Westward Propagating Predecessors of Monsoon Depressions

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ABSTRACT

By examining maps of 24 h change of sea level pressure during July and August over the 10-year period 1969–78, we find that 45 (87%) of the 52 lows and depressions that formed in the Bay of Bengal were associated with predecessor disturbances coming from the east. In 12 (23%) instances, the predecessor was associated with a typhoon or named tropical storm in the South China Sea, while the remaining 33 (64%) were weaker systems originating over a broad region of land and sea.

From examination of time sections over the same period from eastern Thailand to the Burmese coast, we identified 50 westward-moving disturbances, with considerable vertical extent, of which 64% developed into lows or depressions on reaching the Bay. In 60% of the 50 instances, the disturbance could be traced to the South China Sea, 32% being typhoons and named tropical storms and 28% weaker circulations. The remaining 40% of the 50 disturbances appeared to originate over land.

For the three stations along the section line, cross-correlation and power spectrum analyses of departure of the 24 h pressure change at each station from the average of the three station values confirms the existence of westward-moving waves.

The isallobaric maps and time sections and the statistical analysis indicate a period of slightly less than five days, a westward phase speed slightly less than 6 m s^{-1} and a wavelength of ~2300 km. The amplitude of the oscillation of the 700 mb meridional wind component in northwest Thailand was ~5 m s^{-1}. The maps indicate an isallobaric amplitude of ~3 mb day^{-1} while data along the section line indicate a value only about half as large, owing mainly to the failure of the isallobaric centers to lie on the line. These waves appear to be morphologically similar to waves found in the lower and middle troposphere in other tropical longitudes of the Northern Hemisphere.

Although we have not addressed the important physical problems of the origin of the disturbances, or of their development at the surface on arrival in the Bay of Bengal, it appears that our empirical results can be directly applied to forecasting practice and should show considerable skill in predicting the appearance of monsoon depressions.

1. Introduction

During the period of southwest monsoon (June–September), a number of lows and depressions[1] form in the area of the Head Bay of Bengal and move inland in a westward to west-northwestward direction. Some of these develop into deep depressions or cyclonic storms over the Bay or in the course of their travel inland. On an average about two lows or depressions form per month during July and August. A question that has often been asked is whether these low-pressure systems all form without any triggering from outside the Bay or whether some of them develop around nuclei of disturbances which move in from areas outside, especially to the east, such as the Pacific Ocean, the South China Sea, or the land masses of Vietnam, southern China, Laos, Thailand or Burma. It is well known that typhoons and tropical storms are frequent in the western Pacific and the South China Sea between latitudes 10 and 30°N during July and August, and it has been thought that some of these in the course of their predominantly westward motion might cross the Vietnam coast and act as predecessors of low-pressure disturbances in the Bay of Bengal. Iyer (1931, 1935), who first examined the tracks of typhoons of the Pacific Ocean and South China Sea in the years

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[1] We used the India Meteorological Department classification of tropical disturbances in the Bay of Bengal, given below:

Classification	Range of wind speeds (m s^{-1})
Low	<8.5
Depression	8.5–13.5
Deep depression	14.0–16.5
Cyclonic storm	17.0–23.5
Severe cyclonic storm	24.0–31.5
Severe cyclonic storm (Hurricane)	≥32.0

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1884–1930, found that 135 out of 370 affected the weather in India. He found the months July–November to be the chief months in which the residual lows from the typhoons travelled across the hilly country of Indochina or South China and entered the Indian area. It is remarkable that as early as 1932 Iyer had noted that it was not the typhoons but their residual lows which traveled westward across the countries of Southeast Asia. In fact, in his celebrated memoir (1935), he showed the tracks of many typhoon remnants across southeast Asia. Ramanna (1969) compared the number of cyclonic systems of the South China Sea crossing the coast between latitudes 15 and 25°N with the number of cyclonic systems formed in the Bay of Bengal in comparable latitudes within five days on either side of the former during a period of 60 years (1893–1952). Assuming that it would take about 2–5 days for a cyclonic system from the South China Sea to travel across Southeast Asia and provide the nucleus for the Bay system, he concluded that not more than 20% of these systems could have formed in this manner during July and August. Krishnamurti *et al.* (1977), who examined the mean sea level pressure along latitude 20°N for 44 years during June–September, attributed the formation of 35 monsoon depressions to a very slow westward propagating wave group initiated by a typhoon from the western Pacific. However, one also can see a tendency for much faster phase propagation in most of their diagrams. In a recent study using synoptic and satellite data relating to the period 1967–73, Sadler and Kilonsky (1977) concluded that none of the monsoon depressions that formed in the Bay in July and August during the seven-year period had any connection with previous storms in the South China Sea.

The above references make it clear that the earlier workers sought to relate the Bay disturbances with typhoons and tropical storms but not with any other disturbances. The literature contains hints of weaker perturbations which move westward across Southeast Asia and can trigger the formation of monsoon lows and depressions. Koteswaram and Bhaskara Rao (1963) had observed that "the formation of a depression in the Bay of Bengal was generally preceded by a fall of pressure in the northern part of the Bay of Bengal, the isallobaric low moving westward from Burma or farther east." According to them, about four or five low-pressure waves move into the Head Bay per month during the southwest monsoon season, of which two or three intensify into depressions each month while the rest move westward without development. However, these workers presented no data or analyses in support of their statements.

The purpose of the present study is to examine whether there is observational evidence for associating the lows and depressions that form in the Bay of Bengal with disturbances of any sort that propagate from the east and, if so, to what extent. We have selected the 10-year period 1969–78 because of the expectation that the data coverage was more complete then in Southeast Asia, both at the surface and aloft, than before or after.

2. Data and analysis technique

Information regarding the synoptic systems in the Bay of Bengal, particularly the locations of the centers of the lows and depressions, was obtained from the Indian Daily Weather Reports published by the India Meteorological Department. The *Indian Journal of Meteorology, Hydrology and Geophysics*, published by the same department, was also consulted. Similar information for the synoptic systems in the western Pacific, South China Sea and countries of Southeast Asia was obtained from the daily weather maps published by the Thailand Meteorological Department. (The Thai maps were our source of information for some of the Bay disturbances.) Satellite cloud pictures obtained from the NOAA National Environmental Satellite Service were consulted for tracing the movement of tropical disturbances. They gave useful guidance in the few instances in which the disturbance retained a clear vortical structure in the cloud field. In most cases, however, the disturbances were weak and clouds associated with them had little organization which could be discerned through the heavy monsoon clouds associated with the mean monsoon flow. The result was that it was usually impossible to identify the disturbances from satellite cloud imagery alone. During our 10-year period, 52 lows and depressions formed in the Bay of Bengal during July and August. The particulars are provided in Table 1.

In choosing a suitable method of analysis for the proposed study, we had to consider the following conditions:

(i) The disturbances to be traced were likely in many instances to be extremely feeble.

(ii) In the long-term seasonal mean at sea level, a substantial pressure ridge over Thailand separates troughs over the Bay of Bengal and the South China Sea.

(iii) A large-scale pressure oscillation exists which appears to affect all stations in Southeast Asia almost simultaneously.

In view of (i) and (ii), we decided to analyze primarily the 24 h change of sea level pressure rather than the pressure itself. In view of (iii) we relied on the perturbation pressure change, the departure from an estimate of the area-average based on three stations to be mentioned later.

We carried out the analysis in three parts. In the first part, we prepared maps of sea level pressure and its 24 h tendency for the date of first appearance of the low or depression in the Bay and for each of the preceding four days. Data sources included the Northern Hemisphere Data Tabulations (NHDT) published by the NOAA National Climatic Center and the tabulated station data published by the Thailand Meteorological Department. NHDT data through 1972 were available for 1200 GMT. After

TABLE 1. Dates and characteristics of the lows and depressions.

