MAUSAM, 49, 2 (April 1998), 159-166

551.515.1:551.553.21

Role of tropical mid-latitude interaction in the genesis of a monsoon depression - A detailed case study

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(Received 9 May 1996, Modified 13 November 1996)

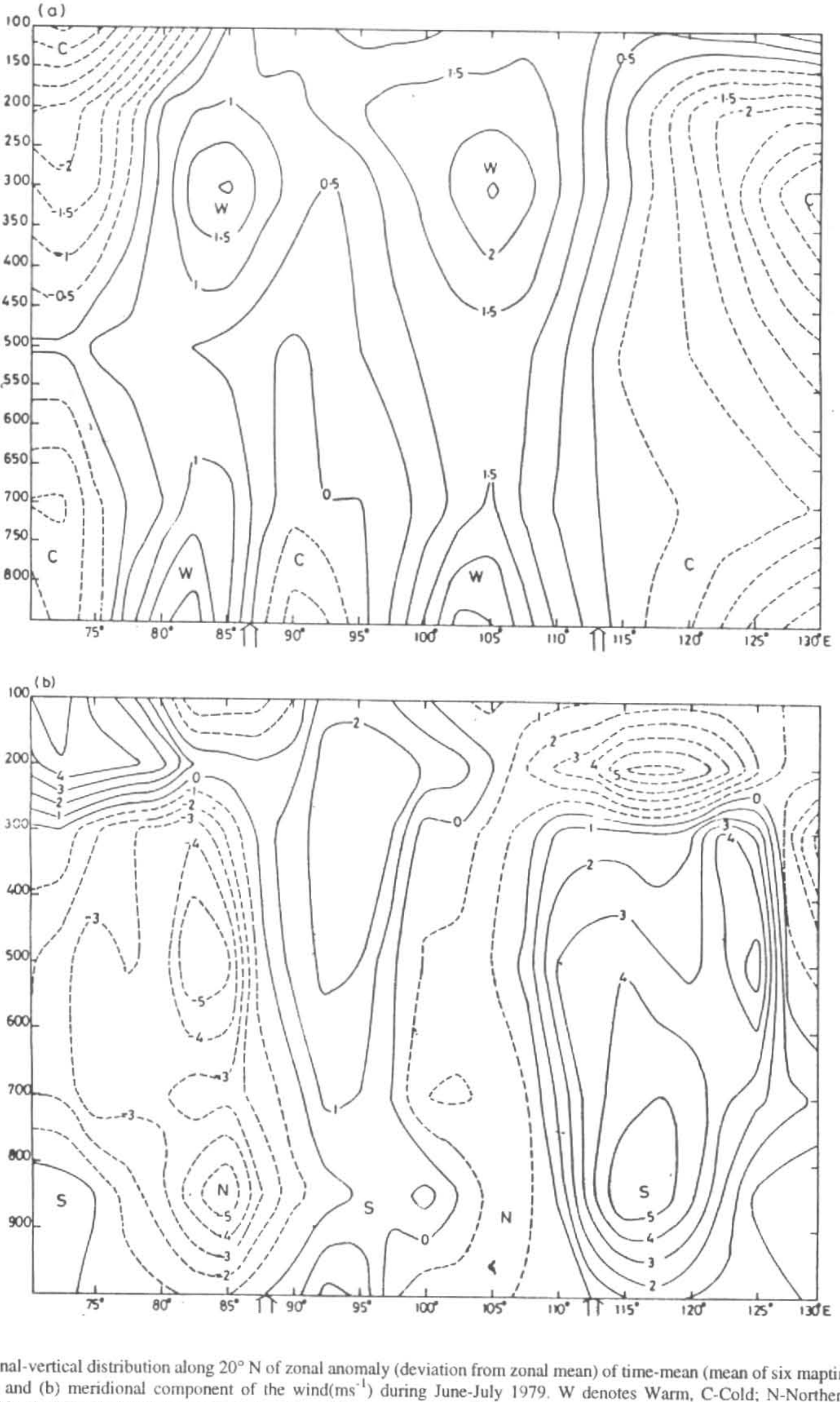
सार — उत्तरी क्षेत्र में ग्रीष्मकाल के दौरान, अप्रगामी मानसून तरंग, अपनी बैरोक्लिनिक संरचना के एक भाग के रूप में तीन स्पष्ट द्रोणियां बनाती है जिसमें से एक-एक द्रोणी अरब सागर, बंगाल की खाड़ी और दक्षिण चीन समुद्र के क्षेत्रों से बनती है। अप्रगामी मानसून तरंग और मध्य-अक्षांशीय बैरोक्लिनिक तरंगों में अन्योन्यक्रिया होती रहती है और इनमें मानसून द्रोणी के बनने के गहन प्रभाव के कारण इनके पूर्वाभिमुखी मार्ग के दौरान विस्तार हो जाता है। इस शोध पत्र में तरंगों से संबंधित तापीय और वायु क्षेत्रों के अल्पकालिक विकास के संकेतों के आधार पर तरंगों की अन्योन्यक्रिया पर चर्चा की गई है। इसमें उष्णकटिबंधीय मध्य अक्षांशीय परस्पर प्रभाव के मामले के विस्तृत अध्ययन की जाँच की रिपोर्ट भी प्रस्तुत की गई है जिससे बनी मानसून द्रोणी के कारण दक्षिण चीन में पश्चिमोन्मुखी मानसून अवदाब उत्पन्न हुआ है।

