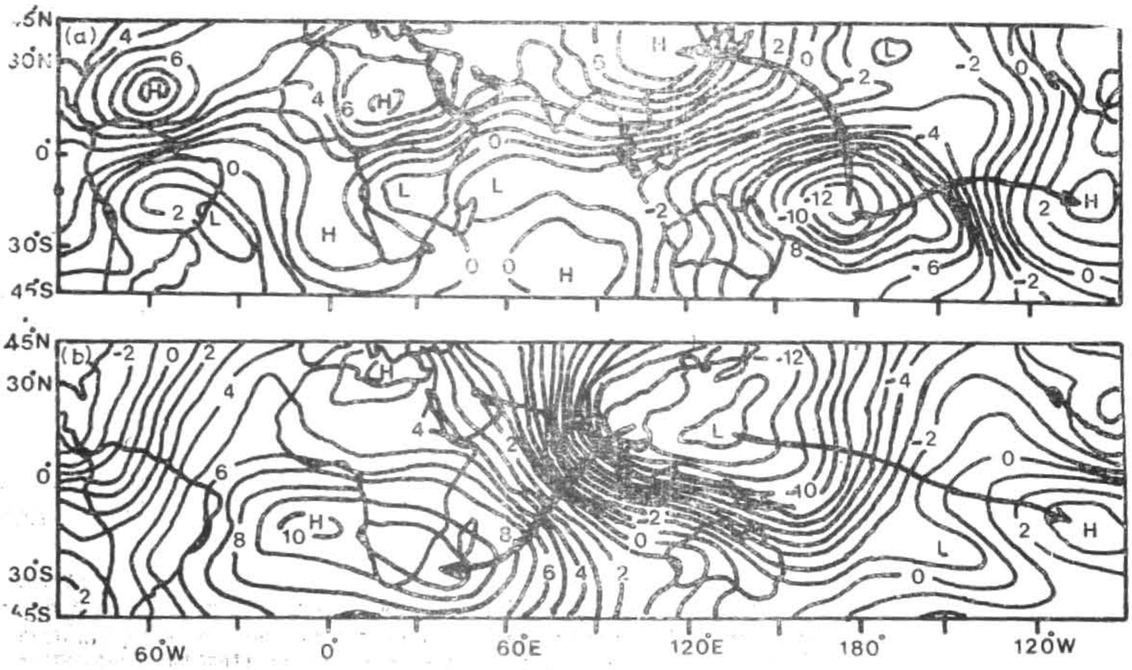

Fig. 1. Velocity potentials : (a) at 200 hPa for the month of January 1979 based on European Center for Medium Range Weather Forecasts (ECMWF) data set; (b) at 200 hPa for the month of July 1979.

(*From* Krishnamurti and Surgi 1987)

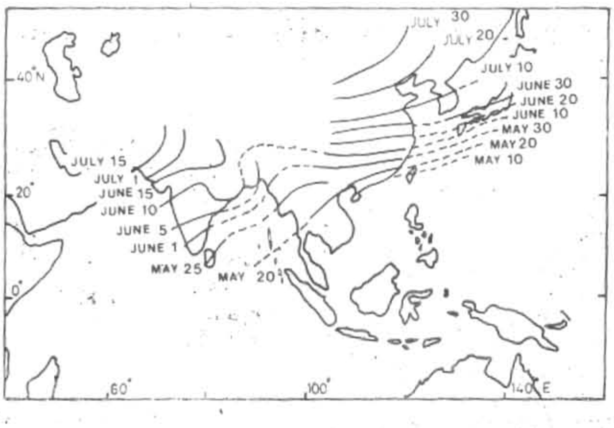

Fig. 2. Mean onset date of the summer monsoon.

(*From* Tao and Chen 1987)

months are characterized by a pair of upper anticyclones located on the poleward sides of the near equatorial lower tropospheric convergence zone. The northern anticyclone migrates poleward from northern Malaysia during the winter months to reach the Tibetan plateau by July. It has its maximum amplitude during August, at the end of the summer monsoon when the rains begin to withdraw, this northern anticyclone moves back equatorward. The annual cycle of the planetary scale monsoons is illustrated by Fig. 1 which depicts the velocity potentials at 200 hPa for January and July 1979 based on European Center for Medium Range Weather Forecast (ECMWF) analyzed fields. These divergent circulations are an important aspect of the planetary scale circulation associated with the global scale monsoon system. Thus, Fig. 1 illustrates the prominent role played by the monsoon system in the global circulations of the northern hemisphere winter and summer seasons. The winter months are characterized by an intense Hadley cell whereas during the summer months, the east-west circulations associated with the global scale summer monsoon system are enhanced. The so-called Walker east-west circulation can also be noted over the Pacific Ocean with an extension well beyond the equatorial belt.

