of the role of nonlinear mechanisms in the concept of naturally-occurring drought, the manner in which these mechanisms can influence climate will be discussed briefly. Essentially the differential equations used in the model, even with all physical "source and sink" terms removed, when integrated forward in time reproduce a non-constant, but bounded, temporal behaviour. This results from the quadratic (nonlinear) terms in these equations, and the fact that the solutions of these equations are intrinsically unstable to small amplitude disturbances (Lorenz 1976). Probably the most powerful demonstration of the fascinating range of behaviours associated with nonlinearities is provided by the simple recurrence relation of Lorenz (1976). In addition to the basic nonlinear nature of the governing equations, the Earth's climatic system has geographically and temporally varying forcing functions, such as convection, snow-cover, etc., which can also act as climatic perturbers. Thus in a multi-annual model integration slight variations in, say, wind velocity and temperature which occur from year-to-year at specific points, thereby alter the local atmospheric fluxes of heat and their divergences. These fluxes are, of course, nonlinear terms. The resulting changes to the temperatures then influence the winds via the thermal wind equation, causing further perturbation to the local heat fluxes, hence the initial disturbance propagates. This is only one example of how nonlinearities can influence the internal dynamics of the climatic system. Since some atmospheric properties, such as cloud formation and convection, appear to have threshold requirements for their activity, the ability of the system to meet these requirements may alter simply because of the variations induced by nonlinear flux terms. Thus, in principle, quite marked local climatic fluctuations can occur from the combination of simple processes such as identified here. Further discussion of the role of nonlinearities, together with examples of their impact on atmospheric variability, can be obtained from Chervin (1986).

This paper will examine in more detail some of the aspects of naturally-occurring drought as represented in the simulation of Gordon and Hunt (1987). The aim is to examine the climatological differences between drought and nondrought situations at a given location, to determine if these differences are common to all locations experiencing this type of drought, and to try to understand how these droughts break. The reality of naturally-occurring drought in nature will also be demonstrated.

2 Naturally occurring drought in Australia

Figure 1 shows the distribution of drought-afflicted or rainfall-deficient areas in Australia for selected periods between 1983 and 1985. The small size of most of the areas, their lack of spatial coherency and the relatively short timespans suggest that these droughts are not the result of a substantial external forcing mechanism. Rather they qualify as examples of naturally-occurring drought. The drought area on the northeastern coast of Australia in Fig. 1 had disappeared by July 1984, and all of the remaining areas by December 1985. The difference between such droughts and an externally-forced drought is dramatically demonstrated by the drought pattern associated with the 1982 El Niño event shown in Fig. 2. The severity of this drought is amply apparent, as is its spatial coherency. The contrast between Figs. 1 and 2 illustrates the importance of an external forcing mechanism in the dynamics of drought. During 1982 the sea surface temperature anomalies in the tropical Pacific Ocean were the largest on record, while in 1984/85 they were small ($\sim 0.5-1.0$ K) and spatially variable.

If naturally-occurring drought is attributable to nonlinear mechanisms, then one characteristic of such drought would be the lack of temporal and spatial coherence in regions where such mechanisms are effective. Observed rainfall variations which support this viewpoint are given by the time series of annual total rainfall for three districts in eastern Australia in Fig. 3. Also indi-

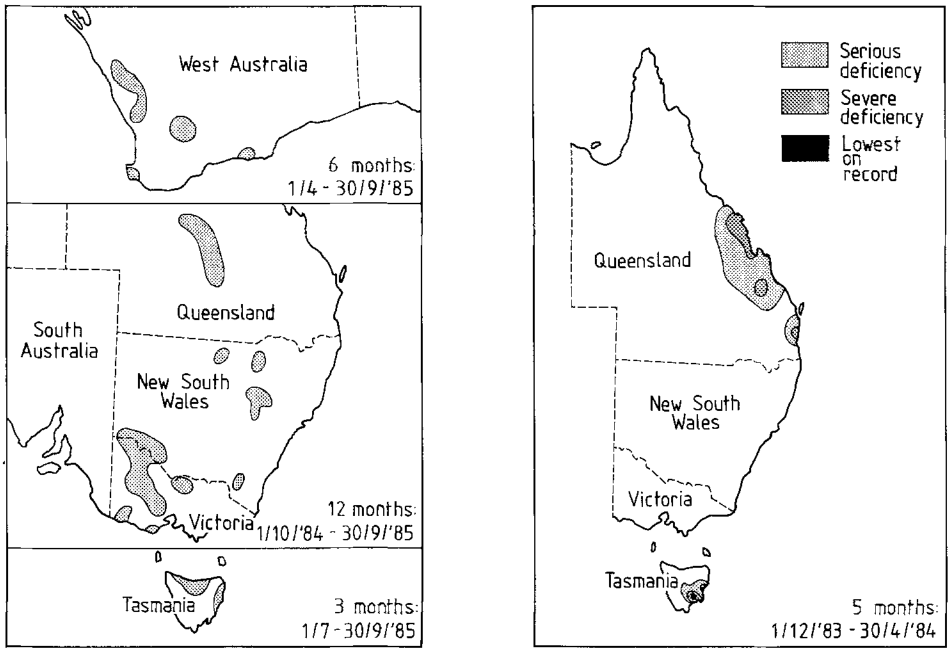

Fig. 1. Examples of regions in Australia affected by localised droughts, tentatively identified as naturally — occurring drought. The dates on the figure identify the timespans of the droughts. The three levels of *shading* refer to precipitation anomalies as defined by the Australian Bureau of Meteorology. Lowest on record is self-explanatory. Serious deficiency identifies regions where the precipitation for a period of at least three consecutive months ranks in the lowest 5% of the historical observations for that period. Severe deficiency is defined similarly except that the 5% ranking is replaced by 10%

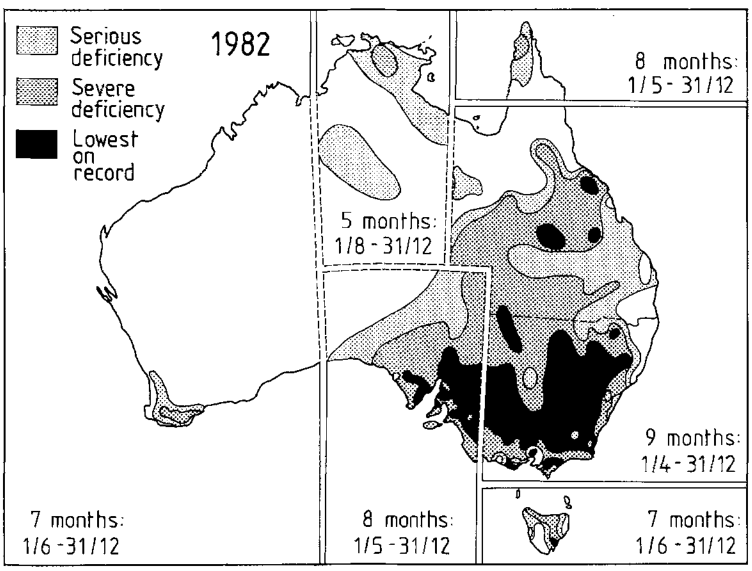

Fig. 2. The widespread very severe drought in Australia associated with the 1982 El Niño event. See *Fig. 1* for definitions of the *shading* used in the figure

cated are the years with El Niño events. It is clear from the figure that each El Niño occurrence is associated with a coherent response from the three rainfall districts. These droughts are examples of externally-forced events. Interestingly, coherent drought responses also occurred in 1951 and 1967 (Fig. 3) although no El Niño events were recorded. This suggests that more than one external forcing mechanism exists which is capable of initiating large-scale droughts in eastern Australia. A broader perspective of the overall precipitation changes can be obtained from Fig. 7 of Streten (1981) where Australian-wide precipitation variations are shown for 1951—1969.