ABSTRACT. During northern summer, a monsoon stationary wave which maintains as part of its baroclinic structure three well-defined troughs, one each in the region of the Arabian sea, the Bay of Bengal and South China sea, frequently interacts with the mid-latitude baroclinic waves which amplify during their eastward passage with profound influence on the development of the monsoon troughs. The paper discusses the mechanism of this wave-wave interaction as suggested by the temporal evolution of the thermal and wind fields associated with the waves and reports the findings of a detailed study of a case of tropical-midlatitude interaction in which the development of a monsoon trough led to the birth of a westward-propagating monsoon depression over South China.

Key words — Genesis of monsoon depression, Tropical mid-latitude interaction, Development of monsoon troughs.

1. Introduction

One of the outstanding problems of tropical meteorology is prediction of genesis of monsoon depressions. Recently, Mak (1987) has reviewed some of the theoretical studies of flow instability, mostly based on quasi-geostrophic theory, which have emphasized the role of barotropic or baroclinic or combined barotropic-baroclinic instability as a plausible mechanism for growth of a perturbation of the scale of a monsoon depression in mean monsoon current. However, it is still unclear as to what identifiable physical factors get involved in triggering a monsoon depression in a given synoptic situation. According to Ramage (1971), monsoon depressions have a tendency to form on pre-existing monsoon troughs over the Bay of Bengal and South China sea. But the reason as to why it should be so has not been elucidated. Some recent observational studies (*e.g.*, Saha and Chang 1983, Saha and Saha 1993 a&b, 1996) find that large-amplitude mid-latitude baroclinic waves frequently interact with monsoon depressions with profound influence on the latter's intensity and movement through baroclinic processes. In the present study, we deal with a case of genesis of a monsoon depression on a monsoon trough over southern China following the interaction of this trough with a large-amplitude baroclinic wave in the mid-latitude westerlies. The interaction led to formation of an extended trough and its eventual fracture into two segments in a manner suggested in some classical studies (for a review of these studies, see Riehl 1954). It is the cut-off tropical part of the extended trough that eventually concentrated into a depression. The event occurred during a period of about



Figs.1(a&b). Zonal-vertical distribution along 20° N of zonal anomaly (deviation from zonal mean) of time-mean (mean of six maptimes) (a) temperature (°C) and (b) meridional component of the wind(ms^{-1}) during June-July 1979. W denotes Warm, C-Cold; N-Northerly and S-Southerly. Double-shaft arrow shows approximate location of the monsoon trough three days commencing 29 June 1979 over a part of China adjoining the South China sea.

