Winter Monsoon Convection in the Vicinity of North Borneo. Part II: Effects on Large-Scale Fields

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ABSTRACT

An observational study of the thermodynamic and kinematic structure and properties of monsoon convective systems and their large-scale environment over the southern South China Sea during the field phase (December 1978) of the Winter Monsoon Experiment (WMONEX) has been carried out. The primary observations used are from three Soviet research vessels positioned in a triangular array off the north coast of Borneo during the period 6–28 December. Computations of thermodynamic fields, divergence and vertical motion have been made for the duration of the field phase based on six-hourly rawinsonde releases at the ship sites.

Analysis of the data indicates that the degree of convective activity over the southern South China Sea is modulated by long-period synoptic forcing (monsoon surges, easterly waves) and also significantly by diurnal forcing (land-sea breeze circulations). A diurnal cycle of convection persists in the region whether the synoptic-scale forcing is weak or strong. Convection over water to the north of Borneo regularly evolves on a diurnal basis from a small group of cumulonimbus clouds into a uniform mesoscale precipitation area having the characteristic structure of those observed in recent years over the tropical eastern Pacific and Atlantic oceans. In their mature stage the precipitation systems contain mesoscale anvil clouds commonly extending from near 500 mb to the tropopause covering a 10^4–10^5 km^2 area. The ship observations provide direct evidence of mesoscale updraft motion within the anvil clouds and mesoscale downdraft below extending to near the surface.

1. Introduction

The recently completed International Winter Monsoon Experiment (WMONEX, 1 December 1978–5 March 1979) had as a major scientific objective an improved understanding of the interaction between atmospheric circulations and processes in the tropics, midlatitudes and between hemispheres (Greenfield and Krishnamurti, 1979). Certain of these interactions in the winter monsoon region of Southeast Asia and Indonesia have been investigated previously; however, many details of the interactions are not well known. Strong evidence has been presented showing a positive correlation between heavy rainfall in the region of the Indonesian "maritime continent" and Malaysia and the intensity of the northeast monsoon over the South China Sea (Ramage, 1968, 1971). Periods of intensification of the winter monsoon, referred to as cold surges, have been found to be closely related to features of the general circulation, particularly the amplitude and movement of midlatitude synoptic-scale disturbances over China and the strength of the midlatitude jet stream near Japan based on forecasting studies (Chin, 1969[1]; Chu, 1978[2]) and diagnostic studies (Murakami, 1977; Murakami and Unninayer, 1977; Chang and Lau, 1980). These investigations show an enhancement of the East Asia Hadley circulation accompanying the onset of cold surges.

Fluctuations in the intensity of the Hadley circulation have periods on the order of a week or more, considerably longer than the life cycle of individual tropical convective systems in the Malaysia–Indonesia region. In fact, it is well known (Ramage, 1971; Riehl, 1979) that in this area of the tropics, radiatively driven local circulations associated with land-sea contrasts and mountain ranges exert a pronounced *diurnal* control on deep convection. Satellite data show convincingly that convection predominately occurs over islands in the afternoon and evening and over adjacent water areas in the late

[1] Chin, P. C., 1969: Cold surges over south China. Hong Kong Royal Observatory, Tech. Note No. 28, 23 pp.

[2] Chu, E. W. K., 1978: A method for forecasting the arrival of cold surges in Hong Kong. Hong Kong Royal Observatory, Tech. Note No. 43, 32 pp.

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night and early morning hours (Short and Wallace, 1980). The mechanisms by which monsoon surges interact with the diurnal convective cycle are not well understood.

Determination of the nature of the tropical convective response to winter monsoonal forcing is a major objective of WMONEX. This paper and a companion paper (Houze *et al.*, 1981) address two aspects of this basic problem: 1) whether the increase in tropical convective activity in response to winter monsoon cold surges takes the form of an enhancement of deep convection in the diurnal land-sea cycle or occurs in some other way, and 2) the life cycle, thermodynamic structure and nature of the airflow of oceanic convective systems of the maritime continent region. Achievement of these objectives, in addition to their value for local weather forecasting in the region, is important for an accurate determination of the total energy budget for the near-equatorial winter monsoon region. In particular, it is clear from the work of Riehl and Malkus (1958) and Riehl and Simpson (1979) that the evaluation of the vertical energy transfer in the equatorial trough zone depends importantly on the assumed draft structures and degree of saturation of downdrafts in tropical convective systems.

Because WMONEX was limited in scope, only partial answers to the above questions can be obtained from the experimental data. Most of the WMONEX special atmospheric sounding data, on which this study is primarily based, were taken from a network of ships covering an $\sim 10^4-10^5$ km^2 area stationed in the southern portion of the South China Sea off the north coast of Borneo.[3] Fortunately, a representative sample of convection occurred in this region and its structure and effects on the large-scale environment were sampled reasonably well by these soundings and other data. This paper reports on the effects of the convection on the thermodynamic and kinematic structure of the large-scale environment sampled by the soundings. In the companion paper, Houze *et al.* (1981) use WMONEX radar data in describing the structure and temporal variation of the clouds and precipitation. Implications of the results of these studies on our understanding of the winter monsoon system as a whole will be discussed.

