Onsets of the Asian Summer Monsoon 1979–82

R. P. PEARCE

Department of Meteorology, University of Reading, Reading, United Kingdom

U. C. MOHANTY

Centre for Atmospheric Sciences, Indian Institute of Technology, New Delhi, India

(Manuscript received 9 May 1983, in final form 7 February 1984)

ABSTRACT

Analyses of moisture and mean tropospheric enthalpy distributions based on FGGE data are described and interpreted for the months of May and June 1979. Their detailed spatial characteristics are inferred using 15-day means for the region 0°–150°E, 40°S–40°N, and the detailed temporal evolutions from time series at daily intervals for two regions—the Arabian Sea and the larger area 0°–150°E, 22.5°S–41.25°N. Vertical motion fields are calculated using O'Brien's method and are used to determine the distributions of moisture convergence and heating. The onset is found to consist of two main phases: 1) a moisture buildup over the Arabian Sea during which synoptic- and mesoscale transient disturbances develop; the relationship of this buildup with planetary wave activity is discussed. This is followed by 2) a rapid intensification of the Arabian Sea winds and a substantial increase in latent heat release, essentially a large-scale feedback process.

The fully established monsoonal flow is interpreted in terms of Gill's model based on linear equatorial beta-plane theory. Then the model flow is found to agree reasonably well with observations, with strong cross-equatorial flow in both lower and upper troposphere, maintained by latent heat release over a large region between 10° and 20°N. A major part of the moisture required for this is supplied by evaporation over the Indian Ocean, depending on the strength and configuration of the low-level winds.

Similar analyses are carried out for 1980, 1981 and 1982, using ECMWF operational analyzed fields, although moisture fields are analyzed only for 1982. Although these show characteristics generally similar to those of 1979, there are some differences. Comparisons are made of the four years, and related to the commencement of rains over India.

1. Introduction

The FGGE data, together with the MONEX, have provided what is undoubtedly the most reliable data base yet assembled for studying the Asian monsoon onset. The results of several preliminary studies have been reported, e.g., in the Proceedings of the International Conference on the Scientific Results of the Monsoon Experiment, 1981. Krishnamurti and Ramanathan (1982) present what is perhaps the most detailed analysis yet carried out of the monsoon onset process, using FGGE and MONEX data and relating the results to a limited area model experiment on the sensitivity of the flow to various imposed distributions of heating.

The main emphasis of this study is on analysis of the moisture and mean tropospheric specific enthalpy distributions, as they evolve during the monsoon onset, and their interpretation. Use is made not only of FGGE and MONEX data, but also of operational analyses for the years 1980, 1981 and 1982 archived at the European Centre for Medium Range Weather Forecasts (ECMWF); however it is only for 1982 that analyses of moisture are carried out. Numerical model experimentation must provide the main approach to the interpretation of the data analyses, particularly of the more subtle aspects determining interannual variability such as, possibly, the influence of the Indian Ocean sea surface temperatures and global features; e.g., the Southern Oscillation. However, some useful insight into the broader features of the established monsoon and its onset is provided by simple analytical models of the response of the tropical atmosphere to heat sources and one of these, rather than numerical simulations, is used for interpretive purposes in this initial study.

Following Section 2, which describes the data sources and analysis procedures, a brief analysis of the FGGE wind fields is presented. The results of the FGGE moisture and specific enthalpy analyses are described in Sections 4 and 5. Section 6 is devoted to interpretation of the analyses. These studies describe successive stages in the evolution of an essentially cross-equatorial circulation resulting from a feedback process involving surface moisture transfer and latent heat release, which commences when a certain moisture threshold is reached over the Indian Ocean. However, it is only at the fully-developed stage that the simple linear model applies, planetary waves and transient systems playing a dominating role in the "setting-up" stages. These
conclusions are supported by analyses based on ECMWF archived data fields originally prepared for operational purposes, for the years 1980, 1981 and 1982, described in Sections 7 and 8. In Section 9, the results for the four years are related to the monsoon onset characteristics over India, and Section 10 summarizes the conclusions.

2. Dataset and analysis procedures

a. The basic data

The data base used for this study is the 1979 FGGE level-IIIb set, produced at ECMWF, and the 1980 to 1982 ECMWF operational analysis fields. The 1200 GMT temperature, relative humidity and horizontal wind fields for the region from 40°S to 40°N and 0° to 150°E (Region A) at nine pressure levels (1000, 850, 700, 500, 400, 300, 200, 150 and 100 mb) for the months of May and June, considered to be the transition period of the establishment of the Asian summer monsoon, are used. The four-dimensional data assimilation scheme, used at ECMWF to produce FGGE level-IIIb as well as 1980–82 datasets, is documented in detail by Bengtsson et al. (1982) and Lorenc (1981). The FGGE level-IIIb data consists of uninitialized mass and horizontal velocity fields, whereas the 1980–82 ECMWF archive consists only of initialized analyses. The latter, however, lead to a damping of the zonally averaged divergent flow in the tropics (Temperton, 1980). The nonlinear normal mode initialization scheme, associated with the operational analysis procedure (1980–82), is not very suitable for the tropics as it reduces the amplitude of the divergent wind by a factor of at least 2 (Bengtsson, 1980) and affects all quantities associated with the vertical velocity (ω) which experiences a noticeable smoothing. A number of changes in the operational analysis scheme at ECMWF were introduced during the period 1980–82. Though some of these improvements have little or no impact on the representation of the basic meteorological variables used in this study, others do have some significant impacts, notably on the relative humidity. Thus, in this study the relative humidity for the 1980 and 1981 monsoon seasons has not been considered; the ECMWF archived data for 1980 consist of only the first guess (6 h forecast) and not the analyzed field, and values for 1981, although improved, suffer some degradation in interpolation from sigma to pressure surfaces. Kanamitsu (1980) inferred from climatological comparisons that the level-IIIb data produced at ECMWF, are of good quality and are suitable for diagnostic studies. Therefore, the main emphasis in this study is placed on detailed diagnostic analyses of the 1979 monsoon onset using FGGE level-IIIb data. This is followed, taking into account the differences between the 1979 and 1982 datasets, by a study of the inter-annual variability of the development of the summer monsoon over the four years 1979–82.