In association with the latitudinal annual migration of the lower tropospheric convergence zone and the northern anticyclone, the principal belt of monsoon rainfall has a similar movement from Indonesia during the northern winter months to the Indo-Gangetic plain and China during the northern summer months.

Fig. 2 gives the mean onset date of the summer monsoon and illustrates quite well the northward migration of the rainfall belt during northern spring. This figure as well as Fig. 1, also demonstrates that the

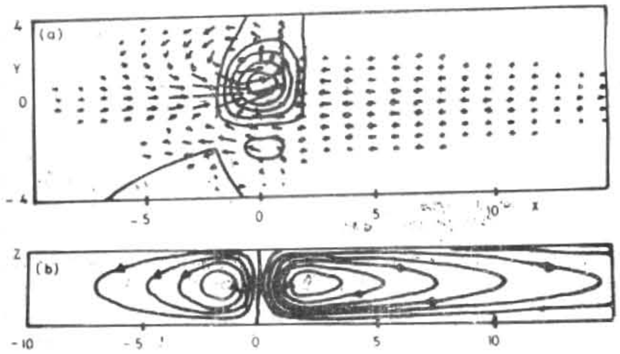

Fig. 3. The solution of the forced shallow-water equations for heating that is confined to the range of longitudes $|x| < 2a_e$: (a) the arrows give the horizontal velocity fields and the solid contours in the upper panel give the vertical velocity, which has a distribution close to that of the heating function. The motion is upward within the contours north of the equator with a maximum near $x=0$, $y=a_e$. The contours in the lower panel are pressure contours and the axes are labelled in units of $a_e$, (b) the meridionally averaged zonal flow (Walker circulation) is interpreted as a baroclinic response.

(*From* Gill 1980)

Indian summer monsoon cannot be separated from the eastern Asian one. There are major differences between the two components such as the establishment of the summer rainfall over the two regions. Whereas the monsoon advances northward in a stepwise fashion in eastern Asia, the first rainfall over India occurs in a quite abrupt fashion. Within less than a week, the monsoon sets up in association with the establishment of the low-level southwest monsoon circulation over the Indian Ocean and the northward migration of the westerly flow and its replacement by the Tropical Easterly Jet (TEJ) in the upper troposphere.

The major role played by the east-west circulations in driving the planetary scale tropical motions has also been emphasized by studies of the energetics of the tropical circulation during the northern summer. Thus, it is shown that an important part of the total variance of the velocity potential (divergent circulation) as well as the covariance of the vertical velocity and temperature is on the planetary scale. The transfer of available potential energy takes place from the synoptic scale perturbations to the planetary scale systems. Tropical depressions, storms and easterly waves with a typical horizontal scale of the order of a few thousand kilometres are particularly active when the east-west circulations are intense. These synoptic scale perturbations do not occur randomly all over the tropics but over certain longitudes, *i.e.*, they are assymmetrically placed in the tropics along planetary waves with maximum synoptic scale activity over the Asian, African and central American monsoon domains. In other words, there is a spatial organization of the synoptic scale systems which favours the transfer of energy from the synoptic scales to the planetary ones. The available potential energy at the planetary scale maintains the east-west and Hadley circulations which give rise, for example, to the TEJ, one of the major components of the northern summer system.

The evolution of the energetics of the planetary scale motions during the onset phase of the Indian summer monsoon has been studied by Pasch (1983) using the FGGE data set. An important increase of kinetic energy on the planetary scale all over the tropics in association with the increase of eddy available potential energy was noted during the onset of the summer monsoon. These results demonstrate the role of the organized heat sources on the planetary scale in the generation of eddy available potential energy. One of the most important identified regions where the eddy available potential energy is released, is the southeastern part of the Tibetan plateau stressing the importance of the Asian monsoon during the northern summer in the general circulation of the atmosphere.