2. Observational network and data

The WMONEX observational network consisted of many component platforms to examine monsoon circulation phenomena on a wide range of space and time scales. The primary observations used in this study are rawinsonde measurements from a triangular array of Soviet research vessels in the South China Sea (Fig. 1): *Ak. Korolov* at 4°N, 111°E from 6–18 December and at 2.9°N, 111°E from 18–28 December; *Ak. Shirshov* at 7°N, 113°E from 6–28 December; and *Priliv* at 7°N, 109°E from 6–28 December (source: Winter MONEX Quick-Look Data Set, World Data Center A, Asheville, North Carolina). Atmospheric soundings were obtained at 6 h intervals (0000, 0600, 1200, 1800 GMT, corresponding to 0800, 1400, 2000, 0200 LST) at the ship sites during the time periods indicated. On several days, 3 h soundings were taken. The ships also provided hourly surface observations and cumulative rainfall measurements every 6 h. Radiosonde observations from Kuching (96413), Bintulu (96441) and Kota Kinabalu (96471) on the north coast of Borneo have received limited use in this study as well as 6 h pilot balloon measurements at Bintulu.

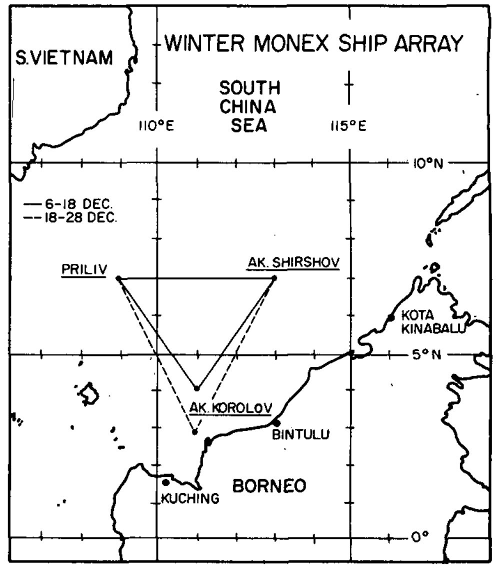


FIG. 1. The Winter Monsoon Experiment ship observation network.

Japanese geostationary meteorological satellite (GMS) data and quantitative radar data from the WMONEX MIT Radar at Bintulu (Houze *et al.*, 1981) have also been incorporated into this study. The radar data do not extend sufficiently far into the area of the ship array to be of direct value in interpreting details in the Soviet sounding data. However, convection tended to form in the radar area and drift into the ship array during its later stages. Consequently, the convective responses detected by the Soviet ship soundings are best interpreted by reference to the results of the radar study. Weather radar data also were recorded by the Soviet vessels, but these data lack sufficient resolution to prove useful in our analysis.

[3] The entire island comprised of the three nations East Malaysia (Sarawak and Sabah), Brunei and Indonesia (Borneo), is referred to in this paper by the single physical geographic name "Borneo".

3. Data analysis procedures

Rawinsonde ascents from the Soviet ships normally extended above 50 mb; however, in several instances soundings were terminated below this level. In addition, there are several missing soundings at each ship during the period 6–28 December (seven at *Ak. Korolov*, seven at *Ak. Shirshov* and one at *Priliv*) and on eight occasions soundings were released 1 or 2 h late. A linear interpolation in time between adjacent soundings was used to estimate missing data. Since diurnal variations are large in this region, the interpolation procedure also includes a correction based on the average deviations for the entire period of variables from adjacent 6 h soundings. Caution has been exercised in the use and interpretation of interpolated sounding data, especially when evaluating kinematically derived divergence fields for the triangle of ships.

The USSR rawinsonde radar-tracking equipment provides a direct determination of balloon height, and pressure is subsequently computed hydrostatically. An independent check of these computations revealed that the reported pressure at sounding release point for *Ak. Korolov* and *Shirshov* was at deck height whereas for the *Priliv* reported values were reduced to sea level. Assuming deck heights of 10 m for *Ak. Korolov* and *Shirshov*, our hydrostatically computed heights for all ships then agree very well (within 10 m) with those reported.

Horizontal divergence was computed at 25 mb intervals using the triangle of ship observations and the divergence theorem:

$$\overline{\nabla \cdot \mathbf{v}} = A^{-1} \oint v_n dl,$$

where A is the area of the triangle, dl a line element on its perimeter, v_n the component of the wind normal to the boundary, and the overbar denotes an area average. Vertical velocities were then computed from the continuity equation in pressure coordinates, assuming $\omega \equiv dp/dt = 0$ at the sea surface and at $p = 87.5$ mb, the average tropopause height. In order to achieve mass balance, a constant correction with height was added to the divergence at all levels (as in Burpee, 1979).

The above triangle method inherently assumes a linear variation of the wind between the triangle vertices, which are ~450 km apart. This assumption is unfortunately not particularly good in this area, where climatological mean circulation charts for the lower troposphere (Sadler and Harris, 1970)[4] show a vortex off the north coast of Borneo during December. A similar vortex circulation was frequently observed during December 1978. Consequently, the quantitative accuracy of the vertical motion field is at times doubtful; however, as will be seen later, there is strong evidence to accept the qualitative features of the computed fields.