The layout of the paper is as follows:

Data and analysis are stated in section 2. The structure and properties of wave disturbances in mid-latitudes and monsoon regions of Asia are briefly reviewed in section 3. Mechanism of interaction leading to formation of an extended trough between high and low latitudes and its eventual fracture is explained in section 4. Synoptic evidence of an actual case of such interaction resulting in the genesis of a westward-propagating monsoon disturbance is presented in section 5. The findings and conclusions are given in section 6.

2. Data analysis and computations

Since the event occurred during the Summer Monsoon Experiment (SMONEX), 1979, when a concerted effort was made to collect maximum possible data over the Asian monsoon region, data coverage available for the study may be said to have been perhaps, the best so far except over the oceanic region where, as usual, data were sparse. Our data are obtained from the synoptic maps of the India Meteorological Department (IMD) at its Headquarters at New Delhi and consist of daily 0000 and 1200 UTC winds, geopotential heights and temperatures at Mean Sea Level (MSL) and pressure surfaces 850, 700, 500, 300, 200, 100 and 50 hPa over an area bounded by latitudes 5° N and 55° N and longitudes 35° E and 130° E during the period 28 June through 3 July. Plotted on maps, these data are analyzed manually to obtain streamline-isotach, isobaric height and isothermal fields. From the analyses, values of the different variables are picked up at 2.5° × 2.5° lat-long grid for further study and computations. Maps showing satellite-observed cloud cover at 1200 UTC daily during the period 28 June through 1 July 1979, were obtained from Krishnamurti *et al.* (1979, 1980). Parameters computed include zonal anomaly (deviation from zonal mean) of temperature and the meridional component of the wind flow, divergence and vorticity, vertical motion and horizontal thermal advection. Vertical velocity was computed from the well-known continuity equation by using the orographic vertical velocity as the lower boundary condition and applying a correction to the computed values so as to reduce the computed vertical velocity at the top of the domain to zero. Other parameters were computed using standard methods.

3. Structure and properties of wave disturbances

(a) *Mid-latitudes*

The mean structure of wave disturbances in the mid-latitudes, where the thermal wind is uniformly westerly, is well-known (*e.g.*, Palmen and Newton 1969, Holton 1979). It consists of a temperature wave made up of a alternate sectors of cold and warm airmasses associated with a geopotential wave comprised of alternate sectors of lows and highs. The troughs and ridges of the geopotential wave tilt westward with height, while the axes of the warmest and the coldest air tilt eastward with height. Thus, in a developing wave, a phase difference exists between the two waves which causes cold advection from the north to the west of the trough and warm advection from the south to the east. This causes a baroclinic development of the wave with cold air sinking in the west and warm air rising in the east, thereby effecting a direct conversion of available potential energy into eddy kinetic energy. Though of the Rossby-wave type which has a westward phase velocity, mid-latitude baroclinic waves usually move eastward because of the strong westerly current in which they are embedded.

(b) *Tropics*

Over the Asian tropics (south of about 30° N), land-sea thermal contrasts during the summer maintain an easterly thermal wind over the region and a stationary wave along the southern boundary of the continent with low pressure over the warm land and high pressure over the cool sea, as identified by zonal anomaly of pressure and temperature. A zonal-vertical cross-section of this wave in the field of zonal anomaly of time- mean temperature and the meridional component of the mean wind along 20° N is shown in Figs. 1(a & b) respectively. According to Saha and Saha (1996), this stationary wave which has three well-defined troughs of low pressure, one each over eastern Arabian sea, the Bay of Bengal and South China sea has a baroclinic structure characterized by the following:

(*i*) it has alternate sectors of warm and cold airmasses as in mid-latitude baroclinic waves;