b. Analysis procedures

Long term statistics show that the date of onset of the monsoon over the Indian subcontinent may be delayed or advanced by about 15 days from its climatological normal date [which is considered to be 31 May over the Kerala coast (see India Meteorological Department, 1979)]. Furthermore, it takes about an additional 15 days to cover the entire subcontinent except Northwest India and Pakistan and to intensify over Southeast Asia. The dates for the two-month period (May–June) are divided into four phases each of fifteen days duration. These periods can be broadly categorized as pre-onset (Period 1), onset (Periods 2, 3), and the well-established monsoon (Period 4). The inadequacy, for diagnostic purposes, of the initialized FGGE vertical motion fields in the tropics, necessitates the use of an alternative method for estimating the ω field by adjusting the divergence field from available uninitialized data records to satisfy mass balance.

A number of techniques have been developed for kinematic estimation of vertical motion (O'Brien, 1970; Kung, 1973). In the present study, O’Brien’s kinematic technique has been used to estimate ω profiles, specifying that the vertically integrated divergence over the atmospheric column to 100 mb vanishes. The validity of this direct method of computation of ω with FGGE level-IIIb data is supported by the close agreement of the direct and indirect estimates of adiabatic conversion of available potential energy (APE) to kinetic energy (KE) (Mohanty et al., 1982a).

Space derivative terms are discretized by centered (second order) finite differences while the trapezoidal rule has been used in the vertical integrations. The mass integration of any scalar variable \( F(\psi, \lambda, p) \) for a limited region bounded by meridians \( \lambda_1 \) and \( \lambda_2 \), latitude circles \( \phi_1 \) and \( \phi_2 \) and isobaric surfaces \( p_1 \) and \( p_2 \) may be expressed as tilda omitted hereafter.

\[
\tilde{F} = \frac{1}{g} \int_{\phi_1}^{\phi_2} \int_{\lambda_1}^{\lambda_2} \int_{p_1}^{p_2} F a^2 \cos \phi d\phi dp d\lambda d\theta,
\]

where \( a \) is the mean radius of the earth, and this expression is evaluated by simple summations over grid areas \( (3.75° \times 3.75°) \).

Areal averages are obtained for the regions 22.5°S–41.25°N, 0–150°E (Region B) and 0–22.5°N, 41.25–75°E (Region C–Arabian Sea).

In all vertical integrations the lower boundary is considered to be the surface; the surface pressure is obtained by the use of the hydrostatic relation, \( p_s = p_t e^{\gamma H} \) where \( H = RT/g \), from the temperature and geopotential height at the nearest available level (L), and using ECMWF operational topography. The contribution to the column from this lowest layer is evaluated by the trapezium rule.

Vertical integrals are denoted by a caret, i.e.,

\[
\hat{\int} = \int_{p_0}^{p_t} \left( \frac{dp}{g} \right).
\]
Fig. 1. Mean wind vectors (scale: 1 mm = 10 m s⁻¹) at 150 mb, 7 mb, and 850 mb: (a) 150 mb period A (1200 to 15 May 1979); (b) 150 mb period B (15 May 1979 to 1200 15 June 1979); (c) 150 mb period C (1200 15 June 1979 to 1200 30 June 1979); (d) 850 mb period D (1200 15 May 1979 to 1200 15 June 1979); (e) 850 mb period E (15 June 1979 to 1200 30 June 1979); (f) main features of Gill's (1980) analytical solution corresponding to a heat source at S. In (c), (d), (f), and (g) the solid line refers to the upper and dashed line to the lower troposphere.
where $p_r = 100$ mb. In the case of the mean tropospheric temperature ($T_m$), $p_r$ is taken as 100 mb and $\bar{T}$ is divided by the mass ($M$) of the column; i.e., $T_m = \bar{T}/M$. Over mountains the values of $T$ were extrapolated from sigma to pressure surfaces as part of the ECMWF archiving procedures.

Time averages are denoted by a bar.

3. The FGGE wind fields during the Asian monsoon onset

The evolution of the tropospheric wind fields as the monsoon develops is well-known—essentially the establishment of low-level southwesterlies over the Arabian Sea and the Indian subcontinent with a strong northwards cross-equatorial flow off the East African coast (the Somali jet), and, at upper levels, a broad band of east to northeast winds extending across the whole of the tropical Indian Ocean into Africa (e.g., see Ramage and Raman, 1972). The daily sequences of 850, 700 and 200 mb winds for May–July 1979, together with satellite images, is given in Krishnamurti et al. (1980a,b,c). The development is summarized in Fig. 1a–d giving the 15-day means winds at 850 and 150 mb over the region for the first half of May and the second half of June 1979. Also shown, in Fig. 1e,f, is a schematic diagram of the flow development with the winds at 850 and 150 mb superimposed, together with a sketch (Fig. 1g) of the flow associated with the first baroclinic mode of an equatorial beta-plane model forced by a heat source situated north of the equator (from Gill, 1980). It is clear that the general character of the observed flow, over Southeast Asia at the premonsoon stage and over the whole Indian Ocean region when the monsoon is well-established in the second half of June, is quite well described by the simple analytical model for a heat source at about 20°N. The model requires a return flow over the Somali jet, but this is not present during the onset. The reasons for this are discussed in Section 6.

The rapid intensification of the low-level flow over the Arabian Sea is apparent in the time sequence in Fig. 7c and is discussed in Section 6d.

4. FGGE moisture fields during the Asian monsoon onset

a. FGGE analyses

These are presented 1) as 15-day averages of total moisture ($\bar{\theta}$) for May and June 1979 for the area 40°S–40°N, 0–150°E (Region A), and 2) as time series of total moisture averaged over the areas 22.5°S–41.25°N, 0–150°E (Region B) and 0–22.5°N, 41.25°S–75°E (Region C—Arabian Sea). (Note that the effects of orography are included so that substantially lower values of $\bar{\theta}$ occur over high ground.)

