The effect of land-surface feedbacks on the monsoon circulation

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**SUMMARY**

The effects of feedbacks from land-surface forcing on intraseasonal monsoon activity are studied by performing idealized sensitivity experiments with a general circulation model. In agreement with observations, the simulated intraseasonal monsoon activity is mainly described by irregular alternations of active spells and break spells associated with fluctuations of the Tropical Convergence Zone (TCZ) between a continental and an oceanic regime. In the model, the spatial characteristic of the intraseasonal monsoon variability is a robust feature which is primarily related to an internal mode of variability of the system, rather than to a response to land-surface feedbacks. Experimentation indicates that the simulation of northward propagating events, related to transitions in the regime, does not require the inclusion of interactive surface hydrological processes. This suggests that the transitions are also mainly related to internal atmospheric dynamics.

The temporal characteristics of the fluctuations between the two TCZ regimes, however, are influenced by an interactive surface. The low-frequency intraseasonal monsoon variability is enhanced by hydrological surface feedbacks. When the surface interacts with the atmosphere, the active and break regimes of the monsoon are equally likely. In the absence of surface feedbacks, the probability distribution is modified and the changes depend on the land-surface conditions imposed. The results show that the probability of a monsoon break exceeds that of an active phase when the imposed land-surface conditions are based on climatological values for July. This asymmetry in the probability distribution affects intraseasonal monsoon variability. In turn, the time-mean monsoon circulation, depending as it does on the statistics of the intraseasonal oscillations (such as frequency of occurrence and mean amplitude), is also modified by the surface feedbacks. It follows that the surface conditions play a role in the interannual predictability of the time-mean monsoon.

**KEYWORDS:** General circulation model Intraseasonal activity Tropical convergence zone

1. **INTRODUCTION**

The physical mechanism for land–atmosphere interaction can be analysed by considering the role of soil moisture in two of the principal cycles of the earth’s climate system—the water cycle and the energy cycle. The most obvious is the role the land surface has in the hydrological cycle. Moisture evaporates from the soil, increasing atmospheric humidity that eventually condenses into clouds whence it may precipitate back to the earth’s surface. The rate of evaporation is a complex function of a number of different parameters, such as the moisture availability in the uppermost layers of the soil, the soil characteristics, the vegetation type and its root distribution, and the near-surface atmospheric conditions. More intricate is the role that soil moisture plays in the energy cycle. The evaporation of soil moisture is tantamount to a flux of latent heat into the atmosphere. Thus, the availability of soil moisture has a strong influence on surface temperature and on the partitioning of incoming radiative energy into sensible and latent heating.

In a global circulation model (GCM), if the soil moisture and snow cover are prognostic variables, the land surface can provide feedback to the atmosphere by altering surface fluxes, in response to precipitation and surface heating. The link between soil moisture and the atmosphere is through surface temperature, evaporation and precipitation. The relationship between soil moisture and evaporation is, however, quite complex and therefore difficult to parametrize. Manabe et al. (1965) were the first

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to incorporate the surface hydrology into a GCM. One of the first, and still widely used, surface parametrization schemes is the so called ‘bucket’ model of Holloway and Manabe (1971). At each grid point, the land surface is represented by a single layer that fills with precipitation, empties by evaporation and may overflow producing runoff. This simple scheme tends to produce an overestimate of evaporation when the soil is wet, and an underestimate when the soil is dry. A number of alternative and more complex schemes have been developed to improve on the bucket model. Most of the recent schemes include several layers in the soil and a more realistic representation of the role of vegetation (Dickinson et al. 1986; Sellers et al. 1986; Viterbo and Beljaars 1995).

Several model studies, using different surface-hydrology schemes, have addressed the importance of the land–atmosphere interaction on the global circulation. Shukla and Mintz (1982) performed two summer integrations with extreme soil-moisture conditions—one with the soil set to saturation and one with dry soil. Significant differences in the global patterns of surface parameters were found. Precipitation in the dry-soil case was much less than in the wet-soil case, except in the Asian monsoon region where precipitation was enhanced. Fennessy et al. (1993) performed experiments in a GCM with interactive soil-moisture using, as initial conditions for soil wetness, either climatological values or proxy observed values derived from the analysis/forecast system of the European Centre for Medium-Range Weather Forecasts (ECMWF). They showed that integrations with the proxy observed initial soil-wetness produced a more realistic simulation of the 1988 drought in north America than integrations with climatological values of initial soil-moisture.

In the Asian summer-monsoon region, the atmospheric circulation is particularly sensitive to land-surface forcing. The Asian monsoon interannual variability may be influenced by the anomalous state of seasonal land-surface conditions such as snow cover and soil moisture over the Eurasian continent (Barnett et al. 1989; Yasunari et al. 1991; Meehl 1994). Several authors have discussed a statistical relationship between Eurasian snow cover in winter and Indian monsoon rainfall in the following summer (e.g. Blandford 1884; Hahn and Shukla 1976; Dickson 1984; Shukla 1987; Sankar-Rao et al. 1996; Yang 1996). These anomalous surface-conditions are provided mainly by an anomalous mid-latitude westerly flow regime during the preceding winter and spring (see, for example, Webster and Yang 1992; Ju and Slingo 1995). In this sense, the land-surface forcing in the boreal summer plays an important role, over this particular region, by conveying signals from the extratropics to the tropics (Yasunari 1994).

