REVIEW

Summer Monsoon Experiment—A Review

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ABSTRACT

This paper presents a short summary of the Summer Monsoon Experiment (MONEX). The review is largely based on those papers that have made use of the summer MONEX observations during 1979. Observational aspects of this study emphasize the annual march of the monsoon rainfall belt from Indonesia to the foothills of the Himalayas, from the northern winter to the northern summer season and a reverse motion thereafter. The excellent FGGE/MONEX data sets have provided a detailed definition of the divergent wind; these are summarized with reference to the Hadley and the Walker circulations.

The manner in which monsoonal circulations respond to the evolving differential heating fields are presented via the mutual interactions among the rotational and divergent wind components. Specific examples of heat sources from the studies of Luo and Yanai highlight their contrast over different regions of the monsoon including the Tibetan Plateau. A problem of considerable interest in this context is the cooling of the Arabian Sea. A summary of results pertaining to this problem—especially the distribution of the wind stress curl—is highlighted.

The planetary boundary layer is another area of investigation which has drawn much interest, especially over the western Arabian Sea where the Somali jet exhibits interesting properties during summer monsoon. These studies cover modeling, theoretical and observational areas.

The onset and active monsoons were monitored by a large array of ship and research aircraft during MONEX. Studies in this area place an emphasis on observational, theoretical stability analysis and numerical weather prediction. The major results with respect to medium range prediction of the onset of monsoon and the formation and motion of a monsoon depression are summarized in the review.

A component of the MONEX observational program that is examined is the structure and maintenance of desert heat lows. A summary of these results includes the structure of the mixed layer, the day-night differences in the vertical motion profiles and the thermodynamic heat budget.

The final section of this review includes studies on low frequency modes—especially on the time scale of 30 to 50 days. It is becoming apparent that modulations of active and inactive spells of the monsoon are related to wave motions on this time scale. These MONEX data sets provide a strong signal for monitoring these waves. These wave motions on the planetary scale move eastward; on a more regional scale they move northward over the monsoon region. Their behavior is illustrated with respect to the onset, active and break monsoons.

1. Introduction

The monsoon experiment MONEX\(^1\) was conducted within the FGGE year. The northern summer component of this experiment was conducted during the months of May, June and July 1979. The purpose, motivation and goals of the Summer Monsoon Experiment have already been described by Fein and Kueptner (1980), and hence they will not be repeated here.

Studies on the Summer Monsoon Experiment have ranged from the low-frequency planetary scale motions to those on local diurnal changes. The present review cannot be exhaustive within the limited pages and thus some omissions are unavoidable. Some of the salient findings from the FGGE/MONEX observations are reviewed here. The research on the various MONEX proposals is by no means complete at this stage; the prospects for further research in most of the following areas appear quite promising.

2. Planetary scale monsoon

As a global problem, the monsoons have received considerable attention in recent years. The time averaged motion field around the global tropics, in the lower and the upper troposphere, describes the prominent place of the monsoon in the global circulations. Figures 1 and 2 show these climatological flow patterns at the 850 and 200 mb levels. In these illustrations we have emphasized the lower-tropospheric confluent asymptote as well as the upper-level divergence patterns in the monsoon region. The lower-tropospheric con-

\(^1\) A list of acronyms appears in Table 1.

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fluent asymptotes are well marked between January and April over the eastern Indian Ocean. (Divergence or convergence is not necessarily implied by diffuence or confluence.) This asymptote also marks climatological regions of monsoon rain and associated cloud cover. The principal belt of the monsoon rainfall performs an annual migration from Indonesia to the foothills of the Himalayas, from the (northern) winter to the (northern) summer season. The reverse motion ensues in the following months. Along this axis, regions of maximum rainfall totals of the order of 300–500 

TABLE 1. List of useful acronyms.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>GARP</td>
<td>Global Atmospheric Research Program</td>
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<tr>
<td>FGGE</td>
<td>First GARP Global Experiment</td>
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<tr>
<td>MONEX</td>
<td>Monsoon Experiment</td>
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<tr>
<td>Tiros N</td>
<td>U.S. Polar Orbiting Satellite</td>
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<tr>
<td>NOAA-A</td>
<td>U.S. Polar Orbiting Satellite</td>
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<tr>
<td>GOES</td>
<td>U.S. Geostationary Satellite</td>
</tr>
<tr>
<td>ECMWF</td>
<td>European Centre for Medium Range Weather Forecasts</td>
</tr>
<tr>
<td>FGG IIltb</td>
<td>Final gridded data produced by ECMWF</td>
</tr>
<tr>
<td>FSU</td>
<td>Florida State University</td>
</tr>
<tr>
<td>JMA</td>
<td>Japan Meteorological Agency</td>
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<tr>
<td>RPN</td>
<td>Canadian Numerical Weather Prediction Group</td>
</tr>
<tr>
<td>LMD</td>
<td>Laboratoire de Meteorologie Dynamique</td>
</tr>
<tr>
<td>NMC</td>
<td>French Numerical Weather Prediction Group</td>
</tr>
<tr>
<td>UKMO</td>
<td>National Meteorological Office of the United Kingdom</td>
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(lower tropospheric) convergence zone. Upper easterlies are found over the convergence zone and similar anomaly features have been noted in reference to the El Niño warming phenomenon over the central Pacific Ocean (Wallace and Gutzler, 1981). The climatological upper anticyclone makes a northward motion from northern Malaysia in May towards the Tibetan Plateau by July. The anticyclone has its largest amplitude in the month of August. Diffuence upper level flows are a characteristic feature above the regions of monsoon rainfall. As the withdrawal of the summer monsoon commences in September, the northern anticyclone moves equatorward. There are, in fact, two upper anticyclones nearly all year round in each hemisphere. The annual cycles of the planetary scale monsoon shown in Figs. 1 and 2 are based on ten years of data. Within this period, large interannual variation in the circulations were noted (Krishnamurti et al., 1984a).

An important aspect of the planetary scale circulation is the divergent circulations (Krishnamurti, 1971). Usually the velocity potential at 200 mb is used to display this field. The depictions for the months of January and July are shown in Fig. 3. The arrow indicates wind direction. These are based on the FGGE data sets. They illustrate a prominent role of the monsoon in these global circulations. In January the Hadley type overturnings are more prominent, while in July the strong gradient of the velocity potential over the Indian Ocean is associated with the active monsoon which has more of an east–west orientation. It is of interest to note that a meridional belt of east–west circulations from roughly 20°S to 30°N is found over the central Pacific Ocean. It should be noted that there are hundreds of daily observations of cloud winds and commercial aircraft wind reports that provide a basis for this information over the Pacific Ocean. Thus, the nature of east–west circulations is far broader than the classical picture of a Walker circulation along the equator. It is apparent that the monsoonal east–west overturnings are a prominent part of the global divergent circulations.

