Low-level air flow circulation over the Arabian Sea during the summer monsoon as deduced from satellite-tracked superpressure balloons. Part II—Analysis of the flow field

By DANIEL CADET and PAUL OLORY-TOGBÉ

Laboratoire de Météorologie Dynamique, Ecole Polytechnique, 91128 Palaiseau cedex, France

(Received 8 February 1978; revised 10 April 1978)

SUMMARY

Trajectories of superpressure balloon flights in the tropical boundary layer over the Indian Ocean during the 1975 summer monsoon are analysed in relation to conventional meteorological observations, mainly ship reports. An assimilation of these randomly distributed observations is performed to compute mean gridded fields of wind and pressure during four periods defined according to monsoon activity over the Indian sub-continent. Mean cloud cover fields over a 2.5° × 2.5° square are also determined from satellite images. The main features of the low-level monsoon circulation are deduced from the two sets of data; these are in conflict with earlier conclusions deduced from the interpretation of local conditions. The differences in meteorological fields between the various phases of the activity of the monsoon over India are studied and discussed.

1. INTRODUCTION

In part I of this paper, henceforth referred as (I), the superpressure balloon experiment in the Indian Ocean during the 1975 summer was presented (Cadet and Ovarlez 1976) and the trajectories of the balloons briefly described. This second part of the paper is devoted to an analysis of the trajectories in connection with other meteorological data available during the same period over the Indian Ocean. First, the trajectories and conventional meteorological data are jointly studied to point the main features of the monsoon flow over the Indian Ocean. Second, mean wind, pressure and cloud cover fields are studied during four periods corresponding to different flow patterns visualized from the trajectories and also to differences in the activity of the monsoon over central India.

2. ASSIMILATION OF THE DATA

Meteorological stations are scarce over the oceanic tropics, particularly over the Indian Ocean with only a few island stations. A special data collection effort was needed. Ship reports are more frequently available along shipping routes and important features of the synoptic fields can remain undetected. Nevertheless, on certain days we have almost 300 surface data over the ocean and these data give a sketchy idea of the synoptic fields during the balloon experiment (Fig. 1). The ships give only sea surface observations whereas the balloons provide observations at an average altitude of 500 m. The altitude difference between these two sets of data, Eulerian and Lagrangian, is not crucial for this study because the change of wind direction with height is weak in the tropics; and also because large-scale features are studied.

On a given day all parameters, wind components and pressure, measured at different synoptic hours, are used to derive daily composite analyses. The grid used is a 2.5° latitude by 2.5° longitude mesh from 35°E to 90°E and from 25°S to 25°N. To derive these daily composite maps a simple scheme is adopted, since the derived data are not used to perform an objective analysis, but to stress main features of the monsoon flow related to the balloon trajectories.
For a given day, $D$, wind components and pressure at each latitude-longitude point, $I, L$, are interpolated as follows – $u$ being any one of the parameters, and $N$ the number of observation points:

$$u(D, I, L) = \frac{\sum_{i=1}^{N} w_i u(D, i)}{\sum_{i=1}^{N} w_i}$$

where $w_i$ is a weighting function defined by $w_i = (d_i^2 - R^2)/(d_i^2 + R^2)$ if $d < R$; $w_i = 0$ if $d \geq R$; $d_i$ is defined as the Cartesian distance of the observation point from the grid station and $R$ the influence radius, taken as 20°.

As described in (I), the balloons were launched during three periods. It was shown by Ramamurthy (1969) that the activity of the monsoon over central India is related to the ITCZ position over the sub-continent: breaks associated with a northward shift of the
ITCZ; an increase of rainfall with a southward shift. The same feature prevailed during the 1975 summer (Olory-Togbé 1977) and this is used to define periods fitting the different patterns of the flow field shown by the trajectories. Fig. 2 gives the average rainfall amount at six stations of central India. Four periods of activity of the monsoon can be defined. The second period, with large rainfall amount, is followed by a week with nearly zero rainfall. This weak activity also appears on rainfall records of stations located along the Indian west coast.

The mean field for each parameter during each of these periods is easily derived by calculating the mean value $\bar{u}(l, L)$.

The Mercator mosaic of the NOAA-4 satellite composite visible images for the period of the experiment is used to perform a nephanalysis. Cloud amounts are estimated in every 2.5° × 2.5° square. Each square is designated 0 to 9 according to the cloud amount: when there is no cloud, zero; when overcast, nine. This cloud amount analysis is made every day from 25 June to 10 August 1975. Mean cloud cover over the Indian Ocean is calculated for the four periods previously defined.

3. MAIN FEATURES OF THE MONSOON LOW-LEVEL FLOW OVER THE INDIAN OCEAN

The balloon trajectories give local quasi-Lagrangian air parcel paths whereas mean fields deduced mainly from ship reports give an overall view of the summer monsoon over the Indian Ocean. The main features of the monsoon flow can be pointed out. The results obtained from the Lagrangian information complemented by the Eulerian fields definitely rule out previous conclusions deduced from an interpretation of local conditions.