Figure 2a shows the $\bar{\theta}$ distribution for Region A for the first half of May and Fig. 2d that for the second half of June (these are subsequently referred to as periods 1 and 4; the intervening two half-months will be referred to as periods 2 and 3); Figs. 2b,c show the changes of the time-means during the intervening period. These diagrams show a substantial increase of moisture over the Arabian Sea and Bay of Bengal, together with increases over India, Southeast Asia and China, values reaching 60 mm in the Bay of Bengal and South China Sea, equal to that of the global maximum north of Indonesia. Over the same period a general decrease of $\bar{\theta}$ occurred over most of the South Indian Ocean.

Figure 2b,c show the progression of these changes. During May (Fig. 2b) the largest increases occurred in the central Indian Ocean (both hemispheres) with smaller increases off East Africa; during May–June (Fig. 2c) increases occurred over virtually the whole of the Indian Ocean southward to 20°S, particularly in the Arabian Sea and Bay of Bengal, with the main buildup of moisture over the South Asian continent (the latter occurred during June).

Figure 3a,b show the time-mean net moisture fluxes (vg) for periods 1 and 4. As to be expected, these vectors closely resemble those of the 850 mb winds (cf. Fig. 1). It is justifiable to regard these diagrams as indicating trajectories of total moisture transport since the contribution of the transient eddies to the water-vapor budget (computed but not shown) is small compared with that of the mean flow virtually everywhere.
Fig. 2. Mean net tropospheric moisture $\hat{q}$ in mm: (a) Period 1, (b) Period 1 and Period 2, (c) Period 2 and Period 4, and (d) Period 4. Solid lines denote positive and dashed lines negative values.
The contribution of the flow to the moisture budget depends on its vertically integrated divergence $\nabla \cdot (vq)$ (the time means are denoted by $D_2$). During May (Fig. 4a,b) significant convergence regions (dashed lines) occur just south of the equator near 80°E, off the East African coast and in the Bay of Bengal. During June (Figs. 4c,d) convergence continues south of the equator and off East Africa, but there is general divergence over the Bay of Bengal. However, there is now moisture convergence over the eastern Arabian Sea and Southeast Asia, increasing considerably in both regions during the second half of the month.

The importance of moisture convergence in determining the net heating is seen in the distributions of the latter for each period in Fig. 5. (These were computed as a residual, as described in Section 6b.)

The time-averaged moisture and flow fields (together with the surface moisture flux distribution—see Fig. 12 for 1982 ECMWF model values) thus describe a moisture buildup during May and June over a major part of the Indian Ocean and, subsequently, India and Southeast Asia. In order to represent the time-development in more detail, time series of the mean moisture content over regions B and C have been computed and these are shown in Figs. 6a and 7a. The time-sequence for Region B clearly shows that over the region as a whole there was an increase in moisture content; furthermore, that the main change occurred

![Diagram](image-url)
FIG. 4. Net moisture (latent heat) flux divergence $\nabla \cdot (\nabla q)$ (W m$^{-2}$) for (a) Period 1, (b) Period 2, (c) Period 3 and (d) Period 4.
b. Accuracy of FGGE moisture fields

It is important to bear in mind that the FGGE IIib humidity analyses for the Indian Ocean, although the best so far available, are the least satisfactory of the FGGE products. A number of changes were introduced during their production resulting in the analyses for 1 Dec 1978 to 4 May 1979 having different weights attached to the surface (SYNOP) data than those for 5 May 1979 onwards. However, even for the latter period the SYNOP data was given low weighting because of its poor quality and this left only the radiosonde data with reasonable weighting in their area of influence.

Cadet (1983) has computed fields of precipitable water for the summer MONSEX area by merging TIROS-N moisture data with the ECMWF moisture analyses; over cloudy areas TIROS-N temperatures were used and the vertical profile of relative humidity assumed. The extent to which his monthly-mean distributions for May and June agree with those given here can be gauged from Table 1, giving values interpolated from contour plots. Cadet estimates his values to be within 10–15%; this should be regarded as an underestimate of the errors here, using the FGGE analyses alone.

over the 10-day period 25 May–3 June. Also shown in Fig. 6b is the mean moisture divergence over the region. This shows an equally rapid change over the period, with no export of moisture until 3 June and import for most of the rest of the month. This implies that until about 3 June, evaporation (E) exceeded precipitation (P) over the region but that, subsequently, P exceeded E. These conclusions are supported in Mohanty et al., 1982b.

There is more variability in the time-sequences for the Arabian Sea (Fig. 7). The net change over the period is somewhat greater than for the larger region as is to be expected since this is where the main change is concentrated. There is also a temporary increase of moisture content during the early part of May, not mirrored in the time sequence for Region B, implying that this represents a transfer of moisture within the larger region. The daily 850 mb flow fields and satellite images for this period (see Krishnamurti et al., 1980) indicate that considerable cross-equatorial flow developed over the western Indian Ocean during 5–10 May in association with strong convergence off Sri Lanka; this moved into the Bay of Bengal after 11 May.

FIG. 7. Time sequences for Region C of daily (1200) values of (a) total moisture \( \bar{q} \) in mm; (b) mean tropospheric temperature \( T_m \); and (c) mean kinetic energy per unit mass of 850 mb flow. Solid curves 1979; dashed curves 1982.
Table 1. Comparison of estimates of monthly mean values of precipitable water (mm) over the Indian Ocean.

<table>
<thead>
<tr>
<th></th>
<th>Central Arabia (45°E, 25°N)</th>
<th>Central Arabian Sea (60°E, 15°N)</th>
<th>Central Bay of Bengal (90°E, 15°N)</th>
<th>Southern Indian Ocean (70°E, 10°S)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>May</td>
<td>June</td>
<td>Change</td>
<td>May</td>
</tr>
<tr>
<td>FGGE IIb data alone</td>
<td>22</td>
<td>18</td>
<td>-4</td>
<td>35</td>
</tr>
<tr>
<td>(Fig. 2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FGGE IIb data merged</td>
<td>22</td>
<td>22</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>with TIROS-N data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Cadet, 1983)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. The FGGE temperature fields during the Asian monsoon onset

Clearly the moisture changes described here occur in association with considerable latent heat release, particularly in areas of net moisture convergence (bearing in mind that surface transfer constitutes a moisture source roughly equivalent to the net convergence). The consequences of this are reflected in the temperature and flow fields (the governing equations are discussed in Section 6). The mean specific enthalpy in an atmospheric column is $c_p T_m$ where suffix $m$ denotes a vertical average (with respect to pressure, 100–1000 mb), and time mean averages $\overline{T_m}$ were computed to investigate the mean tropospheric enthalpy changes over the onset period. (The FGGE IIb temperatures, like the relative humidities, are calculated from the initialized analyses and involve interpolation/extrapolation between $\varphi$- and $\sigma$-surfaces. This introduces errors in mountainous areas.)