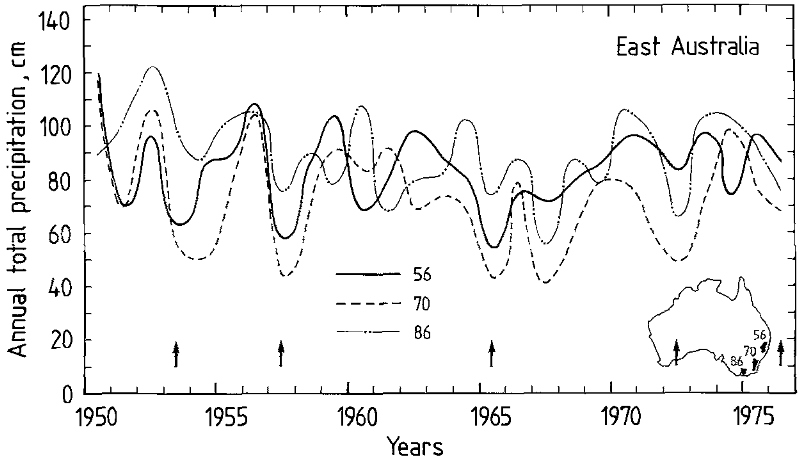

Fig. 3. Time series of annual total precipitation for rainfall districts 56, 70 and 86 in eastern Australia. These districts are identified in the map of Australia inset in the figure. The *vertical arrows* indicate when El Niño events occurred

However, it is the exceptions to the coherent responses in Fig. 3 which are of interest. For example, in 1960 district 56 suffered a moderately severe drought, while district 70 was hardly affected and 86 had a wet year. In 1962 district 70 had a minor drought while the nearby district 56 had a wet year. Again in 1964 while districts 56 and 70 were already experiencing the start of the El Niño-induced drought of 1965, district 86 had a wet year. Finally, in 1974 district 56 had a minor drought while the reverse situation prevailed in the other two districts.

3 Model description

Basic details of the model and its multi-annual simulation have been given in a companion paper (Gordon and Hunt 1987), hence only a minimal description will be given here. The model had two vertical levels, 21 spectral wavenumbers to represent horizontal structures, land-sea contrast, smoothed orography and climatologically defined sea surface temperatures. A seasonally-varying solar cycle was permitted, with the appropriate sea surface temperatures being interpolated daily from the climatological values stored at monthly intervals. Atmospheric moisture was carried only at the lower model level, soil hydrology was incorporated by the elementary bucket method, snow, rainfall and cloud cover were predicted, as was sea ice. The model was run in the nondiurnal mode.

In view of the emphasis on drought in this study the precipitation mechanisms in the model will, however, be discussed in somewhat more detail. Precipitation can be produced by three methods in this model. The first involves the so-called large-scale precipitation mechanism, which requires the minimum relative humidity in the lower model level to exceed 95%. The excess moisture is then precipitated out with the release of latent heat. The remaining two methods produce precipitation from either mid-level or penetrative convection respectively. In the convection scheme sequential tests are made to determine whether mid-level, low-level or penetrative convection can occur, depending on whether an excess of moist static energy exists between appropriate vertical levels in the model. The three types of convection are mutually exclusive. The amount of precipitation produced is proportional to the energy excess at the level considered. As illustrated in Fig. 13, whether or not convection occurs can depend on quite small temperature differences in the model atmosphere.

Given the nature of the results to be presented it is appropriate to enquire if they are model dependent, especially since the current model is restricted to two levels. In general, climatic simulations are model specific in varying degrees, depending on the precise characteristics being compared. This point is amply illustrated by the review of CO_2-induced climatic changes in general circulation models documented by Schlesinger and Mitchell (1987). However, the differences between the model results tend to be in the details, with overall trends being similar. Within any given model it would be expected that similar detailed variations would occur as physical parameterizations were varied. In the present experiment, where convection plays an important role in certain regions, the results could depend on the particular convective formulation used, although comparison with observation suggests that the model behaviour is not unreasonable. Thus the use of an alternative convection scheme, which had somewhat different characteristics, might result in an overall deterioration in the model's performance. Regarding interannual variability, the current two-level model appears to be as capable of simulating gross climatic characteristics (Gordon and Hunt 1987) as models with higher resolution (see, for example, Lau 1981, Hansen et al. 1984 and Chervin 1986). Also experiments with a similar two-level model by Esbensen (1984) involving sea-surface temperature anomalies, and by Qiu and Esbensen (1984) concerned with teleconnection patterns, provide encouraging evidence that such major climatological features can be simulated adequately with this type of model.

A 12-year integration was performed with the first two years of data being discarded as an adjustment period.

4 Some climatological characteristics of naturally-occurring drought

Four semi-arid regions were selected for illustrative purposes, comprising south central U.S.A., Morocco and Algeria, Somalia, and northwest Australia as identified in Fig. 4. In contrast to Gordon and Hunt (1987), where only single points in various geographical regions were considered, the presentation here embraces several adjacent points in a given region so that a clearer indication of the spatial as well as temporal variability can be obtained. Soil moisture is again selected as a convenient measure of drought-like conditions, being more relevant to agriculture than precipitation alone.

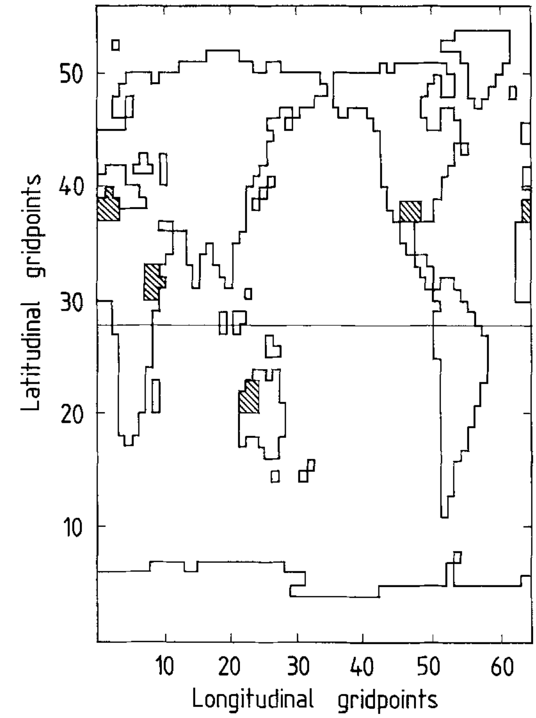

Fig. 4. Identification of the four regions for which results are shown in *Figs. 5—8*. The horizontal resolution of the model can be gauged from the grid pattern identifying the land-sea boundaries