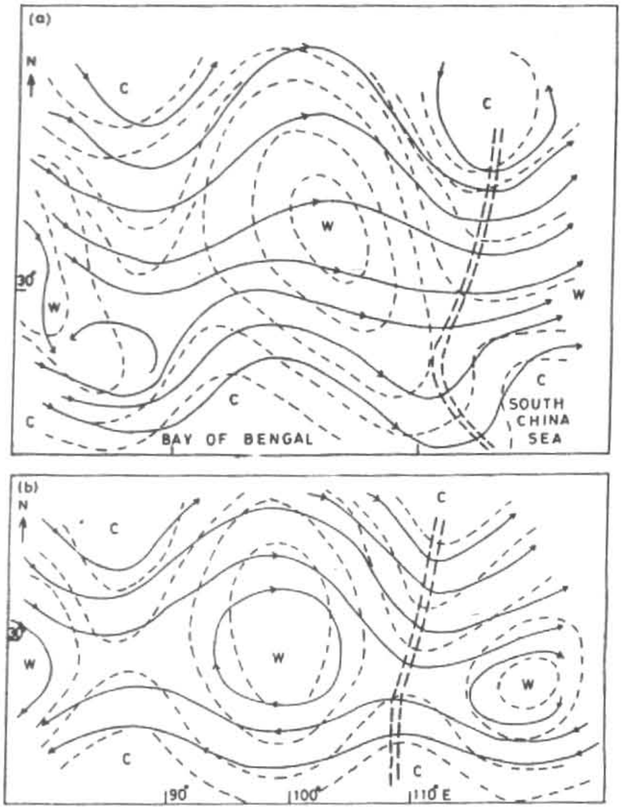
(*ii*) its troughs and ridges tilt eastward with height in the lower troposphere where the prevailing wind is generally westerly and westward with height in the upper troposphere where the prevailing wind is easterly; and

(*iii*) in both the lower and the upper tropospheres, a phase difference exists between the geopotential and the temperature fields (*e.g.*, Saha and Chang 1983, Saha and Saha 1996) so that the temperature wave lags behind the geopotential wave, looking downstream. The phase difference causes warm advection from the north to the west of the trough (ridge) and cold advection from the south to the east in the lower (upper) tropospheres and helps to maintain the trough *via* a west-east overturning with warm air rising in the west and cold air sinking in the east. Thus, a monsoon trough has a baroclinic structure and is maintained by a baroclinic process. Likewise, a monsoon depression which is a slightly deeper low

TABLE 1

A comparative statement of time-mean wave parameters of mid- latitude and tropical depressions (T-Temperature, Phi-Geopotential, C-Cold, W-Warm)

Parameter	Mid-latitude depression	Tropical depression
Latitude belt (Deg.Lat.)	30-60	15-30
Wavelength (km)	3000-5000	1000-2000
Period (days)	5-10	3-5
Amplitude T-field(°C)	5-10	1-2
Phi-field (gpm)	50-100 (often 200)	20-50
Movement direction	Eastward	Westward
Speed(ms^{-1})	5-10	2-5
Thermal wind	Westerly	Easterly
Zonal vertical tilt (Troughs & Ridges)	Westward with height	Eastward (westward) in lower (upper) troposphere
Thermal structure	C to West, W to east	W(C) to west, C(W) to east in lower (upper) troposphere
Thermal structure	C to West, W to east	W(C) to west, C(W) to east in lower (upper) troposphere