Figure 8a shows the distribution of $\overline{T_m}$ over region A for the first half of May and Fig. 8d that for the second half of June. Figs 8b,c show the differences over the intervening periods. The South Asian and African land masses are generally warmer than the rest of the region throughout the period. The differences show that further warming over Arabia and North Africa occurs during May, accompanied by a cooling over the Indian Ocean. During May/June the warming continues over the land (actually less rapidly during June itself) and extends to cover the Indian Ocean down to nearly 40°S.

Since $T$, like $q$, generally decreases with height, low-level mass convergence and upper-level divergence, i.e., mean ascent through the column, imply convergence of $T$, i.e., $D_T = (\nabla \cdot v T) < 0$. The distributions of $D_T$ therefore resemble those for $D_q$ (Fig. 4). Regions of mean descent are characterized by $D_T$ and $D_q > 0$, with a value of $D_T$ of $\sim 0.1$ K kg$^{-1}$ m$^{-2}$. Of particular interest is the subsidence over much of South Asia during May in the vicinity of the subtropical jet (Fig. 1a).

Daily time sequences of $T_m$ for regions B and C are shown in Figs. 6d and 7b. Each shows some variability during May, followed by a pronounced increase during June. Comparison with Figs. 6a and 7a suggests that increases in $T_m$ accompany increases in $q$ with a lag of a few days, although during the second half of June, $T_m$ continues to increase while $q$ tends to remain constant.

6. Physical interpretation of the FGGE analyses

a. Introduction

The basic physical processes involved in the tropospheric flow, moisture and temperature changes as described here have been recognized to some extent in previous studies. These are 1) the warming over the African-Asian land mass as a response to the seasonal increase in insolation (Bannon, 1982), and 2) latent heat release associated with west to southwest low-level winds and evaporation over the North Indian Ocean (Saha and Bavadekar, 1973).

The dynamical response of the atmosphere to heating in low latitudes has been investigated by, among others, Matsuno (1966), Webster (1972, 1973) and, more recently, by Gill (1980). Matsuno’s linear analysis of the normal modes of a two-layer system on an equatorial beta-plane with zero basic current has provided the foundation for subsequent theoretical studies. Webster (1972) describes perturbation analyses of the steady response of the tropics to both orography and heating, specifying climatological zonal mean flows for December–February and June–August. The results suggest that latent heating dominates the response at low latitudes, whereas in the subtropics advective effects and forcing from higher latitudes become more important. However, the results are very sensitive to the assumed dissipation. A subsequent study (Webster, 1973) in which forcing from midlatitudes (the climatological distribution of $v$) is specified as lateral boundary conditions confirms these conclusions.

Gill’s (1980) model is simpler than Webster’s and involves direct expansions of Matsuno’s normal modes about a zero basic current. Nevertheless, his solutions are similar in most respects to Webster’s for both symmetric and asymmetric heat source distributions. One of the main differences is the extent of the cross-equatorial flow in the asymmetric case, which is larger in Gill’s model, suggesting that his may be the more applicable to the Asian summer monsoon with its heating maximum near 20°N in the fully developed stage.
Fig. 8. Mean tropospheric temperature $T_m$ (K) for (a) Period 1 and (b) Period 1 and Period 2. Change of $T_m$ (K, kg m$^{-2}$) between (b) Period 1 and Period 2 and (c) Period 2 and Period 4. (Change in $T_m$ approximately equal to indicated values $\times 10^2$.)
The heat source to which all of these theories relate is latent heat release and therefore the models based on them do not directly relate to the first process.

Since the atmospheric moisture and heat budgets are so intimately related in the tropics through latent heat release and, indeed, the very occurrence of the monsoon depends on this process, a brief review of their interconnection is presented, before discussing the 1979 onset. Particular emphasis is placed on the differences between regions of ascent in which latent heat release occurs and subsiding regions where it does not.

b. Moisture and heat budgets for subsiding and ascending columns

The equations defining the moisture and temperature (enthalpy) budgets for an atmospheric column are

\[
\frac{\partial \tilde{q}}{\partial t} + \nabla \cdot (\tilde{v} q) + \left( \frac{\omega q}{g} \right)_x - \left( \frac{\omega q}{g} \right)_T = E - P, \quad (1)
\]

\[
\frac{\partial \tilde{T}}{\partial t} + \nabla \cdot (\tilde{v} T) + \left( \frac{\omega T}{g} \right)_x - \left( \frac{\omega T}{g} \right)_T = \frac{\tilde{\omega}}{c_p} + \frac{\tilde{Q}}{c_p}. \quad (2)
\]

The symbols have their conventional meanings.

In interpreting the 15-day mean fields, one can neglect the time rates of change and, except in mountainous regions, the terms in \( \omega_x \) and \( \omega_T \), in Eqs. (1) and (2). Thus

\[
\nabla \cdot (vq) \approx \tilde{E} - \tilde{P}, \quad (1')
\]

\[
\nabla \cdot (vT) \approx \frac{\tilde{\omega}}{c_p} + \frac{\tilde{Q}}{c_p}. \quad (2')
\]

Since \( T \) is positively and potential temperature \( \theta \) negatively correlated with \( p \), the sign of \( \tilde{Q}/c_p \) (the same as that of \( \nabla \cdot (v\theta) \), is opposite to that of \( \nabla \cdot (vT) \), at least in columns in which there is either ascent throughout or descent. Thus, for a column which is subsiding at virtually all levels, \( E = 0 \) generally and \( \nabla \cdot (vq), \nabla \cdot (vT), \frac{\tilde{\omega}}{c_p} \) and \( \tilde{E} \) are all \( > 0 \). A steady state is possible only if \( \tilde{Q} < 0 \), corresponding to radiational cooling, off-setting any sensible heat transfer from the surface; i.e., there must be a net radiative cooling of the surface plus the column to offset the import of dry static energy. These conclusions are consistent with (1') and (2). If the column warms up, then this must either 1) be a dynamical (adiabatic) consequence of the large-scale dynamics, 2) result from a net radiative input into the surface plus the column or 3) both.