Zonal harmonic analysis of the velocity potential in the tropical latitudes shows that a significant proportion (>60%) of the total variance is on the planetary scales (Krishnamurti, 1978). The covariance of the vertical velocity and temperature (i.e., the $T$) is also distributed largely on the planetary scale (Krishnamurti et al., 1984b). Thus, the east–west circulations have a major role in driving the planetary-scale tropical motions. A number of tropical depressions, storms and waves, with horizontal scales are of the order of a few thousand km, are usually present in the tropics. It is, however, very significant that these disturbances are asymmetrically placed in the tropics along planetary waves (i.e., the zonally asymmetric ITCZ). This placing results in a substantial release of eddy available potential energy on the planetary scale, and only a small fraction of the energy released drives the storm scales.
Fig. 1. Monthly mean streamlines and isotachs (m s⁻¹) at 850 mb.
Fig. 2. Monthly mean streamlines and isotachs (m s⁻¹) at 200 mb.
Pasch (1983) examined the evolution and energetics of the planetary scale motions of the monsoon. His study was based partly on observations (diagnostic) and partly on the basis of global predictions. Several interesting aspects of the planetary scale emerged from these studies. He noted a marked increase (as a function of time during the monsoon onset) of the planetary-scale eddy kinetic energy over the global tropics. Coincident with that was a marked increase of the eddy available potential energy during the period of onset of monsoon rains over India. In a further diagnosis of this system he emphasized the role of the organized planetary scale heat sources in the generation of the eddy available potential energy. These in turn were converted to the strong planetary scale motions via east-west overturnings. A key element in the planetary scale generation of eddy available potential energy was identified with the strong convection over the southeastern part of the Tibetan Plateau. These results confirm the earlier observational findings summarized by Kanamitsu and Krishnamurti (1978).

### 3. Differential heating and heat sources

An important relation between differential heating and the maintenance of strong circulations can be deduced from simple energy considerations. That relation simply states that in a closed system if the rotational, divergent and available potential energies are increasing (or in a statistical steady state), the maintenance of such a system against frictional dissipation requires a differential heating mechanism. The first application of this principle appeared in a zonally symmetric monsoon model developed by Murakami et al. (1970). A simple zonally symmetric system may be described by the following equations (A list of symbols is provided in Table 2).

#### Momentum Equations

\[
\frac{\partial u}{\partial t} = -v \frac{\partial u}{\partial y} - \omega \frac{\partial u}{\partial p} + f v + F_x
\]

\[
\frac{\partial v}{\partial t} = -v \frac{\partial v}{\partial y} - \omega \frac{\partial v}{\partial p} - f u - g \frac{\partial z}{\partial y} + F_y
\]
Hydrostatic relation

\[
\frac{g \partial z}{\partial p} = -\frac{RT}{p}
\]  

(3)

Mass Continuity Equation

\[
\frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0
\]  

(4)

First Law of Thermodynamics

\[
\frac{\partial \theta}{\partial t} = -\frac{v \partial \theta}{\partial y} - \frac{\omega \partial \theta}{\partial p} + \frac{1}{\gamma_c} \left( \frac{P_0}{p} \right)^{\gamma_c p} H.
\]  

(5)

Here \(H\) denotes diabatic heating.

The energetics of this system may be expressed by the relations:

\[
\frac{\partial}{\partial t} K_u = \langle K_v \cdot K_u \rangle - D_x
\]  

(6)

\[
\frac{\partial}{\partial t} K_v = \langle P \cdot K_v \rangle - \langle K_v \cdot K_u \rangle - D_y
\]  

(7)

\[
\frac{\partial}{\partial t} P = -\langle P \cdot K_u \rangle + G - D_p.
\]  

(8)

where \(K_u, K_v\) and \(P\) denote the zonal, meridional kinetic and available potential energy respectively, over the entire mass of the atmosphere and \(D_x, D_y\) and \(D_p\) denote dissipation of the three aforementioned energy quantities.

In a system that is either exhibiting an increase of \(K_u, K_v\) and \(P\) or is in a statistical steady state the following inferences can be made: If the dissipation terms \(D_x, D_y\) and \(D_p\) are positive definite quantities, then (i) \(\langle K_v \cdot K_u \rangle\) must be positive, (ii) \(\langle P \cdot K_v \rangle\) must be positive and (iii) a net generation (i.e., \(G > 0\)) is required to maintain this system as stated above. The generation term here is simply measured from a covariance of the diabatic heating and temperature.

Murakami et al. (1970) utilized such a framework to simulate a zonally symmetric monsoon in a general circulation model. The model included oceans to the south, and land areas with mountains to the north. Other features were air–sea interaction, convective adjustment, detailed radiative processes and large scale condensation. With the inclusion of mountains and a mean July solar insolation input the model simulated a realistic monsoon including such features as: the monsoon trough, monsoon rainfall, warm troposphere, tropical easterly jet, strong Hadley circulation and lower tropospheric monsoon westerlies.

A similar generalization on the role of differential heating and monsoon circulation for a fully three-dimensional motion was presented by Krishnamurti and Ramanathan (1982). The analogous energetics of a fully three-dimensional system may be written for the rotational kinetic energy \(K_u\), divergent kinetic energy \(K_v\) and available potential energy \(P\) over a closed region:

\[
\frac{\partial K_u}{\partial t} = \langle K_v \cdot K_u \rangle - D_x
\]

\[
\frac{\partial K_v}{\partial t} = -\langle K_v \cdot K_u \rangle + \langle P \cdot K_v \rangle - D_y
\]

\[
\frac{\partial P}{\partial t} = -\langle P \cdot K_u \rangle + G - D_p.
\]

Here \(G\) denotes the generation term and the dissipation terms are denoted by \(D_x, D_y\) and \(D_p\), respectively. It is worth noting that the pressure interactions are absent in the zonal energy equation of a zonally symmetric system since \(\partial p/\partial x = 0\). When the fully three-dimensional system is in cast terms of the rotational and divergent motions, pressure interactions again vanish from the rotational kinetic energy equation. The energetics of the two systems and their interpretations are quite analogous. That is not too surprising since the meridional wind in a zonally symmetric system is entirely divergent and the zonal wind is entirely rotational. Thus, in a situation such as the onset period of the monsoon when the rotational, divergent and available potential energies of the monsoon region are in-

FIG. 5a. The principal term in the energy exchange from the divergent to the rotational wind over a MONEX domain at 850 mb; units m² s⁻³.
creasing with time, a net differential heating is required to generate available potential energy. The available potential energy must transfer energy to the divergent motions. Finally, we can make the statement that divergent motions must transfer energy to the rotational motions. All of the aforementioned arguments presuppose that we are dealing with a closed system.

Krishnamurti and Ramanathan (1982) examined the energetics of the three-dimensional problem in the above context. Figure 4 illustrates the evolution of the rotational and divergent kinetic energy over a MONEX domain, at 850 mb, during the summer months. Similar evolution was also evident at 700 mb. This illustration shows a rapid rise of the rotational kinetic energy in the same one week prior to the onset of monsoon rains over central India. The magnitude of the divergent kinetic energy also exhibits a small increase during the onset period. Figure 5a illustrates the time evolution of the principal term in the exchange of energy from the divergent to the rotational kinetic energy during this period. The large increase of this exchange during the onset and post-onset period is attributed to an evolution of the divergent wind. As the principal rainfall belt migrates from northern Burma towards the Tibetan Plateau, the divergent wind organizes itself with respect to the rotational wind and a rapid exchange of energy from the divergent to the rotational wind occurs. This feature is illustrated in Fig. 5b, c where the fields of the streamfunction, velocity potential and the energy exchange $\nabla \psi \cdot \nabla x$ during the pre- and post-onset periods are shown. The region where large exchange from the divergent kinetic to the rotational kinetic energy occurs shows an interesting evolution of the monsoon.

