The influence of soil wetness distribution on short-range rainfall forecasting in the West African Sahel

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SUMMARY

Surface moisture supply is known to be a factor which can be important in triggering convection. This paper aims to investigate its impact on short-range numerical forecasts of tropical rainfall.

The ECMWF (European Centre for Medium Range Weather Forecasts) operational forecasting model was integrated for 5 days with realistic positive and negative anomalies of the initial surface moisture distribution in the West African Sahel. The large-scale flow is found to be relatively unaffected, but significant differences occur in the rainfall forecasts for about the first 4 days. Rainfall is greatest with a moister surface, except on days 3 and 4 in the south Sahel/Savanna region, for which a decrease in rainfall occurs. The opposite result is seen when an initially drier surface is introduced. The mechanisms involved are investigated by carrying out a detailed hydrological budget, and by studying the evolution of the atmospheric profiles of moisture and temperature.

We conclude that an improved surface moisture analysis is likely to result in some improvement of short-range rainfall forecasts in the Sahel, and presumably also in other tropical regions. In the coming years it should be possible to achieve this using satellite-derived soil wetness maps.

1. INTRODUCTION

The semi-arid region of West Africa known as the Sahel has been severely affected by drought in recent years, which has been partly to blame for the much publicized human and economic suffering. This has stimulated a widespread interest in the problem of forecasting for such regions. Improvements in seasonal and daily forecasts could influence important agricultural decisions, thus leading to higher crop yields. More reliable short-range rainfall forecasts (1 to 4 days ahead) would improve advice given to farmers on activities such as planting, weeding and fertilizing (Konare 1989). It is thus important to evaluate the contribution of the various elements which affect the quality of the forecasts. The aim of this paper is to demonstrate the impact on tropical rainfall forecasts of using estimates of the current soil water content, since this partly controls the location and intensity of the convective precipitation through surface evaporation.

A substantial proportion of the rainfall in the West African Sahel is produced by squall lines, which consist of organized lines of convective cells, oriented roughly in the north–south direction, travelling westward, and lasting for up to 24 hours or more (e.g. Hamilton and Archbold 1945; Aspliden et al. 1976; Houze 1977; Roux et al. 1984). In order to provide a useful forecast of rainfall, the factors influencing the generation, propagation and decay of squall lines must be correctly forecast. Atmospheric conditions required are: conditional instability, a low-level jet, and a moist lower layer with dry air at middle levels. The release of the instability may be triggered by factors such as surface heating, topography, large-scale convergence (e.g. African waves), or surface moisture sources. It is this last factor which is of particular relevance to the present study. An
example of the importance of surface evaporation occurs in the area of marshland surrounding the bend in the River Niger (17°N, 2°E), which has been shown to be a preferred region for squall-line generation when compared with other drier areas of the same latitude (Rowell 1988).

It follows that the parametrization and analysis of soil moisture in numerical forecasting models is likely to be a factor affecting rainfall forecasts, and if these aspects can be improved then the forecasts should also improve. Currently the initial soil moisture field used in operational models is derived either from climatology or from ‘real-time’ rainfall data (this being rather sparse in the tropics), neither of which is likely to give reasonable results. One way to gain a better initial field of surface soil moisture may be to use satellite data, either by using an infra-red channel to measure the diurnal temperature range (e.g. Schmugge et al. 1980; Ward et al. 1982; Milford 1987), or by using microwave data (e.g. Choudhury and Golus 1988; Owe et al. 1988). But before considering exactly how such data might be incorporated into the analysis, the sensitivity of the short-range tropical rainfall forecasts to changes in the initial soil moisture field must be assessed. This paper gives some evidence that numerical models currently used for operational forecasting are in fact quite sensitive to these initial values.