On the other hand, for general ascent in the column, \( \nabla \cdot (vq) < 0 \) and \( \tilde{P} > \tilde{E} \) in accordance with Eq. (1'); also \( \tilde{Q} > 0 \) consistent with latent heat release; so \( \frac{\tilde{\omega}}{c_p} \), like \( \nabla \cdot (vT) \) and \( -\tilde{Q} \), is negative, satisfying Eq. (2'). These general conclusions are summarized in Table 2.

There is an important physical difference on the synoptic and planetary (as well as the smaller) scales between regions of subsidence and regions of ascent. Radiational cooling exerts a strong control over the magnitude of descent in the former case, whereas in regions of ascent, since latent heat release increases with the mass ascent rate, there is not such a strong control exerted by the diabatic heating; regions of ascent are generally more intense and concentrated than regions of descent, tropical convective systems being typical examples. The monsoon onset can be thought of as a redistribution of the moisture sources and of these regions over the Indian Ocean and the surrounding continents—a rapid transition from one quasi-steady climatological state (March–April) to another (June–July).

Equation (2) was used as the basis for computing distributions of \( \tilde{Q}/c_p \) and \( \nabla \cdot (vT) \) were computed directly and then \( \tilde{Q} \) (Fig. 5) obtained as a residual.

c. The establishment of the Somali jet and moisture buildup in the Arabian Sea during the FGGF.

During the first half of May the main region of net moisture convergence in the tropical belt (20ºS–20ºN) is over Indonesia and the western Pacific (Fig. 4a). There are, in addition, smaller regions over the Bay of Bengal, around 15ºS, 80ºE, off East Africa and over the Sudan. Bearing in mind surface evaporation, we note that small values of moisture divergence up to, say, \( 2 \times 10^{-5} \) kg m\(^{-2}\) s\(^{-1}\), also indicate latent heat release. Apart from East Africa and, possibly Saudi Arabia, there is no evidence that latent heat release is occurring over any of the continental region between Egypt and the west coast of India; this area is dominated by subsidence (Fig. 4a—the fields of \( \tilde{\omega} \), not reproduced here, are, as seen from Table 2, generally similar to those of \( D \)); this conclusion is also supported by the general absence of cloud in satellite images (see Krishnamurti et al., 1980a,b). The warming in this region (Fig. 8b) should therefore be regarded as being associated, at least in part, with subsidence.

Figure 1a shows the region from North Africa to northern India to be under the subtropical jet and the subsidence there must be dynamically related to this large-scale flow feature. The standard simplified theory of ageostrophic flow at a jet exit suggests that subsidence

| Table 2. Signs of dominant terms in moisture and heat budget equations. |
|------------------------|--------|--------|--------|--------|--------|
| \( \nabla \cdot (vq) \) | \( \tilde{E} - \tilde{P} \) | \( \nabla \cdot (vT) \) | \( \tilde{Q} \) | \( \frac{\tilde{\omega}}{c_p} \) |
| \( \tilde{\omega} > 0 \) | + | + | + | (−) | + |
| \( \tilde{\omega} < 0 \) | − | − | + | − | + |
must occur on the equatorial side. (However, FGGE data analyses recently carried out by Blackburn, 1983, suggest that the simplified theory exaggerates this effect, much of the divergence associated with the ageostrophic flow component being offset by convergence of the geostrophic component.) Using the hydrostatic relation and assuming that pressure changes in the upper troposphere are small, we note that such warming by subsidence plus that arising from sensible heat transfer from the surface implies a lowering of surface pressure ($p_s$). The observed fall in $p_s$ (mid-April to mid-May) over this region is about 6 mb (White, 1983); with only small changes in $p_s$ south of the equator this must imply an increase in the mean northward cross-equatorial flow at low-levels, as is observed during May. Planetary waves on the Northern Hemisphere subtropical jet with a strong baroclinic component would thus appear to exert a strong, and possibly a controlling, influence on the low-level cross-equatorial flow over the western Indian Ocean during this period.

The region of cooling over Saudi Arabia (Fig. 5a) is interesting since it is also a region of weak ascent. Smith et al. (1982) infer from an analysis of radiation data over this region that an extensive dust layer (top near 525 mb) absorbs sufficient solar radiation to more than offset long-wave cooling. Since only 1200 GMT data have been used in this study, the results for this region could be in error as a result of the neglect of a strong diurnal dynamical response on the regional scale.

During March and April the Southern Hemisphere low-level easterlies extend westwards across the Indian Ocean and northwards towards the equator. During May the mean flow turns northward as the Somali jet and then eastwards over the Arabian Sea. Transient synoptic- and meso-scale disturbances are seen in daily synoptic analyses and satellite images (e.g., see Krishnamurti et al. 1980a,b). However, whereas the mean low-level flow exhibits the progressive development described above, the mean upper-level (200 mb) winds show little change in the mean, remaining generally light (see Ramage and Raman (1972) for 1963/4 monthly means and White (1982, 1983) for 1981 and 1982 15-day means). The daily 200 mb winds, on the other hand, show a variety of divergent outflows, up to 20 m s$^{-1}$, from cloud clusters, sometimes confined to one hemisphere and sometimes crossing the equator. The mean flows for Period 1 shown schematically in Fig. 1e, although generally corresponding to Gill's model (Fig. 1g) over the eastern half of the Indian Ocean, do not do so over the western half. The reason for this is that the mean heating for Period 1 (Fig. 5a) is concentrated in the eastern Indian Ocean; also the maximum is near the equator, around 5°N. The latent heat released in the transient systems in the western half is only just about sufficient to offset the radiative cooling there giving only a small net mean heating. The progressive development of the mean, low-level flow without a corresponding mean flow development at upper levels is an extremely interesting aspect of the monsoon onset, but it cannot be explained by a steady-state model. Its scale, across the whole southern Indian Ocean, suggests that it is associated not only with the Northern Hemisphere jet and heating but also with the establishment of the Southern Hemisphere winter subtropical jet (Figs. 1a,c).