This same scenario was further expanded in a series of numerical weather prediction experiments by
Krishnamurti and Ramanathan (1982). In these experiments with a multilevel primitive equation model, they examined the evolutions of the flow fields using identical initial states for the rotational wind, the sea level pressure and temperature fields. Experiments, however, differed from each other in their initial description of the divergent wind and the humidity fields. The different experiments described the pre-onset conditions of the large-scale flows, while the different configuration of the divergent wind and the humidity fields provided different magnitudes of differential heating initially. In a three to four day prediction, the largest response of the initial state to the differential heating was noted where the initial heating was introduced over northeastern India and the foothills of the Himalayas. In this instance a rapid monsoon onset occurred in a matter of three to four days. The detailed energetics of this experiment essentially confirmed the scenario presented above. Figure 6 shows the evolution of the energy exchange from the divergent to the rotational wind in these three experiments. A differential heating corresponding to the post-onset period exhibits an explosive growth of the monsoon circulations. This experiment strongly suggests the need for a careful determination of the initial heat source in the monsoon prediction problem.

4. Apparent heating and moistening

Yanai et al.'s (1973) definition of the apparent heat source \( Q_1 \) and the apparent moisture sink \( Q_2 \) provides a powerful tool for diagnostic studies of the atmosphere. Figure 7a–d illustrates Luo and Yanai's (1984) estimates of \( Q_1 \) and \( Q_2 \) over four relevant regions; these are over the western and eastern regions of Tibet, the Yangtze River valley over eastern China and the Assam valley of northeastern India. These four regions are characterized by relative dry weather, moderate convective rain, steady stratiform rain and heavy convective rain respectively. The respective vertical distributions of \( Q_1 \) and \( Q_2 \) are shown here. Luo and Yanai noted that over western Tibet, \( Q_2 \) is much smaller than \( Q_1 \), which suggests the absence of deep convection. They attribute the strong values of heating over western Tibet to the dry convective process. However, it is possible that dust and aerosols may contribute to a stronger radiative heating over this region. Over the region of eastern Tibet about half of the net heating is attributed to latent heat release. Region III, which is over the Yangtze River valley, shows apparent heating and drying of nearly the same magnitude; this, according to Yanai and Luo, is a signature of steady stratiform rain.

In region IV, which is over northeastern India, heavy convective rain accounts for large heating rates, \( Q_1 \approx 5^\circ \text{C day}^{-1} \), and the apparent moisture sink \( Q_2 \) has an intensity of around \( 2.5^\circ \text{C day}^{-1} \). Thus a variety of different profiles of \( Q_1 \), \( Q_2 \) are encountered over different regions of the monsoon.

In this context, it is worth mentioning some important recent studies done by Chinese authors on the formation of diurnal mixed layers and heat low on the Tibetan Plateau (e.g., Yeh et al., 1981; Yeh, 1982; and Gao et al., 1981).

Further work remains in areas of geographical and temporal variability of \( Q_1 \), \( Q_2 \) and their relationship to the overall monsoon activity.

5. Planetary boundary layer studies, cooling of the Arabian Sea and the humidity budget

Two major areas of interest in this area of investigation are dynamics (i.e., the cross-equatorial flow dynamics within the PBL) and the thermodynamics (i.e., those related to the air–sea exchanges). The cross-equatorial low-level jet was monitored by some 80 low-level constant level balloons, launched from Diego Suarez located near 15°S, at \( \sim 900 \) mb level (Cadet et al., 1981). The low-level cloud motion vector provided another major data set for studies of the cross equatorial dynamics. This problem was addressed by Stout and Young (1983), Sommeria et al. (1982) and Krishnamurti et al. (1983a). The transition in the balance of forces along the low-level flows from the Southern Hemisphere trades to the northern monsoon trough is dominated by advective acceleration in the near-equatorial latitudes. The transition from a near-Ekman type balance, at \( \sim 20^\circ \text{S} \), to an accelerating flow along the low jet, near the equator, results in a strong role for the horizontal as well as the vertical advection terms. In this near-equatorial region the essential balance is among frictional, advective and pressure gradient forces. Parcels of air within the PBL experience a strong backing of winds with height at \( \sim 15^\circ \text{S} \). As these parcels...
approach the equator the role of advective accelerations becomes quite important. With the diminished role of the Coriolis force, the departure from Ekman balance is prominently noted in the balance of forces. The equatorial region is characterized by either weak backing or weak veering of wind with height depending on the past history of the parcel speeds. The parcels arrive with a stronger backing of wind with height over the Southern Hemisphere subtropics. As they arrive over tropical latitudes this configuration results in a layer-averaged diffuent wind and downward motions over the eastern Indian ocean. Downstream from the maximum wind of the Somali jet a reverse picture in the boundary layer dynamics is found. Here the transition from a near-equatorial advective to a more Ekman-type boundary layer dynamics results in a downstream increase of veering within the PBL. An asymptote of convergence and a gradual increase of height of the PBL is noted in this region as the monsoon convection increases.

a. Cooling of the Arabian Sea

The Arabian Sea oceanographic experiment was an important component of MONEX. The emphasis in these studies has been on equatorial waves, the Somali current and the mixed layer structure (over selected sites). In this review we shall present some of the major
findings on the cooling of the Arabian Sea based on ship observations during MONEX.

An anomalous feature of the sea surface temperature (SST) over the monsoon region is the cooling of the Arabian Sea during June. Between 10 and 20°N from June through August a warming of the SST nearly always occurs over the Atlantic and the Pacific Oceans. The Arabian Sea alone exhibits cooling during this period over comparable latitudes. Düing and Leetmaa (1980) and Krishnamurti (1981) among others have addressed the problem. The magnitude of this cooling is of the order 3–4°C over large areas of the Arabian Sea. The cooling starts to occur dramatically over a period of 5–6 days soon after the winds strengthen. Figure 8 illustrates the time evolution of the surface wind speed (top panel) and of the SST (bottom panel) during the Monsoon Experiment. These measurements were made by a Soviet research ship (with the call sign UMAY) around 60°E, 6.7°N. The wind speeds build up from the 10th to the 15th of June (from roughly 4 to 14 m s⁻¹), while the SST drops from ~30 to ~27.5°C at this location. Similar response of the ocean to the strengthening of the winds was noted at several other locations. Several possible mechanisms for the cooling have been proposed (these are reviewed in Krishnamurti, 1981):

1) The onset of monsoons brings in extensive cloud cover with large amounts of high-level cirrus over the Arabian Sea. This acts to diminish the incoming solar radiation. The cooling of the Arabian Sea is generally not attributed to this effect because the oceanic response to solar radiation has a lag of one to two months, while the observed cooling starts almost immediately after the onset of strong winds.

2) Southward flux of heat by ocean currents is contributed by clockwise oceanic eddies over the western Arabian Sea. This was estimated by Düing and Leetmaa (1980); the related cooling of the northern Arabian Sea by equatorward transport appears to be quite small.