Several modelling studies (e.g. Walker and Rowntree 1977; Shukla and Mintz 1982; Xue and Shukla 1993) have underlined the importance of the surface characteristics of the continental land masses in determining the structure of the monsoons. In particular, soil moisture is considered to be an active component in the evolution of the monsoon system and it requires careful modelling. Soman et al. (1994) showed an improvement of the simulated monsoon circulation when a ‘no flux’ boundary-condition was introduced in the surface parametrization. They found that, with the fluctuations in soil temperatures determined from the energy input, the monsoon flow in the lower and upper troposphere and the intraseasonal monsoon variability were enhanced.

The intraseasonal monsoon variability can be considered as alternations between the active and break monsoon spells associated with the TCZ continental and oceanic regimes. Some studies have suggested that the oscillation between the two regimes is related to the interaction between organized convection and dynamics (Goswami and Shukla 1984; Gadgil and Srinivasan 1990; Najundiah et al. 1992), indicating that these intraseasonal monsoon oscillations represent internal modes of the system.
Webster (1983), and subsequently Srinivasan et al. (1993), suggested that moist processes at the surface of the continents could introduce feedbacks resulting in intraseasonal monsoon variability. The hypothesis was that the interplay between ground hydrology and the atmospheric circulation did not allow the system to reach an equilibrium, and that the northward propagation of convection was the result of such instability. To test this hypothesis, Webster (1983) used a zonally symmetric atmospheric model coupled to a mixed-layer ocean and a simple surface hydrological system. He showed that the existence of northward propagation depends upon the representation of an interactive surface hydrological system. Using the same model, Srinivasan et al. (1993) studied the sensitivity of the period of the propagating events to the parametrization of the ground hydrology.

Ferranti et al. (1997) suggested that the interannual variability of the mean monsoon circulation is influenced by the temporal and spatial characteristics of the intraseasonal modes. Their results give support to a non-linear paradigm, proposed by Palmer (1994), which is based on the assumption that the intraseasonal fluctuations between active and break spells are intrinsically chaotic. In this picture, interannual variability of the mean monsoon is governed by the frequencies of occurrence of the continental and oceanic regimes.

It is of great interest, therefore, to analyse the factors that can modulate the structure and temporal characteristics of the active/break cycles. As one possible factor, the present study investigates the land–atmosphere feedbacks on the monsoon intraseasonal variability.

The experimental design is described in section 2. In section 3, the impact of land–surface interaction on the mean and on the variability of the monsoon circulation is discussed. Section 4 deals with the effect of the land–atmosphere interaction on the oscillation between active and break monsoon spells. The evolution of surface parameters over India is analysed in section 5. Implications of the results are discussed in section 6.

2. Experimental design

The purpose of the present study is to elucidate the role of land-surface feedbacks in determining the intraseasonal behaviour of the monsoon. In order to remove other possible effects associated with the annual cycle and with the boundary conditions over the oceans, simulations in ‘perpetual July’ mode have been performed. These idealized simulations also have the advantage of providing a sufficiently long unbroken series for the month of July using a relatively short period of integration.

Perpetual January and perpetual July simulations have been used extensively as a laboratory tool to investigate different aspects of general circulation models (GCMs). For example, Slingo et al. (1994) used perpetual January conditions to describe the model’s tropical time-mean climate, its variability and its sensitivity to convection parametrization; Schlesinger and Oh (1993) tested a cloud-evaporation parametrization by performing an ensemble of perpetual July and perpetual January simulations; Ose et al. (1994) studied the GCM sensitivity to two different sea surface temperature (SST) data-sets by using perpetual January integrations.

To simulate perpetual July, the orbital parameters were kept fixed throughout the whole integration, at their value on 1 July. The initial conditions for SST and soil moisture were climatological values for July computed from the ECMWF re-analysis data set (Gibson et al. 1995). The SSTs were maintained at their July climatological
values throughout both integrations. When the integrations were made, the full reanalysis data-set from 1979 to 1993 was not available. Consequently, the soil-moisture climatology was based on the period July 1979 to July 1984, while the SST climatology was the mean for July 1986 to July 1993. Differences between the SST climatology used in the integrations and the SST climatology for the whole re-analysis period are small, especially over the Pacific Ocean, Arabian Sea and Indian Ocean. The soil-moisture climatology used in the integrations is slightly dryer over the Western Ghats, Sri Lanka and Indonesia than that for 1979–1993. Considering the idealized nature of the simulations, these differences in the climatologies are not thought to be significant.

Figure 1 shows the climatology of soil wetness in the root zone used in the perpetual July integrations, expressed as a percentage of the soil water available for evaporation. The areas where this percentage is between 25 and 50 are represented by the lightest stippling. The darkest areas are the wettest, with more than 100% of soil water available for evaporation.