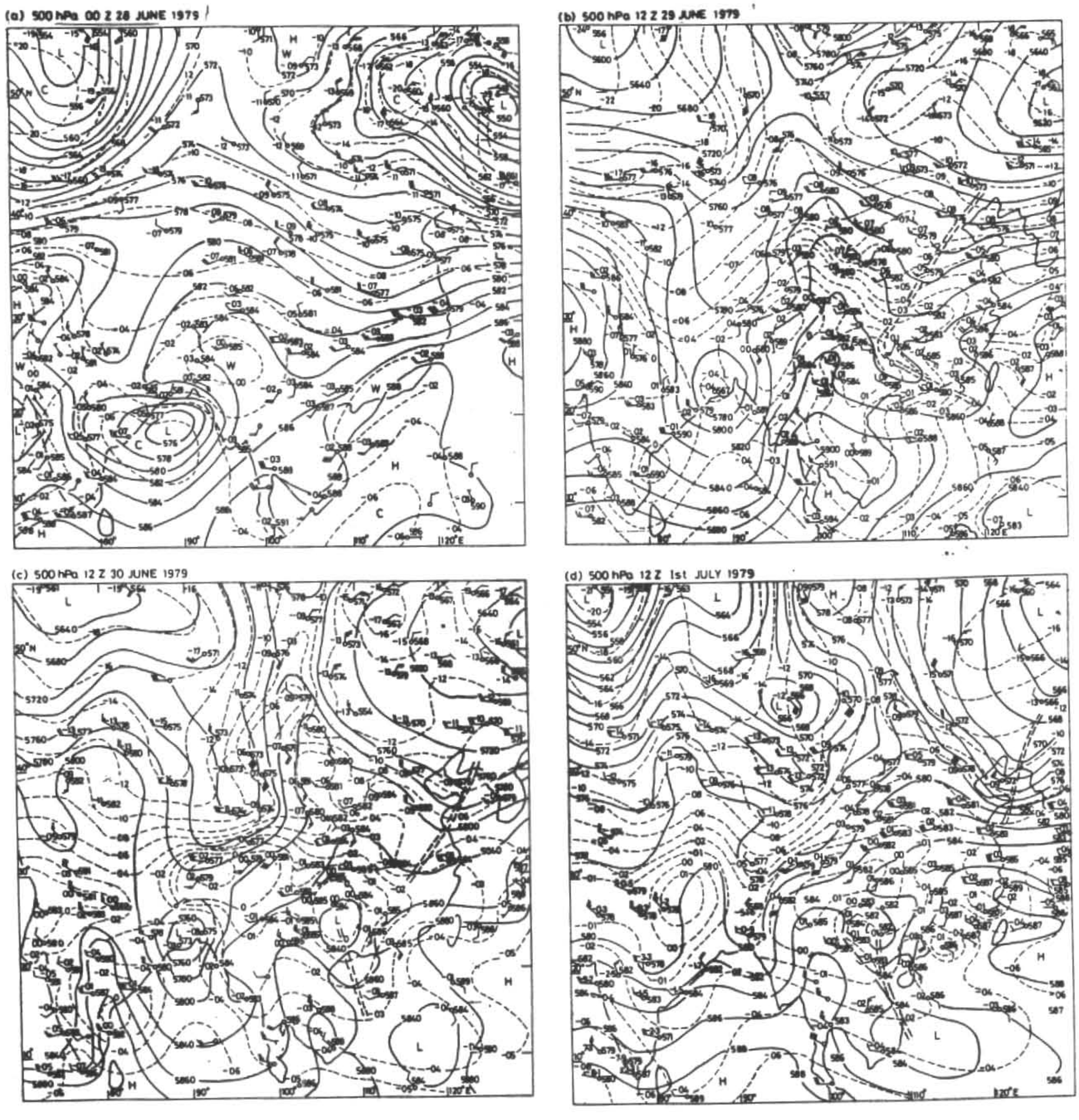
Figs.2(a&b).Schematic showing midlatitude-tropical interaction over Asia in the fields of temperature and wind. Double-dashed line denotes the troughline: (a) Lower troposphere (below 500 hPa) and (b) Upper troposphere (500-200 hPa)

pressure system than a monsoon trough has a baroclinic structure (Saha and Saha 1993b) and is controlled by the same baroclinic process as in a monsoon trough. Some salient features of the time-mean structure and properties of mid-latitude and tropical depressions mentioned above are summarized in a comparative statement presented in Table 1.