The experiment to be presented here investigates the influence on short-range Sahelian rainfall forecasts of soil moisture anomalies which might realistically occur on a week to week time-scale. These might occur after several days of above average rainfall, or after a dry spell of several days. Studies conducted by other authors have looked only at the impact of anomalies associated with climatic changes (e.g. Sud and Fennessy 1984; Cunnington and Rowntree 1986), or with mesoscale variations of soil water content (e.g. Ookouchi et al. 1984; Anthes 1984). The basic strategy we follow here is similar to that of Rowntree and Bolton (1983), viz. a global general circulation model (GCM) is integrated, and comparisons made between a control run and runs with initially moister or drier surface conditions. However, apart from the anomalies being much smaller, different techniques are also employed to analyse and present the results.

2. The model

The experiment was carried out using the version of the ECMWF model which was operational in the early part of 1987. A brief description of that model now follows; further details may be obtained from the references cited.

It is a global spectral model with T106 truncation (and a 1.125° × 1.125° Gaussian grid for computing the physics) (Baede et al. 1979), and 19 levels in the vertical. The parametrization schemes used are: surface fluxes and turbulent diffusion (Louis 1979; Louis et al. 1982); an interactive radiation scheme (Geleyn and Hollingsworth 1979; Ritter 1984) which separately computes short-wave and long-wave components and allows for the effects of fractional cloud cover (computed from the humidity profile, Geleyn et al. 1982) and varying aerosol and trace gas amounts; deep convection (based on Kuo 1974); shallow convection (Tiedtke et al. 1988); large-scale precipitation; envelope orography (Jarraud et al. 1986); gravity wave drag (Palmer et al. 1986); and a three-layer soil model (Budyko 1971; Deardorff 1978).

The soil model is illustrated in Fig. 1. The depths of the layers are such that the soil temperature responds to both diurnal and medium-term thermal forcing. Climatological values of moisture and temperature in the bottom layer are kept fixed throughout each forecast, and are changed each month. Exchanges of heat and moisture between the layers obey simple diffusion equations. Runoff occurs from the surface layer when its soil water content, \( W_s \), exceeds 20 mm, and from the middle layer when its water content,
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Figure 1. Schematic representation of the soil parametrization used in the ECMWF model. \( T \) and \( W \) represent the temperature and moisture content of the surface, deep and climatological layers.

\( W_d \) exceeds 120 mm. Evaporation from the surface is linearly dependent on surface soil water content when the latter is less than or equal to 15 mm, and independent when it is greater than 15 mm.

The soil moisture analysis is produced by taking appropriately weighted rainfall observations from within 333 km of each grid point, adding the previously analysed value of surface moisture content, and subtracting the forecast evaporation over this 6-hour period. The exchange of moisture between layers is also accounted for. If no precipitation measurements are available within 333 km of the grid point (this is often the case in data-sparse tropical regions, such as the Sahel), the soil water content is simply relaxed towards a climatological value.

3. The Experiment

The model was integrated for 5 days, using three different initial fields of surface moisture content. All other fields, and other aspects of the model, were identical for the three experiments. The 'control' experiment was carried out with the initial data used for the operational forecast of 2 August 1985, for which the surface moisture content (Fig. 2(b)) was similar to the August mean. For the 'wet' experiment the transition zone between the dry Saharan soil and the moist soil of the deep tropics was moved 4° to 5° further north over West Africa (from approximately 15°W to 15°E), and this new initial surface moisture field is shown in Fig. 2(a). For the 'dry' experiment this transition zone was shifted 4° to 5° further south, as shown in Fig. 2(c). East of about 25°E the wet and dry experiments had the same moisture content as the control, with a smooth transition of moisture from 15°E to 25°E. It is emphasized that the moisture content of only the surface soil layer was altered.

Note that the initial atmospheric fields are not affected by the modifications of the surface state, which although not completely realistic (as will be shown by the results) should not affect the meaning of the following study.

