Numerical experiments on the sensitivity of the monsoon circulation to differential heating

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SUMMARY

Some numerical simulations from real data were carried out to examine the response of the monsoon circulation to moist processes. Two cases were selected: one for the monsoon onset and the other for the active (fully established) period. The results show that latent heat is the main feed-back process in the monsoon circulation. The south-west monsoon current from the Arabian Sea to the South China Sea in the lower troposphere and the easterly jet stream over southern Asia in the upper troposphere are greatly enhanced by this process both in the onset and active periods. The surface latent heat flux (mostly over the ocean) is important in the maintenance of the circulation during the active period but is less important for the onset.

1. INTRODUCTION

During the development of the summer monsoon circulation over the Asian and southern African continents two main features appear: at low levels there is a south-westerly flow over the Arabian Sea with a strong northward cross-equatorial current extending eastwards to the South China Sea and the west Pacific, while in the upper troposphere a broad band of east to north-east winds flows from the South China Sea across the whole of the tropical ocean into Africa (Ramage and Raman 1972). The mechanism for the development of such a broad-scale circulation is still not well understood.

Krishnamurti and Ramanathan (1982) (hereafter referred to as KR) studied in detail the link between differential heating and the evolution of the monsoon circulation, and showed with numerical experiments the sensitivity of the monsoon onset to the initial fields of differential heating. Ji and Tibaldi (1984) carried out a series of numerical experiments to investigate the influences of the Tibetan Plateau, of the southern hemisphere circulation and of diabatic heating on the seasonal change of the general circulation over Asia in summer 1979. They pointed out that the field of differential heating seems to be of primary importance for the establishment and maintenance of the major components of the monsoon circulation. Recently Pearce and Mohanty (1984) (hereafter PM) analysed the moisture and enthalpy budgets of the monsoon. The evolution of the circulation was divided into three phases. Two phases are in the onset period, i.e. a moisture build up over the Arabian Sea during which synoptic and mesoscale transient disturbances develop, followed by a rapid intensification of the Arabian Sea winds associated with a substantial increase in latent heat release, essentially a large-scale feedback process. The third phase is the fully established period in which the circulation is maintained by latent heat release over a large region between 10° and 20°N, with moisture supplied by evaporation from the Indian Ocean.

The aim of this study is to clarify the response of the monsoon circulation to the latent heat release and surface evaporation both in the onset and active (fully established) stages. A set of numerical experiments was designed to test those effects. Table 1 gives a list of the experiments for the case of onset (O . . .) and active (A . . .) periods. The following sections are devoted to an examination of the results of these experiments.

The 1982 summer monsoon was chosen for this study because it had a 'normal' onset (PM). According to KR, variation of low-level kinetic energy over the Arabian Sea

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region is a good index for the evolution of the monsoon, and they define the ‘dynamic onset’ as occurring where there is an increase of kinetic energy prior to the onset of the monsoon rain over India. This event is accompanied by the strengthening of the East African low-level jet (LLJ).

The variation of low-level kinetic energy over the Arabian Sea, $0^\circ$–$22.5^\circ$N, $41.25^\circ$–$75^\circ$E, (Fig. 1(a)) indicates that 5 June 1982 can be considered as the date of the dynamic onset, and 10 June the starting date of the active monsoon period*. The two cases selected for the numerical experiments started at 12 GMT 5 June for the onset (second phase) and at 12 GMT 14 June for the active period (third phase).

The model used for the experiments was the limited area version of the ECMWF global model (Burridge and Haseler 1977). There are 15 levels in the vertical with a grid length of 1.875° in both longitude and latitude. The parametrization of physics includes radiation, condensation and subgrid-scale physics (Tiedtke et al. 1979). The area of integration chosen was $40^\circ$S–$60^\circ$N $0^\circ$–$180^\circ$E, which includes the monsoon area $25^\circ$S–$35^\circ$N $15^\circ$E–$170^\circ$E as defined by Ramage (1971). Boundary values required for the integrations were obtained from analysed data.

2. CONTROL EXPERIMENTS

Cumulus convection plays a crucial role in the tropical circulation, therefore it is important to select the scheme that is capable of parametrizing this process in the best way. Two widely used in numerical weather prediction are the Arakawa–Schubert (1974, hereafter A–S) and the Kuo (1974) schemes.