Only relative humidity analyses are reported in this study. Further thermodynamic analyses await our efforts to determine the accuracy of corrections that have been applied to the midday (0600 GMT or 1400 LST) sounding for solar-induced temperature error.

4. Observed character of convection over ship array

This section will describe several aspects of the behavior of convection over the South China Sea off the north coast of Borneo as determined by WMONEX observations during December 1978. During this month the mean flow was characterized by: at low levels, 20–30 kt northeasterly flow over virtually all of the South China Sea ending as a broad cyclonic circulation center near the North Borneo coast southwest of Bintulu; at middle levels (near 500 mb), 15–20 kt uniform easterly flow over the North Borneo-ship array region; and at upper levels (near 200 mb), rather uniform 15–20 kt southeasterly flow over the same region.

a. Long-period variations in the degree of convection: Designation of synoptically undisturbed and disturbed periods

The Soviet ships were on station from 6 to 28 December, during which time three moderate surges occurred in the northeast monsoon over the South China Sea (on 11, 15 and 23 December). In Fig. 2, two indexes of surge intensity are shown in the form of sea level pressure differences along 115°E between central China and Hong Kong (30–22°N) and between Hong Kong and *Ak. Shirshov* (22–7°N). The buildup of pressure and its north-south gradient over China precedes that over the South China Sea by about one day on the average, and the latter pressure difference correlates quite well with the average surface wind speed at *Priliv* and *Ak. Shirshov* at 7°N. Point rainfall measurements are not good indicators of overall convective activity; however, the record at *Ak. Korolov*, nearest the Borneo coast, does show a general increase in precipitation during the surge periods. Rainfall at *Priliv* was nil and only small amounts were recorded at *Ak. Shirshov*. Average satellite cloudiness in the region bounded by 0°N, 10°N, 110°E and 115°E (adapted from Cheang and Su-Siew, 1980)[5] increases, in general, at times of

[4] Sadler, J. C., and B. E. Harris, 1970: The mean tropospheric circulation and cloudiness over Southeast Asia and neighboring areas. Sci. Rep. No. 1 (AFCRL). Hawaii Institute of Geophysics, University of Hawaii, Honolulu, 38 pp.

[5] Cheang, B. K., and P. L. Su-Siew, 1980: The Winter Monsoon, 1 December 1978 to 5 March 1979. Winter MONEX Field Phase Report, FGGE Operations Rep. No. 7, WMO, 1–36.

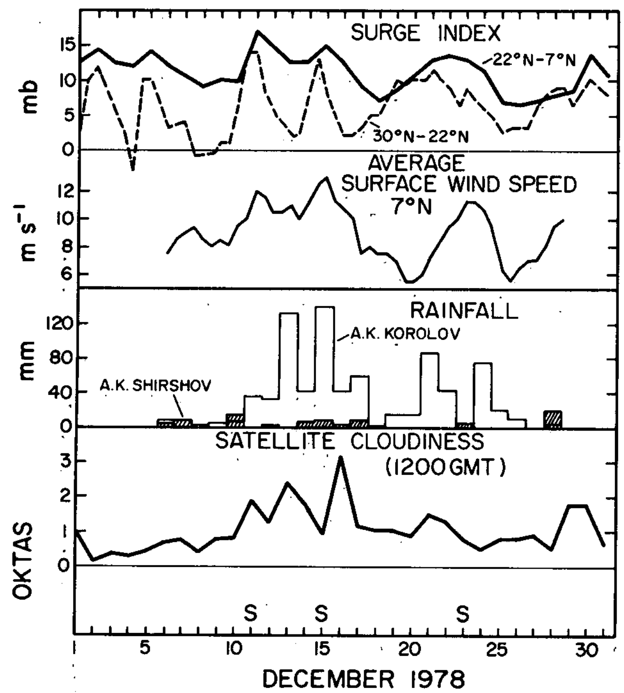


FIG. 2. Time series of surge index, average surface wind speed at two Soviet ships at 7°N, rainfall at two ships and satellite cloudiness at 1200 GMT (2000 LST) over the region bounded by 0°N, 10°N, 110°E and 115°E for December 1978. Tick marks on abscissa at 0000 GMT (0800 LST). S indicates surge.

monsoon surges. Houze *et al.* (1981) prepared similar computations of satellite cloudiness separately over land (northern Borneo) and water (southern South China Sea) and also concluded that cloudiness is enhanced by monsoon surges and other synoptic-scale forcing mechanisms; however, they find the increase occurring primarily over water, with little, if any, modulation by monsoons over land.

In an effort to delineate synoptically disturbed periods from undisturbed periods, we first present time series of relative humidity at *Priliv* and *Ak. Shirshov* (Fig. 3). The most significant feature seen at both ships is a substantial moistening of the mid-troposphere during 11–17 December, roughly overlapping and extending slightly beyond the period of the first two surges. A weaker moistening in the middle troposphere occurs on the 22nd and 23rd, corresponding to the time of the third surge. A similar variation is observed at *Ak. Korolov* (Webster and Stephens, 1980). Values above 300 mb are not considered reliable and are believed to be excessively moist, as also noted in an analysis of USSR sondes used in the 1974 GATE (GARP Atlantic Tropical Experiment) (Reeves *et al.*, 1976).