4. Results

The results of the experiments are displayed as spatial averages of the variable of interest plotted (or tabulated) against time. Averaging was performed over two 5° × 30°
Figure 2. Initial moisture content (mm) of the surface soil layer for the (a) wet, (b) control and (c) dry experiments.

areas, roughly matching the regions for which the initial soil moisture was altered. They run from 15°W (approximately the coast of West Africa) to 15°E, with the northern strip encompassing the north-western Sahel/sub-Sahara (15°N to 20°N), and the southern strip being Savanna and south Sahel (10°N to 15°N).

We first summarize the changes to the rainfall and soil moisture forecasts, then carry out a detailed hydrological budget, and finally look at the impact on the atmospheric fields in order to help explain the differences in rainfall. The broader implications of the results are discussed in the final section.

(a) Soil moisture and rainfall

Figure 3 shows how the surface soil moisture fields evolve through the forecasts (note that the vertical scale is in centimetres). For both regions the major part of the
In the northern area, the changes to the initial soil wetness cause fairly substantial differences to the rainfall during the first 3 to 4 days, with increased precipitation over the moister surface, and decreased precipitation with an initially dry surface. The differences are somewhat reduced towards the end of the forecast, but still not negligible.

In the southern area, although there are also significant differences in the convective rainfall rates of the three experiments, these are not as might be expected. During the middle part of the forecast greatest rainfall occurs in the experiment with the driest surface, and least rainfall in the experiment with the wettest surface. Section (c) will discuss in more detail possible reasons for the rainfall anomaly reversing sign during the middle part of the forecast.
Figure 4. (a) to (c): Forecast evolution of convective precipitation rate (mm/day), averaged over the Sahel/sub-Saharan region (15°N to 20°N). (a) Wet minus control; (b) control; (c) dry minus control. (d) to (f): As (a) to (c), but for the Savanna/Sahel region (10°N to 15°N).
It may also be noted that we found the spatial pattern of rainfall to be broadly similar between all three experiments (not shown), though differences on the scale of a few grid points give rise to some quite substantial local anomalies.

We have now seen how two of the main variables of interest evolve during the 5-day integrations, and demonstrated the rainfall forecasts to be sensitive to the initial surface moisture conditions. In order to gain understanding of the link between them, we now look at a more complete picture of the hydrological cycle.

(b) Hydrological budgets

Table 1 shows the hydrological budget for the Sahel/sub-Saharan region. One of the most striking points to note is that, in terms of excess of precipitation over evaporation, the three experiments diverge for the first 3 or 4 days, i.e. the soil in the wet case gets wetter and in the dry case gets drier (relative to the control). But note that this refers to the whole soil depth, not just the surface, since for the latter the three experiments converge (Fig. 2). The extra rainfall of the wet experiment, plus the extra moisture in the surface layer, diffuses into the deep soil, with probably further moisture transfer to the climatologically fixed reservoir, as the model continuously tries to reach equilibrium. Note also that runoff is zero for this area as the surface layer never reaches saturation in any part of the region.

Looking at the atmospheric moisture budget for the northern region, it can be seen that in all three experiments there is a loss of 7 or 8 mm of water. Although the wet experiment loses more moisture through the excess of precipitation over evaporation, this difference from the other experiments is mainly compensated for by an increase in

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**TABLE 1. HYDROLOGICAL BUDGET FOR THE SAHEL/SUB-SAHARAN REGION (15°N TO 20°N). UNITS ARE MILLIMETRES OF WATER OVER THE FORECAST PERIOD**

<table>
<thead>
<tr>
<th>Forecast period (h)</th>
<th>Experiment</th>
<th>Change in moisture of surf. layer</th>
<th>Precip. (P)</th>
<th>Evap. (E)</th>
<th>P-E</th>
<th>Drainage to deep soil layer + runoff</th>
<th>Advec. into area</th>
<th>Change in atmos. storage</th>
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</thead>
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<td>-1.4</td>
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moisture advection into the region. For all three experiments, more than half of the atmospheric moisture loss occurs on day 5, when the Sahel/sub-Saharan was dominated by subsidence, leading to relatively large moisture divergence over the region and little precipitation. On the other days there is usually a net advection of moisture into the area, though (except for day 3) not enough to compensate for the loss to \( P-E \) (precipitation−evaporation).