Date of appearance in Bay	Source	Days of isallobaric continuity	Association with tropical storms	Isallobaric amplitude (mb day^{-1})	Speed of isallobaric minimum (m s^{-1})	Wavelength (km)	Period (days)
13 Jul 69	J	2	Tess (indirect)	2.8	6.5	2700	4.8
19 Jul 69	J	4	SCS	2.1	7.0	2800	4.6
28 Jul 69	W	3	Land	1.4	9.0	1600	2.1
4 Aug 69	W	4	SCS	1.8	4.5	2400	6.2
13 Aug 69	W	3	Betty (indirect)	3.1	6.0	2600	5.0
29 Aug 69	M	3	Land	1.8	6.5	3000	5.3
5 Jul 70	J	4	Land	1.5	4.5	2700	6.9
18 Jul 70	J	4	Ruby (indirect)	2.1	8.0	3600	5.2
26 Jul 70	W	3	Land	2.1	6.5	3200	5.7
16 Aug 70	J	3	Land	1.8	8.0	2400	3.5
21 Aug 70	W	4	SCS	3.2	7.0	2300	3.8
14 Jul 71	W	2	Land	0.6	5.0	1300	3.0
25 Jul 71	W	4	Lucy (direct)	8.4	8.0	2100	3.0
7 Aug 71	W	4	SCS	2.1	4.5	2600	6.7
23 Aug 71	W	0	*In situ*	—	—	—	—
4 Jul 72	W	3	Land	3.3	7.0	2800	4.6
11 Jul 72	J	4	SCS	2.4	4.5	3700	9.5
29 Jul 72	W	0	*In situ*	—	—	—	—
11 Aug 72	W	4	Land	2.2	4.5	2300	5.9
27 Aug 72	W	4	SCS	1.4	4.0	1600	4.6
4 Jul 73	W	4	SCS	1.5	8.0	2400	3.5
11 Jul 73	W	4	Anita (direct)	4.6	6.5	1900	3.4
18 Jul 73	W	2	Dot (indirect)	2.6	7.5	2700	4.2
15 Aug 73	W	0	*In situ*	—	—	—	—
25 Aug 73	W	4	Joan (direct)	3.8	7.0	2000	6.1
29 Aug 73	W	4	Kate (direct)	4.4	4.4	1900	5.0
8 Aug 74	W	2	SCS	1.8	5.5	2100	4.4
12 Aug 74	W	2	Land	1.8	4.0	2200	6.4
17 Jul 75	J	0	*In situ*	—	—	—	—
3 Aug 75	W	4	Land	2.9	9.5	2400	2.9
11 Aug 75	W	3	Land	3.2	5.5	2700	5.7
16 Aug 75	W	3	Land	2.5	6.5	2200	3.9
16 Jul 76	W	4	Land	1.6	4.0	1900	5.5
28 Jul 76	W	4	Violet (indirect)	1.4	5.5	1600	3.4
31 Jul 76	W	4	SCS	1.6	8.5	2400	3.3
12 Aug 76	W	0	*In situ*	—	—	—	—
24 Aug 76	W	4	SCS	1.8	4.0	2400	6.9
1 Jul 77	W	4	Land	1.9	5.0	2200	5.1
17 Jul 77	M	0	*In situ*	—	—	—	—
23 Jul 77	W	3	Sara (indirect)	5.7	6.0	2900	5.9
29 Jul 77	W	4	Land	4.0	6.0	3000	4.3
3 Aug 77	W	4	SCS	2.2	9.5	1800	2.2
18 Aug 77	W	2	Land	1.8	6.0	2300	4.4
30 Aug 77	W	1	Land	3.0	8.5	3700	5.0
11 Jul 78	W	3	Land	1.6	7.5	2700	4.2
21 Jul 78	M	3	Land	2.9	8.5	3100	4.2
2 Aug 78	J	0	*In situ*	—	—	—	—
8 Aug 78	M	3	SCS	2.7	7.0	3300	5.5
13 Aug 78	W	1	Bess (indirect)	0.4	11.0	1600	1.3
19 Aug 78	M	4	SCS	2.4	7.5	3000	4.8
25 Aug 78	W	3	SCS	1.5	6.0	2900	4.2
30 Aug 78	W	4	Elaine (direct)	8.7	7.0	1900	3.1
Mean		2.8		2.6	6.5	2460	4.3

W: Indian Daily Weather Report.
J: *Indian Journal of Meteorology, Hydrology and Geophysics.*
M: Thailand Meteorological Department Maps.
SCS: South China Sea or farther east.

that time, 0000 GMT observations also were available.

In the second part of the analysis, we prepared time sections of 24 h change of sea level pressure at 1200 GMT through 1972, 0000 GMT thereafter, at three stations oriented east-southeast to west-northwest across Southeast Asia. They were Udon Thani (17°26′N, 102°46′E), Chiangmai (18°47′N, 98°59′E) and Akyab (20°08′N, 92°53′E). In 1978 Udon Thani was replaced by Khon Kaen (16°20′N, 102°51′E). The observations from Akyab were often missing in the NHDT, our only regular source of data for Burma. In these instances we either used observations for Sandoway (18°28′N, 94°21′E) instead, or recovered Akyab observations from the plotted Thai maps, or made estimates by interpolating in time or space between other relevant observations.

To obtain an idea of the presence and structure of the disturbances aloft, we analyzed time sections of wind observations at Chiangmai for the standard pressure levels up to 200 mb. The lack of soundings at this station in 1977 and 1978 required use of data from Szemoa (22°42′N, 101°E) instead.

In the final part of the investigation, we undertook some statistical analysis, principally of the time series of perturbation pressure change, to find out whether the subjective findings from the isallobaric maps and time sections could be supported by objective calculations. We performed this analysis for 1971–73, 1977 and 1978 when the time series of station data were most complete. For this purpose we replaced Udon Thani by Ubon Ratchathani (15°15′N, 104°53′E), a station farther east for which the data at 1200 GMT were more complete than at Udon Thani or Khon Kaen.

3. Isallobaric maps

Our aim in the present section is to see how many of the 52 Bay disturbances had predecessors coming from the east. For this purpose we plotted maps of sea level pressure and its 24 h change as indicated above for the region bounded by 80 and 125°E longitude and by the equator and 35°N latitude. No attempt was made to use ship observations, but the surface wind observations at coastal stations were used as a qualitative guide in drawing the isobars over the Bay each day, and hence in determining the pattern of interdiurnal pressure change.

These map series disclose a variety of circumstances preceding the appearance of the low or depression. The locations of first appearance are shown in Fig. 1, along with the locations of the associated 24 h isallobaric minima on the first day they were detected. The number of prior days when an associated isoallobaric minimum could be detected is given in Table 1. An indication of association with a named tropical storm in the South China Sea is also included. Table 1 shows that in only seven of the 52 cases was there no indication of an isallobaric predecessor from the east. (We did not examine the possibility of influence of disturbances from the west or from the north across the Tibetan plateau.) In 83% of the cases, isallobaric continuity from the east could be traced for at least two days, while 4-day continuity was found in 46% of the cases. There was an association with a named tropical storm from the South China Sea for 12 (23%) of the cases, in reasonable agreement with the finding of Ramanna (1969). The association was direct in five instances and indirect (to be illustrated later), in an additional seven. The association in the remaining majority of the sample was with a weaker disturbance, with an apparent source over land in 19 cases and over the South China Sea or farther east in 14 cases.

From Fig. 1 it is seen that the origin of the isallobaric centers ranged as far north as central China and as far east as the Philippines, with a preference for Thailand. Lack of abundant data over the South China Sea, and our imposition of a 4-day limit for prior continuity, certainly has some influence on the distribution of points in Fig. 1, but in a number of instances it seemed clear that the isallobaric path indeed started over land.