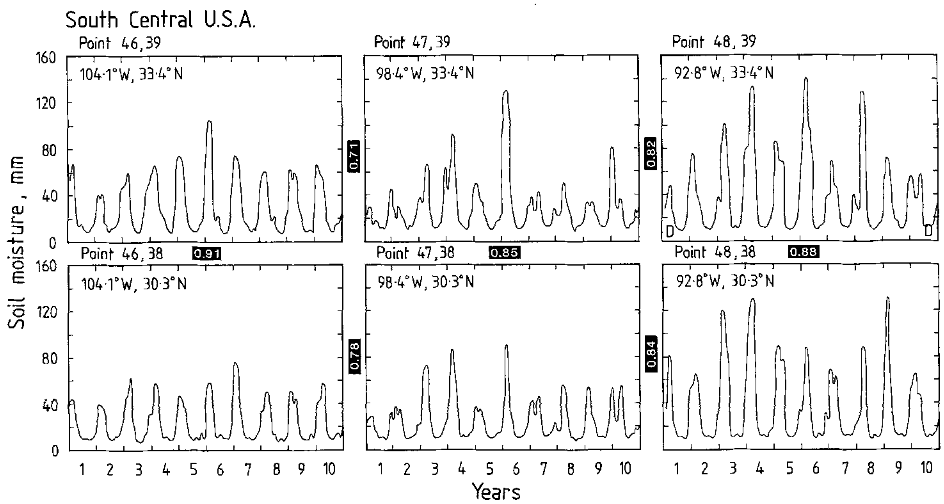

Fig. 5. 10-year time series of monthly mean soil moisture for south central USA illustrating the interannual variability at a given gridpoint and the spatial variability between adjacent gridpoints. The *numbers* on the individual panels refer to the longitudinal and latitudinal references of a particular gridpoint. See *Fig. 4* to identify these gridpoints in the model's global framework. The latitudes and longitudes of the gridpoints are given in the individual panels. The *highlighted numbers* indicate the correlation coefficient of soil moisture variability between adjacent points. *D* in the figure identifies where drought, as defined in the text, occurs

The 10-year model-generated time series for the soil moisture variations in the four selected regions are shown in Figs. 5—8. The overwhelming impression from a detailed study of these figures is the uniqueness of the behaviour in each region. None of the regions have two adjacent points where there is a consistent temporal correlation for the whole of the 10-year period. Nevertheless, substantial correlations exist between adjacent points as indicated on the figures. Given the scale size of typical atmospheric systems, such coherence is to be expected, subject to the inevitable interannual variability of these systems. The lack of internal consistency in a given region suggests