In one simulation, the ‘prescribed soil-wetness’ (PSW) simulation, the land–atmosphere feedbacks are inhibited (by maintaining July climatological values of the soil moisture everywhere throughout the integration). In a second ‘interactive soil-wetness’ (ISW) simulation, the land surface interacts with the atmosphere in the zonal band between 40°N and 40°S. As Zwiers and Boer (1987) showed, applying land–surface interaction to this limited near-tropical band gives a more realistic mean climate at higher latitudes in the northern hemisphere than does applying it globally. In particular, it avoids an excessive dryness of the surface there in response to the persistent July insolation. In both simulations, the surface temperature is allowed to evolve according to the meteorological conditions.

The atmospheric model used in the present study is the ‘Integrated Forecast System’ (IFS version 13r4) which was used in operational forecasting at ECMWF at T213 resolution from April 1995 to January 1996 (Courtier et al. 1991; Hortal and Simmons 1991; Ritchie et al. 1995). Since this model is also the basic version for the reanalysis,
the surface fields derived from the reanalysis which define the boundary- and initial-conditions for the perpetual July simulations are compatible. The surface parametrization is that of Viterbo and Beljaars (1995). For temperature and moisture, the scheme has four prognostic layers in the soil. The bottom boundary conditions are zero heat-flux and free drainage. The integrations are made at triangular truncation T63 with 31 vertical levels. Both simulations are integrated for 390 days, which is long enough in perpetual July mode to give a reasonable description of the intraseasonal variability. In order to eliminate most of the spin-up effects, the first 30 days of the integrations are discarded and only the subsequent 360 days are included in the following analysis.

3. EFFECT OF LAND-SURFACE FEEDBACKS ON THE MEAN CIRCULATION AND ITS VARIABILITY

(a) Mean circulation

The impact of the land-surface interaction on the mean monsoon flow is analysed by comparing the mean precipitation with the lower and upper tropospheric mean circulation from the two integrations. Figure 2 shows the precipitation averaged over 360 days for the ISW and PSW simulations, and for the difference between the two. The mean distribution of rainfall for the ISW integration (Fig. 2(a)), typical of the established monsoon period, shows precipitation over almost all of the Indian subcontinent, over the Bay of Bengal, and over the Indian Ocean. In the PSW simulation (Fig. 2(b)), most of the rainfall is over the Indian Ocean while the subcontinent is relatively dry, indicating a phase locking into the monsoon-break/oceanic-regime of the TCZ. The difference panel (Fig. 2(c)) shows that the main effect of the interactive land-surface is an enhancement of rainfall over the Indian subcontinent and the Arabian Sea, accompanied by a relatively smaller decrease of precipitation over the equator. In both integrations, the rainfall is systematically underestimated over Thailand.

The statistical level of significance associated with the precipitation differences between the ISW and PSW simulations has not been evaluated. However, the amplitudes shown in Fig. 2(c) are larger than the differences between the seasonal means in the five Atmospheric Intercomparison Project (AMIP) runs discussed by Ferranti et al. (1997) which differed only in their initial conditions.

Figure 3 shows the differences in mean wind and divergence given by the two simulations. Figure 3(a) shows the differences for 200 hPa and Fig. 3(b) for 850 hPa. Figure 3(c) shows the low-level mean wind at 850 hPa given by the ISW integration. The upper-level differences (Fig. 3(a)) show a region of divergence between 25°N and 8°N and convergence south of 8°N. The lower-level differences (Fig. 3(b)) exhibit an increased convergence over the Western Ghats area and northern India, consistent with the precipitation differences seen in Fig. 2(c). This dipole pattern, evident at both levels, suggests that land–atmosphere interactions reinforce the local Hadley circulation over India, implying a more intense monsoon circulation.

The mean monsoon flow at 850 hPa with interactive land-surface (Fig. 3(c)) shows strong westerly winds across India, decreasing in intensity towards south-east Asia. The simulated July mean monsoon circulation at both 200 and 850 hPa compares well with the ECMWF re-analysis climatology for the monsoon season given by Annamalai et al. (1999). This suggests that the technique of using perpetual July simulations with fixed soil-moisture in middle and high latitudes is largely successful.

The availability of soil water for the root zone was averaged throughout the ISW integration and is shown in Fig. 4. Over the Indian subcontinent, the soil is wetter than in the climatology shown in Fig. 1, consistent with the enhanced rainfall seen in
Figure 2. Mean precipitation (mm d$^{-1}$): (a) values from interactive soil-wetness (ISW) simulation; (b) values from prescribed soil-wetness (PSW) simulation; (c) difference between (a) and (b). For (a) and (b), contours are for 1, 4, 8, 16 and 32 mm d$^{-1}$ with graduated stippling above 4 mm d$^{-1}$. For (c), contours are for ±1, ±4, ±8, ±16 and ±32 mm d$^{-1}$, with stippling above +1 mm d$^{-1}$.
Figure 3. Mean wind: vector differences in values given by the interactive soil-wetness (ISW) and prescribed soil-wetness (PSW) simulations (a) at 200 hPa and (b) at 850 hPa; (c) 850 hPa from the ISW integration. Arrows denote the vector wind on the separate scales shown for each panel. Contours of divergence in (a) and (b) are at intervals of $2 \times 10^{-6}$ $s^{-1}$, with negative values pecked and the zero contour suppressed. In panel (c), light stippling denotes wind speeds in the range 5–10 m $s^{-1}$, and heavier stippling wind speeds greater than 10 m $s^{-1}$. 
Fig. 4. Mean percentage of soil water available to the root zone in the ISW simulation. Light grey stippling denotes 25–50%, grey 50–75%, dark grey 75–100%, and black more than 100%.