Time series of divergence and vertical velocity are shown in Figs. 4 and 5. Three extrema in divergence in the upper and lower troposphere on 9–10, 14 and 22 December, apparently associated with the three surges, are seen in Fig. 4. There is also some suggestion of increased mid-tropospheric convergence at the times of the surges. The upper tropospheric divergence and lower tropospheric convergence maxima precede the maxima in the surge index for 22–7°N and surface wind speed for 7°N (Fig. 2) by about one or two days. These divergence extrema coincide best with periods of *acceleration* of the low-level flow at 7°N (Fig. 2), rather than the time of the maximum surface wind speed, suggesting that surges in the monsoon over the South China Sea are characterized by a propagation of a wind maximum equatorward over some finite interval of time rather than a simultaneous intensification of winds over the entire span of sea from China to near the equator. Chang and Lau (1980) obtain a similar result for several December 1974 surges that were studied. It must be recognized when interpreting results in Fig. 4, however, that the computed divergence is for a very limited area and therefore may not be representative of the entire equatorial winter monsoon region. Major upward motion maxima in the mid to upper troposphere (Fig. 5) are seen during 12–17 and 21–24 December. The maxima correlate well with those in Fig. 3 (relative humidity), again strongly

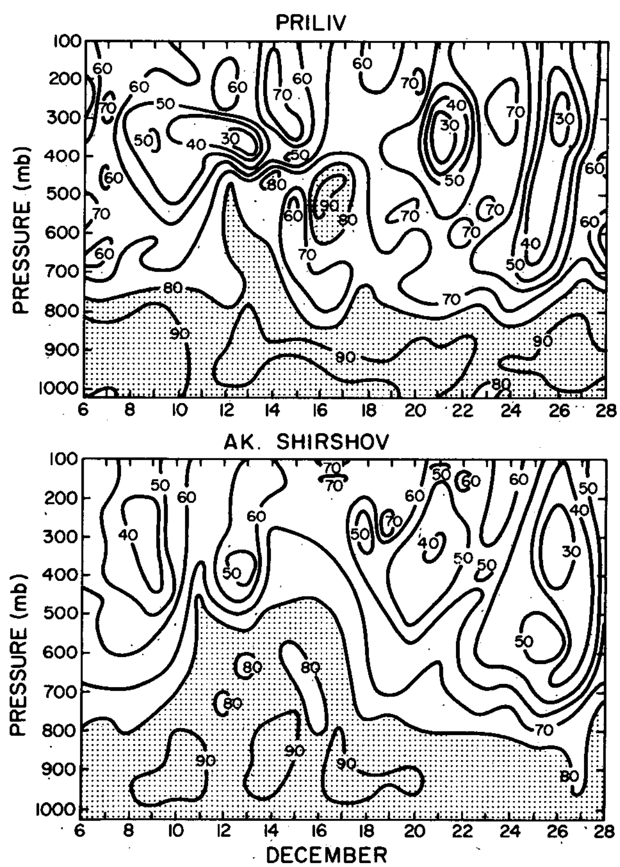


FIG. 3. Time series of daily-averaged relative humidity (%) at *Priliv* and *Ak. Shirshov*.

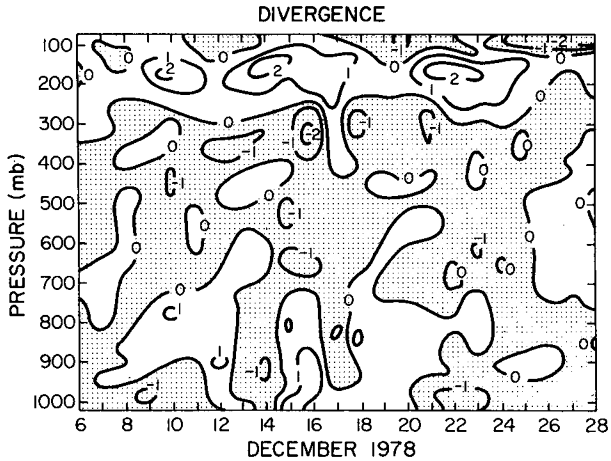


FIG. 4. Daily averaged divergence time series. Units: 10^{-5} s^{-1}. Areas of convergence are shaded.

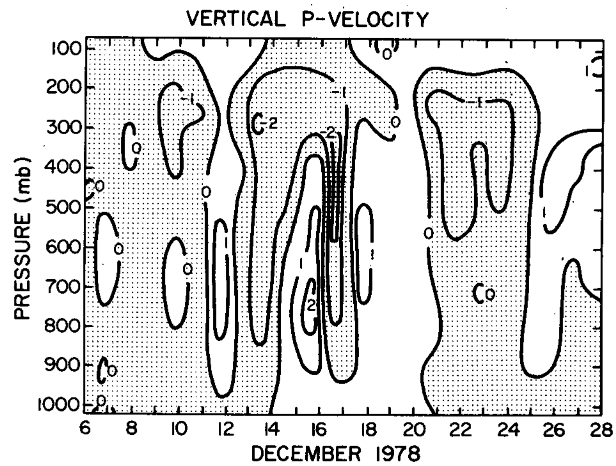


FIG. 5. Daily averaged vertical p-velocity ($\omega \equiv dp/dt$) time series. Units: 100 mb day^{-1}. Upward motion is shaded.

suggesting that deep convection increases to the north of Borneo during surges. Several downward motion maxima near 700 mb also appear during the period 11–18 December. These features will be later interpreted in light of the structure that is deduced for the convective systems that traverse the region.