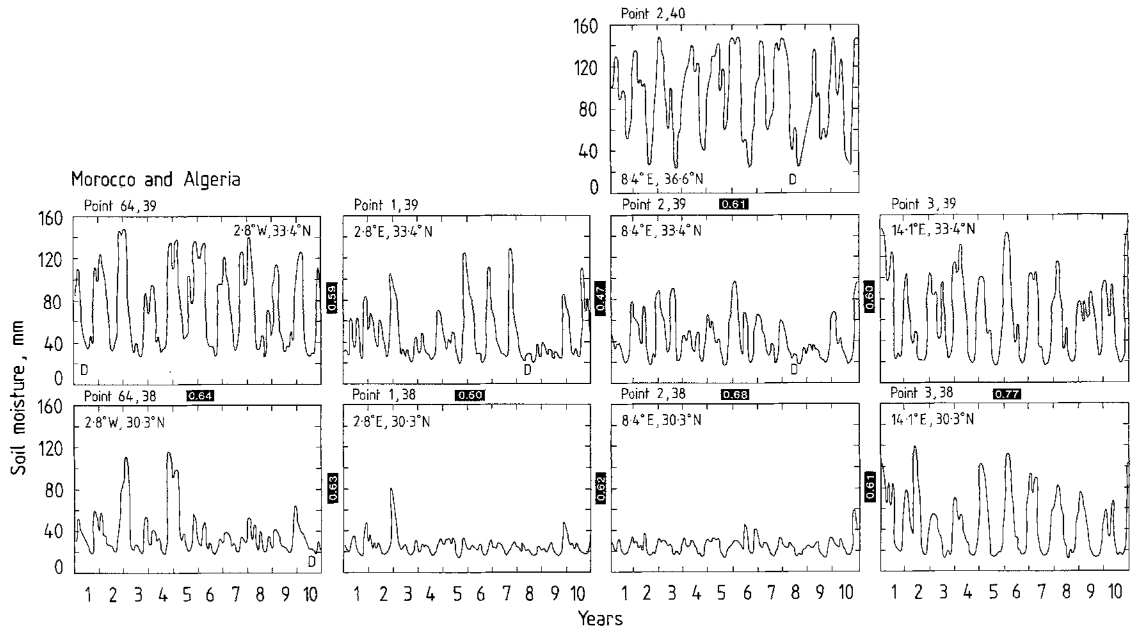

Fig. 6. As for *Fig. 5* but for Morocco and Algeria

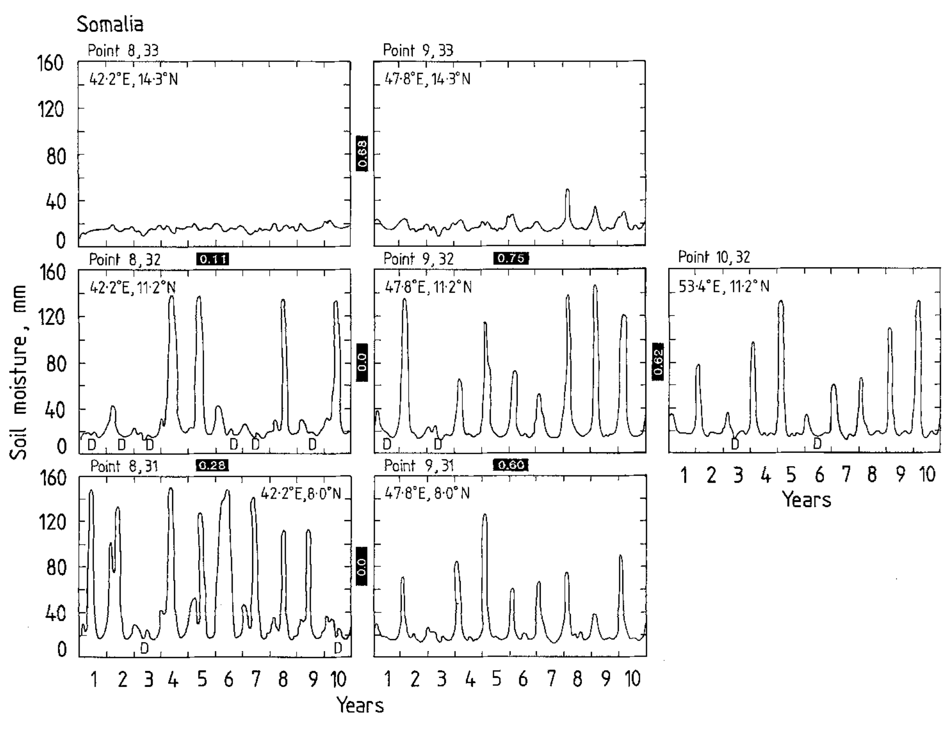

Fig. 7. As for *Fig. 5* but for Somalia

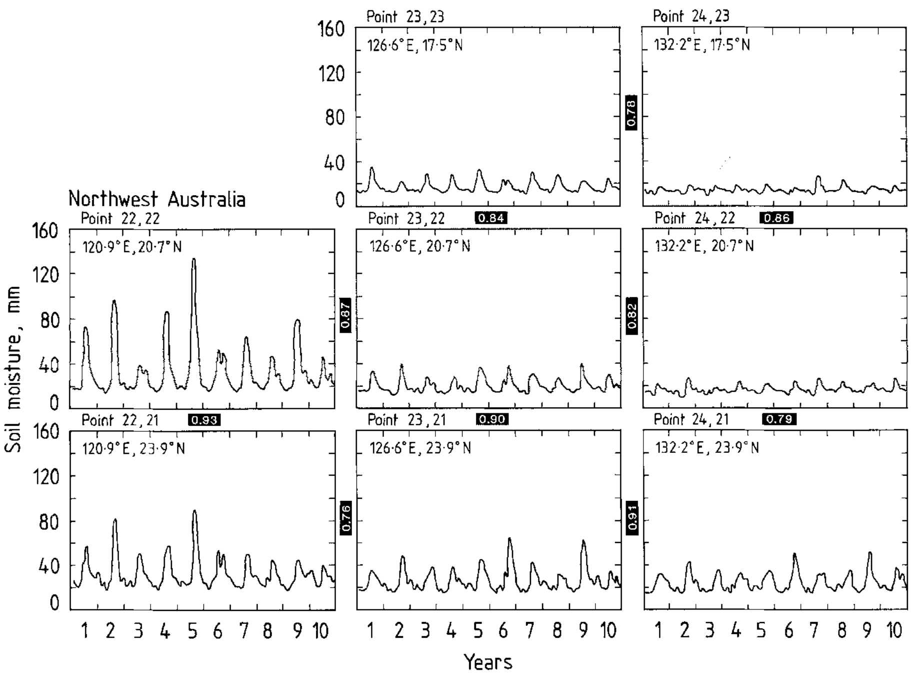

Fig. 8. As for *Fig. 5* but for northwest Australia

that there was not a dominant forcing mechanism operating, such as El Niño, and the highly visible interannual variability was caused by the internal dynamics of the model, specifically the nonlinear interactions. Thus the situations shown in Figs. 5—8 are not unrepresentative compared to the observations in Fig. 3, particularly when allowance is made for the presence of a large-scale external forcing mechanism in the latter.

In order to obtain a quantitative indication of the frequency of naturally-occurring drought, it was arbitrarily decided to define drought as existing at an individual point when the soil moisture in a given year was 25% below the 10-year average given by the computed time series for that point. Locations with drought are identified by a 'D' in Figs. 5—8. Although this is not a particularly severe definition of drought it resulted in relatively few drought events, a part from the Somalian region. Given the identification of these droughts with nonlinear mechanisms, their relative infrequency appears to be reasonable and in broad agreement with Australian observations.

A different perspective of the soil moisture time series for the four regions is given in Fig. 9, where both area-averaged and normalised results are presented. In general the area-averaged time series show a broader seasonal variability, lower peak values, and considerably more similarity overall than do the individual point values. The differences between point and area-averaged values are minimal for the south central USA region, but are quite marked for Somalia. Interestingly, on an area-averaged basis, drought in Somalia is reduced to one event in year three. The normalised (departure from long term mean divided by the standard deviation) area-averaged time series in the lower half of Fig. 9 reveal, surprisingly, that the Somalia and Morocco/Algerian regions experienced the lowest degree of climatic variability in the model, with the Australian and American regions having the highest. This result was unexpected, especially for the Australian region, but is consistent with the limited occurrence of drought for these regions identified in Figs. 5 and 8.

For brevity the subsequent presentation of the climatological characteristics of the simulated naturally-occurring drought will be concentrated on the Somalian region (see Fig. 7), but some results will also be given for other regions to indicate the similarities and differences. The Somalian region was selected as it represents the most extreme situation and may therefore be easier to interpret. In this regard the contrast between the time series for points (8, 32) and (8, 31) in Fig. 7 is of particular interest, as very substantial differences over a rather small spatial scale occurred.

In models of the atmosphere, and hopefully in the real world, atmospheric relative humidity is an important criterion for determining the onset of precipitation. Thus in Fig. 10 the monthly mean relative humidity at 750 mb is compared for two Somalian points and two south central U.S.A. points for the 10-year timespan of the simulation.

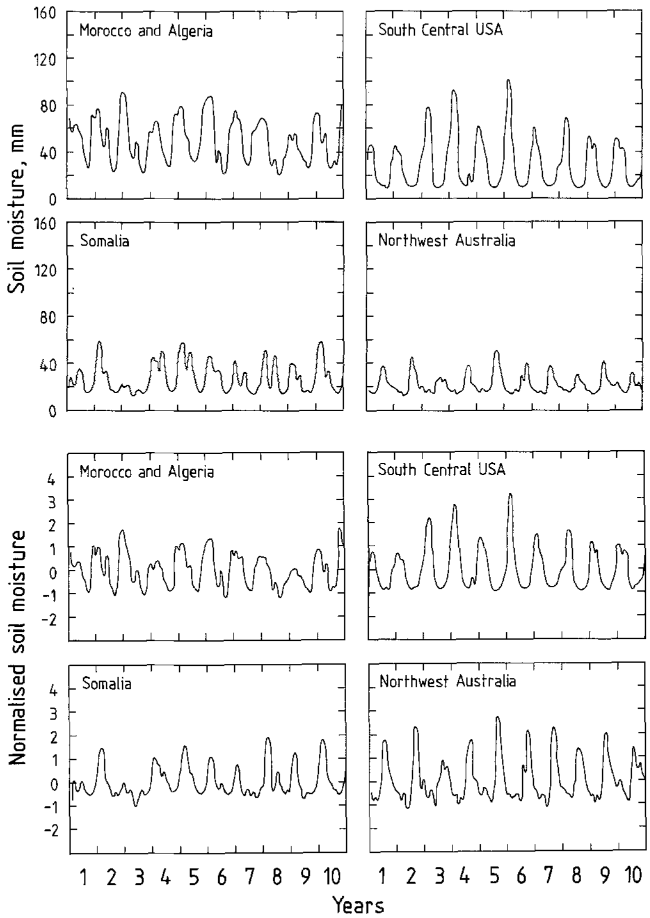

Fig. 9. Time series of area-averaged soil moisture for the four regions presented individually in *Figs. 5—8* are given in the *upper half* of the figure. In the *lower half* normalised (departure from the long term mean divided by the standard deviation) soil moisture time series averaged for the four regions are illustrated

In contrast to the soil moisture values in Fig. 7, the relative humidities over Somalia exhibited no marked changes associated with drought years, and, although there was considerable interannual variability, a consistent annual cycle can be seen at both points. The relative humidity at the northern, drier location, point (8, 31), was somewhat lower than at point (8, 31), but this difference was minor compared to the precipitation histories at these two points implied by the soil moisture distributions in Fig. 7. At both points the relative humidities in Fig. 10 ranged between about 40% in the dry season to about 90% in the wet season (whether it occurred or not!). Individual daily values would have exceeded these limits. For point (8, 32) the relative humidity peak generally coincided with the peak soil moisture, but at (8, 31) the soil moisture lagged by 3—4 months. Similar relative humidity profiles occurred over the desert to the north of these points and over the Indian Ocean to the east. The relative humidies at these points are very highly correlated as indicated on the figure.