Fig. 5. Mean difference in surface temperature between the interactive soil-wetness (ISW) and prescribed soil-wetness (PSW) integrations. Contour interval 1 K, with the zero contour suppressed. Pecked contours denote negative values. Graduated stippling begins above a mean difference of 1 K.

Fig. 2(c). Over Thailand, by contrast, the soil is much dryer than the corresponding climatological values. In the PSW case the model does not respond to the wetter soil by producing precipitation. This is probably because, over this region, the surface in the PSW simulation (as suggested by Fig. 5) is relatively cool compared to the surroundings.
Surface temperature differences between the ISW and PSW simulations are given in Fig. 5. In the Asian summer monsoon region, the largest temperature differences are over Thailand and the south coast of China. In the ISW simulation, these regions are about 5 K warmer than in the PSW integration, implying a strengthened land–sea thermal contrast east of 90°E. In the Ganges plain, the temperature differences are small, despite the large increase of soil moisture in the ISW experiment (Fig. 4). The cooling effect of increased soil water is noticeable in Pakistan, where, in the ISW integration, the temperature is about 3 K lower than in the PSW; to a lesser extent, the same is true over western India.

(b) Variance distribution

We investigate the effect of land–atmosphere interactions on monsoon intraseasonal activity by analysing the time variability of precipitation. Figure 6(a,b) shows the standard deviations of precipitation for the two simulations. The differences are largest where the mean precipitation has relative maxima (Fig. 2). Over the Bay of Bengal,
despite similar mean precipitation, the variance from the ISW simulation is about 50% larger than that from the PSW run.

The land surface interacts with the atmosphere via surface evaporation, with timescales that depend on soil type, vegetation cover and meteorological conditions. The ECMWF surface model has 152 mm of water in the root layer available for evaporation (Viterbo and Beljaars 1995). For a typical summer value of net radiative forcing at the surface of 150 W m$^{-2}$ (the energy equivalent of 5 mm day$^{-1}$ of evaporation), the soil reservoir would dry out in 30 days, suggesting an evaporative timescale of a month. The effect of the land-surface interaction may therefore be apparent mainly at low frequencies.

Since the dominant periods of intraseasonal monsoonal activity lie between 10–20 days and 30–60 days (see, for example, Gadgil and Asha (1992)), the standard deviations of precipitation have been partitioned into two components: one corresponds to ('high-frequency') fluctuations with period shorter than 30 days and the other to ('low-frequency') fluctuations with period longer than 30 days and the other to ('low-frequency') fluctuations longer than 30 days. The high-frequency variability (not shown) does not exhibit large differences between the two experiments. Figure 6(c,d) presents the percentage of the precipitation variability associated with low frequencies for ISW and PSW. Consistent with the total variance distributions (Fig. 6(a,b)), the ISW integration shows enhanced low-frequency variability over the Bay of Bengal and over the coast of Myanmar (90°E–100°E, 10°N–20°N) compared with the PSW simulation. Over India, where there is the largest mean rainfall difference (see Fig. 2(c)), the percentages associated with low-frequency variability are similar, implying that the effect on the variance distribution is not necessarily related to the change in the mean values.

4. Effect of land-surface feedbacks on the monsoon oscillations

(a) Empirical orthogonal function analysis

In previous sections, we have discussed the impact of land-surface processes on the mean circulation and low-frequency variability over the Asian summer monsoon region. The present section focuses on the effects of the interactive surface hydrology on the dominant modes of the monsoon intraseasonal variability.

The spatial structure of the dominant components is studied by performing an empirical orthogonal function (EOF) analysis of daily precipitation values for each integration. The leading EOF modes from the two simulations are then compared.

The temporal modulation effect of the land surface is analysed by considering the time characteristics of the first EOF from the ISW simulation and its projections on to the daily precipitation fields from the PSW integration.

(i) EOF analysis of ISW integration. The leading EOF from the ISW simulation describes 17.5% of the total daily precipitation variance; it is the dominant mode of variability since it explains more than twice the variance associated with the next EOF. Its distribution (Fig. 7) shows one band of anomalous rainfall extending from 25°N to 10°N, and the other band, with opposite sign, lying between 10°N and 10°S. This zonal structure is suggestive of the two preferred locations for the TCZ discussed earlier which correspond to the active/break cycles of the monsoon circulation. Positive values of the time coefficient of the first EOF are associated with active monsoon spells, whereas negative values correspond to break spells.
Such a mode is very similar to that found in the AMIP integrations (see Ferranti et al. (1997)) where both seasonal and interannual variability were simulated. Interannual variability is not simulated in the present integration, so there is no possibility that it has projected on to the intraseasonal variability.