A consequence of the mean low-level cross-equatorial flow is that moisture is transported into the Arabian Sea from south of the equator. However, the convective activity there is not extensive enough to prevent a general moisture buildup (Fig. 6a). A surface evaporative source of about the same magnitude as the moisture convergence also contributes (see Figs. 12a,b for 1982 values). The subsequent fields of moisture convergence and diabatic heating are shown in Figs. 4b,c,d and 5b,c,d). As the convective activity increases during May, latent heat release provides an increasing heat source over the Arabian Sea and continental India (Fig. 5) accompanied by a strengthening of the low-level cross-equatorial flow and moisture transport into the Arabian Sea.

\subsection*{d. The rapid intensification phase and establishment of the fully-developed monsoon during the FGGE}

Moisture divergences were computed for each day during the latter 1½-month period for region B with the results shown in Fig. 6b. The main characteristics of the moisture changes in Regions B and C have been discussed here, particular attention being drawn to the moisture buildup and temperature increase in both regions, and the lag between them. This suggests that the release of convective instability occurs when $\dot{q}$ reaches a certain threshold value (about 40 mm in the Arabian Sea) and that the heat released subsequently leads to a general increase in mean temperature of the whole region. It is interesting that the threshold of $\dot{q}$ is not subsequently much exceeded over the large region B, but that $\dot{q}$ does continue to increase over Region C (Fig. 7a). However it is near here that the highest values of mean temperature are reached so that the moisture threshold for convective instability in this region should be expected to increase also. Fig. 7c shows the time development of the kinetic energy of the 850 mb flow over the Arabian Sea (in agreement with the result of Krishnamurti and Ramanathan, 1982). The increasingly rapid response of the wind, implying increasing evaporation, along with that of the temperature (but lagging the moisture buildup) from the beginning of June is apparent. This is consistent with a strong feedback involving latent heat release. Fig. 6c shows that this coincided with a large-scale jump in the APE-KE conversion rate.

The fields of $\check{v}$ (Fig. 1d), $\check{q}$ (Fig. 2d), $\check{T}$ (Fig. 8d), $\check{Q}$ (Fig. 5d) all show the intensification of the feedback, with a substantial heat source now extending from
Indonesia across Southeast Asia and India to the east coast of Africa. Its influence extends over virtually the whole of the region 0°–150°E and well into the Southern Hemisphere, as indicated by the extensive upper-level easterlies (Fig. 1d). The schematic diagram (Fig. 1f) shows the flow fields at both upper and lower levels in the latter half of June, corresponding to steady latent heat release of up to 300 W m⁻² concentrated in the region 10°–20°N, 60°–120°E (see Fig. 8b) to agree quite well with Gill's linear model (Fig. 1g); his asymmetric solution is for heating in a region ~ 40° of longitude wide concentrated north of the equator, rising from zero to a maximum at 20°N, falling to zero again at about 35°N. Substituting typical values for the tropical atmosphere into his model, we note that a column latent heat release of 300 W m⁻² corresponds to an 850 mb convergence maximum of 3 × 10⁻⁴ s⁻¹ which is 0.1 nondimensional units, implying a maximum low-level southwest (and upper-level northeast) wind of about 17 m s⁻¹, just equatorward of the heating maximum (Fig. 1g). In consideration of the simplicity of the model and the larger longitudinal extent of the observed heat source, its simulation of this stage is remarkably realistic.

The moisture and heat budgets for region B suggest that at the fully developed stage the export of heat from the region, together with longwave radiative cooling, is able to offset the latent and sensible heat input from the surface and that, by extending its influence to the global scale, the system has reached a quasi-steady state.

An interesting feature of the fully developed monsoon circulation is the moisture and moisture convergence maximum in the Southern Hemisphere near 80°E and 10°S (Figs. 4c,d). This is clearly a region of considerable activity (as satellite pictures confirm), and the upper-level diverging anticyclonic winds associated with it reinforce upper equatorial north-westerlies and the cross-equatorial flow. A similar feature, but less pronounced, is present in the wind fields for 1980, 1981 and 1982, and in the moisture fields for 1982.

7. The 1982 onset

The data coverage over the Indian Ocean in 1982 was appreciably poorer than for the FGGE: for instance, there were no ships' radiosoundings, drop-windsondes, buoys or aircraft winds. Part of any differences between the years can, therefore, be expected to arise from analysis errors, bearing in mind that the ECMWF operational analysis scheme places more emphasis in data-sparse areas on a model-dependent first guess.

It is impossible to quantify these differences without, say, carrying out analyses of the FGGE data omitting observations from sources not available in 1982 and comparing the results with those based on level IIb data. Some encouragement can be gained, however, from the number of ships' surface observations from the Indian Ocean which were incorporated in 1982, shown in Table 3. These are mean daily totals covering four observing times. The average for the entire oceanic region 30°S–30°N, 40°–100°E was 108. This compared with approximately 60 for 0000 GMT alone for the same dates of the FGGE. Also temperatures from orbiting satellites were regularly used in 1982 although, as in the FGGE analyses, given only low weighting. Thus, at a rough comparison, the input of observed surface winds, temperatures and humidities into the 1982 ECMWF analyses over the Indian Ocean was approximately half that during the FGGE. The 1982 moisture and temperature time sequences for regions B and C, based on ECMWF operational analyses, are shown in Figs. 6 and 7. These are generally similar to those for 1979 apart from a time lag. The main sustained moisture buildup in both regions, with its accompanying rise in mean temperature, commenced around 15 May, compared with 25–31 May in 1979.