An example of a case in which the association with a named tropical storm was direct and clear is shown in Fig. 2. Anita 1973 developed over the South China Sea on 7 July and crossed the northern coast of Vietnam during the 8th, thence moving west-northwestward across Laos and Burma before emerging into the Head Bay on the 11th. In this case not only did Anita's isallobaric minimum move directly to the Bay, but there appeared to be continuity for a single low-pressure center, which is unusual. The satellite cloud pictures (not shown) and the 24 h rainfall pattern in Fig. 2 also showed west-northwestward continuity across southeast Asia.

What we mean by indirect association with a tropical storm is illustrated in Fig. 3. Tropical Storm Dot 1973 became well organized on 15 July, moving north-northwestward in the South China Sea. On the 16th, maximum pressure falls directly associated with the storm were on the Chinese coast west of Hong Kong, while a separate isallobaric minimum appeared in Thailand in the western-most fringes of the storm circulation. This latter center moved westward during the next two days with a depression forming on the 18th. Notice that the isallobaric field on the 18th shows two centers of pressure rise, one directly associated with northwestward moving Dot and the other with the separate westward moving perturbation. This type of sequence was observed a number of times.

In the light of the case histories illustrated in Figs. 2 and 3, it is difficult to understand Sadler's and Kilonsky's (1977) assertion that no monsoon depres-

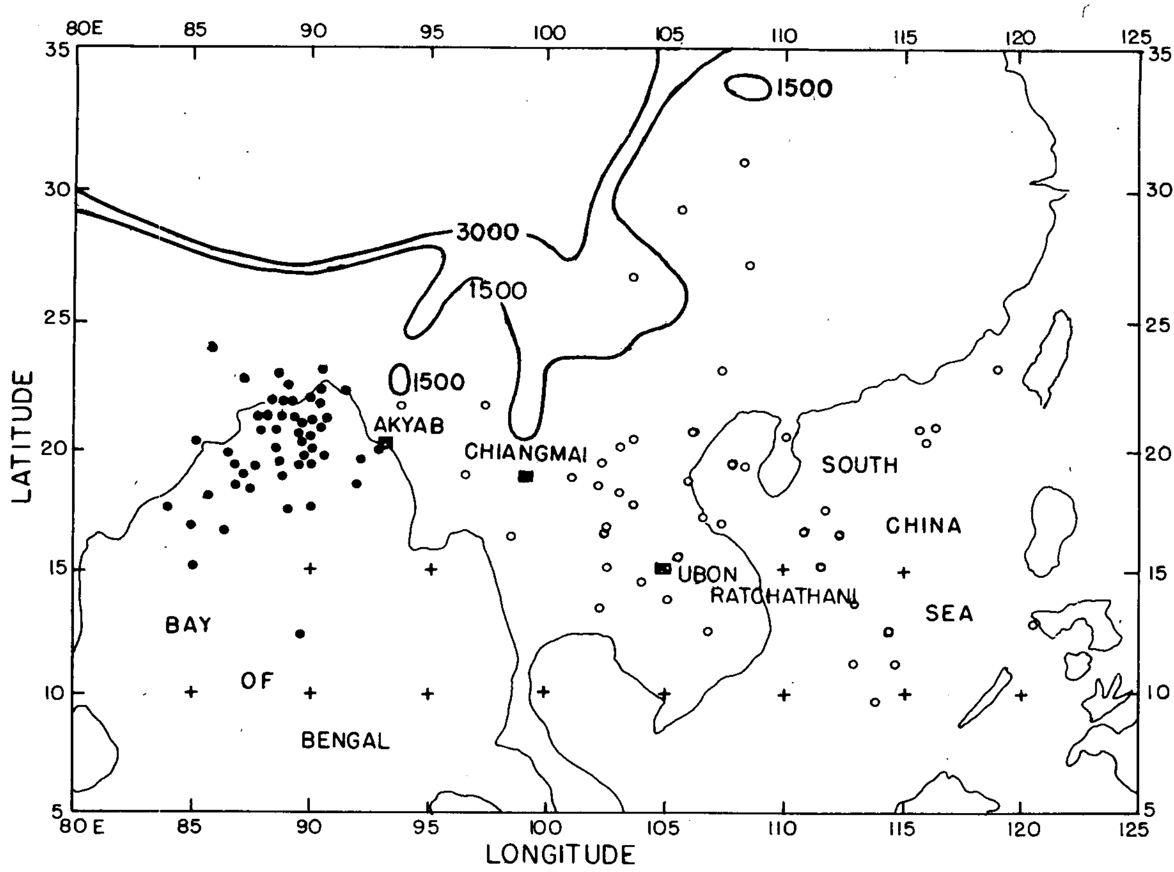

FIG. 1. Locations of first appearance of a low or depression in the Bay of Bengal (filled circles) and locations of the associated 24 h isallobaric minimum on the first day it was detectable (open circles). Squares indicate the location of stations used in Fig. 6. Heavy lines represent land elevation (m), averaged over 1° quadrilaterals.

sion during the period June–August in 1967–73 was associated with a typhoon in the South China Sea. It is possible that reliance was placed on satellite cloud imagery, which only rarely (as in the case of Anita) shows structure associated with the moving disturbance. In Fig. 4 we present the tracks of five tropical storms which, according to our analysis, had direct association with lows and depressions in the Bay during the period 1969–78. Four of these, as well as three of our additional cases of indirect association, fell within Sadler's and Kilonsky's period.

An example of the most frequent type of situation, not involving a tropical storm, appears in Fig. 5. On 23 August 1972 pressures since the preceding day had risen over most of Southeast Asia, but a center of weak falls lay over northern Thailand, A trough of low pressure extended from the Vietnam coast northwestward to a weak center on the Chinese border. This weak center appeared to have moved westward from the South China Sea. Heavy precipitation had fallen during the preceding 24 h over northern Vietnam. During the following four days the center of pressure fall and a following center of pressure rise, moved slowly and erratically northwestward, as did the precipitation area. The latter became especially intense on 26 August along the Burmese shoreline, when strengthening southwesterly flow in the northeastern Bay of Bengal impinged upon the mountainous coast. The cyclonic circulation center of the depression, which first took shape on the 26th, was over water only briefly as it had moved inland in the vicinity of Calcutta only a day later.

The properties of the isallobaric wave were estimated from the series of maps. The phase speed was taken, for each case, as the mean speed of the minimum during the interval when continuity could be maintained. The wavelength was taken to be twice the distance from the isallobaric minimum to the associated maximum to the east, averaged over the same interval. This association was ambiguous on some occasions, when continuity and a value not excessively removed from characteristic values in clearcut cases guided our judgement. The amplitude was taken to be one-half of the isallobaric difference, maximum minus minimum, again averaged over the interval of continuity. The period was obtained by dividing the wavelength by the