The hydrological budget for the Savanna/Sahel region is shown in Table 2. Considering the totals for the whole experiment, in contrast to the northern region, it is the dry experiment which receives the most rainfall, and the wet experiment the least, though the differences are not great. This is also reflected in values of \( P-E \), where precipitation now goes to runoff as well as moistening the soil. The increase of precipitation in the dry case occurs on days 3 and 4 (despite the surface moisture still being less than the other experiments). Also note that water drainage to the deep soil, plus runoff at the surface, is large in this region, with daily amounts being of the order of the 5-day totals in the northern region.

Again there is a net loss of atmospheric moisture over the 5 days, this being about 6 or 7 mm for each experiment. The advection of moisture into the area is, for all experiments, much larger than in the northern region (causing the much higher values of precipitation than in the north). This indicates that although the changes made to the initial surface wetness have a significant local impact they do not modify the general pattern of the large-scale flow.

We now have a clearer picture of the evolution of the moisture content of the atmosphere and soil, the exchange of moisture between them, and of the hydrological sources and sinks. The next section completes our investigations by looking in more detail at the atmospheric structure and how this can help explain the anomalies in the precipitation forecasts.

<table>
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<tr>
<th>Forecast period (h)</th>
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(c) **Atmospheric changes**

We consider the effects of the surface moisture on the model atmosphere, by again averaging over each of the northern and southern regions. Figures 5 and 6 show how the mean vertical profiles of relative humidity and temperature evolved during the control experiment, and how the anomaly profiles evolved during the wet and dry experiments (wet minus control, and dry minus control).

Firstly, the anomaly fields of the wet experiment in the northern region are considered. From Fig. 5(a) it is seen that increased evaporation from the moister surface raises the humidity (specific, as well as relative humidity) of about the lowest 200 mb of the atmosphere, with differences of up to 15% occurring. This helps to maintain the convective instability and results in an increase of moisture available for convection (which is dependent upon the vertically integrated moisture accession, i.e. moisture convergence plus evaporation). This results in greater moistening at cloud-top levels, and greater drying of the middle atmosphere; both points are demonstrated by Fig. 5(a). Increased latent heat release (due to increased precipitation) warms the middle troposphere, as seen in Fig. 6(a). This diagram also shows a cooling of the lower troposphere, which is due to higher surface evaporation reducing the surface temperature, and also more intense evaporative cooling in the sub-cloud layer.

It is clear then, that a local enhancement of the hydrological cycle occurs, and plays an important role in increasing the precipitation. However, the results of the hydrological budget have shown that values of $P-E$ are also larger. This can only be explained by an increase in the moisture advected in by the large-scale flow, as well as a reduction in the atmospheric storage of moisture. It suggests a positive feedback mechanism, through increased warming in the mid troposphere, leading to more ascent, leading to greater moisture advection into the area. We also suggest that this increased moisture advection is from the south (Table 2 shows a decrease in the net advection into the south) and plays an important role in determining the rainfall anomalies there (see below).

For the dry experiment in the northern region the opposite picture is valid, except that the changes are generally smaller, because the magnitude of the initial surface moisture anomaly is less than that of the wet experiment. Evaporation from the drier surface is less than the control, and so the humidity (specific and relative) of the lower troposphere is reduced (Fig. 5(c)), and likewise the moisture accession. Hence convection is less intense, precipitation is reduced, and the local hydrological cycle is less vigorous. $P-E$ is also reduced, due to a decrease in the moisture advected in by the large-scale flow (Table 1). Corresponding changes in the moisture profile occur; a little less drying of the mid troposphere, and slightly less moistening at cloud-top levels (Fig. 5(c)). A decrease in mid-tropospheric warming is just apparent in Fig. 6(c), and a warmer boundary layer is also seen, due to a shift in the Bowen ratio leading to higher surface temperatures, and also due to less evaporative cooling in the sub-cloud layer.