The relative humidities at point (47, 39) and point (47, 38) in the USA shown in Fig. 10 differ from the Somalian points only in having more clearly defined annual cycles and slightly lower amplitudes. It should be noted that no anomalous behaviour in the relative humidity time series can be identified with the peak soil moisture for the 6th year at point (47, 39). Contrasting Fig. 10 with Fig. 5 or Fig. 7 clearly indicates that, in the sense of large-scale precipitation, a lack of available atmospheric water vapour was not responsible for the interannual and spatial variability of the soil moisture at these points.

Clarification of the role of advection of atmospheric water vapour in creating the interannual variability in the soil moisture at the two Somalian points was sought by plotting zonal and meridional water vapour fluxes for the first 5 years of the experiment (not shown). Overall the flux vectors were fairly similar at both points with strong westward fluxes, advecting moisture from the Indian Ocean, dominating the flow. No substantial interannual variability could be seen, suggesting that noticeable differences in advection of atmospheric moisture were not the prime cause of the naturally-occurring drought at these points. A similar conclusion was obtained for corresponding moisture fluxes for points in south central U.S.A. Attempts to use these fluxes to perform moisture budget analyses proved unsuccessful, as flux divergences cannot be evaluated meaningfully at individual points for discrete time intervals.

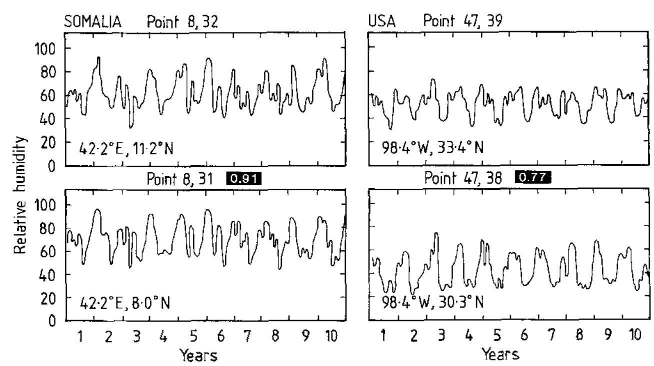

Fig. 10. Monthly mean relative humidities computed by the model for adjacent points in Somalia and southcentral USA are shown in the *left* and *right* panels of the figure, respectively. The *highlighted numbers* indicate the correlation coefficients between the adjacent points

A telling example of the differences between drought and non-drought points is given in Fig. 11 where surface temperatures for the Somalian points (8, 31) and (8, 32) in the model are plotted for the first 250 days of the 10th year of the model simulation. For this particular year, point (8, 32) was a wet year while point (8, 31) was dry (see Fig. 7). For the first 100 days and last 50 days the surface temperatures at these two points were in basic agreement, presumably indicating that they were influenced by common synoptic events. During both of these periods the soil moisture content at these points was similarly low. After about day 100 both points experienced a considerable rise in surface temperature as the summer season approached. However, at point (8, 32) convective precipitation rapidly increased the soil moisture, permitting strong evaporation from the surface. Since evaporation is a far more effective cooling mechanism than sensible heat flux (see Hunt 1985), a sustained decrease in surface temperature of about 7 K was obtained at point (8, 32). Both points experienced some weak, large-scale precipitation, but this provided only a minor contribution to the soil moisture budget.

The individualistic behaviour of the surface temperatures in Fig. 11 during the wet season means that different tropospheric temperature profiles would have been produced at these two points. Thus compared to the first 100 days a perturbation would have been fed back into the dynamics of the region via the thermal wind equation. Hence the occurrence of drought at point (8, 31) would have influenced the local climate.

At point (8, 31) the failure of the wet season was the exception rather than the norm (see Fig. 7), and this emphasises the unique behaviour of this point in Fig. 11. Why, when judging by Fig. 11, points (8, 31) and (8, 32) were responding in unison early in the year, did precipitation fail to occur at (8, 31)? What environmental factors specific to point (8, 31) caused this failure? To clarify this matter a more detailed analysis of such a situation will now be attempted.

We will contrast the differences in the meteorological behaviour of adjacent model points at which naturally-occurring drought was present or absent. At most points a combination of convective and large-scale precipitation was experienced, and their separate roles will be emphasised.

The ability of any model to simulate the complex and myriad processes involved in precipitation in the real world is very limited, hence the possibility exists that the results obtained are model restricted. Nevertheless, only by analysing in detail such aspects of a model's performance can possible deficiencies be identified and improvements developed.

(a) Somalia

Returning to points (8, 31) and (8, 32) in Somalia, Fig. 12 shows their soil moisture time series with the convective heating rates at 750 mb superimposed. A unique relationship (see correlation coefficients given on the figure) between the oc-

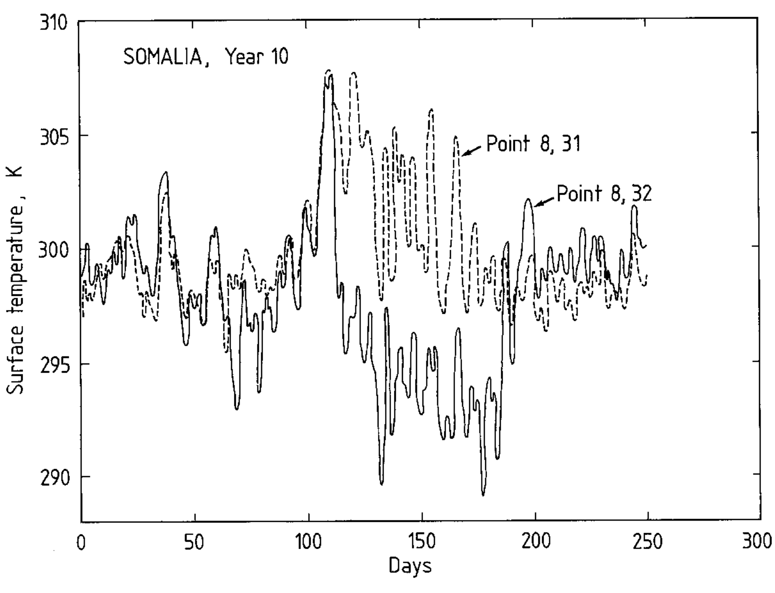

Fig. 11. Surface temperature variations at points (8, 31) and (8, 32) in Somalia for the 10th year of the model simulation. A drought occurred at point (8, 31) and a wet year at point (8, 32)

currence of convection, and thus precipitation, and high soil moisture is quite evident from the figure. While some large-scale precipitation also existed (see below) its overall role was rather limited at these particular points, and the figure clearly reveals that drought resulted whenever convective activity was lacking. The role of large-scale precipitation can be judged to some extent from the minor, early peaks in the seasonal variation of the soil moisture; for example, in the 2nd, 5th, 7th and 8th years at point (8, 31) in Fig. 12.