Annamalai et al. (1999), studying the monsoon from two different re-analysis data sets (ECMWF and the United States' National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR)), showed that intraseasonal variability has a flatter spectrum than the interannual counterpart. In their study, the intraseasonal lowest EOF explains only about 10% of the variance whereas the first two dominant interannual modes describe about 50%. The present EOF analysis indicates a similar variance distribution for the model intraseasonal fluctuations.

Spectral analysis of the PCI time series indicates that the dominant mode mainly describes the low-frequency (>30 days) behaviour of the monsoon, again consistent with the results of Annamalai et al. (1999).

In order to visualize the monsoon active and break periods, described by this pattern, we have averaged, separately, all the cases with time coefficient greater than one standard deviation (> +s) and all the cases with time coefficient less than minus one standard deviation (< −s). The corresponding precipitation composites (Fig. 8) show an almost total shift of precipitation between the two preferred locations of the TCZ, similar to the composites of active/break cycles found by Webster et al. (1998).

The spatial structure of the active and break phases, based on compositing pentad fields from the Global Precipitation Climate Project (GPCP) (Huffman et al. 1995), is shown in Fig. 9. During the active phase (Fig. 9(a)) the maximum rainfall is positioned over the Bay of Bengal, the coast of Myanmar and southern India. This distribution is well represented by the ISW integration (Fig. 8(a)). The break phase (Fig. 9(b)) is characterized by a rainfall maximum over the equatorial Indian Ocean, and is also well simulated by the model (Fig. 8(b)), although the precipitation reduction over the Bay of Bengal and the coast of Myanmar in the model is too strong.

Despite the fundamental differences between the set-up of the integrations for the AMIP discussed by Ferranti et al. (1997), and the present idealized simulations,
the leading EOF pattern in Fig. 7 is spatially correlated with their first canonical correlation (CCA) precipitation mode (Fig. 3.8(a) of Ferranti et al. (1997)). This similarity suggests two points. Firstly, the zonal structure of the dominant mode of the monsoon intraseasonal variability is not strongly model-version-dependent since it is detected in two very different experimental set-ups using different versions of the same ECMWF model. Secondly, the spatial structure of the dominant mode of intraseasonal variability is not dependent only on the SST forcing. Indeed, similar spatial characteristics are also found in the perpetual July integrations with climatological boundary conditions and in the AMIP integrations. This supports the idea, discussed by several authors (Goswami and Shukla 1984; Gadgil and Srinivasan 1990; Nanjundiah et al. 1992), that active/break monsoon spells associated with fluctuations between the two favourable locations of the TCZ are mainly a manifestation of an internal mode of variability of the system.

(ii) **EOF analysis of PSW integration.** EOF analysis applied to the daily precipitation data from the PSW simulation reveals two dominant modes of variability, explaining 12.6% and 10.9% of the total variance. The first pattern (EOF1, Fig. 10(a)), despite having most of its amplitude over the Indian ocean, shows a zonal structure with a weak positive anomaly between 5°N and 20°N and a strong negative anomaly between 5°N and 10°S. The second pattern (EOF2, Fig. 10(b)) has its maxima near the zeros of the first. This suggests that the two EOFs may describe two distinct phases of the same oscillation, provided that there is a non-random lag-correlation function between the two corresponding principal components.

The correlation between the first two principal components, \( C_1(t) \) and \( C_2(t) \), computed as a function of various lags gives a maximum absolute value for a lag--lead of about 5 days, although the values are less than 0.5. This suggests that the first two leading EOFs describe an oscillation with an average period of about 20 days. A four-component composite of precipitation, computed by selecting those days when \( C_2 > s_2, C_1 > s_1, C_2 < -s_2 \) and \( C_1 < -s_1 \) is shown in Fig. 11. Here \( s_1 \) and \( s_2 \) denote the standard deviations of the coefficients \( C_1 \) and \( C_2 \) respectively.

Viewing it as an oscillation with phases going from panel (a) to panel (d), Fig. 11 mainly describes the meridional movement of the TCZ over the ocean. During the active phase (Fig. 11(b,c)), there is a rainfall anomaly of 3 to 4 mm d\(^{-1}\) over the Indian
Figure 9. Monsoon precipitation composite from Global Precipitation Climate Project (GCPC) data (mm d\(^{-1}\)):
(a) active phase; (b) break phase. Graduated stippling begins above 4 mm d\(^{-1}\).

subcontinent, whereas, during the break phase (Fig. 11(a,d)), over the Indian Ocean
the anomaly exceeds 16 mm d\(^{-1}\). This indicates that the symmetry in the amplitude of
rainfall between active/break spells, observed in the ISW simulation (Fig. 8(c)), is not
present in the PSW integration. As a consequence, the dominant oscillation (Fig. 11)
is biased towards the break monsoon regime, consistent with the reduction of the mean
monsoon rainfall shown in the previous section (Fig. 2).

Time-lagged composite maps (not shown), computed as an average of the fields that
occurred 5 days later than the fields in each of the panels of Fig. 11, indicate that the
alternation between the two leading EOFs is a definite component of the intraseasonal
variability in the PSW simulation.