## 3. Theoretical framework to understand the monsoon circulation

The monsoon circulation discussed in the previous section can be understood within the framework of equatorially trapped waves. In a now well-known paper, Gill (1980) wrote down the theoretical basis. In that paper, he studied the dynamical response in the equatorial region to a heating source in the form of steady forced motions with small friction of the shallow water equations, by using an approximation called the equatorial beta plane. Simple solutions in the form of equatorially trapped waves may be found for heating that is confined to a particular region near the equator. For a maximum heating at about 10° N and covering 40° of longitude, *i.e.*, the Asian monsoon region (maximum heating between 90° and 140° E longitude), the solution (Fig. 3a) shows vertical motion and mainly northward velocity in the region of heating. To the east of the forcing region, a forced Kelvin wave propagates eastward. In this region, corresponding to the eastern Indian Ocean and the Pacific Ocean, the flow is parallel to the equator and symmetric about the equator.

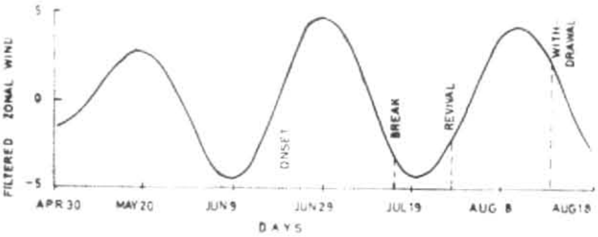

Fig. 4. The 30-40 day filtered data of the zonal velocity for the 120-day period from 28 April through 25 August 1979 over the Arabian Sea. (Units : $ms^{-1}$)

(*From* Krishnamurti & Subrahmanyam 1982)

To the west of the forcing region, the solution corresponds to a forced long planetary (mixed Rossby-planetary) wave. This wave propagating westward from the forcing region decays faster than the Kelvin wave and covers a smaller area corresponding roughly to the Indian Ocean. There is a meridional motion so the equatorward return of the air moving poleward in the heating region is found to the west. The result is a cyclonic centre on the west flank of the heating region. These patterns can be compared to the 850 hPa flow over the Indian Ocean with the easterly trade winds on the northwest flank of the Mascarene high pressure crossing the equator in the western Indian Ocean and converging toward the Indo-Gangetic trough.

Fig. 3 (b) shows the meridionally averaged circulation which is due to the part of the forcing that is symmetric about the equator. Rising motion is found over the longitude of the heating region, and sinking elsewhere. To the east of the heating region, the corresponding circulation over the Pacific Ocean is the so-called Walker circulation. The difference in the zonal extension of the descending branches on both sides of the heating region is stressed. To the west, the returning branch lies over the western Indian Ocean characterized during the northern summer by a strong marine inversion layer.

At this point, it must be pointed out that solutions can be obtained for a heating source symmetric about the equator corresponding to the release of latent heat over Indonesia during the northern winter months. The analytic solutions describe quite well the northern winter monsoon circulation with two upper tropospheric anticyclones on the poleward sides of the heating region.

### 4. Some aspects of the monsoon circulation

In opposition to the trade winds of other longitudes and to the January flow over the Indian Ocean, the most distinct difference in southern Asia during the northern summer is the intense low-level flow of the monsoon circulation. During the 1979 summer, a large number of platforms, *viz.*, GOES geostationary satellite research aircraft flights, constant-level balloons were centred over the area from which a good description of the dynamics has emerged : A prominent signature of the Asian monsoon is the cross-equatorial wind component directed into the summer hemisphere. It is strongest along the east coast of Africa and forms the so-called Somali jet (Young 1987). This feature has been studied to understand the modification of the tropical boundary layer at the crossing of the equator in order to elaborate a theoretical framework for the friction boundary layer at low latitudes. The transition from a near-Ekman type balance, near 20° S, to an accelerating flow, near the equator indicates the role played by the horizontal and the vertical advection terms. When an air parcel approaches the equator, the role of the advective acceleration becomes important and there is an important departure from the Ekman balance (Reverdin and Sommeria 1983). Further the strong surface winds have a major impact on the upper ocean circulation, giving rise to the Somali current, one of the fastest mean currents in the world. The Somali current normally develops major eddy circulations, which are evolving during the northern summer.