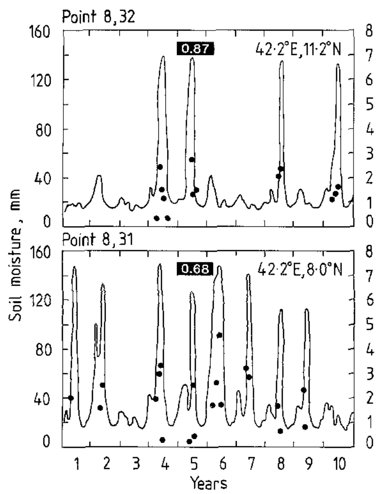

Fig. 12. Time series of the soil moisture variations at points (8, 31) and (8, 32) in Somalia with occasions of convective heating superimposed. Note the lack of convection during drought years. The *highlighted figures* represent the correlation coefficient between the soil moisture and the convective heating time series

In complete contrast, the land points eastwards, (9, 31), (9, 32) and (10, 32) in Fig. 7, never experienced convection so that large-scale precipitation dominated there. This behaviour is thought to be attributable to the inflow of moist air from the Indian Ocean, activating the large scale precipitation mechanism while simultaneously preventing convection from occurring by modifying the moist static energy.

Whether convection is generated or not is a very sensitive matter. This will be illustrated by comparing the completely different behaviour at point (8, 31) and point (8, 32) in year 1 where drought happened at one point but not at the other. In Fig. 13 the variables which essentially determine the onset of mid-level convection are plotted for these two points for year 1 of the simulation. For this particular situation mid-level convection initiated and dominated the initial convective activity. The overall behaviour of the variables for the two points in Fig. 13 is basically similar. The essential features are a progressive warming at level 3 (750 mb) and a corresponding cooling at level 1 (250 mb), attributable to the seasonal variation of insolation. Associated with the lower-level warming is a steady increase in the atmospheric moisture content, although the relative humidity (see Fig. 10) remained relatively static. Convection first occurred at point (8, 31) on day 110 when the combination of the growing temperature contrast between the levels and the increasing absolute humidity finally enabled the criterion for convective onset to be met. Mid-level convection ceased after day 114, as might be expected

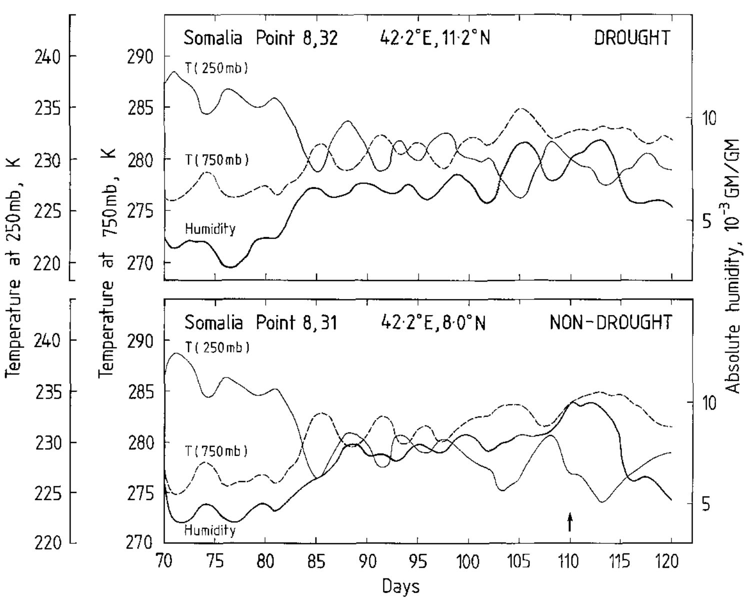

Fig. 13. Variations in the model air temperatures at level 1 (250 mb) and level 3 (750 mb), together with the atmospheric humidity at level 3, for the first 120 days of the simulation. Results for points (8, 32) and (8, 31) in Somalia are shown in the *top* and *bottom* of the figure, respectively. The onset of convection at point (8, 31) is indicated by the *arrow* at day 110

from the trend of the curves in Fig. 13, but penetrative convection energised by the high evaporation rate from the earlier precipitation maintained the precipitation. In fact convective precipitation in one form or another existed from day 110 to day 145. In contrast, at point (8, 32) conditions at the peak temperature differences on days 105 and 113 in Fig. 13 just failed to meet the criterion for mid-level convection; on day 105 because the humidity value was too low, while on day 113 because the temperature difference was too small. The criteria for the onset of low-level or penetrative convection were not achieved by a considerably larger margin for this particular situation. A comparison of the two sets of curves in Fig. 13 for days 100—120 suggests that even if convection had occurred at point (8, 32) only weak activity would have resulted. Thus, slight modifications to the model's formulation to ease the criteria for convective onset would not be expected to lead to substantially different results.

In practice the precipitation history at a given point is rather more complicated than might be inferred from the above discussion, as considerable variability can exist even for individual wet years. Figure 14 illustrates this situation for the first two years at point (8, 31) in Somalia. In year 1, apart from some very minor large-scale precipitation around day 30, there was no further precipitation until convection set in at day 110, as discussed above. The resulting very heavy precipitation rapidly saturated the soil, allowing the evaporation to proceed at the potential rate with a consequent dramatic impact on the surface temperature (see also Fig. 11). Very substantial convective precipitation continued for the next 30 days, further lowering the surface temperature so that a drop of 20 K occurred during the course of the wet season. Large-scale processes were responsible for the two minor precipitation events centred on days 150 and 170 in Fig. 14.

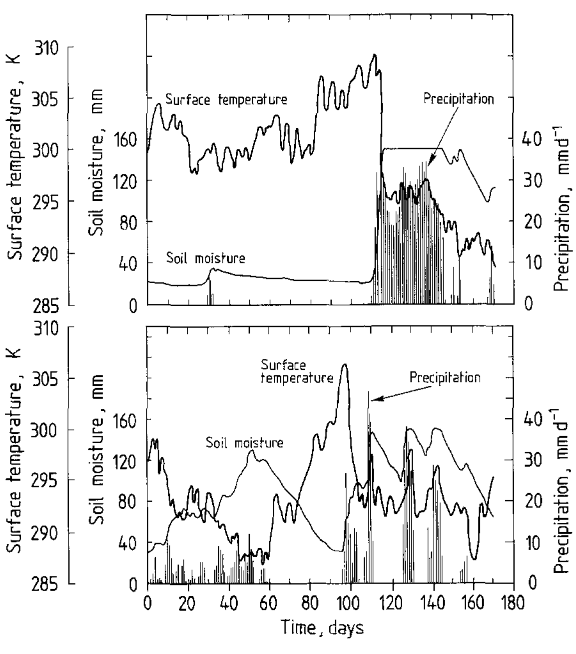

Fig. 14. Time series of soil moisture content, surface temperature and precipitation at daily intervals for the first 170 days of years 1 and 2 of the model simulation for point (8, 31) in Somalia are shown in the *top* and *bottom* of the figure, respectively

In contrast, during the second year shown in Fig. 14, there was considerable large-scale precipitation early in the year, which was followed by a series of multi-day convective situations which created a secondary peak in the soil moisture time series (see Fig. 12 for a more general perspective). Note the responses of the soil moisture and surface temperature to the individual convective situations shown in Fig. 14.