3) Coastal upwelling and downstream shedding of cold eddies: The premise that pockets of cold anomalies form in the Somali and Arabian upwelling regions and are advected eastward by the broadscale Somali currents is a possibility. There is some evidence of that from satellite observations. The rapid response of SST to the rapid evolution of strong winds in central and eastern Arabian Sea during the onset precludes this possibility since this requires an eastward advective speed of the cold pockets, from the upwelling regions off the east African coast, comparable to wind speeds in the low-level atmospheric jet. The oceanic advection is known to be much smaller to account for a sufficient divergence of flux and the known cooling of the ocean.

4) Strong evaporation in the region of strong winds is a possible candidate. However, the available budgets of evaporative cooling again do not favor such an intense cooling. We feel that this effect needs to be assessed in detail with the boundary-layer humidity flux measurements for disturbed and undisturbed conditions. The sea state over this region was highly turbulent during the onset of monsoon. Flights made with low-level aircraft exhibited a very large number of white caps with a greenish color of water, indicating almost hurricane force surface winds during the passage of the onset vortex. With the large sea spray and strong winds, it is conceivable that evaporative cooling was underestimated in the past.

During the onset of monsoons, the cooling of the Arabian Sea also occurs over the interior of the Arabian Sea where the winds increase explosively. Figure 9a–d illustrates the possible role of the wind stress over the interior Arabian Sea on this problem.

The parameters shown here are zonally averaged across the Arabian Sea for 55–70°E (i.e., over the eastern Arabian Sea) and are based on once daily FGGE/MONEX observations. Surface wind speeds during the onset period developed explosively from 5 m s⁻¹ to almost 25 m s⁻¹ between 11 June and 17 June 1979 around 10°N. Over the regions of the southern trades around 10°S, the surface winds lie between 5 and 10 m s⁻¹ during most of this period. The evolution of the strong winds around 10°N arises from a superposition of the westerlies to the south of the onset vortex and the Somali jet. The surface wind stress increases sixfold from around 1 dyn cm⁻² prior to the onset to around 6 dyn cm⁻². Over the southern trades the stress during the onset period remains at around 1–1.5 dyn
The wind stress curl shows a positive and a negative axis on either side of the axis of the low-level wind maximum. The positive wind-stress curl region nearly coincides with the region of the Arabian Sea cooling illustrated in Fig. 9d. These calculations are strongly suggestive of the role of the evolution of the interior ocean stress in the cooling of the Arabian Sea. Further studies on this problem require observations and modeling of the mixed layer. In summary, there is a need for more work on this problem. Coupled models may be very helpful in our understanding of this problem.

b. Humidity budgets

Although research aircraft were deployed within the PBL during MONEX, the fluxes of sensible and latent heat and their vertical distribution have not been evaluated to date. Studies on the humidity budget over the monsoon region were evaluated by Greco (1984). These budget studies are somewhat revealing of the monsoon activity and the latent heat fluxes. Using Tiros-N precipitable-water estimates in three layers, 1000–700, 700–500 and 500–300 mb pressure levels and the FGGE/MONEX winds at 1000, 850, 700, 500, 400
and 300 mb pressure levels, Greco estimated humidity budgets over a MONEX domain. The results of mean zonal water vapor fluxes during the pre- and post-onset periods are of considerable interest. These are vertically integrated measures (Fig. 10). They show a substantial divergence of flux of water vapor by the zonal winds, suggesting strong evaporative fluxes over the Arabian Sea during the post-onset periods. A similar calculation of the divergence of flux of moisture by the meridional wind across the Arabian Sea, between the equator and 20°N, shows that the cross equatorial transport of humidity is substantial. The humidity transport across the equator and the evaporation from the Arabian Sea seems to be equally important for the Indian Monsoon rainfall.

Thermodynamic variations of the planetary boundary layer along the low-level flows over the Arabian Sea deserve to be studied further. The surface fluxes, their vertical distributions, their interactions with the cloud layer, effects of vertical wind shear, effects of large scale vertical velocity and downstream variations of the height of the planetary boundary layer are some of the presently unresolved areas. Much of our present understanding of the planetary boundary layer has come from studies over other oceans. The Atlantic Trade Wind Experiments (ATEX) and several experiments in the Pacific such as the Airmass Modification Experiment (AMTEX) have provided relevant information in these areas. The Arabian Sea is unique in having the deserts to the north of a strong low-level westerly jet. In that sense, we believe that this region deserves a stronger focus on PBL investigation.

6. Monsoon onset

During the monsoon onset various dramatic changes are known to occur in the large-scale atmospheric structure over the monsoon region. Some of the well-known elements of the onset are a rapid increase of daily precipitation rate, an increase in the vertical integrated humidity (manifested as a meridionally propagating deep moist layer) and an increase in the kinetic energy, especially of the low-level flows. Although the mode of onset does vary somewhat from one year to the next, one or more of the aforementioned events are known to occur during the period of the onset. As these low-level winds grow in intensity, a cyclonic storm has been known to form on the cyclonic shear side of this wind current near 10°N, 65°E. It appears that in some four out of six years there has been evidence, based on 80 years of observation, of the occurrence of
FIG. 11. 850 mb streamlines and isotachs (m s$^{-1}$) over the MONEX domain. (a) 1200 GMT 1 June 1979. (b) 1200 GMT 18 June 1979.

Fig. 12. Time-longitude section of zonal velocity (m s$^{-1}$) at 850 mb. These are based on zonal averages between 50 and 70°E. an onset vortex (Krishnamurti et al., 1981a). It usually forms on the cyclonic shear side of the low-level jet in the lower troposphere over the eastern Arabian Sea; frequently, it moves meridionally towards the northern Arabian Sea and subsequently its motions are more westward usually toward the Arabian Coast, where it is known to dissipate. It has also been noted to first form in the middle troposphere over the eastern Arabian Sea and subsequently cyclogenesis occurs in the lower troposphere. Figure 11a, b illustrates two 850 mb charts for the formative stage of the onset vortex and the dramatic increase of monsoonal southwesterly flows over the Arabian Sea. Formation of the onset vortex has been attributed to the instability arising from
the explosive increase of horizontal shear of the broadscale monsoon current.

**a. Barotropic dynamics and the onset vortex**

Figure 12 shows the time evolutions of the zonal shear flows as a function of latitude. Here the zonally averaged (between 50°E and 70°E) daily values at 850 mb are shown. The onset vortex formed on 14 June at this level, and ~10°N over a region of marked cyclonic shear. Krishnamurti et al. (1981a) examined various aspects of the barotropic dynamics to assess the role of the horizontal shear flows. These included:

i) An examination of the meridional gradient of absolute vorticity over the Arabian Sea in order to assess the so-called inflection point instability (see Fig. 13b),

ii) An examination of the linear barotropic growth rates as a function of scale following Yanai and Nitta (1968) (see Fig. 13c),

iii) An evaluation of the nonlinear barotropic energy exchange from zonal flows to the eddies over the Arabian Sea. (see Fig. 13d), and

iv) A barotropic forecast experiment during the formation of the onset vortex.