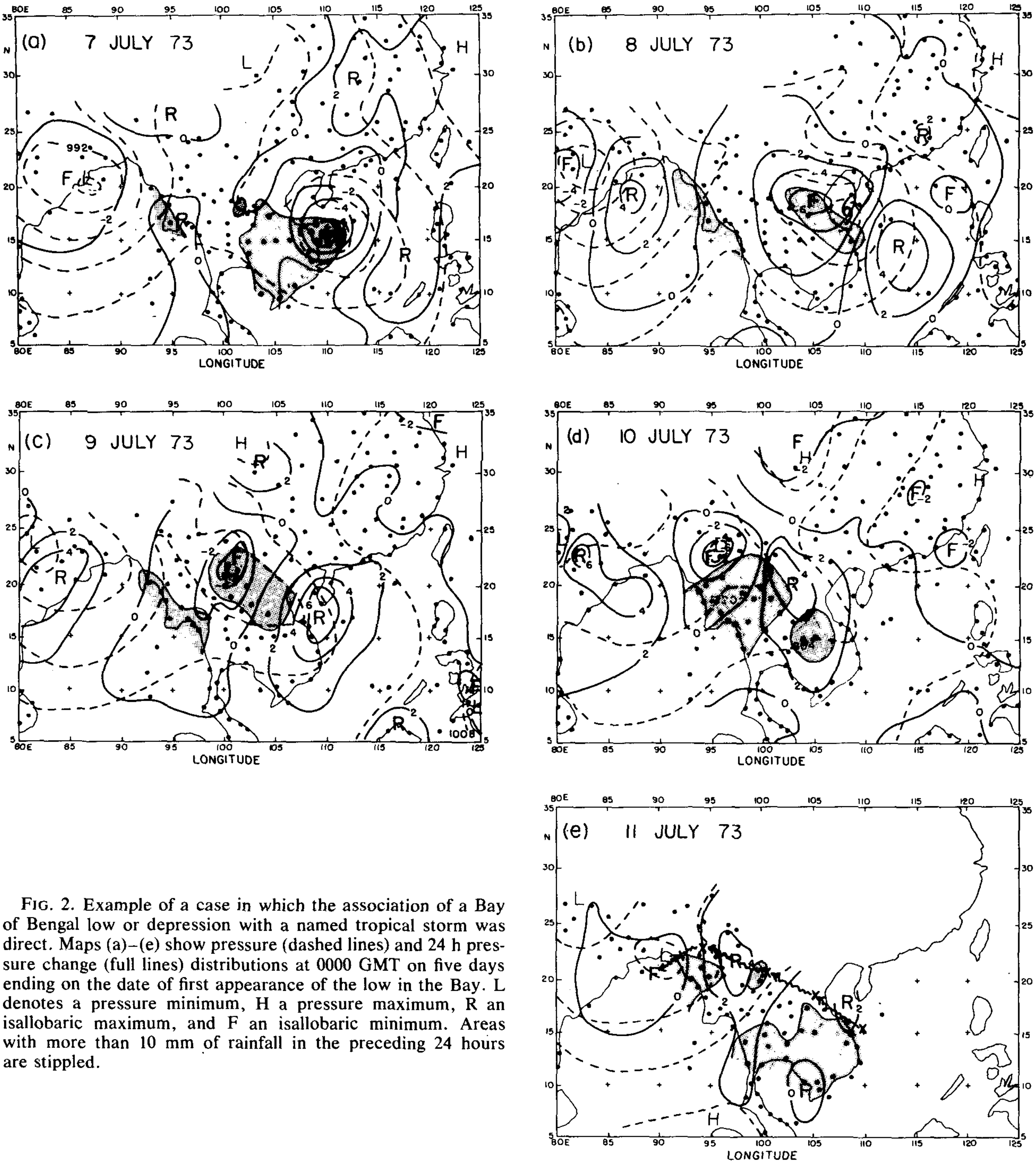

FIG. 2. Example of a case in which the association of a Bay of Bengal low or depression with a named tropical storm was direct. Maps (a)–(e) show pressure (dashed lines) and 24 h pressure change (full lines) distributions at 0000 GMT on five days ending on the date of first appearance of the low in the Bay. L denotes a pressure minimum, H a pressure maximum, R an isallobaric maximum, and F an isallobaric minimum. Areas with more than 10 mm of rainfall in the preceding 24 hours are stippled.

phase speed. Results are listed in Table 1, indicating an overall mean isallobaric amplitude of 2.6 mb $(\mathrm{day})^{-1}$, wavelength 2460 km and period 4.4 days.

4. Time sections

To identify the existence of a westward-moving disturbance in the time sections, examples of which are shown in Figs. 6 and 7, we required that a perturbation isallobaric minimum, of negative sign, occur first at Udon Thani, Ubon Ratchathani or Khon Kaen, next at Chiangmai, and last at Akyab or Sandoway. We also required that the meridional component of the upper wind at Chiangmai or Szemoa change from northerly to southerly at two or more consecutive standard pressure levels at the

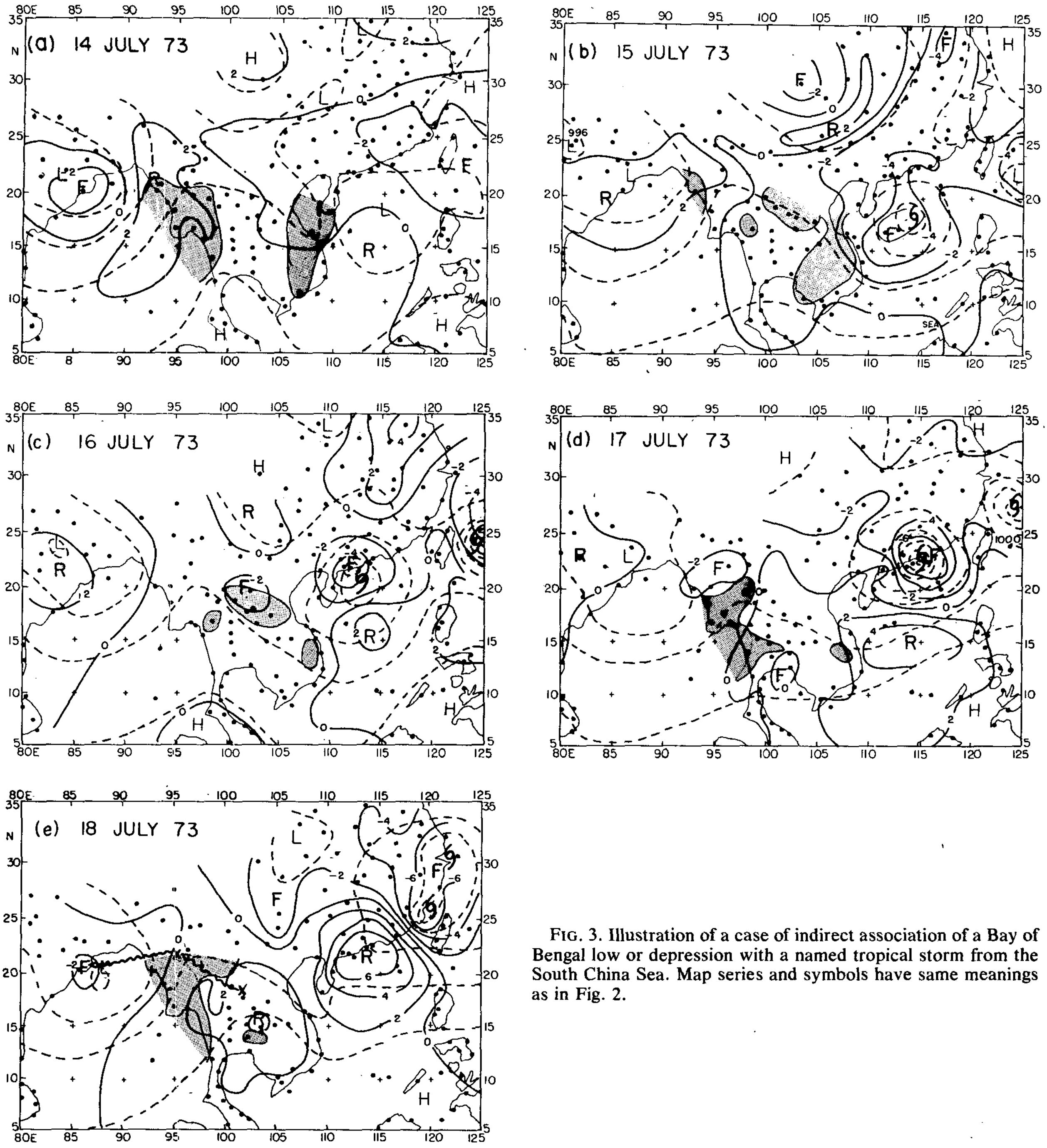

FIG. 3. Illustration of a case of indirect association of a Bay of Bengal low or depression with a named tropical storm from the South China Sea. Map series and symbols have same meanings as in Fig. 2.

appropriate time, indicating the westward passage of a trough. The vertical depth through which the wind change occurred, varied considerably with the nature of the disturbance. In most cases of typhoons and tropical storms, it extended from near ground to at least 300 mb, whereas weaker disturbances produced changes at fewer levels, more often between 700 and 400 mb than at other levels.