4. Mechanism of interaction

Disturbances of middle and low latitudes which move zonally in their respective latitudinal belts as stated in Table1often do not interact with each other across the subtropical belt which separates them. However, observations reveal (*e.g.*, Saha and Saha 1993 a,b) that a number of mid-latitude disturbances during their eastward travel amplify, extend their influences to lower latitudes and interact with the monsoon stationary wave, or even a monsoon low or depression if one happens to be present. The process of interaction involves both the thermal and the geopotential fields. In the thermal field, the cold and warm sectors of one belt interact with the cold and warm sectors of the other either in the same phase (*i.e.*, cold with cold and warm with warm) or in the opposite phase (*i.e.*, cold with warm and warm with cold). Since the warm and the cold sectors of the monsoon stationary wave move away little from their mean geographical locations during the season, it is the warm and the cold sectors of a mid-latitude wave which during their eastward travel interact with those of the monsoon stationary wave either in the same phase or the opposite phase. During an interaction in the opposite phase, that is when the warm sector of the midlatitude belt interacts with the cold sector of the tropical belt, the result is usually a weakening of the monsoon wave. However, an interaction in the same phase leads to coupling and amplification of the disturbances, as shown schematically in Figs.2(a &b) which depict the thermal and wind fields in the lower and the upper tropospheres respectively.

It may be noted that the structure of the fields in the two layers is somewhat different, due largely to the difference in the zonal-vertical tilts of the troughs of the two belts in relation to the warm and cold airmasses, as stated in Table1. An extended trough signifying coupling, therefore, appears to figure more prominently in the upper troposphere than in the lower troposphere. During coupling, warm air diverging



Figs.3(a-d). 500 hPa Synoptic maps at: (a) 0000 UTC 28 June, (b) 1200 UTC 29 June, (c) 1200 UTC 30 June and (d) 1200 UTC 1 July 1979.

from the mid-latitude warm high appears to converge strongly into the monsoon trough zone from the west in the lower troposphere and from the east in the upper troposphere. The process leads to rapid development of the monsoon trough into a low or depression. But since the waves move in opposite directions, the extended trough soon gets fractured into two segments which start moving away from each other. It is the southern segment that under sustained warm advection from the mid-latitude wave develops into a monsoon depression.

5. Synoptic evidence

Our analyses of observed data, presented in Figs.3(a-d), appear to support the mechanism suggested in the preceding section regarding the genesis of a monsoon depression on a trough of the monsoon stationary wave over southeastern China. Fig.3a, which relates to 500 hPa at 0000 UTC on 28 June, shows two large-amplitude code troughs, one along about 75° E and the other along about 127° E separated by an intense warm ridge along about 95° E over the mid-lati-

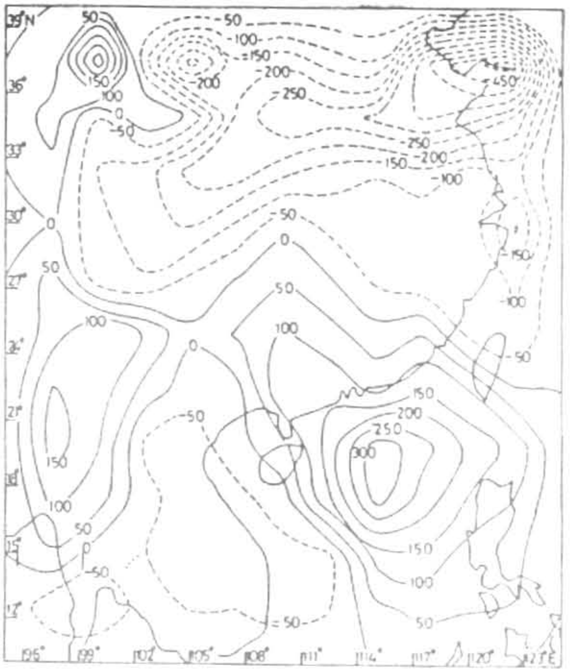


Fig.4. Vertically-integrated thermal advection (unit: Wm^{-2}) at 1200 UTC on 1 July 1979. Positive values indicate cold advection and negative values warm advection.

Fig.5. Distribution of vertical velocity (unit: 10^{-4} hPa s^{-1}) at 500 hPa at 1200 UTC on 1 July 1979. Positive denotes downward and negative upward.

tudes. A deep depression centered at about 19° N, 89° E lies over the Bay of Bengal.