The trajectories show that southwesterlies giving rise to monsoon activity over India
are not distinct from the southeast trades of the southern hemisphere, deflected largely by
the Coriolis force after crossing the equator. The balloon experiment ends discussion about
the origin of the low-level southwest winds in the Arabian Sea. The wind fields (Figs. 3(a)
and (b), 4(a) and (b), 5(a) and (b), 6(a) and (b)) show a fundamental difference between the
eastern and western equatorial Indian Ocean. East of 60°E there is a confluence zone
characterized by weak cross-equatorial flow (5 knots), whereas in the western Arabian Sea
there is an area of strong winds with strong cross-equatorial flow. The maximum wind
intensity is found near Socotra where a weak flow from the northern hemisphere meets the
cross-equatorial flow – weak westerlies sometimes blowing from the Aden Gulf. In fact, the
cross-equatorial flow, which transports water vapour across the Arabian Sea and affects
India, is very close to the east African coast and is concentrated into the low-level jet
blowing off the Somalia coast (Findlater 1969). The mean pressure and cloud fields (Figs.
3(c) and (d), 4(c) and (d), 5(c) and (d), 6(c) and (d)) also show a well-marked difference
between eastern and western equatorial Indian Ocean. Thus, the meridional pressure
gradient is stronger along the east African coast than at 80°E. The cloud cover is small in
the eastern Indian Ocean whereas it is larger near 70–90°E.

The wind fields and balloon trajectories give an answer to the question of the origin of
westerlies over the Indian Ocean. Wind measurements deduced from successive balloon
positions (I) show that westerlies, and even northwesterlies, can be found up to 10°N. In
fact, in the Arabian Sea they do not extend northwards of about 10°N and westwards of
about 60°E. These westerlies do not correspond to the northern hemisphere flow, as has
been deduced by some meteorologists from local data, but to southeast trades deflected by
the Coriolis force and pressure forces due to the occurrence of an equatorial trough. Thus
during the third phase, westerlies are found in the eastern Arabian Sea and south Bay of
Bengal and their contribution to the monsoon activity over India must be weak. The pressure
and cloud fields show the existence of the equatorial trough related to the westerlies over the
Figure 5. As Fig. 3 but during phase 3.

Figure 6. As Fig. 3 but during phase 4.
eastern Indian Ocean (Figs. 3(c) and (d), 4(c) and (d), 5(c) and (d), 6(c) and (d)): the pressure gradient is weak and cloud cover is large.

Another important feature of the monsoon circulation over the Indian Ocean is the occurrence of transient phenomena, tropical disturbances (Cadet and Olory-Toğbê 1977), which can influence the monsoon circulation over the ocean and the activity of the monsoon over India.

4. METEOROLOGICAL FIELDS DURING THE DIFFERENT PHASES OF MONSOON ACTIVITY

As presented in section 2, rainfall records over central India reveal the existence of four periods showing the three different phases of monsoon activity: moderate, strong and weak. The study of break and active monsoons is often restricted to the analysis of satellite-determined cloudiness over the ocean and the study of the relationship between this field and rainfall over India (Srinivasan 1968; Ramaswamy 1971; Hamilton 1977). The analysis presented in this section is supported by wind and pressure fields. Thus the evolution of these fields can be followed during the different phases.

One particular feature to study is the occurrence of break conditions over India during phase 3. The evolution of the different fields can be followed from phase 1 to 3. During the break period, the wind field is characterized by weak westerlies. These weaker winds are found over the eastern equatorial ocean and are well extended in the southern part of the ocean. Thus during this particular phase the cross-equatorial flow is non-existent over this part of the Indian Ocean. It can also be noted that the wind intensity near the western coast of India is weaker during this phase. As for the wind fields, there is an evolution in cloudiness and one can follow the extension of cloudiness over the equatorial ocean from phases 1 to 3. This corresponds to the maximum development of a trough in that region as revealed by pressure fields. Thus the meridional pressure gradient continuously decreases near 80°E from phase 1 to 3, and during the break phase the trough is well marked. These results agree with Murakami’s work (1976) showing a well-marked negative correlation between cloudiness changes over central India and the equatorial Indian Ocean. Thus Murakami shows that during weak activity, the monsoon trough over India is shifted towards the foot of the Himalayas and the second trough intensifies over the eastern equatorial Indian Ocean, reducing the cross-equatorial flow in this area. The slow evolution of the meteorological fields from moderate to weak activity is also in good accordance with the quasi-biweekly oscillation of the broad-scale monsoon elements as shown by Krishnamurti and Bhalme (1976).

5. CONCLUSION

An analysis of the summer monsoon over the Indian Ocean has been completed using Lagrangian trajectories and assimilated conventional data. The main features of the monsoon flow over the ocean have been stressed. An analysis of meteorological fields during different phases of monsoon activity reveals that the fields are substantially different between the phases. Furthermore it is shown that the fields over the Indian Ocean during break conditions correspond to the results of an evolution of the fields. During the occurrence of a break, typical features can be noted: an intensification of the southern hemisphere equatorial trough and an extension of cloudiness over the eastern equatorial Indian Ocean.

This study also shows that conventional ship data can be used to study meteorological fields over the Indian Ocean. Up to now, these are the only data available over the Indian Ocean; valuable information can be obtained from the analysis of such data.
ACKNOWLEDGMENTS

Many thanks to G. Arkhipoff for his able programming assistance. We are also indebted to all the people who provided us with meteorological observations over the Indian Ocean area.

REFERENCES