On the basis of these criteria, we found that 50 disturbances moved across Southeast Asia to the Bay of Bengal in the 20-month period of study. Of these, 32 (64%) produced lows or depressions in the Bay. The failure of the rest to do so appeared to be attributable mainly to their arrival in the Bay with minimal intensity, or to the prior existence of a system in the Bay at the time of arrival of the

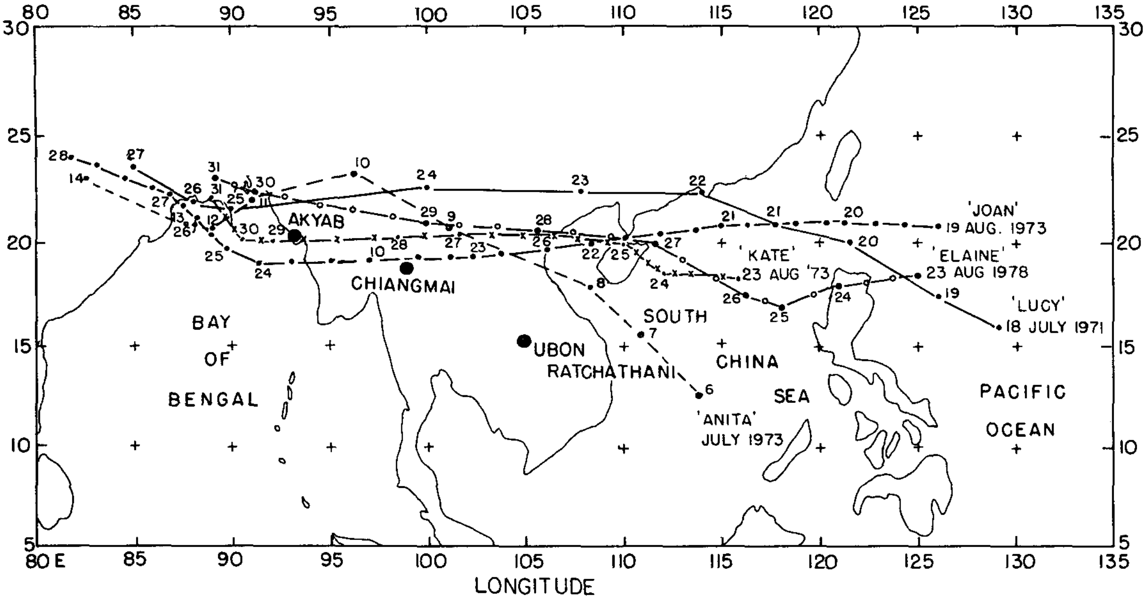

FIG. 4. Tracks of five tropical storms which had direct associations with lows and depressions in the Bay of Bengal.

travelling disturbance, or both. Of the 50 disturbances, 16 were associated, directly or indirectly with a named tropical storm or typhoon, 14 could be traced (in the Thai maps) to the South China Sea or the southwestern Pacific Ocean and 20 apparently originated over land. Some of the last 20 may have had a maritime origin, as tracking was difficult without the detailed isallobaric analyses described in the preceding section.

Estimates of the wave properties were obtained from the time sections in 1971–73, 1977 and 1978, for comparison with values obtained from the isallobaric maps, and from the statistical analysis to be described later. These years were selected, as mentioned above, because of the relative completeness of data. For the 26 disturbances identified on the time sections for the five years, the mean perturbation isallobaric amplitude, taken as half the difference between the minimum and the following maximum, was 1.4 mb day^{-1}. The corresponding value from the maps for the same five years was 3.0 mb day^{-1}. The smaller value from the time sections reflects in part the removal of part of the synoptic-scale tendency by the process of averaging over the three stations, but is due mainly (as suggested by the points of origin in Fig. 1) to the failure of the isallobaric centers on the maps to track exactly along the section line. At times the deviation was so large, in fact, that the isallobaric system could not be identified on the section line despite its clear presence in the mapped isallobaric analysis. The period (twice the time from perturbation isallobaric minimum to maximum at a given station) was 4.7 days, the phase speed (from the mean time difference between passage of an isallobaric minimum at the eastern and western stations, together with the distance between them) was 5.2 m s^{-1}, and the implied wavelength was 2100 km. These values are relatively close to the corresponding mean values from the isallobaric maps for these five years, which in turn differ only slightly from the values presented in Table 1 as well as from the statistical analysis to be described later (see Table 2).

The mean amplitude of the meridional component of the upper level wind fluctuation at Chiangmai or Szemoa during the entire period of study was estimated at 700 mb. This level was taken as the lowest we felt was representative of the free atmosphere, as the rugged terrain probably exerts a significant influence on the 850 mb winds as well as on the surface flow. This mean amplitude was 4.9 m s^{-1}. These disturbances should be largely under geostrophic control, as the Rossby number ($2\pi c/fL$) is ~0.3. In this expression, c is the phase speed of the waves, L the wavelength, and f the Coriolis parameter. Under geostrophic balance,

$$\hat{v}_g = \frac{2\pi \hat{p}}{L\rho f},$$

where $\hat{v}_g$ and $\hat{p}$ are respectively the amplitudes of the sea level geostrophic wind and pressure waves (both as experienced along the section line), and ρ is the air density.

To estimate $\hat{p}$ at Chiangmai we first estimated the deviation isallobaric amplitude and period from the