The situation over the South China sea region appears to be somewhat complex, in that due to its interaction with the large amplitude mid-latitude trough in the opposite phase the monsoon stationary wave here has almost lost its identity. However, with continued eastward movement of the mid-latitude wave, the situation changes rapidly during the next day and, as shown in Fig.3b, which relates to 500 hPa at 1200 UTC on 29 June, an interaction of the monsoon stationary wave with the mid-latitude wave in the same phase leads to coupling of the waves so as to form an extended trough over eastern China. Strong warm advection occurs at this stage from the warm sector of the mid-latitude disturbance to the west of the monsoon trough and cold advection from the South China sea to the east of the trough, causing rapid development of the monsoon trough into a westward-propagating low or depression, while the mid-latitude segment of the extended trough, now fractured, continues its eastward movement. These developments are well brought out by Fig.3c which pertains to 500 hPa at 1200 UTC on 30 June.

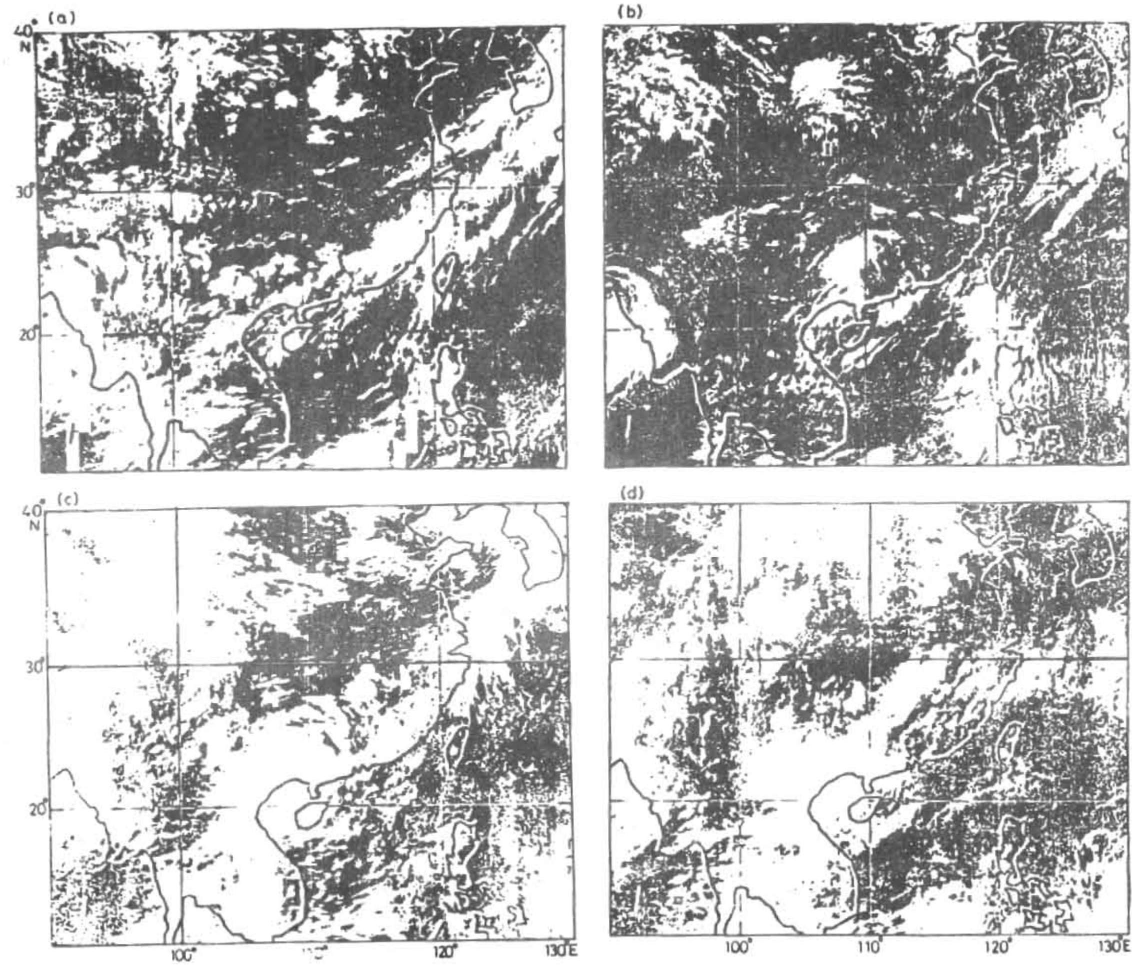
Fig.3d which relates to 500 hPa at 1200 UTC on 1 July shows continuance of warm and cold advections as on the preceding day and further longitudinal separation of the monsoon depression and the mid-latitude trough as they keep moving in the opposite directions. The monsoon depression continues to move westward but weakens somewhat as it negotiates the mountains and hills of central Myanmar. Two days later, *i.e.*, at 1200 UTC on 3 July, it appears as a well-marked trough of low pressure across the Arakan coast of Myanmar (Saha and Shukla 1980).