The lag of the temperature rise behind the moisture buildup is not evident in 1982 for region B. However, in 1982 the "threshold" mean total moisture value of 40 mm was exceeded for the whole period for region B, and from about 6 May for the Arabian Sea. The mean temperature over region B was also somewhat higher in early May in 1982. As in 1979, there was a lag of a few days between the first moisture "surge" in the Arabian Sea and the subsequent warming; also the first warming in 1982, around 12 May, was followed by a period of slight cooling, but a much shorter one than in 1979. If 1982 is taken as the reference (i.e., normal) year, the 1979 onset can be regarded as anomalous both from the point of view of the lower mean moisture content over the tropical Indian Ocean in early May and of the time of the monsoon onset over India.

The 1982 wind fields were generally very similar to those for 1979 and are not reproduced in full here. Only those for the first half of May are shown (Figs. 9a,b). The main differences between the two years can be summarized:

1) The Somali jet and Easterly flow over the near-equatorial Indian Ocean was weaker, though the latter was more extensive, in 1982 than in 1979 during the first half of May; there were no equatorial westerlies
around 80°E in 1982. However, the low-level westerlies over the Indian Ocean north of the equator in the second half of May were stronger in 1982 than in 1979—consistent with the earlier onset in 1982.

2) At 150 mb the trough in the subtropical jet over the Eastern Mediterranean, present in 1979 from the second half of May onwards, was apparent in the first half of May in 1982. Also the equatorial easterlies over the Eastern Indian Ocean were less extensive in the first half of May 1982, and subsequently, than in 1979.

The computed mean moisture distribution for the first half of May 1982 is shown in Fig. 10a. This lacks the moisture minimum of 35 mm just south of the equator near 80°E present in 1979; also there is a maximum on the equator at 90°E but no maximum in the Bay of Bengal as in 1979. This comparison typifies the differences between the subsequent mean moisture distributions for the two years; the buildup in 1982 follows the same general pattern as that for 1979, reaching the distribution shown in Fig. 10b for the second half of May; at this stage the maxima occur in the same locations as in 1979—in the North Arabian Sea, the Bay of Bengal, over Southeast Asia and, as already mentioned above, just south of the equator near 90°E.
The 1982 mean tropospheric temperatures, initially very similar to those for 1979, show the same general change, extending well into the Southern Hemisphere, between the first half of May and the first half of June as that for 1979 two weeks later (Fig. 11).

Figure 12a,b, showing the mean surface latent heat flux for the first half of May and the second half of June 1982 as computed by the ECMWF prediction model using a bulk aerodynamic formula have already been referred to. These emphasize the importance of evaporation as a primary energy source for the monsoon, the total evaporation over a large part of the Indian Ocean increasing by a factor of two to three from the pre-onset to the fully developed stage. The values are consistent with those inferred from ship observations of sea-surface temperature, from the first and second S MONEX-79 polygons in the Arabian Sea (see Nuzhdin, 1982). These give values of total (sensible plus latent) heat flux of between 30 and 100 W m$^{-2}$ until about 6 June, a fall to 70 W m$^{-2}$ on 11 June and then a substantial increase to about 200 W m$^{-2}$ on 13 June.

**Fig. 10.** Mean net tropospheric moisture ($q$) in mm for (a) Period 1 (1-15 May) and (b) Period 2 (16-31 May) in 1982.
Although it is the differences between 1982 and 1979 which have been emphasized here, the main conclusion from the comparison of the two onsets is that the sequence of events in the two years is essentially the same. The significance of the differences is discussed in Section 10.

8. The 1980 and 1981 onsets

The only comparisons which are made here are of the wind and temperature fields, and these are only briefly described.

The onset characteristics (low-level wind and temperature) for 1980 are summarized in the time series of $T_m$ (Region B) and kinetic energy of the 850 mb flow (Arabian Sea) in Figs. 13a,b. The archived ECMWF operational analyses for May and June 1980 not being as comprehensive as those for subsequent years, further analysis is not attempted. The buildup of $T_m$ over Region B commenced at the beginning of May, but there was a cooling during the latter part of May preceding the second intensification on 4 June. Interestingly, the second intensification occurred after the onset of rains over southern India.

In 1980 and 1981, the low-level winds over the tropical Indian Ocean in the first half of May (not reproduced here) closely resembled those for 1982. In the second half of May 1981, however, there was a pronounced southerly flow to the southeast of Madagascar, linking with the Somali jet. The spatial distributions of mean temperatures (not reproduced here) in both 1980 and 1981 also changed between the first half of May and the second half of June in the same way as for 1979 and 1982, the increase after the maximum intensification affecting both hemispheres. The time sequences of mean tropospheric temperature (Region B) and kinetic energy of the 850 mb flow Arabian Sea) in Figs. 13a,b show an increase in 1981 which is more gradual than those which occurred in 1979, 1980 and 1982.

These analyses, as far as they go, describe onset characteristics broadly similar to those for 1979 and 1982.

9. The monsoon onset over India—interannual comparisons

The enormous economic consequences of the monsoon arise from its impact on India and her neighbors. In particular, the date of the onset of the monsoon rains and their intensity and distribution, which vary from year to year, have important impacts on agriculture and water management. The dates of onset over India are therefore compared with the start of the intensification of the large-scale monsoon circulation as deduced from the studies previously described. This is a simple enough exercise with hindsight since all that is required are the dates of commencement of the generally substantial rises of $\bar{q}$ and $T_m$ for each year as given by the time sequences. Since the larger scale trends (Region B) are easier to identify than those for the Arabian Sea, these have been adopted for this purpose although the Arabian Sea winds are used. The onset dates are defined as the dates of commencement of monsoon rains over Kerala, Southern India (at approximately $10^\circ$N). The results are shown in Table 4.
The onsets in 1980, 1981 and 1982, as indicated by the outbreak of rains over S. India, are all 'normal'. Analyses of the larger-scale characteristics indicate, however, that there are some differences between the three years, notably in the area mean temperature and 850 mb wind build-up. Thus in 1981 the increase in the 850 mb wind commenced several days earlier than in 1980 and 1982. The onset in 1979 differed in important respects from those in 1980, 1981 and 1982, being both later and more rapidly intensifying. In interpreting these dates the possible analysis errors, particularly for 1980 and 1981 should be borne in mind.