The anomaly fields for the southern region are now considered. There is little difference in the relative humidity of the boundary layer for the three experiments (also specific humidity), except at the start of the dry case. This is because over much of the area the surface soil layer is near or above 75% saturation, so that the evaporation rate equals the potential rate, and is no longer proportional to surface wetness, i.e. evaporation is the same for all experiments.

Consider first the wet experiment. For about the first 6 hours evaporation exceeds that in the control by up to 50 W/m² (1.8 mm/day), and this results in an increase in rainfall, through the same mechanisms as described for the northern region, i.e. a more vigorous local hydrological cycle, and increased moisture convergence producing a positive feedback effect. However, during the first 36 hours, evaporation in the control
Figure 5.  (a) to (c): Forecast evolution of the mean vertical profile of relative humidity (%) in the Sahel/sub-Saharan region (15°N to 20°N). (a) Wet minus control; (b) control; (c) dry minus control. (d) to (f): As (a) to (c), but for the Savanna/Sahel region (10°N to 15°N). Contour interval of anomaly plots is 2.5%. Differences of more than 5% are stippled, and differences of less than -5% are hatched.
Figure 6. As Fig. 5, but for temperature (K). Contour interval of anomaly plots is 0.25 K. Differences of more than 0.5 K are stippled, and differences of less than -0.5 K are hatched.
and dry experiments rapidly reaches the potential rate. After this, the differences in rainfall between the experiments reflect the changes in moisture advection from the south to the north (as mentioned above, and also evidenced by the hydrological budget on days 3 and 4 and the mid-tropospheric loss seen in Fig. 5(d)). This decrease in net moisture advection into the south results in a reduction of rainfall there for the wet experiment. On the final day there is little convection in the northern region, and so little difference in the moisture advection from south to north, between the control and wet experiments. Evaporation, however, was slightly larger for the wet experiment (Table 2), as was the total atmospheric moisture content, and together these factors led to larger amounts of rainfall than the control, presumably aided by positive feedback through latent heat release and increased local moisture convergence.

The reverse arguments may be applied to the differences between dry and control experiments in the south. The differences, however, are smaller and the evidence less striking. Initially evaporation in the south in the dry case is small, and so convection is less intense, causing a reduction in rainfall. However, after one or two days, evaporation in the south reaches the same level as that of the control, but is still much reduced in the north. Decreased moisture advection to the north allows greater moisture accession in the south. Hence precipitation becomes greater than in the control experiment. On the final day there is little difference between the experiments in the north and their effect on the south, so that rainfall in the dry experiment is affected by the slightly drier surface, and the smaller total atmospheric moisture content, leading to reduced rainfall in the south, as well as the north.

5. DISCUSSION AND CONCLUSIONS

It has been shown that variations in the initial distribution of surface moisture in the ECMWF GCM have a significant impact on local Sahelian rainfall forecasts for 3 to 4 days. This occurs through changes in the local recycling of moisture, and local changes in advection. However, the large-scale atmospheric flow is relatively unaffacted, and still dominates the large-scale rainfall distribution, particularly in the south Sahel/Savanna region. This is in contrast to the experiments of other authors (e.g. Sud and Fennessy 1984; Cunnington and Rowntree 1986), who not only imposed much larger initial changes to the surface hydrology, and in most cases over a much larger area, but also maintained these differences. They found the large-scale flow to be significantly altered, and the modelled rainfall to be substantially affected for a much longer period of time. Our experiment, done with a fully interactive model of soil wetness, reveals less dramatic changes, but is not in conflict with other studies since it is concerned with the much smaller changes that might be observed when forecasting tropical precipitation in an operational context.