The comparison between the two dominant oscillations from the ISW and PSW
simulations, suggests that land–atmosphere interaction plays an important role in parti-
tioning the intraseasonal monsoon variance among the most dominant modes. However,
the zonal pattern of the active and break monsoon phases related to the continental and oceanic TCZ regimes appears to be a common feature of both simulations. This indicates that the impact of surface hydrology on the spatial structure of the dominant mode of variability is not such as to alter the major features of the monsoon active-phase regimes.

(b) Modulation of temporal characteristics by the land-surface processes

In order to compare the time characteristics of the dominant modes of monsoon variability between the two simulations, we used a ‘reference’ spatial pattern, representative of the monsoon active/break phases. Since the zonal structure of the leading EOF pattern from the ISW simulation describes the observed spatial characteristics of
the active/break monsoon spells fairly well, we considered the ISW simulation as the 'control' integration, and used its leading EOF pattern as the reference mode.

We computed projections of daily precipitation fields from the PSW integration on to this reference mode. The percentage of PSW variance explained by the reference mode is only 8%, implying that projections on to it represent the temporal modulation associated with the land-surface processes only partially.

Figure 12 shows the time coefficient of EOF, from the ISW (solid line) and the projections of the daily precipitation fields from the PSW (pecked line). Time fluctuations of the reference mode display longer periods in the ISW than in the PSW simulation and might therefore explain the differences in the low-pass standard deviations (Fig. 6). The ISW experiment shows an increase of low-frequency variability over the Bay of Bengal (Fig. 6), the region where the EOF1 pattern has the largest loading (Fig. 7). In the following section, additional evidence is presented to support the hypothesis that ISW changes the temporal characteristics of intraseasonal variability.

The two leading principal components of the PSW integrations (not shown) fluctuate around zero with slightly higher frequency than the fluctuations of the first principal component of the ISW simulation (solid line in Fig. 12). Their probability density functions (PDFs) are unimodal and centred around zero.

PDFs of the reference mode for the ISW (solid line) and for the projections on to it of PSW daily fields (pecked line) are shown in Fig. 13. The PDF for the ISW integration exhibits a weak bimodality which indicates that the transition time between the two regimes is faster than the residence time. The PDF for the PSW experiment is unimodal and biased towards negative values. This indicates that the probability of occurrence of
the monsoon-break regime is larger than that for the active-monsoon regime. This is consistent with reduced mean monsoon rainfall over India in PSW (shown in section 3), and with the structure of the dominant oscillation (Fig. 11) in PSW which itself is somewhat biased toward the break monsoon regime).

(c) Northward propagation

In order to investigate the extent to which northward-propagating events in the model are sensitive to the land-surface interaction, we compared time-lagged correlations of precipitation between the two simulations. For data averaged between 80°E and 100°E, time-lagged correlations were computed between each point and all the other points in the latitudinal band 30°N–50°S. Such a method was used by Ferranti et al. (1997) and efficiently separates the northward-propagating events from other components of the precipitation variability. Figure 14 shows the time-lagged correlation between the precipitation at 10°N with all the other points for the ISW and PSW simulations. The tilting from south-west to north-east of the isopleths of positive correlation is indicative of northward propagation. In the ISW simulation the northward propagation
of precipitation does not extend polewards of 20°N, whereas in the PSW integration it reaches higher latitudes.

The time-lagged correlations for all latitudes (not shown) indicate the existence of northward propagation between 4°N and 15°N in both simulations. The average speed of propagation is around 1 degree of latitude per day for both integrations.

In contrast to the results of Webster (1983), the GCM simulations presented here suggest that the existence of northward-propagating events does not depend on the representation of land–atmosphere interaction. However, their temporal characteristics are affected by the surface–atmosphere feedbacks, a point which will be further developed in section 5.
5. Effect of Land-Surface Feedbacks on the Evolution of Surface Parameters over India

Since the purpose of this section is to investigate the impact of temporal fluctuations in soil wetness on the monsoon variability, the following analysis is confined to land areas. India, one of the main continental areas of the Asian summer monsoon, is chosen to be representative of the effect of the land–atmosphere interaction. The time-mean surface parameters averaged over India from both integrations are given in Table 1.

The mean precipitation in the ISW simulation is larger than that for the PSW, consistent with the mean maps shown in Fig. 2. Associated with enhanced precipitation, a lower value of surface solar radiation is found, implying an increased cloudiness. In turn, the lower solar radiation leads to a reduction of the latent-heat flux despite the increase in precipitation. Consistent with the increased precipitation, the soil is wetter and slightly cooler when the land-surface feedbacks are considered.

In order to visualize the evolution of the surface conditions over India, different surface parameters have been analysed. For example, daily series of surface sensible- and latent-heat fluxes and surface solar radiation (not shown) indicate that the fluctuations of the sensible-heat flux and latent-heat flux are in phase opposition to the solar radiation variations. This implies that the fluctuations of these terms are such as to satisfy the energy balance at the surface. A positive correlation (not shown) between the cloud cover and the precipitation is also noted.

Series of Indian precipitation anomalies for the ISW and PSW integrations, are presented in Fig. 15. The ISW series (Fig. 15(a)) exhibits a greater low-frequency component than that for PSW (Fig. 15(b)). This is consistent with the results from the reference mode projections (Fig. 12) discussed previously. It is also seen that the amplitude of the fluctuations in precipitation is larger when the land and atmosphere interact.