During December 1978 four lower tropospheric easterly waves (Chang, 1970) were tracked, based on satellite data and synoptic chart analyses, across the western Pacific to the South China Sea along 5–10°N. These waves additionally interacted with convection off the north coast of Borneo (Chang *et al.*, 1979). Tracks of the waves in the latitude belt 2–12°N are shown in Fig. 6. The first wave passed the position of the ship array (near 110°E) on the 5th and eventually produced heavy rain over the Malay Peninsula over 5–7 December. The second wave weakened and dissipated over the Philippine Islands. The third was quite strong as it entered the South China Sea on the 14th, at which time it became a weak tropical depression (see Fig. 8 later), and interacted with a preexisting circulation and convection to the north of Borneo on the 16th and 17th (Greenfield and Krishnamurti, 1979).

Based on the above information on the timing of synoptic-scale disturbances over the South China Sea, we have selected two periods for detailed study of convective activity:

(i) Undisturbed period (minimum synoptic-scale forcing): 7–10 December.

(ii) Disturbed period (maximum synoptic-scale forcing): 11–17 December.

Strictly speaking, the first of the two periods was not "undisturbed", i.e., deep convection occurred somewhere in the region on every day of the month (e.g., see Figs. 9 and 10 of Houze *et al.*, 1981). What we mean by undisturbed here is the fact that during this period synoptic-scale forcing by cold surges and tropical waves was at a minimum, whereas during most of the disturbed period synoptic-scale forcing was at a maximum (Figs. 2 and 6). Observations on and after 18 December are not included in the above periods, primarily because *Ak. Korolov* changed its position on the 18th from 4 to 2.9°N, the latter position being very close to the Borneo coast. December 6 was not included in the undisturbed period because of probable residual effects from the first easterly wave. December 10 could be considered a transition day, but was included in the undisturbed period because 1) there was a relative minimum in the 22–7°N surge index early on the 10th (Fig. 2) and 2) satellite photographs show diurnally varying cloudiness to be the predominant form of cloudiness on the 10th.

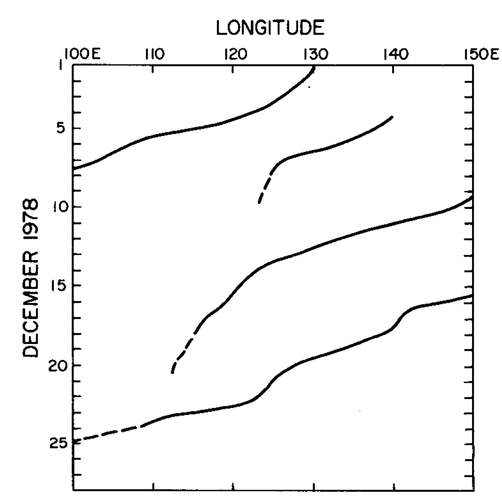


FIG. 6. Time-longitude section of tracks of easterly waves in the latitude band 2–12°N.

b. Diurnal variations during undisturbed and disturbed periods

Houze *et al.* (1981) give a detailed documentation of the diurnal variation of convective activity during December 1978 over northern Borneo and the southern South China Sea. They show that convection in the area of Bintulu (Fig. 1) is strongly modulated diurnally, with peaks in cloud and precipitation coverage occurring at 0800 LST offshore (over water) and at 2100 onshore (over land). The offshore precipitation feature regularly develops around midnight as a group of relatively small convective cells and expands by 0800 into a large (mesoscale) continuous precipitation area over 200 km in diameter as illustrated in Fig. 7. This system later propagates to the west-northwest at an average speed of $\sim$6 m s^{-1} (in the direction of the upper tropospheric flow), out of the field of view of the MIT Bintulu radar and across the southern portion of the ship array, eventually dissipating in the vicinity of *Priliv* (see also Figs. 4 and 11 of Part I). The location of *Ak. Korolov* in the path of the convection accounts for the considerably greater rainfall there than at the other ships (Fig. 2). The sequence of events illustrated in Fig. 7 for 10 December is typical of the diurnal convective cycle on all undisturbed days (7–10 December). During the disturbed monsoon surge periods there was an increase in overall convective activity; however, the diurnal modulation of convection to the north of Borneo persisted (Fig. 8). The illustration for 14 December is typical of other days during the disturbed period, although the tropical depression (upper right-hand corner of photographs) probably contributed to additional cloudiness on this day.