Figure 13a also includes the profiles of the mean zonal flows over the Arabian Sea for this period, which exhibits a marked increase during this period. Figure 13b shows that the necessary condition for the existence of barotropic instability was satisfied by the zonal flow profile—especially during the formative period of the onset vortex. It furthermore shows that the barotropic growth rates for horizontal scales of the order of 3000 km were indeed quite large during this period. These large growth rates, especially around 15 June, implied an $e$-folding time of the order of a couple of days. The results of nonlinear barotropic energy exchange show a significant exchange from the local zonal flows to the eddies throughout the onset as well as the post-onset period. The lack of disturbance activity during the post-onset period is usually attributed to the cooling of the Arabian Sea and the buildup of strong easterly vertical wind shear; here, it was of the order of 40 m s$^{-1}$ over a 650 mb depth of the troposphere.

On the other hand, wind shears over the Bay of Bengal are usually quite weak during the post-onset period (Raman et al., 1981). Furthermore, the activity of monsoon over northeastern India results in a compensating general descent and dry troposphere over the Arabian Sea, thus providing an additional stabilizing influence. These features can be deduced from the geometry of the velocity potential field at 200 mb.

A barotropic forecast experiment (Krishnamurti et al., 1981a) resulted in the formation of a closed circulation near the region of the onset vortex. That was based on a conservation of absolute vorticity. The initial state was derived from the 850 mb motion field on 13 June, some two days prior to the formation of the onset vortex. The formation of the closed circulation was very clearly due to a transformation of shear vorticity into curvature vorticity in this experiment.

The aforementioned analysis is strongly suggestive of the importance of the barotropic dynamics during the formation of the onset vortex. This was also confirmed by Mak and Kao (1982). It should be stated, however, that the onset vortex is not a necessary ingredient for the onset of monsoon rain over India. Its presence in 1979 appeared to enhance the low-level westerlies on its equatorward side. The more important aspect of the onset of monsoon is the establishment of deep moist westerlies that are evidently related to a broader scale pattern of differential heating discussed in Section 3.

**b. Numerical weather prediction**

Numerical weather prediction of the onset of monsoon in 1979 was addressed by a number of large scale modeling groups. The modeling groups included the ECMWF, LMD, FSU, RPN, JMA, UKMO and NMC. All of these groups utilized global models with different degrees of horizontal and vertical resolution. All of the modeling groups utilized identical initial states based on the FGGE IIIb data (ECMWF multivariate optimal interpolation and four-dimensional assimilation analysis). The results of the intercomparison experiments have been documented by Temperton et al. (1983). The experimental forecasts started at 1200 GMT 11 June 1979. That was almost a week prior to the onset of monsoon rains over central India and was the period of commencement of the explosive increase of low-level kinetic energy. The formation of the onset vortex, the establishment of deep moist westerlies, the prediction of rain and the evaluation of root mean square error statistics were the goals of these experiments. We shall not go into an extensive review of these results here since they have been presented in some detail elsewhere. The most promising results were those produced by the ECMWF, LMD and the FSU models. The onset of monsoon was found to be most sensitive to the cumulus parameterization procedures. The use of an unusually strong heating (a plume convection model utilized by the UKMO) resulted in the formation of a hurricane-like vortex over the Arabian Sea. The drastic effect of this simulation was that low-level flows over India were strong easterly—rather than the southwesterly monsoon. On the other hand, the use of very weak convection (classical Kuo's scheme) resulted in persistent dry northwesterly winds at the low levels over India. An improved version of the Kuo's scheme based on Krishnamurti et al. (1983c) provided a reasonable simulation of the monsoon westerlies and the onset of monsoon rain. It required the use of steeper orography, called the Envelope mountains (Wallace et al., 1983), for a realistic prediction of the onset vortex, monsoon rains and the southwesterlies. Figure 14 illustrates the initial 850 mb flows for 1200 GMT 11
June for this experiment. The 6-day forecast and observed fields of the motion field at 850 mb are shown in Fig. 15a, b. The track and the formation of the onset vortex were reasonably predicted by the global model. The onset of rains on 15 June was reasonably handled by this model; the observed and predicted precipitation fields on day 4 are shown in Fig. 16a, b. The FSU global model is described in Krishnamurti et al. (1983b, 1984b). These experiments describe some of the first successful efforts on medium range numerical weather prediction over the tropics.

7. Monsoon depressions

During the Summer Monsoon Experiment of 1979, a number of tropical depressions formed over the Arabian Sea and the Bay of Bengal. Two of these were well documented in the literature largely because of the special observing systems that were deployed during their life cycle. A number of previous studies on such depressions dealt with descriptions when they had already formed and were located over a region well covered by the continental radiosonde network. The monsoon experiment provided a unique opportunity to examine two of these disturbances during the formative stage and during their entire life cycle as well. One of these was the disturbance over the Arabian Sea discussed in Section 6.

In a recent study, Lindzen et al. (1983) ascribed the growth of a Bay of Bengal monsoon depression to the horizontal shear flow instability mechanism. Lindzen examined the asymptotic response to pulse perturbations. These are the instabilities generated from localized perturbations in horizontal shear flows. Lindzen concludes that, in the month of July, the barotropic instability appears to be the most likely mechanism. He also de-emphasizes the role of vertical shear, stating that it must be quite weak. The role of CISK is negated from considerations of vertical momentum transport (cumulus friction) which he finds has a stabilizing influence. Observations over the Bay of Bengal do not seem to substantiate a barotropic vertical structure; the horizontal temperature gradients are large and the equatorward slope of the disturbance towards cold air is quite substantial.

Observationally, Douglas (1984) noted a strong vertical tilt of the depression toward colder air aloft, suggesting the importance of vertical shear. Figure 17a-c, obtained from a detailed and careful analysis of Douglas, shows a pronounced equatorward tilt. Douglas made use of nearly all of the available platforms of the FGGE/MONEX observing system to arrive at this structure: the data sets included marine ship observations, WWW, cloud winds, detailed collections of commercial aircraft, dropwindsonde data from research aircraft and soundings from FGGE/MONEX
research ships. Douglas' analysis appears to substantiate the theoretical findings of Arakawa and Moorthi (1982) who have emphasized the importance of vertical shear and CISK in the growth of monsoon depressions. Arakawa and Moorthi (1982) examined the growth rates for the classical Green Modes in easterly shear. Weak easterly vertical wind shear is a characteristic feature of the flows over the Bay of Bengal during the summer monsoon months. They noted that for a reasonable easterly wind shear of the order of 20 m s$^{-1}$/800 mb, large growth rates for horizontal scales of the order of 1000–2000 km is possible with an $e$-folding time of a couple of days. Furthermore, they noted that in the energetics of the amplifying modes the role of cumulus convection is not only to generate eddy available potential energy, but also to provide an enhancement of the baroclinic energy conversion. Saha and Chang (1983) and Shukla (1978) have also examined the depression/dynamics.

Nearly similar results on the energy conversions, based on observational analysis of a depression (after the formative stage) were shown by Krishnamurti et al. (1976). It is indeed surprising that during the formative stage, the role of vertical shear and cumulus convection has been shown to be significant since the horizontal shears are in fact quite large. A close examination of satellite imagery during the incipient stage of the depression does show some organization of cumulus convections over the eastern Bay of Bengal (Warner, 1984). Sanders (1984) examined the quasi-geostrophic omega equation over this region and noted the importance of the baroclinic forcing mechanisms in determining the field of quasi-geostrophic vertical motions. That is perhaps also suggestive of the mechanism proposed by Arakawa and Moorthi (1982).