In the Kuo scheme it is assumed that convection occurs in conditionally unstable layers. The parcel moving upwards from the base of these layers has a profile of temperature and moisture given by a dry adiabat below the cloud and a moist adiabat within the cloud. The moist static energy of this profile is greater than that of the environment. This excess of energy of the cloud, supplied by the latent heat contained in the moisture accumulated within the column by advection and diffusion, is redistributed by convection. Hence, the moisture and temperature of the environment are modified.

In the Arakawa–Schubert scheme the subgrid-scale dynamics of the cloud is considered. There is assumed to be a thin column where the air is transported from one level to another higher up within the conditionally unstable layer. Environmental air can

* Here, the active period is defined as the period for which there is a strong south-west current from the Arabian Sea to the South China Sea during the whole period; this may be somewhat different from the definition of the ‘active monsoon’ based on rainfall over India. In other words, this is the third phase (fully established) according to PM.
flow into or out of the cloud. An ensemble of clouds can exist within a model grid box. In the cloud, detrainment occurs only at the top level and entrainment is proportional to the cloud mean flux. This is determined by the assumption that generation of cloud-available potential energy by large-scale flow and destruction due to clouds are in quasi-equilibrium. In the ECMWF model, it is assumed that cloud water, instantaneously converted to precipitable water, is detrained at the cloud tops and that rain re-evaporates in sub-cloud layers as well as within the environmental air of cloud layers.

Simulations of the atmospheric general circulation (Tiedtke 1983) and of the Asian summer monsoon circulation (Mohanty et al. 1984) with the two schemes suggest that the A-S scheme operates more efficiently than the Kuo scheme over tropical regions. Experiments with two schemes for the present cases of onset (OAS, OKUO) and active (AAS, AKUO) monsoon support the results from Mohanty et al. A clear indication of the inadequacy of the Kuo scheme in these situations is given in Fig. 1(a). Here kinetic energies from experiments with the A-S and Kuo schemes are compared with results from the diagnostic study of PM. It is evident that both in the onset and active cases the kinetic energy over the Arabian Sea region for forecasts with the Kuo scheme is much lower than observed, while it is quite realistic for the A-S scheme. On the basis of these results the A-S scheme was used in the experiments whenever parametrization of convection was needed.

In this section the ability of the model to forecast the upper- and lower-level circulations with the A-S scheme is analysed for the two cases.

(a) Onset of the monsoon

Figure 2(a) shows that the initial flow at 850 mb (12 GMT 5 June) had a weak East African LLJ already established, but the low-level south-west current was limited to only south of 10°N. From now on the LLJ strengthened and the SW flow spread northward and eastward. By the fifth day, Fig. 2(b), the LLJ reached 20 m s⁻¹ and the SW monsoon that had invaded the Indian subcontinent and the Bay of Bengal extended to the South

![Graph](image-url)
Figure 2. 850 mb wind field for: (a) 12 GMT 5 June 1982 (initial analysis); (b) 12 GMT 10 June 1982 (verifying analysis); (c) Experiment OAS, 5-day forecast (A-S convective scheme). Thin solid lines are isotachs (m s$^{-1}$) and heavy solid lines indicate main south-west current.
Figure 3. As Fig. 2 but for 200 mb. Heavy solid line indicates the main easterly jet.
China Sea. A series of synoptic-scale disturbances appeared in the current over the Bay of Bengal and the South China Sea. This is in agreement with the results of PM about the development of synoptic-scale disturbances during the onset.

Figure 2(c) presents the results of the 5-day forecasts for experiment OAS. The East African LLJ turns east and the wind speed increases up to 20 m s$^{-1}$; the location and intensity are similar to those of the analysis. The SW flow spreads north and east but the strong wind south of India is under-predicted. Also the disturbances in the monsoon current are slightly weaker than in the analysis.

At 200 mb the easterlies were already present in the initial data (Fig. 3(a)), but only in the region from 60° to 110°E; this is similar to the pre-monsoon situation (PM). Five days later a broad-scale easterly flow became established around 10°N from 140° to 40°E (Fig. 3(b)). Part of the current turned into the southern hemisphere between 90° and 110°E as a return flow due to the low-level northward cross-equatorial current near East Africa. Experiment OAS predicted the easterlies both in location and intensity (Fig. 3(c)); the cross-equatorial return flow also appeared, but it is 20° east of that analysed (between 110° and 130°E).