The important point arising out of these two examples is that the onset of convective precipitation, and therefore the occurrence of a wet year, is not determined by some soil moisture threshold value or preconditioned by earlier large-scale precipitation. This suggests that convection plays a major role in creating "local" climatic anomalies, while soil moisture perturbations have a more subtle interaction with the atmosphere than implied by elementary wetting experiments with models.

(b) USA

The interannual variability of precipitation was examined next for south central USA (see Fig. 5). This variability is much lower than that for Somalia, suggesting that different dynamical regimes prevail. This was confirmed by comparing the convective activities in these two regions. Convection was almost totally confined to the easternmost points, (48, 38) and (48, 39) in Fig. 5, and even when it occurred it was rather weak judging by the convective heating rates. The maximum value was found to be only 0.56 Kd^{-1}, compared with typical values of 3 Kd^{-1} for Somalia (Fig. 12) where maximum values approached 6 Kd^{-1}. However, over the Gulf of Mexico heating rates exceeding 3 Kd^{-1} were obtained during summer. Plots of the variables involved in determining the onset of mid-level convection for the USA points revealed similar behaviour to those shown in Fig. 13 for Somalia, but with overall lower temperatures at 750 mb which prevented the criterion for convection being attained. Consequently, the precipitation for the various U.S.A. points in Fig. 5 was essentially due to large-scale processes, which required only relative humidities greater than 95%.

In order to investigate why the large-scale precipitations were different, the absolute humidities at 750 mb were plotted at daily intervals in Fig. 15 for years 4 and 5 at point (47, 39) (see Fig. 5). Year 4 was a reasonably wet year while year 5 was relatively dry. Year 6 was excluded from this comparison as it was the only year of this series which experienced some (weak) convective activity and was therefore deemed anomalous. Most of the precipitation at point (47, 39) occurred in the first 50 days, with occasions where the rates exceeded 1 cm d^{-1} being indicated by arrows in Fig. 15.

Although the absolute humidities in Fig. 15 cannot be directly related to relative humidities,

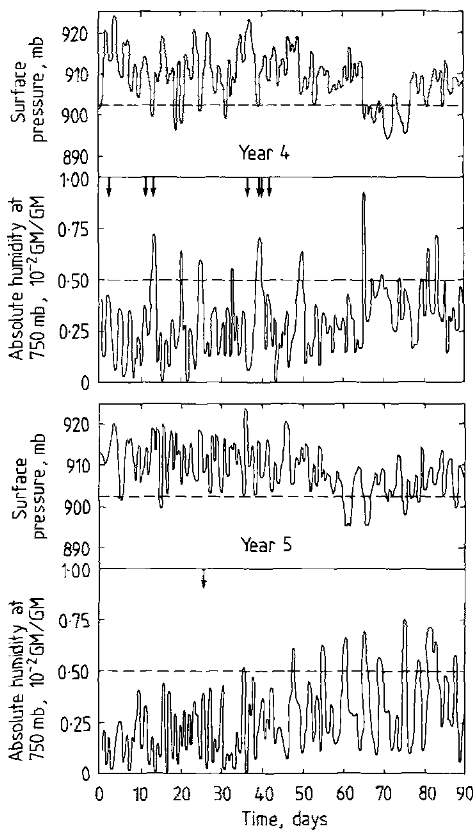

Fig. 15. The variations of the absolute humidity and surface pressure for the first 90 days of year 4 (wet) and year 5 (dry) at model point (47, 39) in southcentral USA are shown in the *top* and *bottom* panels, respectively. The *dashed lines* in the figure are used to provide a common reference level for comparison. The *vertical arrows* indicate times when precipitation exceeded 1 cm d^{-1}

and thus large-scale precipitation possibilities, some essential differences emerge when the two years are compared. Year 4 had high humidity values on a larger number of occasions compared with year 5, at least during the first 50 days, and most of these were associated with high precipitation events. As can be seen from the figure, these events occurred during the passage of low pressure systems, as might be expected. In contrast, year 5 experienced only one high precipitation event, and high humidity values or particularly intense low pressure systems were rare compared with year 4. A close comparison of the two surface pressure time series in Fig. 15 reveals that the synoptic activity had a lower frequency in year 4, which probably also contributed to the differences between the two years.

While other variables could be used to illustrate differences between the two years, the likelihood is that no unequivocal, causal factor would be identified. The question then arises: Why did the synoptic activity vary from one year to the next? But surely the more fundamental question is: Why shouldn't it? Given the complex physical processes and nonlinear interactions involving in generating synoptic systems there is every reason to expect differences. This merely highlights the intrinsic difficulty (impossibility?) of predicting long term regional behaviour in the absence of well defined external forcing functions such as El Niño-type sea surface temperature anomalies.

(c) Morocco and Algeria

The final region examined was in northern Africa, which also exhibited considerable interannual variability in the model (see Fig. 6). A detailed investigation was made for the two points (2, 40) and (2, 39) in northern Algeria, which revealed that the precipitation was a combination of convective and large-scale processes, with the interannual variability being attributable to perturbations in both of these processes. Hence the behaviour of this region had characteristics belonging to the Somalian and USA regions discussed above.

The differences in precipitation between a dry and a wet year are illustrated for point (2, 39) in Algeria in Fig. 16. Year 5 had some trivial convection in October, while year 6 experienced convection in June and July, which was fairly modest by Somalian standards. The daily precipitation values in Fig. 16 were quite low for year 5, with June to August being almost rain-free. The soil mois-