This strong cross-equatorial atmospheric flow is also important for the water vapour balance of the Indian monsoon. It is important to study the water vapour transport and its maintenance to understand how the large-scale circulation affects the monsoon rainfall. Several studies have shown that the bulk water vapour transport by the Somali jet from the southern hemisphere constitutes the major water vapour source (Cadet and Greco 1987 a & b). However, the same studies also have suggested that the evaporation over the Arabian Sea is not a negligible source.

MONEX was marked by a major upgradation of the observational network over and around the Tibetan plateau from which a certain number of studies have been performed. The Tibetan plateau as a huge massif of high elevation does not only exert a strong barrier effect on the monsoon flow but also constitutes an elevated heat source generating temperature gradient with the surrounding atmosphere. During the summer, the plateau creates a heat contrast which can be at least as large as the land-ocean contrast at the surface. Luo and Yanai (1984) evaluated the apparent heat source and moisture sink as residuals of the thermodynamic and moisture equations. Over the western part of the plateau, the sensible heat source is important indicating the development of dry convection whereas large values of apparent heat source and moisture sink are noted over the eastern plateau. The existence of an important heat source over the plateau has consequences on the regional summer monsoon circulation : development of a low pressure system and upper-level Tibetan anticyclone. The dynamics of the circulation is simple. When the plateau is heated, it induces convergent motion towards the plateau in the middle and lower layers with a compensating divergent flow outward from the plateau in the upper layer.

### 5. The low-frequency mode of the Asian summer monsoon

The existence of a low-frequency oscillation over the western Pacific Ocean was discovered at the beginning of the 70's by Madden and Julian (1971). After being forgotten for a certain number of years, several studies performed prior to MONEX revealed its importance over the Indian Ocean and its influence on the activity of the monsoon. The break and active cycle of the Indian summer which is its major mode of oscillation is characterized by an out of phase relationship between convection over central India and equatorial latitudes. The transition between break and active monsoons has been investigated by Yasunari (1979) and Sikka and Gadgil (1980) who showed that east-west oriented cloud band over the Indian longitudes has a tendency to move northward with the first northward movement at the time of the onset of the monsoon. The break/active cycle in cloudiness change takes place concurrently over the entire Asia including the Indian Ocean and the western Pacific Ocean.

One of the major findings of FGGE/MONEX has been the demonstration of the relationship between the phase of the global low-frequency mode in the tropics and the activity of the monsoon (Fig. 4). Krishnamurti and Subrahmanyam (1982) identified motion systems propagating meridionally from the equatorial latitudes to the Himalayas. The active and break cycles of the monsoon are closely coupled to the passage of troughs and ridges of these systems over India.

These systems over Asia only represent a facet of a global phenomenon which has been investigated by a large number of authors during the recent years. The understanding of the physics behind the low-frequency mode of the tropics is one of the present day challenges in meteorology. The mode has been studied using Outgoing Longwave Radiation (OLR) and wind data.

It appears as a wavenumber 1 eastward propagating mode in the tropics which can be identified all year around (Lorenc 1984). Its phase speed depends on the longitude. It appears quite active over the Indian Ocean and the western Pacific Ocean with a season of convection over these two regions.

Different hypotheses have been put forward to explain the excitation and subsequent motion of the global mode and its regional aspect over Indain longitudes. Most recent studies have identified the global mode as a Kelvin wave modified by convection. The models of Emanuel (1987) and Neelin *et al.* (1987) hypothesize that the waves arise from an air-sea interaction instability driven wind-dependent surface fluxes of moist entropy. Concerning its meridional propagation, Webster and Chou (1980) suggested the importance of ground hydrology over the Asian continent. Goswami and Shukla (1984) demonstrated a meridional motion in response to maximum heating and associated convection and static stability fluctuations.

### 6. Conclusions

The summer monsoon experiment provided with the most comprehensive data set ever collected for the study of the Asian summer monsoon on the global and regional scales. Our understanding of the phenomenon has considerably improved during the last decade. Further analysis of the monsoon is necessary for example to understand the physics of the low frequency mode, its role on the onset date of the Indian summer monsoon, its potentiality for long range forecasting, etc. Further efforts are needed about numerical modelling.

One of the research trends in the area of monsoon research concerns the understanding of the interannual variability of monsoons : relationships between rain amounts, and a certain number of parameters such as SST, antecedent climate anomalies, etc.

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