(b) *Active monsoon period*

The initial data (12 GMT 14 June) already showed a well-developed East-African LLJ (Fig. 4(a)) with maximum winds in excess of 15 m s$^{-1}$. The flow extended to the South China Sea with a shear line forming over southern China which caused heavy precipitation, the Mei-yu (plum) rain*. A disturbance developed in the Bay of Bengal during the next four days. Experiment AAS shows a well-predicted monsoon circulation (Fig. 4(c)), although over the Bay of Bengal the simulated disturbance is 5° west of that observed. The anticyclonic circulation (marked ‘A’ in Fig. 4) over the Indian Ocean, which maintains the cross-equatorial current, was quasi-stationary during the four days covered by the analyses. It is also well simulated in AAS although the northerly cross-equatorial current east of the anticyclone appears weaker than in the analysis.

At 200mb the initial data (Fig. 5(a)) show that the southern Asian easterlies were established and that the cross-equatorial current between 80°E and 120°E was pronounced. Four days later the upper easterlies strengthened a little and extended further eastward to 40°E (Fig. 5(b)). Experiment AAS predicts these changes (see Fig. 5(c)); however, the easterly jet is stronger.

From these results it appears that the ECMWF grid point model with the A-S scheme can capture the evolution of the monsoon circulation. Thus it can be used as a control experiment to examine the effect of latent heat release and surface evaporation on the monsoon circulation.

3. **Influence of Latent Heat Release on the Monsoon Circulation**

In this section we consider the response of the monsoon circulation to the release of latent heat from both large-scale ascent and convection in the monsoon circulation. Numerical experiments were performed with the ‘dry’ model (without latent heat release) for the onset and the active monsoon periods; these are experiments OLH and ALH respectively.

* The start of the plum rain season over eastern China is accompanied by the establishment of the SW monsoon (Staff Members 1957).
(a) Onset of the monsoon in the ‘dry’ model

Figures 6(a) and (b) show the wind fields at 850 and 200 mb from the 5-day forecast of experiment OLH. Comparison with the control experiment OAS (Figs. 2(c) and 3(c)) reveals the following:

(a) In experiment OLH the low-level onset does not occur; only a weak LLJ appears off the African coast. The flow turns sharply southwards at 60ºE and forms an anticyclonic vortex over the Arabian Sea instead of turning eastwards and flowing across the sea. The marked south-westerly flow from the Arabian Sea to the South China Sea found in OAS and the analysis is very weak in OLH, with wind speeds less than 5 m s⁻¹. The mean kinetic energy over the Arabian Sea decreases in OLH instead of increasing as in the control (Fig. 1(b)).

(b) The predicted upper easterlies over southern Asia are very weak in experiment OLH. After five days of integration, the broad band of easterlies that, in experiment OAS, extended from 140ºE to India over the tropical zone at 200 mb is considerably reduced and almost disappears in the ‘dry’ experiment (Fig. 6(b)). For example, over the Indonesian region the wind speed is decreased from 20 m s⁻¹ in experiment OAS (Fig. 3(c)) to 5 m s⁻¹ in OLH. The easterly flow is restricted to the Gulf of Aden. These results are similar to those obtained by Ji and Tibaldi (1984) for the onset of the 1979 monsoon. Moreover, a large trough develops in the westerlies along 90ºE and this extends south into the Bay of Bengal covering the southern Asia subtropical high and causes a southward shift of the westerlies over that region. Such development is not seen in OAS and the analysis.

(c) The vertical cross-section of the difference between the D+5 forecast wind fields of experiments OAS and OLH along 80ºE is presented in Fig. 7(a). Positive (negative) values mean that the westerlies (easterlies) are stronger in OAS than in OLH. The features are similar to those found in the structure of the monsoon over India (Staff members 1957), i.e. with the westerly flow (positive values) in the lower troposphere below 500 mb, the easterlies (negative values) in the upper troposphere, and the westerlies at 200 mb north of the Tibetan Plateau. From this we can infer that the latent heat release is essential to the development of the monsoon wind structure.

(d) The field of the difference between the meridional circulations along 80ºE in experiments OAS and OLH is shown in Fig. 7(b). Features similar to the direct meridional circulation found over India during the monsoon season (Chen et al. 1964) are apparent, with warmer air ascending north of 15ºN and colder air descending south of that latitude. This suggests that the meridional circulation associated with the monsoon is a response to the latent heat release. The response can be explained by quasi-geostrophic theory (Hoskins 1980); upward vertical motion enhanced by latent heat and subsidence over the surrounding area establishes a direct circulation south and north of the region of maximum latent heat release. This circulation is important in the budget of angular momentum and kinetic energy of the low-level monsoon circulation (Chen et al. 1964).