It is to be expected on physical and dynamical grounds that the later the intensification occurs, the larger is the initial temperature contrast between the Northern Hemisphere continent and the Southern Hemisphere ocean, the former having been exposed to a longer period of solar heating. From the simple hydrostatic argument used above, the low-level cross-equatorial flow may thus be expected to be stronger and the intensification more rapid. This is a hypothesis which needs to be tested using a numerical model; the data sets for 1979 and 1982 are particularly suitable for this purpose.

10. Discussion and conclusions

Analyses of the FGGE data, particularly moisture and enthalpy budgets, have enabled the 1979 monsoon
onset to be described in more detail than hitherto, particularly the role of moisture. The onset may be divided into two phases leading to the third (fully established) phase:

1) A large-scale moisture buildup, particularly over the Arabian Sea, during the latter part of May and the first week of June. This is accompanied by transient convective activity generally organized in synoptic-scale systems within about 10° of the equator, affecting both hemispheres. The 15-day mean low-level flow crosses the equator off East Africa and extends eastwards into the Arabian Sea, but the mean overlying upper winds remain light even though local transient convective outflows are strong. The heating maximum (about 200 W m\(^{-2}\)) is located near the equator, near 85°E during the first half of May, moving to 70°E by the first half of June. The mean temperature increases by 1–2°C over North Africa and South Asia in association with heating and large-scale subsidence.

During the first week of June a transition occurs from mean descent to mean ascent over the whole tropical belt from 0–150°E implying an increase in latent heat release and a change-over from moisture export to import, and the low-level winds over the Arabian Sea start to intensify.

2) From about 10 June, the date of onset of rains over southern India, the Arabian Sea winds intensify rapidly, and strong overlying cross-equatorial, upper-level east-north-easternlies are set up.

3) By the middle of June the monsoon becomes fully established, with large-scale cross-equatorial flow at both upper and lower levels (in opposite directions) and maxima in moisture, moisture convergence and heating (up to 300 W m\(^{-2}\)) in the strip 10°–20°N between 60 and 120°E.

It is not appropriate to apply steady-state linear theory to stages 1) and 2), although a simple hydrostatic argument relates the northward cross-equatorial mean flow at low levels to heating and planetary wave developments. According to this it is primarily the heating over South Asia and subsidence warming near the sub-tropical jet which increases the low-level mean flow into the Arabian Sea. This leads eventually to the rapid intensification phase, dominated by strong moisture feedback.

On the other hand, at the fully developed stage 3) a quantitative comparison with Gill’s model can be made since an extensive asymmetric latent heat source is established near 20°N, the moisture being supplied by evaporation over the Indian Ocean. The firm linkage of the sub-tropical jets in the two hemispheres by the monsoonal upper northeasterlies at this stage is particularly striking.

Comparisons with onsets in subsequent years suggest that this is the normal onset sequence. Small differences between years can be identified, e.g., the absence of an eastern Mediterranean trough at 150 mb in 1979 suggests that planetary wave activity affecting the subsidence regime over North Africa and South Asia may have contributed to the anomalously late onset. Otherwise the main differences are in timing of the onset stages and the rapidity of the main intensification in stage 2).

Linear theory, although most valuable in interpreting the major features of the established monsoon, is thus inadequate to explore the details of the onset process and the more subtle aspects associated with interannual variability. These involve delicate balances between surface transfers of moisture and heat, radiation and planetary waves—the structures of the pre-onset synoptic-scale transients and their role in the moisture buildup in the Arabian Sea, for example,—and can only satisfactorily be explored using numerical models. The analyses presented here provide a basis for a series of model experiments using real initial data. Results from such models as those described by Gilchrist (1981) are encouraging insofar as they do simulate the monsoon onset.

Table 4. Monsoon onset characteristics 1979–82.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Arabian Sea 850 mb KE</td>
<td>20 May</td>
<td>7 May</td>
<td>1 May</td>
<td>16 May</td>
</tr>
<tr>
<td>Onset of monsoon over</td>
<td>1 June</td>
<td>17 May</td>
<td>10 May</td>
<td>20 May</td>
</tr>
<tr>
<td>southern India</td>
<td>1 June</td>
<td>30 May</td>
<td>31 May</td>
<td></td>
</tr>
</tbody>
</table>
Finally, the overriding need for more accurate moisture and wind measurements, particularly over the Indian Ocean if any meaningful interannual monsoonal comparisons are to be made, is apparent. The onset involves the organized release of convective instability in which the moisture distribution throughout both the lower and middle troposphere plays a crucial role. Such questions as those concerning the role of evaporative downdraughts and of wave disturbances in the upper troposphere during the crucial initial stages cannot be addressed without an adequate data base, from which the precise role of moisture can be inferred.

Acknowledgments. The authors are most grateful to the Director and staff of ECMWF for making readily available their archived data and providing access to their facilities. Dr. U. C. Mohanty wishes to express his appreciation of financial support under the Technical Cooperation Scheme of the U.K. Overseas Development Administration which enabled him to work on the monsoon project at Reading University and ECMWF for six months as a visiting scientist, and to the Director of the Indian Institute of Technology, New Delhi, for supporting this visit. Finally, both authors are most grateful to Mrs. Nan Spicer for typing the manuscript and Mrs. V. Daykin for preparing the diagrams.

REFERENCES


India Meteorological Department, 1979: Monsoon Rainfall Summary: June to September, 1979. 24, Kartika, Pune, India.

Kanamitsu, M., 1980: Some climatological and energy budget calculations using the FGGE IIIC analysis during January 1979. Seminar on Data Assimilation Methods, ECMWF, Shinfield Park, Reading, U.K.


Nuzhdin, P., 1982: On laws governing fluctuations of the Arabian Sea active layer thermodynamic properties and air-sea energy exchange characteristics during the south-west monsoon. Int. Conf. on Scientific Results of the Monsoon Experiment. ICSU/WMO, Geneva.