The satellite sequences (Figs. 7 and 8) indicate that the Soviet ship triangle intercepts varying fractions of the large convective system under study. In

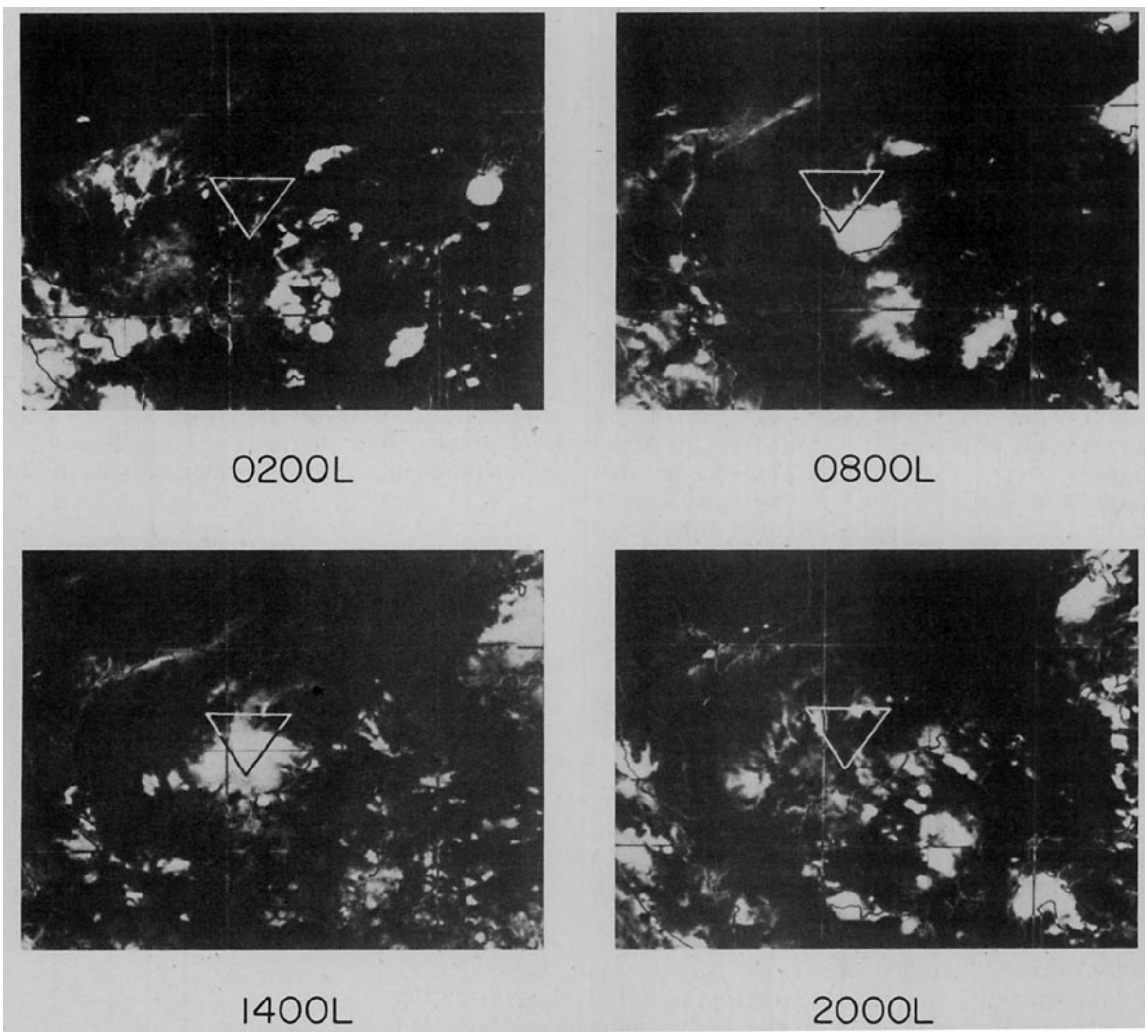


FIG. 7. Sequence of satellite pictures over the WMONEX region for 10 December. Triangular ship array is indicated.