(e) The 24 h accumulated precipitation predicted for day 3 is shown in Fig. 8. It shows the general features of the precipitation in the model, i.e. large amounts of precipitation concentrated over Indonesia, the Bay of Bengal and the Arabian Sea, and the region between 15º and 20ºN. This feature is similar to that from latent heat release during the monsoon onset of 1979 (KR and PM). A diagnostic study of heat sources during the summer monsoon carried out by Li et al. (1983) also shows the large latent heat source over the northern part of the Bay of Bengal. Yeh and Gao (1979) emphasized that the Tibetan Plateau acts as an elevated heat source (both latent and sensible) in the general circulation over Asia in summer. Note that there is little rain over the plateau. Li et al.
Figure 4. 850 mb wind field for: (a) 12 GMT 14 June 1982 (initial analysis); (b) 12 GMT 18 June 1982 (verifying analysis); (c) Experiment AAS, 4-day forecast (A-S convection scheme). Thin solid lines are isotachs (m s⁻¹), heavy solid lines indicate main south-west current, and 'A' the anticyclonic circulation over the Indian Ocean.
Figure 5. As Fig. 4 but for 200 mb, heavy solid lines indicate main easterly jet.
did not find maxima of heating over that area. On the other hand, Ji and Tibaldi (1984) showed that the onset takes place even in an experiment without the Tibet Plateau. Therefore the thermal forcing of the plateau needs to be examined further.

(b) Active monsoon period

A 'dry' experiment, similar to that described in the previous sub-section, was carried out for the active period of the monsoon. This is experiment ALH, which is to be compared with the control experiment AAS. Some deductions about the results of experiment AHL are listed below:
(a) In the dry run the LLJ near the East African coast at 850 mb is still present (Fig. 9(a)) with the same strength as in AAS (Fig. 4(c)), but its flow is limited to the east coast of Africa and as it turns south along the western Indian coast an anticyclonic circulation forms over the Arabian Sea. The LLJ over the eastern Arabian Sea is weakened compared
with AAS and the analysis, and the kinetic energy over the region decreases (Fig. 1(b)). The monsoon flow, with a wind speed reduced to less than 5 m s\(^{-1}\) over southern Asia, is broken between India and the South China Sea.

(b) At 200 mb, the speed of the easterlies over southern Asia drops from nearly 20 m s\(^{-1}\) in experiment AAS (Fig. 5(c)) to below 10 m s\(^{-1}\) in ALH (Fig. 9(b)), except in the vicinity of the South China Sea and the East Africa coast. The upper westerlies, as in the onset case (dry run OLH), also appear as a southern extension of the mid-latitude westerlies. In the analysis and AAS, the westerlies are limited to north of 25°N over Asia while in the dry run they penetrate a further 5° southwards.

Note that the intensity of the easterly flow over the Gulf of Aden is better predicted in the ALH case. This may indicate that there is excessive latent heat release in the AAS experiment over that region.

c) In the control experiment, AAS, the Arabian LLJ was well developed; for example, the vertical cross-section along 71°E at D + 4 forecast (Fig. 10(a)) shows winds of 20 m s\(^{-1}\) extending up to 500 mb. A direct circulation with upward motion north and subsidence south of the LLJ region was present, and the easterly jet in the upper troposphere above
the LLJ had a maximum speed of 40 m s\(^{-1}\). Similar features were also observed after the onset in 1979 (Bengtsson et al. 1982). The vertical wind structure in experiment ALH (Fig. 10(b)) shows a dramatic change: the Arabian LLJ has disappeared, and only a weak westerly flow (5 m s\(^{-1}\)) is present in the lower troposphere between 20°N and 30°N. The wind speeds of the upper easterlies and subtropical westerlies are reduced to one third of the value found in experiment AAS. On the other hand, the associated vertical circulation has also disappeared. Chen and Dell'Oso (1984) found a similar behaviour when they considered the effect of latent heat release on the LLJ over China during the monsoon season.