For the ISW integration, Fig. 16 shows the evolution of the soil-water content over India, for the surface (solid line), root (dotted line), and deepest layers (pecked line). The dotted straight lines correspond to the field capacity and permanent wilting point values which represent, respectively, the unstressed and maximum stressed transpiration in the ECMWF model. The interval between these two values is the water content available at the surface.

The water fluctuations at the surface and in the root layer follow the variations of precipitation, while the soil water in the deepest layer varies on much longer timescales. The water in the root zone oscillates around the maximum value with a period of about

<table>
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<tr>
<th>TABLE 1. Time-mean Values of Surface Parameters Averaged over India (10°N–24°N, 70°E–90°E Land Points Only) for the ISW and PSW Simulations</th>
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</thead>
<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>----------------------------------</td>
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<tr>
<td>Precipitation (mm d⁻¹)</td>
</tr>
<tr>
<td>Short-wave radiation (W m⁻²)</td>
</tr>
<tr>
<td>Surface latent-heat flux (W m⁻²)</td>
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<td>Bowen ratio</td>
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<tr>
<td>Surface temperature (K)</td>
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<td>Top-layer soil water (m³m⁻³)</td>
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<td>Root-layer soil water (m³m⁻³)</td>
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<td>Bottom layer soil water (m³m⁻³)</td>
</tr>
</tbody>
</table>
Figure 15. Daily series of precipitation anomalies over India (mm d$^{-1}$): (a) for the interactive soil-wetness (ISW) simulation; (b) for the prescribed soil-wetness (PSW) simulation.

Figure 16. Daily series of soil wetness (m$^3$ m$^{-3}$), averaged over India, for the surface layer (solid line), for the root zone (dotted line) and for the deepest layer (pecked line).
40 to 60 days. The plant canopy over this region is hardly under stress during the whole simulation period.

The power spectra of precipitation and soil wetness in the root zone (Fig. 17) show that the soil-moisture fluctuations correspond to a low pass filtered version of the precipitation in agreement with the statements of several authors (Delworth and Manabe 1988; Milly and Dunne 1994; Viterbo and Beljaars 1995). Differences in the spectra of precipitation between the ISW and PSW integrations indicate that the surface interaction enhances the low-frequency component of the atmospheric variability.

Under suitable approximations, it can be shown that the soil-wetness fluctuations are regulated by the amount of precipitation minus surface runoff, through an exponential decay term and a nonlinear term (see Ferranti 1997). The exponential term represents the damping due to potential evaporation. The nonlinear term describes the vertical transfer of water between the root zone and the deeper soil layers. When the deeper layer is drier (wetter) than the root zone, the water flux is downwards (upwards). In dry conditions with low conductivity, this term can introduce longer timescales than those associated with the evaporation effect.
A simple estimate of the damping due to the evaporation is given by using the Budyko definition of potential evaporation \( (E_p = R_{\text{net}}/L) \), where \( R_{\text{net}} \) is the net downward radiative flux at the surface and \( L \) is the latent heat of evaporation \( (=2.5 \times 10^6 \text{ J kg}^{-1}) \). The potential evaporation value, computed by using characteristic values of the net radiative flux over India \( (R_{\text{net}} = 120 \text{ W m}^{-2}) \) is equal to \( 48 \times 10^6 \text{ kg m}^{-2} \text{s}^{-1} \). We take the mass of water available for transpiration per unit area as \( 152 \text{ kg m}^{-2} \), and estimate the evaporation damping as \( 48 \times 10^{-6} \text{ kg m}^{-2} \text{s}^{-1}/152 \text{ kg m}^{-2} = 0.31 \times 10^{-5} \text{s}^{-1} \), corresponding to a timescale for decay of about 37 days.

An independent estimate of the timescale associated with evaporation, using the values for the latent-heat flux and the root-layer soil-moisture listed in Table 1, gives a similar value. Over India, the mean latent-heat flux is 93.6 W m\(^{-2}\), equivalent to 3.3 mm d\(^{-1}\), and the root-layer available soil-water is 130 mm. The timescale under which the soil would dry as a result of evaporation is then estimated to be 39 days.

The contribution of the nonlinear term involving the fluxes of moisture between soil layers is estimated by using the mean values of soil wetness in Table 1. Since the mean soil-wetness in the root layer is close to the field capacity, the values of hydraulic diffusivity and conductivity are chosen to be those for conditions when more than 67% of soil moisture is available (see Viterbo and Beljaars (1995) and Table D.1 of Ferranti (1997)). These parameters imply a timescale of about 48 days.

In conclusion, over India the estimated timescales associated with both evaporation and the vertical water-transfer have values between 35 and 50 days, consistent with the typical period of the fluctuations of the water in the root zone shown in Fig. 16.

Delworth and Manabe (1988), in a study of the temporal variability of soil moisture from the Geophysical Fluid Dynamics Laboratory (GFDL) model with a simple ‘bucket model’ surface scheme, showed that their formulation of soil-moisture parametrization is mathematically similar to a stochastic process. According to their model, forcing of a system by an input white-noise variable (such as precipitation) will yield an output variable (soil moisture) with a red spectrum, the redness of which is controlled by a damping term that is proportional to the potential evaporation. They found a decay timescale over India of between one and two months which does not conflict with the present result.