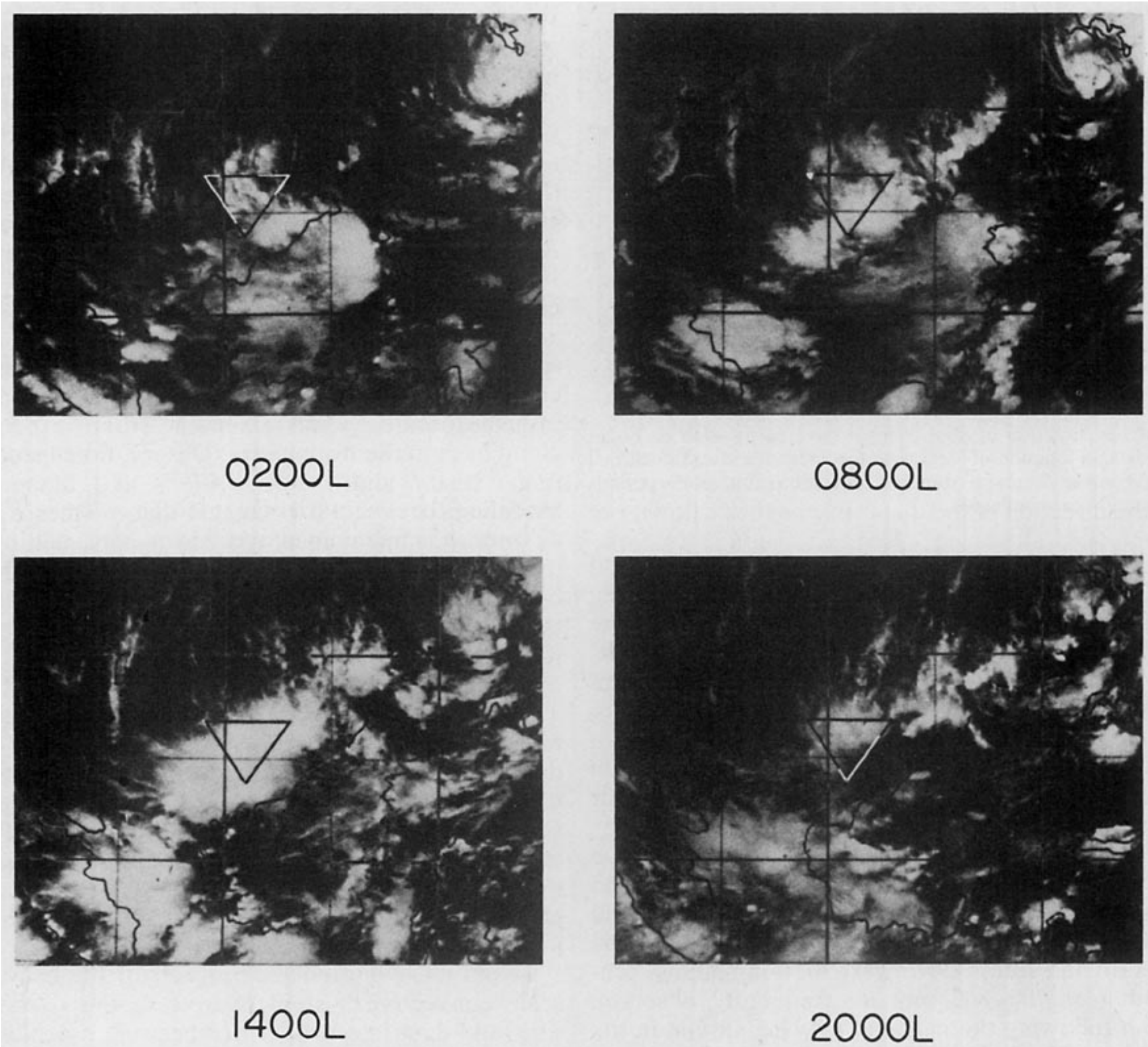


FIG. 8. As in Fig. 7 except for 14 December. Weak tropical depression appears in upper right-hand corner of photographs.

Fig. 9 the fraction of the triangle area occupied by bright or high clouds (based on infrared satellite images) is shown as a function of time. A strong diurnal cycle is clearly evident during both periods with an average 18% more cloudiness during the disturbed than the undisturbed period. Maximum coverage occurs near midafternoon in each case (75% at ~1400, disturbed; 62% at ~1600, undisturbed). The diurnal cycle of cloudiness for the ship triangle closely resembles that determined by Houze *et al.* (1981) for the region of the MIT radar at Bintulu (Fig. 6 of their paper) with the cloudiness maxima and minima occurring ~2 h later over the ship array. Qualitative inferences from the satellite pictures and the quantitative results shown in Fig. 9, though recognizing that the latter are for a limited area, illustrate the persistence of the diurnal oscillation. It is suggested from Fig. 9 that 1) synoptic-scale disturbances (cold surges and tropical waves) increase overall convective activity and 2) the diurnal cycle continues during disturbed periods with only a slightly reduced peak-to-trough amplitude. These findings indicate that at 1400 a substantial fraction of the triangle is covered by dense upper tropospheric clouds so that the computed divergence and vertical motion fields at this time should reflect rather well the circulations associated with the clouds contained therein. This is supported by observations that indicate or suggest relatively weak vertical motion (subsidence) in clear regions surrounding clouds.

Time series of divergence for the two periods are shown in Figs. 10 and 11. During both periods several recurring diurnal features are evident. These features have similar phases, although the maxima have slightly greater magnitude during the disturbed period. Most notable is a maximum divergence centered at a rather high level near 175 mb or 14 km at

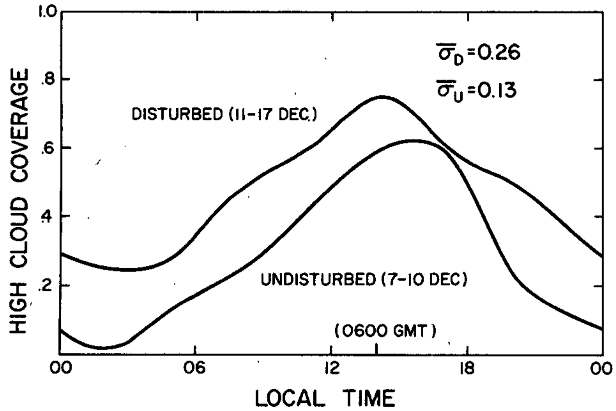


FIG. 9. Fraction of ship triangle covered by high or bright clouds as a function of local time for undisturbed and disturbed periods. The average standard deviations for both periods ($\bar{\sigma}_u$ and $\bar{\sigma}_d$) are indicated.

or slightly before 1400 during the undisturbed period and near 1100 (except on the 11th and 13th) during the disturbed period. Near the surface there is some evidence of a maximum convergence near 1400 during the first period, but a systematic variation is not apparent during the second. In the middle troposphere near 400–500 mb there appears to be a periodic variation of convergence with a maximum near 1400 during both periods, although the levels of the maxima vary from one day to the next.