(c) Kinetic energy budget analyses

The kinetic energy equation in the \(\sigma\) coordinate system can be written as

\[
\frac{\partial (p_s k)}{\partial t} + \nabla_{\sigma} \cdot (p_s k \mathbf{V}) + \frac{\partial (p_s k \dot{\sigma})}{\partial \sigma} = -p_s \mathbf{V} \cdot (\nabla_{\sigma} \phi + RT \nabla_{\sigma} \ln p_s) + p_s R_k.
\]

Here \(\sigma = p/p_s, p_s\) being the surface pressure; \(\mathbf{V}\), the horizontal wind; \(\dot{\sigma} = d\sigma/dt\), the vertical wind component; \(\phi\), the geopotential; and \(k = \frac{1}{2}(u^2 + v^2)\), the kinetic energy of horizontal flow. The terms on the left-hand side are the local change and the horizontal and vertical flux convergences. The calculation was carried out on \(\sigma\) surfaces using the method described by Savijärvi (1983). The selected area for the calculation (41°–140°E, 0°–22°N) is where the monsoon circulation dominates.

From the results shown in Fig. 11, there are two maxima of the local change of kinetic energy in the control OAS, located at 700 mb and 200 mb. They are associated with the enhancement of the lower south-west monsoon and upper easterlies in the onset period; in the dry experiment (OLH), the local change is negative below 200 mb, which shows that no large-scale development took place in the troposphere. The generation of kinetic energy also has two peaks: one in the planetary boundary layer and the other near 100 mb. The values in OAS exceed those in experiment OLH by a factor of three in the boundary layer and by a factor of five in the upper troposphere. Latent heat produces a large amount of kinetic energy generation in the tropical atmosphere. This is in agreement with the thermal direct vertical circulation induced by latent heat release discussed in sub-section 3(a).
Figure 9. Experiment ALH (no-latent-heat model) 4-day forecast of (a) 850 mb and (b) 200 mb wind field (initial data 12 GMT 14 June 1982). Solid lines indicate the main current in the tropics.

In the control there is divergence of the vertical fluxes of kinetic energy near 200 mb and convergence at 100 mb showing the vertical transfer of kinetic energy in the upper troposphere. This feature is weaker in the dry experiment. On the other hand, the horizontal flux divergence of kinetic energy is also greatly reduced in this experiment.

For the active period, the difference of the budgets between control and dry is similar to that in the onset. The local change is negative in the dry while it is positive in the control. Kinetic energy generation is also greatly enhanced by the ageostrophic wind induced by latent heat.

4. EFFECTS OF THE SURFACE LATENT HEAT FLUX

The total amount of released latent heat depends on the moisture content of the atmosphere and on the moisture fluxes over the ocean and land. The 4-day mean of the
forecast surface latent heat flux during the active monsoon period is given in Fig. 12 for experiment AAS. A large area of latent heat flux appears over the central Arabian Sea and the Bay of Bengal; the maximum over these regions is 400 W m$^{-2}$. Rao et al. (1981) found that only 40% of the evaporation from the Arabian Sea during the monsoon season is converted into precipitation—the other 60% being transported over India.

In the following two experiments for the onset (OSLHF) and active (ASLHF) periods of the monsoon, the surface latent heat flux is excluded from the model to show its effect on the monsoon circulation.
Figure 11. (a) Kinetic energy budget in domain 41°–140°E 0°–22°N for 4–5-day forecast in OLH no-latent-heat run; (b) as (a) but in OAS, control run; (c) kinetic energy budget in domain 41°–140°E 0°–22°N for 3–4-day forecast in ALH, no-latent-heat run; (d) as (c) but in AAS, control run. Thick lines denote the local change, thin lines the horizontal flux divergence, thick dashed lines the dissipation and dotted lines the vertical flux divergence.
In the ECMWF grid point model, the sea surface temperature and moisture were constant during the integration (monthly mean values were used). Therefore, switching off surface latent heat flux should not cause severe problems. Over the land, the surface temperature was predicted from the surface heat balance equation (Tiedtke et al. 1979) in which surface evaporation was taken into account. Thus, excluding land evaporation will alter the predicted surface temperature as well as the sensible heating. The problem is how large is such a change. Comparing the land sensible heating in the control and no surface latent heat flux experiments shows that the main differences are about 20 W m\(^{-2}\), which is much smaller than the sea surface evaporation in the control (Fig. 12). Thus the differences of the simulated circulation between the two experiments may be mainly due to sea surface evaporation. On the other hand, excluding the land surface evaporation in the model means that the impact of soil moisture on the circulation is disregarded. The part of solar radiation previously engaged in evaporating the moisture over land (the precipitation area) is diverted into heating the land surface. Hence, the sensible heating is increased. But such increasing of sensible heating does not alter the circulation significantly because its magnitude is only one tenth of that of the latent heat release (Webster 1981).