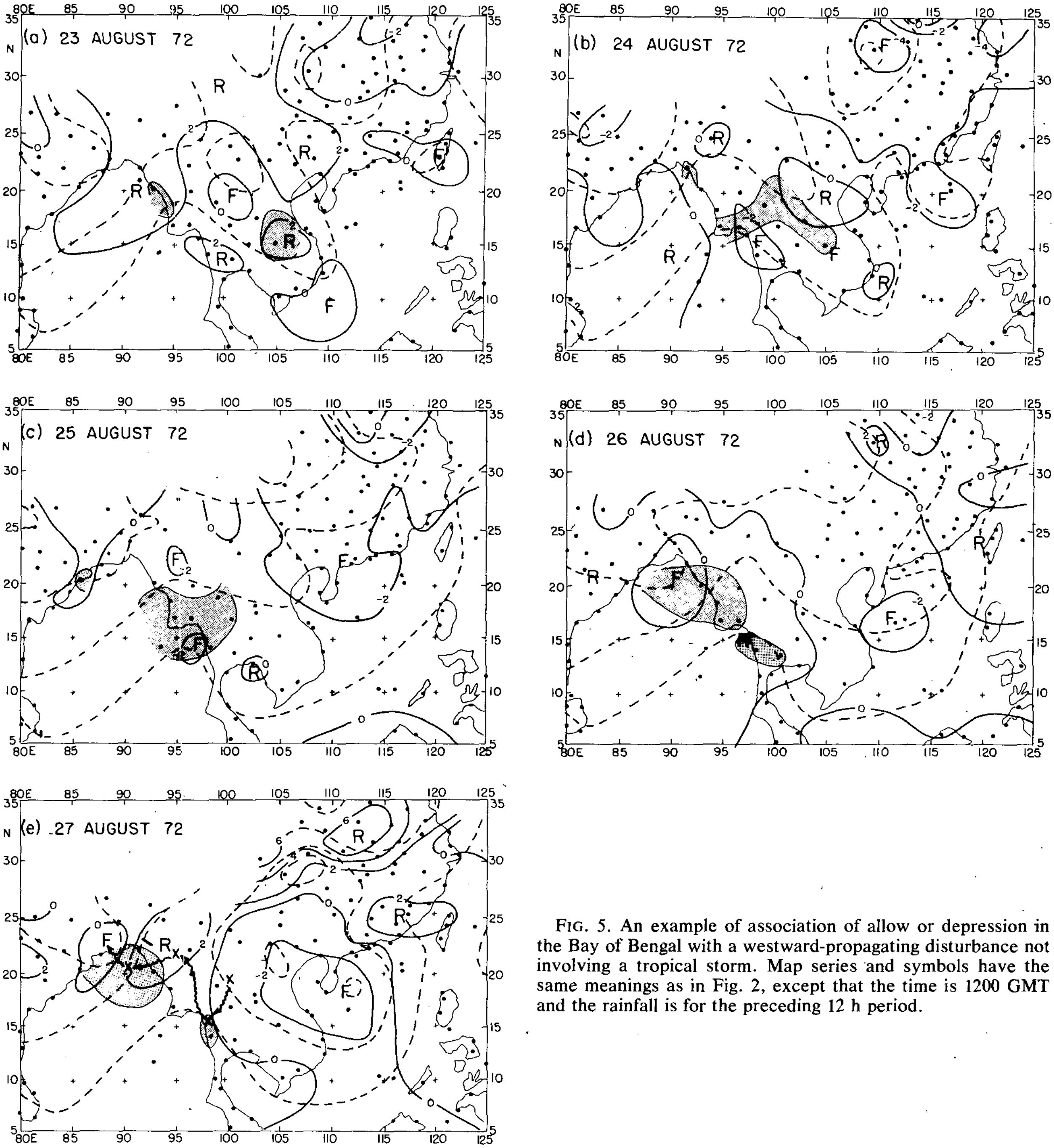

FIG. 5. An example of association of allow or depression in the Bay of Bengal with a westward-propagating disturbance not involving a tropical storm. Map series and symbols have the same meanings as in Fig. 2, except that the time is 1200 GMT and the rainfall is for the preceding 12 h period.

time sections. Values are 1.1 mb day^{-1} and 5 days. Correcting for time truncation error in estimating the instantaneous isoallobaric amplitude and for removal of some of the amplitude by averaging, we estimate that $\hat{p}$ was $\sim$1.45 mb and $\hat{v}_g$ $\sim$7 m s^{-1}. This geostrophic value for sea level is close to the amplitude of the observed wind at 700 mb. If the latter flow is in geostrophic balance, there is feeble evidence for a warm core in the layer, but the excess virtual temperature in the layer would be only a fraction of 1°C.

5. Statistical analysis

The results presented so far rely in part on the subjective judgement of the analysts. In order to find whether these results were supported by objective treatment of the data, we calculated lag cross correlations of perturbation pressure change among the three stations shown in Fig. 1 for the five years of most complete data coverage, as mentioned earlier.

For a given pair of stations (i,j) and for time lag τ, the correlation is given by

$$R_{ij}(\tau) = \frac{\overline{P_i'(t)P_j'(t+\tau)}}{\sigma_i\sigma_j} ,$$

where P' is the departure of the perturbation 24 h pressure change from its time mean and σ its standard deviation. In our calculations, j is the station farther west and positive τ means that the value at this station is taken later. Generally, the lag was a multiple of 24 h, with a given year yielding 62 pairs. In 1973, 124 pairs were obtained for Ubon Ratchathani and Chiangmai, as data were used for both 0000 and 1200 GMT. In 1972 lags referring to Akyab could be obtained only for odd multiples of 12 h because of differences in the time of available data. Correlations for all multiples of 12 h lag were calculated only for 1973, when the data were unusually complete. The range of lags was from −5 days to +5 days, with results illustrated in Fig. 8. The curve representing the average result was based on only integer values of τ because of the data limitations discussed above.

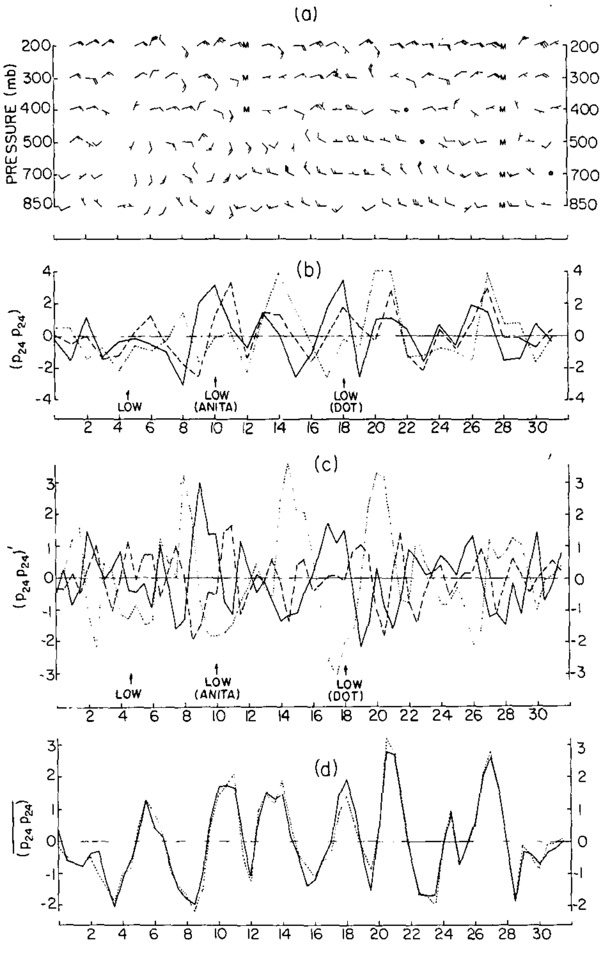

FIG. 6. Time sections for July 1973. (a) Daily upper winds at Chiangmai at 0000 GMT; M denotes missing data. (b) Observed 24 h change of sea-level pressure, $(p_{24}p_{24})$, at Ubon Ratchathani, (full line), Chiangmai (dashed line) and Akyab (dotted line) at 0000 GMT. Units: mb (day)$^{-1}$. (c) Perturbation 24 h sea level pressure change $(p_{24}p_{24})'$, at Ubon Ratchathani (full line), Chiangmai (dashed line) and Akyab (dotted line) at 0000 and 1200 GMT. (d) Area-average 24-h change of sea-level pressure $(\overline{p_{24}p_{24}})$: full line based on seven stations (Akyab, Sandoway, Chiangmai, Chiangrai, Phitsanulok, Udon Thani and Ubon Ratchathani) and dotted line based on three stations (Akyab, Chiangmai and Ubon Ratchathani).

The date of first appearance of a Bay system (low or depression) is indicated on the abscissa. Association with a named tropical storm, if any, is also indicated.

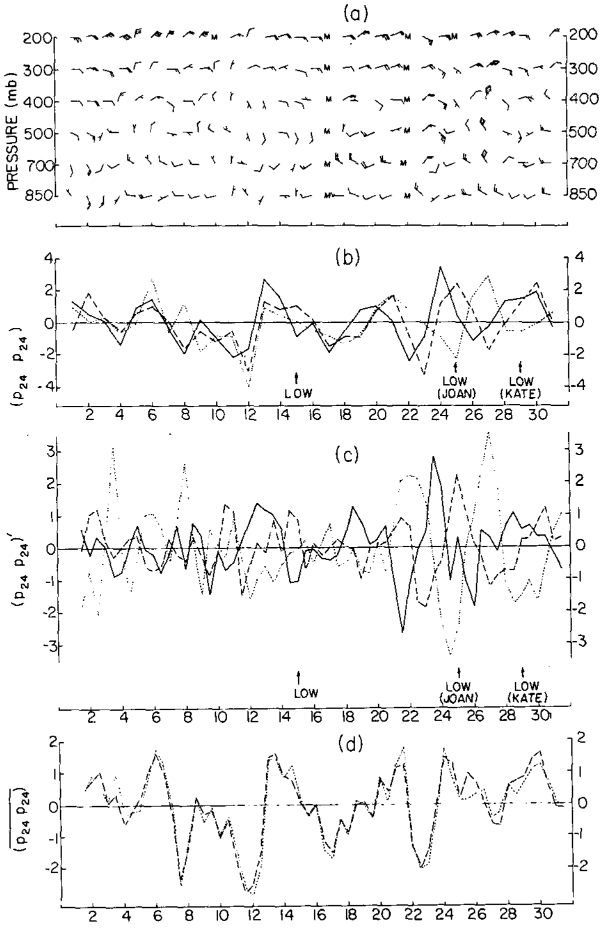

FIG. 7. Time sections for August 1973. Legend as in Fig. 6.