A further step in such an analysis would be a detailed numerical weather prediction of a depression and a subsequent diagnosis of the results. That was carried out in two recent studies by Krishnamurti et al. (1983a, 1984a).

These studies were based on a global spectral model. Medium range forecasts were made with real initial data. The initial state for these experiments was taken from the FGGE/MONEX observations at 1200 GMT 1 July 1979. The depression formed over the Bay of Bengal on 5 July and arrived at the coast of India on 7 July.

The global spectral model is resolved via a triangular truncation consisting of 42 waves and 11 vertical sigma levels (Krishnamurti et al., 1984a). The use of a semi-implicit time differencing algorithm enables use of a time step of $\sim$15 minutes providing a considerable saving of time for medium range numerical weather prediction. The mountains in these series of experi-
ments are defined by the so-called "Envelope Orography" following Wallace et al. (1983). The basic data sets are the FGGE/MONEX observations available as of 1983. The FGGE IIIb analysis produced by the European Centre for Medium Range Weather Forecasts (ECMWF) were used as a first-guess field in our analysis of the MONEX observations. The analysis scheme used by ECMWF is a multivariate optimal interpolation scheme and a four-dimensional assimilation scheme using a 6-hour forecast assimilation. The MONEX data sets were added on via a successive correction method. The initialization for the present series of experiments is based on physical and dynamical initialization; this is described in some detail in Krishnamurti et al. (1984a). The cumulus parameterization method deployed here is a variant of Kuo's (1974) scheme and is described in detail by Krishnamurti et al. (1983c). Over regions of dynamical ascent of absolutely stable saturated air, large-scale condensation is involved. The model includes a fairly detailed parameterization of the radiative processes where the diurnal change, cloud feedback processes and energy balance of the earth's surface are included following Chang (1979). The surface layer fluxes are determined by similarity theory where the exchange coefficients are stability dependent. The vertical variation of the surface fluxes in the planetary boundary layer are defined by a mixing length $K$-theory. The model included a dry convective adjustment for the removal of superadiabatic lapse rates.

The FSU model was adapted from the original version proposed by Daley et al. (1976) and extended by the author and his colleagues. The prediction of the monsoon depression was successful on the medium range time frame of six to seven days. The success of prediction was due to several factors such as data sets, improved analysis of the initial state and an improved model. It is difficult to isolate any single major factor without a further series of carefully constructed numerical experiments. Figure 18a illustrates the initial flow field 1200 GMT (1 July 1979) at 850 mbs. It shows general westerly flows over the Bay of Bengal. The northern part of the Bay of Bengal exhibits a region of cyclonic horizontal shear. At 200 mb the flows exhibit broad easterlies over the Northern Bay with an easterly shear of around 30 m s$^{-1}$ over a 650 mb depth of the troposphere. Over the Eastern Bay and northern Burma dense convective clouds were apparent from satellite imagery (Krishnamurti et al., 1979). The depression that formed on 4 July in the middle troposphere was apparent at the 850 mb level by 5 July. Figure 18b shows the observed flow field for July. The 6-day forecast of the depression is illustrated in Fig. 18c. Several vertical cross sections and time sections of the predicted storms were also constructed. They revealed that the initial formation of the storm did occur at the middle troposphere. It is usually assumed that the result of (i) linear stability analysis, (ii) observational energetics, and (iii) energetics based on numerical simulation or
Fig. 15. (a) Observed and (b) predicted 850 mb wind field (m s$^{-1}$) at 1200 GMT 17 June 1979 over the MONEX domain. Speed m s$^{-1}$. (Note that this is a 6-day forecast).
Fig. 16. (a) Observed and (b) Predicted rainfall rate at 1200 GMT June 15 1979. (Note that this is a 4-day prediction). Units: mm day$^{-1}$.

Prediction are three different stories. However, it appears that in some gross sense the mechanism suggested by Arakawa and Moorthi (1982) is indeed borne out by the observational energetics and by the results based on the aforementioned numerical weather prediction experiment.
The observational energetics for these same storms were also carried out by Surgi (1984). Surgi averaged the results of Lorenz (1960) energetics for two separate periods; i.e., for the formative and the postformative periods. In order to address the interpretations and ambiguity of the boundary fluxes she calculated open domain energetics over 18 different-sized boxes. From these she selected a domain that provided the smallest boundary fluxes of kinetic and potential energy. Thus, her results were considered as being valid for a closed system. Figure 19 illustrates the results of her calculations from 75 to 105°E, and between the equator and 35°N through the troposphere. These results show that in the formative stage the eddy kinetic energy $K$ is enhanced by the barotropic as well as the baroclinic energy conversions, while the depression stage shows a more dominant role for the baroclinic process. Although Surgi did not explicitly evaluate the generation terms, it appears that the maintenance of the eddy available potential energy (which was slowly decreasing during this entire period) required a generation mechanism. The most likely mechanism appears to be cumulus convection since there were no other apparent energy sources on the scale of the depression.

The results of the energetics from multilevel global spectral model forecasts (Fig. 20) were evaluated by Krishnamurti et al. (1983a) over a domain extending from 10 to 30°N, 50 to 100°E through the depth of the troposphere. The abscissa in this diagram denotes the time axis (i.e., the ten days of the medium range forecast). The barotropic conversion $\langle K_t \cdot K_e \rangle$ is considerably smaller and is even negative during the formative period compared to the baroclinic conversion $\langle P_e \cdot K_e \rangle$. A sharp
standing of the structure and life cycle of organized convective elements within the depressions, Warner (1984) has provided a detailed observational analysis of the convective elements as seen from satellite imagery and aircraft photogrammetry. Those data sets need to be examined in the context of the generation of eddy available potential energy and the scale of the depression.

8. Breaks in the monsoon

During MONEX, a major break in the monsoon was evident between 10 and 25 July 1979. The characteristics of this break were similar to those described by Ramamurthy (1969). The principal rainfall belts were located close to the equator, ~80°E, and near the foothills of the Himalayas. The time scale of breaks is usually of the order of several days or longer. That suggests the possibility of a pressure rise over the region of the monsoon trough from low-frequency phenomena during this period (Sadler and Harris, 1970; Krishnamurti and Ardanuy, 1980). Sadler and Harris identified meridionally propagating ridge lines from the equatorial latitudes toward central India, while Krishnamurti and Ardanuy identified westward propagating systems on the time scale of 10–20 days. More recent studies by Yasunari (1981), Sikka and Gadgil (1980), Krishnamurti and Subrahmanyan (1982), Lorenc (1984), Krishnamurti et al. (1985), M. Murakami (1984) and T. Murakami et al. (1983) have also examined the active-break cycle of the monsoon and their relationship to various aspects of the low-frequency oscillations. Krishnamurti et al. (1985) noted a superposition of the westward propagating ridge lines on the 30–50 day time scale. Power spectral analysis and wavenumber frequency spectra around latitude circles show that these are among the dominant low-frequency modes of the tropical sea-level pressure field. The relevant scales for 30–50 days are the long waves, i.e., zonal wavenumbers 1, 2 and 3. Those relevant in the 10–20 time scale are zonal wavenumbers 4, 5 and 6. Figure 21a, b shows x-t diagrams of these respective pressure waves covering the break period. The data sets include the entire 365 days of the FGGE year. Of interest is the passage of ridges over central Indian longitudes during the period of the Break, i.e., 10–25 July 1979. A rise of sea level pressure by ~2 mb occurs during the superposition of these two families of low-frequency systems. This feature is further emphasized in Fig. 21c.