The main effects of the surface latent heat fluxes are revealed in Fig. 13, which shows the D+5 850 mb and 200 mb wind forecasts of experiment OSLH. Note that the East African LLJ is 5 m s\(^{-1}\) weaker than in the control, OAS (Fig. 2(c)). The kinetic energy over the Arabian Sea decreases from day 3, as does the amount of precipitation (figure not shown). However, the SW monsoon still develops, travels north and extends from India to the South China Sea. At 200 mb (Fig. 13(b)), the tropical easterlies are set up, especially from the Arabian Sea to the Bay of Bengal, although the easterlies are 5 m s\(^{-1}\) weaker than in the analysis and OAS (Figs. 3(b) and 3(c)). On the whole, the broad-scale monsoon circulation components are reproduced even without surface evaporation.

In the active monsoon period, the kinetic energy over the Arabian Sea in the lower troposphere shows a marked decrease in experiment ASLHF (Fig. 1(b)). Figure 14 shows
that the speed of the low-level westerlies over the Arabian Sea and East Africa drops from 15 m s\(^{-1}\) (experiment AAS) to 5 m s\(^{-1}\) and the anticyclonic circulation over the Indian Ocean is weaker in ASLHF. At 200 mb the speed of the easterly flow is reduced to one third of that in the control experiment AAS (figure not shown).

In the pre-monsoon stage of 1982, the main build up of atmospheric moisture over the Indian Ocean, and subsequently over India and South-east Asia, was around 15 May (PM). This means that at the end of May there is already sufficient moisture available for the onset. The monsoon onset can take place as a pure moist dynamic process without the supply of moisture from the ocean. After the onset, the low-level monsoon westerlies strengthen, causing an increased latent heat flux from the ocean; the strengthening current plays a crucial role in transporting moisture to the east of India. According to
PM, during the period from pre-onset to the fully developed stage in 1982, the mean evaporation over a large part of the Indian Ocean increased between two and threefold. In our experiments, the mean evaporation from the Arabian Sea and Indian Ocean increased from nearly 150 W m$^{-2}$ in experiment OAS to nearly 250 W m$^{-2}$ in AAS. Therefore we can certainly conclude that the sea surface evaporation is a primary energy source in the active (fully established) period.

5. CONCLUDING REMARKS

Two cases, one for the monsoon onset and the other for the active period, were selected for a real data numerical simulation study of the response of the monsoon circulation to differential heating. The main results are as follows:
(a) The ECMWF grid point model with the A-S scheme has the ability to predict the evolution of the monsoon circulation. Results obtained by using the Arakawa–Schubert parametrization scheme seem better than those obtained with the Kuo scheme. Two cases are not sufficient to draw any general conclusions about this problem; however, they do show that the monsoon circulation is sensitive to the type of convective parametrization scheme used. Moreover, it appears that the bulk properties of convection in the monsoon area are not of the penetrative type as treated by Kuo (1974). Further detailed studies to investigate the temporal and spatial differences between results obtained with these schemes seem useful to understand the nature of differential heating in the monsoon circulation.

(b) Latent heat is the most important feedback process in the monsoon circulation, not only for the onset but also in the active period. The feedback process affects the broad-scale features—the whole tropospheric circulation system undergoes a radical change when latent heat is excluded in the model. In the dry simulation, the lower tropospheric south-west current and upper south Asian easterly jet stream decrease quite quickly in both cases. Thus no onset takes place in the onset period and the monsoon is broken in the active period. Latent heat also induces a typical monsoon meridional circulation and generates kinetic energy to maintain the circulation. Any theory of the monsoon must contain a good description of the moisture process. On the other hand, further improvements in convective parametrization schemes are necessary to advance monsoon forecasting.

(c) During the pre-monsoon period, moisture in the Asian–African tropical region builds up gradually and attains quite a large value, so that the onset of the monsoon could take place without any direct moisture supply from the ocean (although it would appear rather weak). After the onset, evaporation increases due to the strengthening surface wind. A large amount of moisture is transported to the east of India from the Arabian Sea to compensate for monsoon rainfall over Indo China. Hence, evaporation from the ocean is quite important during the active period.

Although the fundamental causes of the monsoon are the differential heating and cooling of the land and the ocean, and the rotation of the earth, moist process must be considered in order to simulate the onset and maintenance of the circulation. Numerical simulations confirm the results from Webster (1981) and PM; such large-scale feedback processes determine the distinctive features of the monsoon. A detailed investigation into the role of moisture in the monsoon circulation would give a better understanding of monsoon dynamics.

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