Although the effects on the rainfall forecasts were reduced by day 5, important differences still remained in the moisture distribution and content of the surface soil layer and the model atmosphere, which could have had at least a small influence on the intensity and distribution of rainfall for at least a few more days. During the 5-day integration there was a large difference between the experiments in the diffusion of moisture from the surface to the deep layer, and if at least some of this difference remained in the deep layer (rather than being removed by moisture exchanges with the climatological layer) it too would have continued to affect the rainfall forecasts, through its influence on the surface layer.

This experiment has also revealed the importance of how moisture movement within the soil is modelled. Had a simple ‘bucket model’ of soil moisture been used (such as
that of Cunnington and Rowntree 1986), the greater excess of precipitation over evaporation in the wet experiment would have caused the initially moister surface to have become wetter still, and the surface in the dry case would have dried further relative to the control, i.e. a continuing positive feedback on to the changes made, and a completely different result from that found. However, using a more realistic Deardorff (1978) type parametrization, we produced a negative feedback effect on the anomalies, with the initial differences being absorbed into the lower layers of the soil. Further advances in surface parametrization schemes should continue to improve soil–atmosphere interaction. For example, the scheme currently used by ECMWF, which includes the effects of vegetation and dew deposition, has been found to have a noticeable impact on rainfall forecasts.

The parametrization of soil moisture is just one aspect of numerical models that must be improved in order to move towards useful forecasts of tropical precipitation. Of particular importance is the parametrization of convection (e.g. Slingo et al. 1988) in terms of its ability to respond correctly to the prevailing atmospheric conditions, and also its feedback on the distributions of moisture and temperature. Krishnamurti et al. (1980) found that, given a good analysis, some convection schemes are able to provide useful calculations of rainfall in tropical oceanic areas. However, precipitation forecasting in continental regions is somewhat harder, because of the strong diurnal and spatial variability of surface fluxes, and the influence of orography. Another problem with many convection schemes is that the net accession of moisture is all released in one model time step. This does not allow for excess moisture storage in the boundary layer, which can occur on spatial scales greater than the model grid length and can survive or increase through the population of shallow non-precipitating clouds. In the real atmosphere this is often a preliminary stage to deep convective events, particularly over land. A further weakness of Kuo-type schemes, such as the one used here, is that the partitioning between precipitation and environment moistening is represented through a single parameter (the ‘beta’ parameter), which oversimplifies the interaction between clouds and their environment. A physically more realistic parametrization is given by mass-flux type schemes in which a simple cloud model is embedded. Such a scheme has recently been introduced into the ECMWF operational model, and has had a significant and positive impact on the tropical forecasts (Tiedtke 1989).

Another part of the model in which improvements might be made is the radiation scheme, this being linked to convection through the influence of clouds on radiative transfer. Indeed, the ECMWF physics has evolved towards tighter links between these two aspects. The first step, incorporated in the formulation used here, was to allow convective cloud cover to depend upon the maximum convective precipitation rate over a 3-hour period (Slingo 1987) (the full radiation computation is performed at the end of the same 3-hour period, and this dictates how the radiative forcing responds to the cloud fields). The second, more recent step has been to specify the cloud liquid water content and droplet spectrum according to cloud type (Morcrette 1990a). This enables the model to provide much more realistic inputs of cloud optical properties to the radiation scheme, and also improves the outgoing long-wave radiation field (Morcrette 1990b).

One of the main problems in the tropics (perhaps the major problem) is the lack of data from which to construct the initial conditions for running the model. The sparsity of the conventional observing network is likely to remain, with the main alternative being to make better use of satellite data. The use of such data to initialize numerical prediction models has not yet been fully explored, and many avenues of research remain. This study has looked at the impact that satellite-derived soil wetness maps would have on short-range Sahelian rainfall forecasts, and has shown that locally the forecasts are likely to
be significantly altered. Since the use of satellite information should improve the initial analysis, it is likely that the changes in the resulting forecasts will be at least some improvement. This is expected to be true of other tropical regions, where broadly the same interactions, feedbacks and processes occur. It is recommended, then, that if satellite estimates of surface moisture content become available they should be used in the initialization of forecasting models.

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