9. Heat lows

The southwesterly moist currents of the African and west Asian monsoon lie to the south of a major belt of desert heat lows. The role of the heat lows with respect to the activity of the monsoon is not well understood at the present time. Most general circulation models do describe dry conditions over the deserts and
the neighboring moist monsoon simulations are indeed quite realistic (e.g., Hahn and Manabe, 1975). What has been lacking is a systematic effort to define and carry out sensitivity experiments on the relationship of the heat low to the monsoon activity. Charney (1975) pointed out a paradox: tropical and subtropical deserts were in fact heat sinks. That was noted from satellite measured estimates of the Earth’s radiation budget. Over most of the tropics the incoming solar radiation exceeds the net outgoing radiation, while over deserts the converse is the case. Since the thermal stratification appears to remain nearly invariant from one day to the next, its maintenance requires that energy be imported laterally to offset the energy loss at the top of the atmosphere.

To address some of these questions from an observational perspective, a field experiment was conducted within MONEX in 1979 (Ackerman and Cox, 1982; Blake et al., 1983). The experiment provided direct measurements of the up and down irradiances for the solar and the longwave component via aircraft probes over the heat low of Saudi Arabia. The aircraft also provided atmospheric soundings of temperature, pressure and humidity over this region for the entire troposphere below the 250 mb level. An analysis of these data sets has been carried out in the aforementioned studies. They cover the day and night periods for selected days during May 1979. In Fig. 22a–c we show some of the salient MONEX observations during this period. The day and night vertical profiles of divergence and vertical velocity are shown in Fig. 22a, b. Descending motions extend all the way to the surface at

Fig. 19. Energetics based on pre-onset and post-onset data sets during two different periods, July 1979. The units of energy quantities are m$^2$ s$^{-3}$ while the exchanges are in m$^2$ s$^{-3}$. This is based on Surti (1984).

Fig. 20. Results of energy exchanges from (a) zonal kinetic energy to eddy kinetic energy and (b) eddy available potential to eddy kinetic energy. These results are based on a 10-day global prediction of the life cycle of monsoon depression. The results shown here are integrals from 100 mb to the earth’s surface over a MONEX domain.
night while the lowest 100 mb shows upward motion within the heat low during the day time. The mixed layer depth is determined from a composite data set and shows that the potential temperature and specific humidity are nearly well mixed up to the 650 mb level (Fig. 22c). Since superadiabatic lapse rates only exist in the lowest 100 meters over the desert it is apparent that this mixed layer cannot be described by simple dry convective adjustment methods.

In most large-scale numerical weather prediction models, dry convective adjustment replaces an unstable potential temperature profile by a constant $\theta$ (in the vertical) such that the integral of potential temperature remains invariant during the adjustment. That tends to describe a rather shallow mixed layer. It is apparent that the vertical eddy flux of heat deserves a more sophisticated parameterization over the desert areas. It is also noted that the observed depth of 350 mb during MONEX is not a fixed entity. Examination of numerous soundings over Riyadh shows that the depth of mixed layer does vary considerably, and it appears to have some relationship to the overall depth of the dust and aerosol layers. Further observational and modeling studies are needed in these areas. The vertical distribution of up and down radiances is extremely interesting in this region. The downward directed shortwave irradiance is presented in Fig. 23a. The solar radiation reaching the ground is of the order of 800 W m$^{-2}$, which is much smaller than the solar constant (1375 W m$^{-2}$). Thus, it is apparent that a considerable warming of the troposphere occurs from the direct solar radiation. Usually the clear sky warming rates from direct solar radiation are of the order of 0.5–1°C day$^{-1}$, and the much larger warming rates over the desert region suggests a possible role of aerosols and dust (Ackerman and Cox, 1982). The upward directed short wave radiation (Fig. 23) is of the order of 350 W m$^{-2}$ over most of the troposphere; the earth’s surface albedo is of the order of 375/850 = 45% and the earth’s atmospheric albedo (at the top) is of the order of 300/1100 = 27%. The downward directed longwave radiation, shown in Fig. 23d, decreases from around 400 W m$^{-2}$
at the earth’s surface to about 100 W m\(^{-2}\) at around 250 mb. The upward directed long wave radiation (Fig. 23c) decreases from 500 to about 350 W m\(^{-2}\). A net divergence of long wave irradiance of around 400 W m\(^{-2}\) is experienced by the atmosphere. The long- and shortwave heating and cooling rate (Fig. 24), which corresponds to a net cooling of around 4°C day\(^{-1}\), is slightly smaller than the heating rate by solar radiation over the deep troposphere between 900 and 400 mb. The nighttime profiles of radiation are not presented here (see Blake et al., 1983). It is important to note, however, that over a 24-hour average a net longwave cooling dominates over the daytime net warming of the troposphere by solar radiation, thus resulting in the aforementioned net radiative losses as are measured at satellite altitude. The stratification is thus largely maintained by adiabatic warming associated with the downward motions. The compensating upward mass flux occurs over distant convective areas (see Blake et al., 1983). This can best be portrayed from an analysis of the divergent wind, which shows the active monsoon over Northern Malaysia, Southern Indochina and the western Pacific Ocean. The high-level divergent streamlines emanate from this region, and exhibit an eventual confluence into the region of these desert heat lows as well as several other regions. The upper level inflow of mass also brings in a steady supply of energy (Blake et al., 1983). Thus, the maintenance of the thermal stratification against radiative heat loss is attributed to the descent of air which in turn is supplied by lateral flux of enthalpy from the remote monsoon areas. It is within the well-mixed layer that the role of dry convection appears to be significant in the maintenance of the stratification.

FGGE IIIb analysis provides a useful synoptic structure of the heat low that can be found from the west coast of Africa to the deserts of Pakistan. Observational composite studies on the structure of the heat lows over the Sahara, Arabia and Pakistan are worthy of further investigations.

Another dry region of equal relevance is the western part of the Tibetan Plateau, which was addressed in Section 3.

10. Low-frequency motions of the monsoon

The monsoon season is only about 3–3.5 months long. Thus, within a season the relevant low-frequency motions are those whose time scales are less than the seasonal time scale. There are, of course, several other lower frequencies such as the semiannual, the annual, the quasi-biennial and the Southern Oscillation that are evidently important for the monsoon problem. In this review we shall not address the latter but confine our attention to the major findings from the FGGE/MONEX observations and related theoretical findings. The most important low-frequency motions seem to be those in the 30–50 day and the 10–20 day time scales. From the perspective of the monsoons, the 30–50 day time scale was first emphasized by Yasunari (1981). He noted zonally oriented cloud lines that propagated meridionally from the equatorial latitudes to the Himalayas. Krishnamurti and Subrahmanyan (1982) identified distinct motion systems on this time scale. At the 850 mb surface, a train of zonally oriented troughs and ridges were shown to exhibit a near-steady meridional propagation. The troughs were associated with rising motions and clouds while the ridges were essentially cloud free. The phenomena of onset, active and break monsoon appeared to be related to the passage of these low-frequency systems. Figure 25 shows a sequence of the low-frequency wind analysis at 850 mbs from Krishnamurti and Subrahmanyan (1982). The meridionally moving troughs and ridges tend to form near the equator, amplify as they arrive at \(\sim 10^\circ\)N and finally appear to dissipate as they arrive near the Himalayas. These low-frequency systems are thermally direct in the sense that warmer air ascends in the troughs and cold air descends in the ridges. Calculations
FIG. 22. Vertical velocity $\omega$ and horizontal divergence $D$ over the Saudi Arabian heat low during May 1979: (a) daytime vertical profiles, (b) nighttime vertical profiles, (c) vertical profiles of potential temperature and (d) specific humidity. They illustrate the depth of the mixed layer (Blake et al., 1983).
Fig. 23. Vertical profiles of upward and downward irradiances during the daytime over the Saudi Arabian heat low: (a) shortwave up, (b) shortwave downward, (c) longwave downward, and (d) longwave upward. (Blake et al., 1983).
of the energetics of this system were carried out by Krishnamurti et al. (1985) and Murakami et al. (1983).