In Fig. 8a the maximum positive correlation across the total span from Ubon Ratchathani to Akyab falls at $\tau = +3.0$ days. Since the distance between these stations is ~1400 km, a phase speed of 5.4 m s^{-1} is indicated. Any ambiguity concerning

TABLE 2. Wave properties of the westward-moving disturbances of Southeast Asia July–August, 1971–1973, 1977, 1978.

	Source			
Property	Isallobaric maps (25 cases)	Time sections (26 cases)	Lag cross-correlation time section (10 months)	Power spectrum time section (10 months)
Isallobaric amplitude (mb day^{-1})	3.0	1.4	—	—
Period (days)	4.3	4.7	5.1	5.6
Phase speed (m s^{-1})	6.7	5.2	5.4	—
Wavelength (km)	2500	2100	2300	—

the direction of propagation of the dominant waves is removed by noting that the maximum positive correlations from the eastern to central stations and from the central to western stations fall at lags of approximately +1.3 and +1.4 days, respectively. Note that for each pair of stations the lag difference between the two maximum correlations, representing the dominant wave period, is nearly 5 days. Thus a wavelength of ~2300 km is implied.

We further computed power spectra for the once-daily time series of perturbation pressure change for the five years at Ubon Ratchathani, Chiangmai and Akyab employing the fast Fourier transform technique (Cooley and Tukey, 1965).

Results appearing in Fig. 9 show prominent maxima between 5 and 6 days at the easternmost

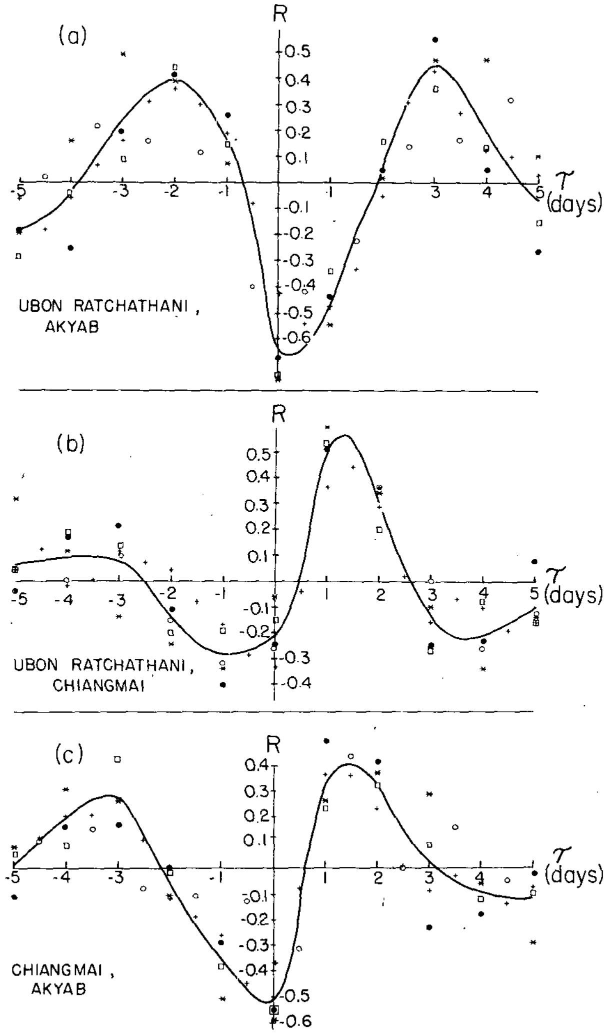

FIG. 8. Lag cross correlations of 24 h perturbation pressure change (a) between Ubon Ratchathani and Akyab, (b) between Ubon Ratchathani and Chiangmai, and (c) between Chiangmai and Akyab. Values for July–August during individual years are indicated as follows: (dot) 1971; (circle) 1972; (cross) 1973; (asterisk) 1977; (square) 1978. The line represents the 5-year average.

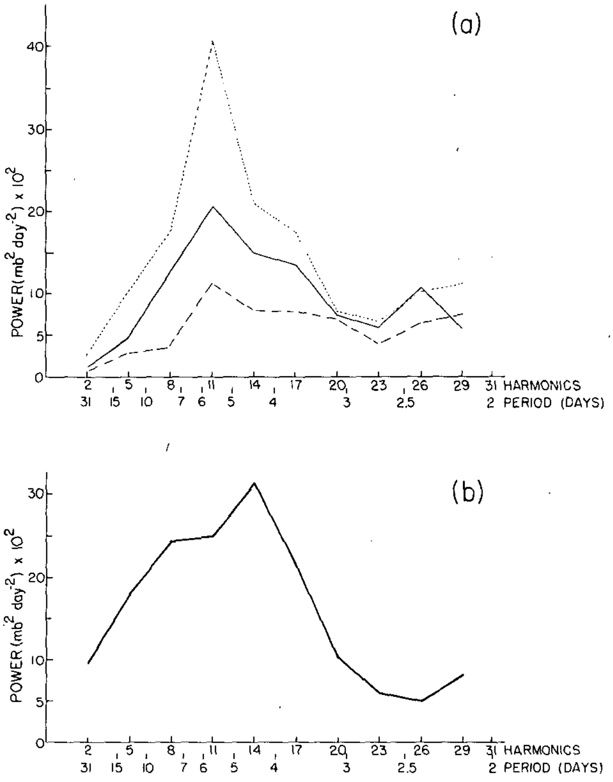

FIG. 9. Mean power spectrum of 24 h perturbation pressure change for July–August for five years 1971–73, 1977 and 1978. Each point represents the sum of power for three successive harmonics and is plotted at the central value: (a) for individual stations, the solid line representing Ubon Ratchathani, the dashed line Chiangmai, and the dotted line Akyab; (b) for the three-station average value.

and westernmost stations, with a corresponding weaker maximum at Chiangmai. Since there is a large negative cross correlation between Ubon Ratchathani and Akyab at zero lag (see Fig. 8), the three-station mean does not remove as much of the synoptic-scale variability at these stations as at Chiangmai. Hence the weakness there. Aside from this computational effect, the large value of power at Akyab in this range of periodicity indicates the beginning of intensification which occurs when the disturbance reaches the Bay of Bengal.

The power spectrum for the three-station average pressure change, also appearing in Fig. 9, confirms the presence of a large-scale pressure variation, with maximum power in a broad spectral band centered near 5 days.[2]

In all, the statistical analyses support the existence of westward-moving perturbations in Southeast Asia, as determined from the maps and time sections. All approaches yield consistent values of the wave parameters.

6. Waves in other tropical longitudes

Many investigators have identified synoptic-scale, westward-moving, lower tropospheric waves in various Northern Hemisphere tropical longitudes. A compilation is given in Table 3. Ours is only a recent contribution to this list. It appears that the 5-day, 2500 km wave (broadly speaking) is nearly ubiquitous. We are prompted to ask whether anyone has consciously sought such waves in the northern tropics and failed to find them. The only example that comes readily to mind is Burpee's (1972) study, which found no significant amount of such activity in upper wind time series at Aden and Khartoum, in eastern African longitudes. Perhaps the high, rugged terrain there disrupts them. Since one finds these waves at places far removed from the special topographical situation which, according to Burpee, favors wave development south of the Sahara, either there must be alternative modes of generation, or there must be modes of maintenance for periods long after the waves have forgotten their origin. It is not the purpose of this paper to pursue these speculations.