The results of our computation of vertically-integrated thermal advection and vertical motion, examples of which for 1200 UTC on 1 July are presented in Figs. 4 and 5 respectively, would appear to be consistent with the satellite-observed cloud cover over southeastern Asia shown in Figs.6(a-d). Deep convective clouds appear in areas where there is strong warm advection and upward motion and clear skies in regions where there is cold advection and downward motion. These results would appear to support the hypothesis advanced in the present study regarding the genesis of a monsoon depression.

6. Findings and concluding remarks

The findings of the present study may be summarized as follows:

(*i*) A zonal stationary wave in the geopotential field with troughs over warm land and ridges over cool sea, which exists over southern Asia during the northern summer, interacts frequently with mid-latitude large-amplitude eastward-propagating baroclinic disturbances, whenever the latter move on a track which lies sufficiently equatorward of their usual track.



Figs.6(a-d). Satellite-observed cloud imagery at 1200 UTC on: (a) 28 June, (b) 29 June, (c) 30 June and (d) 1 July 1979 (From Krishnamurti *et al.*, 1979, 1980).

(*ii*) Since the wave troughs in the two latitudinal belts are associated with warm and cold sectors, the interaction is reflected in both the geopotential (or wind) and the thermal fields.

(*iii*) An interaction in the opposite phase, *i.e.*, between the cold sector of the mid-latitude disturbance and the warm sector of the monsoon disturbance, or *vice versa*, leads to a weakening of the monsoon disturbance. An interaction in the same phase, *i.e.*, between the warm (cold) sector of one belt and the warm (cold) sector of the other, has an amplifying and developing effect on the monsoon disturbance through enhanced thermal advection.

(*iv*) Interaction in the same phase leads to a coupling of the troughs of the two belts and formation of an extended trough which later breaks up into two segments. It is the tropical segment of the fractured trough that develops into a westward-propagating monsoon low or depression.

(*v*) The afore-mentioned hypothesis appears to be well supported by a detailed study of a case of genesis of a monsoon disturbance over southeastern China.

In conclusion, it may be remarked that though the present study concentrates on the role of a mid-latitude disturbance of the northern hemisphere in the genesis of a monsoon depression, one cannot rule out the possibility of similar influences coming off and on from mid-latitude disturbances of the southern hemisphere. In fact, some observational studies (*e.g.*, Sikka and Gray 1981) have revealed that during eastward passage of large-amplitude mid-latitude waves over the southern Indian ocean, pulses of relatively cooler air from the cold sectors of these waves cross the equator and converge onto the monsoon trough zones. It is conceivable that an enhancement of cold advection to the cold sector of a monsoon trough zone from the south in tandem with that of warm advection to its warm sector from the north may lead to rapid cyclogenesis and formation of a deep depression or a cyclonic storm.

Acknowledgement

The authors' grateful thanks are due to the Director General of Meteorology, India Meteorological Department, New Delhi, for several facilities extended during preparation of this paper. They also thank an anonymous reviewer whose comments and suggestions on the first draft were found helpful in arriving at the final text.

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