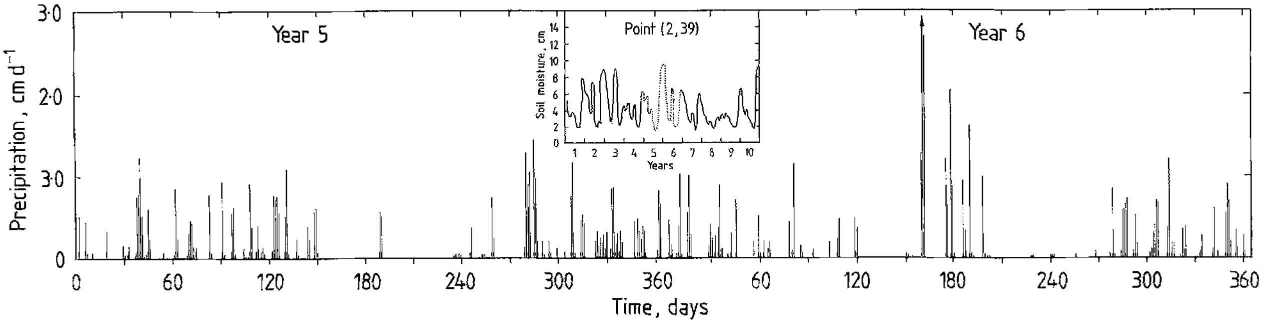

Fig. 16. Daily precipitation rates for year 5 and year 6 at point (2, 39) in Algeria. Year 5 was a dry year while year 6 experienced convective precipitation in June and July. The 10-year soil moisture time series simulated for this point is shown inset in the figure, with years 5 and 6 highlighted

ture time series inset in Fig. 16 clearly reproduces this summer situation. Increasing large-scale precipitation late in year 5 and early in year 6 produced the peak soil moisture value for this particular 10-year time series. However, in June and July of year 6 convective precipitation occurred which caused a secondary peak in the soil moisture. In fact, for each of the years with convection at this point, years 2, 3, 4, 6 and 7, a secondary soil moisture maximum can be seen in summer in the time series in Fig. 16. Interestingly, years with convective activity also tended to be years with somewhat higher large-scale precipitation as judged by the soil moisture values. Failure of convection to occur was usually attributable to the temperature at 250 mb in the model being too high. Overall the temperatures at this level were systematically higher than those for Somalia, thereby accounting for the relatively weak convection in the Algerian region. As shown in Fig. 16 the convection in year 6 arose from a series of isolated "storms", which completely altered the seasonal rainfall characteristics. Such anomalous summer storms also happen in the real world at many locations, and, apart from being disruptive, are usually of little agricultural value because of the high evaporation rates at this time of year. Nevertheless, this example illustrates the problem of forecasting seasonal precipitation in regions where convective storms are a feature. As discussed in relation to the Somalian points above, the difficulty arises in determining the onset of convection because it is delicately influenced by slight variations attributable to nonlinear flux terms.

5 Discussion of results

The ability of the model to simulate a number of disparate climatic types as demonstrated here, and in Gordon and Hunt (1987), implies that the interpretation of the results concerning the interannual variations of precipitation have some relevance to the real world. The significant point which has emerged is that while the interannual variability is caused by perturbations in the convective and/or large-scale precipitation processes, it is the rather minor changes in the basic atmospheric variables of temperature and absolute humidity which are the critical factors involved. Thus atmospheric temperature differences of 2—3 K or absolute humidity differences of 10—20% are sufficient to decide whether a given point in the model experienced a wet or a drought year. Another important feature is that the interannual variability obtained was limited to individual points, that is, no spatially coherent response was obtained such as occurs during El Niño events. This implies that each point in the model was able to exhibit some individuality in order to permit the simulated responses to be obtained, even though this and surrounding points were obviously part of a broad-scale synoptic system. It is the overall environment produced by such systems which prevents substantial differences in atmospheric temperature and absolute humidity from arising between adjacent points.

The fundamental question is how and why do such differences occur? In the absence of any other identifiable mechanisms, they are attributed here to nonlinear interactions in the large-scale dynamic processes within the model. This statement does not preclude sea ice, cloud cover, surface albedo changes due to snowfall etc., which are all computed variables in the model, from contributing to interannual variability, but identifies any interannual changes in these variables themselves as being initiated by the nonlinear interactions. Although it would be useful to have a quantitative assessment of the individual contributions of these terms to the interannual variability, this would require separate experiments in which these terms were specified, and this is beyond our limited computer resources. Nonlinearities are a natural characteristic of the climatic system, arising, for example, from baroclinic instabilities associated with synoptic activity. Since synoptic activity varies from year to year (partly owing to nonlinear interactions within individual synoptic systems), it is not surprising that the nonlinear mechanisms create interannual variability. This point is amply supported by the results, for example, of Gates (1984), Esbensen (1984) and Shukla and Wallace (1983), who have all noted the vagaries introduced into interannual variability by nonlinear processes.

Thus, nonlinearity-induced drought, or naturally-occurring drought as we have termed it, must be recognised as an intrinsic feature of the climatic system. The reverse phenomenon can also exist, i.e., anomalous wet years in a basically arid region can be induced by nonlinearities. This might be the situation which exists at the Somalian point (8, 32) in Fig. 7. While in principle a naturally occurring drought can be expected in any geographical region, in practice the model results indicate that it is more likely to happen in semiarid regions, presumably because in these regions the meteorological systems operate at all times closer to the threshold as regards precipitation.

Despite the characteristic that these nonlinearly-induced perturbations are local in extent, the overall result is important because such perturbations are essentially unpredictable (see, for example, Chervin 1986). While unpredictability is an inherent characteristic of natural, i.e., unforced, nonlinear systems, the present problem is compounded by the very modest changes in temperature and absolute humidity associated with such local perturbations. Fortunately, for large scales which are obviously of more importance, the situation is more hopeful (Nicholls 1985) and considerable progress can be expected.

6 Conclusions

This paper has endeavoured to establish the existence of naturally-occurring drought in the real world, and then to identify the peculiarity of such drought in a model simulation. Naturally-occurring drought is characterised by its very local, isolated extent and its occurrence in an otherwise drought-free situation. In contrast, forced drought is usually large scale, coherent, and in many cases has a recognised excitation mechanism, usually sea surface temperature anomalies. Observations for Australia permitted both of these drought types to be identified.

Various examples of simulated naturally-occurring drought have been given in this and its companion paper (Gordon and Hunt 1987). The results clearly show the localised spatial characteristics of this drought, but also reveal that considerable variability exists from one geographical region to another. Accepting the limitation that only convective or large-scale precipitation can occur in the model, analysis of three distinct geographical regions revealed interesting combinations of these precipitation types; and examples of extreme variations in precipitation histories from one year to the next. Detailed comparisons of dry and normal years showed, surprisingly, that relatively minor changes in basic atmospheric variables occurred, but that these were sufficient to suppress the precipitation mechanisms in the drought years. Diagrams presented illustrated this point very clearly.

In the absence of any "external" forcing mechanism in the model, these interannual variations can be attributed to the nonlinear mechanisms associated with the dynamical processes. Rather little is known about the properties and behaviour of nonlinearities in the climatic system, and this is undoubtedly a major area of future research (see Hunt 1988). Models will play a critical role in such research because of the capacity they present for systematic, controlled experimentation and evaluation. Although the nonlinearities are components of the synoptic systems, the present results indicate that they are able to cause only local changes within such systems, not to modify the systems as a whole. Since these nonlinear interactions are essentially unpredictable, the occurrence of local, naturally-occurring drought, or anomalous wet conditions, is likewise unpredictable. Fortunately, the isolated nature of such events means that, while they may be disastrous locally, surrounding regions are unaffected. In contrast, large-scale droughts with identified forcing functions would appear to be inherently predictable, at least when the required technologies are in place.

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