So far as the large-scale wave is concerned, we offer only confirmation of what has been found by others (see Table 3) concerning global-scale tropical tropospheric waves. Our data, of course, are much too restricted in areal coverage to permit any independent estimate of the large-scale oscillation.

7. Regeneration and prediction of Bay disturbances

The basic mechanism for formation and development of monsoon disturbances in the Bay of Bengal is still inadequately understood. Our findings leave unanswered the question of surface redevelopment. Shukla (1977, 1978) examined the joint CISK-barotropic-baroclinic instability of the mean zonal flow along 90°E and suggested that the barotropic instability of the mean zonal flow in the lower troposphere may be the primary mechanism for the generation of perturbation kinetic energy which is further amplified by the latent heat of condensation. This mechanism can either generate an incipient disturbance over the Bay of Bengal or, as is evidently more often the case, amplify a pre-existing weak disturbance which propagates from farther east. For the disturbances forming *in situ*, barotropic instability may be a necessary requirement for the disturbance to form. However, for the westward-moving disturbances the primary mechanism of amplification will be the latent heat of condensation, although barotropic instability may have been required earlier and farther east. Conditions for the cooperative interaction of the wave dynamics and moist convection are not well known, either for monsoon disturbances or for any tropical wave and are not addressed in the present paper.

The present findings, however, have obvious forecasting implications on a purely empirical basis. We have found that 32 of the 50 disturbances identified on a single time section were associated with development of a low or depression in the Bay of Bengal on crossing the Burmese coast. On the other hand, of 52 observed cases of such development, 45 were prefigured by at least one day of isallobaric continuity from the east. Taking the existence of a disturbance on the section as a forecast of Bay development, the widely used "threat score" given by

$$T = \frac{C}{F + O - C},$$

where C is the number of correct forecasts of the phenomenon, F the total number of forecasts of the phenomenon, and O the total number of observations of the phenomenon, would have been 0.46. While this score is difficult to interpret, it is generally considered that it represents considerable forecast skill.

Alternatively, in terms of probability statements for each of the 620 days of the 10-year period, a forecast probability of development, given a disturbance, is 0.64 (32 of 50), while the forecast probability otherwise is 0.04 (20 of 570). If the relative frequencies of the event remained stable, so that the forecasts were reliable, the P-score (Brier, 1950) would be 0.0483 for the forecasts based on the time section and 0.0769 for an invariant control forecast

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[2] It should be mentioned that the spectra of the time derivative of a time series will inevitably produce a peak at some intermediate frequency. However, such a peak need not necessarily occur at a period of 5–6 days as is the case here. Thus, while the results of the spectral analysis by themselves would not be sufficient to establish a 5-day period, their consistency with other independently derived results makes them noteworthy.

TABLE 3. List of other investigations on characteristics of waves in the lower and middle tropical troposphere.

(a) Synoptic scale (lower troposphere)

				Wave characteristics				
				Amplitude				
Region	Investigators	Method of analysis	Data	Pressure (mb)	Meridional component of wind (m s^{-1})	Period (days)	Phase speed (m s^{-1})	Wavelength (km)
Caribbean	Riehl (1945, 1948, 1954)	Synoptic	Sea level pressure (SLP) and upper air data, 1944	—	—	3–4	6.5	1500–2000
Western and central Pacific	Palmer (1952)	Synoptic	Winds at surface and aloft, 1946	—	—	3–4	5.5	1650
	Rosenthal (1960)	Spectral	Winds, 1956	—	—	4	—	—
	Yanai *et al.* (1968)	Spectral	Winds, 1968	—	—	4–5	16	6000
	Wallace and Chang (1969)	Spectral	Upper air data, 1963 (including other parts of tropics)	—	—	4–5	8	3000
	Chang *et al.* (1970)	Spectral	Winds, 1964	—	3 (central)	4–5 (central)	—	—
					8 (western)	6–7 (western)	—	—
	Nitta (1970)	Spectral	Upper air data, 1962			4–5	14	5–6000 (western) 8–10 000 (central)
	Reed and Recker (1971)	Compositing technique	Upper air data, 1967		3–4 at 800 mb	5	9	3500–4000
Western Africa	Carlson (1969)	Synoptic	Surface and upper air data, 1968	1.4		3.2	7	2000
	Burpee (1972)	Spectral	Upper air data, 1960–64		1–2	3–5	12	4000
India	Keshavamurty (1973)	Spectral	Wind at 850 mb, 1967	—	—	5.6	—	2200
	Bhalme and Parasnis (1975)	Spectral	SLP gradient, 1961–70	—	—	5–6	—	—
	Krishnamurti and Bhalme (1976)	Spectral	Nine selected parameters of monsoon system 1957, 1967	—	—	4.5	—	—
	Murakami (1976)	Spectral	Upper air data, 1962	—	—	4–5	7	3000

(b) Global scale

				Wave characteristics				
				Amplitude				
Region	Investigators	Method of analysis	Data used	Pressure (mb)	500 mb height (m)	Period (days)	Phase speed (m s^{-1})	Wavenumber
Global	Eliasen and Machenhauer (1965, 1969)	Spherical harmonics	1000 and 500 mb heights, 1956, 1957	—	—	5	—	1
	Wallace and Chang (1969)	Spectral	Surface pressure, 1963	1.0 (at equator)	—	4	100	1
	Madden and Julian (1972)	Spectral	Sea level pressure and 500 mb height	0.5	5	5	—	1
	Misra, B. M. (1972)	Spectral	Surface pressure, 1957–58	—	—	4–5	—	1

based on the climatological frequency, 0.08 (52 of 620). The forecast would show a 37% improvement over the control score, displaying considerable skill.

The use of a single time section is a limitation, of course. If data and resources permit, in the operational context, more could be prepared and perhaps greater skill could be achieved. The long isallobaric continuity in many instances suggests some skill in forecasts with a lead time longer than the single day implied by our suggested application, but the uncertainty as to the track of the predecessor disturbance over many days will limit skill in the Bay unless an accurate synoptic-scale prediction is available for many days. In this event, the problem of prediction of the Bay disturbance may be directly tractable, without resort to our empiricism.

8. Conclusion

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

1) During July and August of the 10-year period 1969–78, a total of 52 lows and depressions formed in the Bay of Bengal. All but 7 of these appeared to display continuity in the field of 24 h change of sea level pressure, with westward moving dis-

turbances for periods ranging up to 4 days in advance of their development in the Bay. This finding suggests that most of the Bay disturbances form around nuclei of disturbances which propagate from the east.

2) Time sections of pressure change from eastern Thailand to the Burmese coast, and of upper winds in northwestern Thailand, revealed westward propagation of 50 disturbances during the same period. Of these, 32 were associated with a subsequent development in the Bay. Sixteen of these disturbances were associated directly or indirectly with typhoons or named tropical storms, 14 with disturbances from the South China Sea, and 20 with disturbances that appeared to originate over the land mass of Southeast Asia.

3) Results of lag cross-correlation and power spectrum analysis provide objective statistical support to our subjective conclusions regarding westward propagation of synoptic-scale disturbances across southeast Asia.

4) Synoptic-scale wave properties as determined from the various analyses for 5 of the 10 years, are summarized in Table 2. The large discrepancy between the isallobaric amplitude obtained from the maps and from the data in the time sections was due to frequent avoidance of the section line by the isallobaric centers. These waves in the lower and middle troposphere appear to resemble closely those found in other tropical longitudes of the Northern Hemisphere. A larger scale wave of comparable amplitude and period also was evident in the data.

5) It appears that the results of the present study can be adopted empirically in forecasting practice for predicting the formation of monsoon lows and depressions in the Bay of Bengal. It should be possible to achieve a moderate degree of skill one day in advance. At least, some skill is probable at longer ranges.

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