6. DISCUSSION AND CONCLUSIONS

In this study, the effects of land-surface hydrological feedbacks on the simulated monsoon circulation have been analysed. In particular, two perpetual July simulations have been studied, one with soil moisture prescribed to climatological values and one using soil moisture as a prognostic variable.

Despite the idealized nature of these integrations, the simulated time-mean monsoon climate is quite realistic. Mean differences between the two integrations indicate that surface-hydrology feedbacks into the atmosphere are essential to representing a realistic amplitude of monsoon rainfall over India in this model.

An EOF analysis, performed separately for each integration, reveals that the leading modes of intraseasonal variability all show the typical signature of active/break monsoon spells associated with the TCZ continental/oceanic regimes.

However, the characteristics of the time fluctuations between the two regimes are influenced by an interactive hydrology. When the surface hydrology interacts with the atmosphere, the two regimes are equally likely. In the absence of surface feedbacks, the oceanic TCZ regime becomes more likely than the continental TCZ regime. This
asymmetry in the probability distribution affects the intraseasonal monsoon-variability. In turn, the time-mean monsoon circulation, which depends on the statistics of the intraseasonal oscillations (such as frequency of occurrence and mean amplitude), is also significantly modified by the surface feedbacks. Consistent with the greater likelihood of the oceanic TCZ regime, a reduction in mean monsoon rainfall over India is observed in the simulation where the soil-wetness values are fixed.

It is possible that the prescription of different soil-wetness values, for example using climatological values for May, would produce a different PDF for the TCZ regimes. Whereas the PSW integration showed a bias towards the oceanic regime, a bias towards the continental regime could be produced.

In a paradigm proposed by Palmer (1994), the active and break periods are associated with the two regimes of the model of Lorenz (1963), and the seasonal-mean monsoon rainfall comprises aperiodic active and break spells with a symmetric PDF between the two regimes. When a particular forcing is applied to the system, the PDF changes so that one regime becomes more probable than the other. As a consequence, although the monsoon continues to fluctuate periodically between active and break spells, the seasonal mean is biased towards the most populated regime. Palmer (1994) proposed that it is principally the lower boundary forcing, such as that associated with SST anomalies, which influences the probability of occurrence, without affecting the structure of the regimes themselves.

In the context of this picture, with the land–atmosphere interaction considered as the 'external' forcing, the above results can be interpreted as follows. Firstly, the spatial structures of the monsoon regimes are mostly related to internal dynamics rather than to surface hydrology feedbacks. The existence of regime transitions is also not strongly dependent on the surface interaction. Secondly, the large difference between the PDFs from the two integrations, suggests that the external forcing can change the probability of occurrence of the regimes quite dramatically. Here the land–atmosphere interaction is the external forcing which may be essential to make the probability of occurrence of the TCZ regimes symmetric. It follows that this interaction is crucial for monsoon intraseasonal variability and for the predictability of the mean monsoon circulation.

The interaction between land surface and atmosphere has an important impact on the frequency of monsoon variability. For example, analysis of variance shows that the surface hydrology enhances the low-frequency precipitation variability over the Bay of Bengal and over the coast of Myanmar.

The analysis of temporal fluctuations of both precipitation and soil-wetness over India reveals that the soil-moisture fluctuations correspond to low-pass-filtered fluctuations of the precipitation. The potential evaporation and vertical water-transfer between soil layers are the physical mechanisms which control the filtering timescales.

A simple mathematical picture for this increase in atmospheric low-frequency variability can be described using the Lorenz model ‘coupled’ to a simple storage device (Palmer 1996) which in this context represents the hydrological processes. The storage device, having a form of a red-noise process, is able to introduce ‘memory’ into the system without affecting its time-mean state.

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REFERENCES


Delworth, T. L. and Manabe, S. 1988 The influence of potential evaporation on the variabilities of the simulated soil wetness and climate. *J. Clim.*, 1, 523–547


Ferranti, L. 1997 ‘The Asian summer monsoon and its predictability’. Thesis submitted for the degree of Doctor of Philosophy, University of Reading, UK


Gibson, J. K., Hernandez, A., Källberg, P., Nomura, A., Serrano, E. and Uppala, S. 1995 ‘The ECMWF re-analysis (ERA) project—plans and current status’ in proceedings of the Seventh AMS Symposium on Global Change Studies, AMS, Boston, USA


On the relationship between Eurasian snow cover and the Asian summer monsoon. *Int. J. Climatol.*, 16, 605–616


A simple biosphere model (SiB) for use within general circulation models. *J. Atmos. Sci.*, 46, 2757–2782


'The simulation of the Indian monsoon in a seasonal integration of UGCM and its sensitivity to convective and land surface parametrization'. UGAMP Tech. report No. 36, University of Reading, UK


An improved land surface parametrization scheme in the ECMWF model and its validation. *J. Clim.*, 8, 2716–2748


ENSO—snow—monsoon associations and seasonal interannual predictions. *Int. J. Climatol.*, 16, 125–134