From a global perspective, the aforementioned regional description is not altogether complete. Krishnamurti and Gadgil (1985), Krishnamurti et al. (1985) and Lorenc (1984) have examined various aspects of the 30–50 day oscillations over the globe during the FGGE year. Krishnamurti and Gadgil examined the global FGGE data sets for the entire FGGE year. Five variables \((U, V, T, Q, p)\) at six levels \((1000, 850, 700, 500, 300, 200\) mb) were examined on this time scale. They noted that a length of 365 days of data record was better suited for studies of 30–50 day oscillations than a short seasonal data set as was used previously. The surprising finding was that the amplitude of the oscillations on the 30–50 day time scale were not only dominant over the region of the summer monsoon, but also at higher latitudes near 50°N and 50°S near the 200 mb level. From the time-filtered data sets of the zonal wind on this time scale, it is possible to map the isentropes of the maximum wind in a given season (Krishnamurti and Gadgil, 1985). Figure 26a–d shows these distributions for the winter, spring, summer and fall months, respectively.

During northern winter, a distinct maximum velocity \(\sim 5.5\) m s\(^{-1}\) is found near 160°W that turns out to be another interesting source region for the low-frequency motion systems. The first appearance of a monsoonal low-frequency wind maximum occurs in the spring season over Malaysia and Indochina. As was stated earlier, this region encounters the onset of monsoon in early May. Thus, it appears that the oscillation over the monsoon region, which extends northward by the summer season (see Fig. 26c), may be related to monsoon activity. During these summer months the large amplitude of the zonal wind oscillation covers the region between 10 and 20°N and from the Arabian Sea to the Pacific Ocean. The amplitude lies between 3 and 5 m s\(^{-1}\). In the fall months the amplitude of the low-frequency activity over the monsoon region diminishes considerably (see Fig. 26d). Although it is somewhat apparent that low-frequency motion systems modulate the monsoon activity, the converse (i.e., how monsoon activity might play a role in exciting the low-frequency motions) is not altogether clear.

Another major observational finding on the 30–50 day time scale relevant to the monsoon problem are the divergent motions on the planetary scale. Using empirical orthogonal functions to represent the temporal behavior of the divergent wind, Lorenc (1984), identified a planetary scale (mostly zonal wavenumber 1) wave that propagates from west to east in roughly 30–50 days. Furthermore, he noted that this wave can be identified nearly all year around. Krishnamurti et al. (1985) examined this wave in some detail by mapping it for the entire year. Figures 27–29 show a sequence of the low-frequency velocity potential at 200 mb on this time scale around the period of the monsoon onset in 1979. The divergence center arrived over southwestern India around 14 June close to the period of commencement of rain over that region.

Theoretical aspects of this problem have been addressed by Webster (1983), Dunkerton (1983) and several others.

11. Concluding remarks

The data sets for the Summer Monsoon Experiment were unique. They provided some of the best descriptions ever obtained of the planetary and regional scale monsoon. Special observing systems over the Indian Ocean provided high resolution cloud winds, soundings from research ships, winds from constant level balloons, winds from commercial aircraft, enhanced world weather watch and dropwindsonde measurements of atmospheric soundings deployed from research aircraft. In addition, high resolution estimates of the earth's radiation budget were obtained from geostationary (Indian Ocean GOES) and polar orbiting satellites (Nimbus-F, Tiros-N, NOAA-A), retrieval soundings of temperature and precipitable water, and direct measurements of long- and shortwave irradiances from research aircraft. A special collection of marine data over the Indian Ocean also provided some of the unique observations that were complemented by FGGE and its special observing systems over the rest of the globe.
Fig. 25. A sequence of low-frequency streamline and isotach (m s$^{-1}$) charts on the time scale of 30–50 days over the MONEX domain. (Krishnamurti and Subrahmanyam, 1983).
Fig. 26. Seasonal maximum wind speed (m s⁻¹) charts of the low-frequency motions on the time scale of 30–50 days over the globe: (a) winter, (b) spring, (c) summer and (d) fall months during the FOGC year. (Krishnamurti and Gadgil, 1984).
Fig. 27. A sequence of low frequency charts of the 200 mb velocity potential on the 30–50 day time scale. These are based on the entire FGGE year of analysis.
Fig. 28. A sequence of low-frequency charts of the 200 mb velocity potential on the 30–50 day time scale. These are based on the entire FGGE year of analysis.
Fig. 29. A sequence of low frequency charts of the 200 mb velocity potential on the 30–50 day time scale. These are based on the entire FGGE year of analysis.
Some of the major achievements of MONEX are:

- Use of an unprecedented volume of observations from ships, aircraft, satellites, constant level balloons and augmented WWW.
- Most detailed four-dimensional descriptions of the evolution of the 1979 summer monsoon.
- The planetary scale monsoon, the associated circulations, thermal structure and heating distributions are better understood because of the unprecedented data sets.
- The role of the Tibetan Plateau in its overall effect on the evaluation of the monsoon has been approached by many scientists. The most promising accomplishments are in the areas of the definitions of the heat sources.
- The onset scenario focussed on (i) the role of horizontal shear in the onset vortex dynamics and (ii) the role of differential heating in the establishment of broad scale zonal flows and divergent circulations.
- The geostationary satellite located over the Indian Ocean during MONEX provided imagery and cloud winds that enabled the most complete descriptions of the monsoon over the oceans. This was simply not possible prior to 1979. Use of these data sets, have played a key role in the determination of air–sea interactions.
- Major success is evident in the areas of numerical weather prediction, especially with global models. The onset and active phases (depressions) have been reasonably predicted on the medium range time frame.
- A number of major research groups participated in FGGE intercomparison experiments on medium range numerical weather prediction. The experiments have been most revealing on the sensitivity of the onset of monsoon to different parameterizations of cumulus convection.

Further analysis of the monsoon during 1979 in most of the aforementioned areas is necessary. A better synthesis of observational, theoretical and modeling studies and finding is undoubtedly expected from further efforts.

The future research trends in this area are already evident from the current emphasis. Research on inter-annual variability of monsoon on several space–time scales is being pursued by several groups. Relationships and sensitivity of monsoon rain, floods and rain to a variety of parameters such as sea surface temperatures, antecedent climate anomalies, Himalayan snow cover and overall heat sources and sinks are important areas of future research.

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