The vertical motion field (Figs. 12 and 13) also shows a strong diurnal cycle with upward motion maxima in the upper troposphere between 0800 and 1400 LST during both periods (except near 2000 on the 11th and 13th). Downward motion maxima centered near 700–800 mb are frequently observed 2–6 h following the peaks in upward motion in the upper troposphere. The divergence and vertical velocity extrema generally coincide with the time of maximum high cloud coverage within the ship triangle (Fig. 9).

Time series of relative humidity for the two ships *Ak. Korolov* and *Priliv*, which are in the path of the diurnal mesoscale convective system (Fig. 7), show corresponding diurnal fluctuations in moisture. To illustrate this effect the time series at *Ak. Korolov* for the undisturbed period is shown (Fig. 14). Diurnal variations at the other ships are shown in the form of composites in the next section. A pronounced diurnal oscillation in the relative humidity occurs in the mid to upper troposphere with maxima occurring near 1400. A systematic variation in the lower troposphere is not readily apparent, although significant drying is seen below 700 mb on the 10th. Further discussion of these and other features of the diurnal convective cycle is given in the next section.

5. Interpretation of observed behavior

The companion study of Houze *et al.* (1981), as noted earlier, has shown that mesoscale convective systems in this region consist in their mid-to-late stages primarily of large anvil-type cloud structures with associated widespread stratiform rain beneath. These cloud systems possess a number of features similar to those observed in mesoscale cloud clusters in the tropical eastern Atlantic during GATE (Houze, 1977; Leary and Houze, 1979a), in the eastern Pacific (Zipser, 1969), and over tropical South America and Africa (Betts *et al.*, 1976; Fortune, 1980). These and other studies have discussed the circulation features associated with mesoscale anvils, noting two important draft structures: 1) a mesoscale downdraft extending from near anvil cloud base (500–600 mb) to near the surface, and 2) a mesoscale updraft extending from near anvil cloud base to the tropopause. Observational studies (e.g., Leary and Houze, 1979b) and numerical modeling (Brown, 1979) suggest that the mesoscale downdraft is maintained by hydrometeor melting in the mid-troposphere and in the lower troposphere by evaporation while the mesoscale updraft is maintained by the release of latent heat. Differential radiative heating effects also may influence the mesoscale updraft (Webster and Stephens, 1980).

The divergence and vertical velocity time series presented in the previous section provide direct evidence that the anvil-cloud systems generated diurnally over the sea north of Borneo contained mesoscale circulation features similar to those described above. In order to facilitate interpretation, explanation and discussion of these features, 24 h composites of the fields have been prepared for both undisturbed and disturbed periods.

To put the evolution and progression of the mesoscale convective system relative to the sounding sites and data into proper perspective, a depiction of the average cloudiness and lower (300 m) and upper (200 mb) tropospheric winds for the undisturbed period is shown in Figs. 15a and 15b. Con-

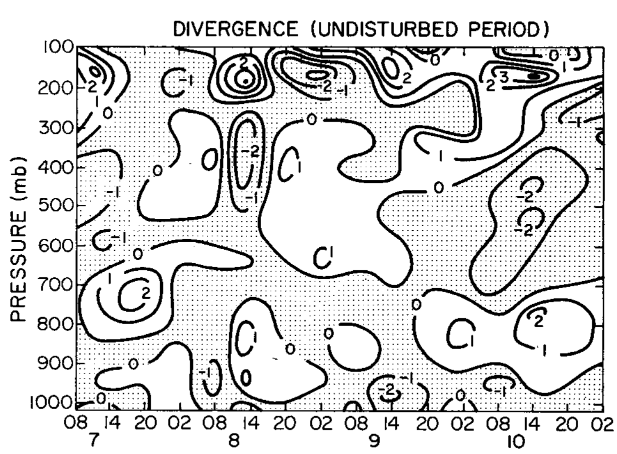


FIG. 10. Divergence (10^{-5} s^{-1}) during undisturbed period. Six-hourly time designations on abscissa correspond to rawinsonde release times.

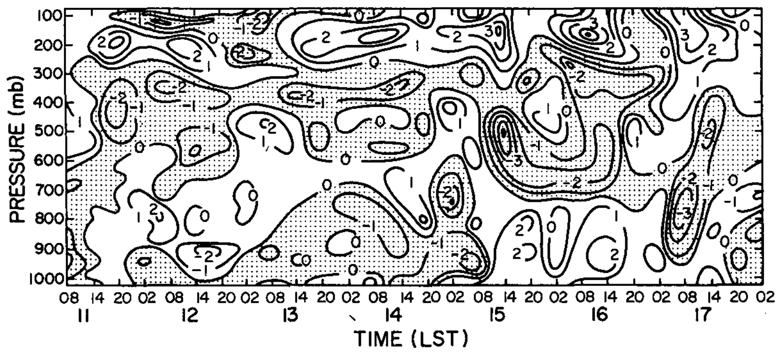


FIG. 11. As in Fig. 10 except for disturbed period.

tours indicate fractional area of high cloudiness (in tenths) for 7–10 December at four times of the day. The cloud amounts were determined by estimating the fraction of each 1° latitude × 1° longitude square covered by bright infrared satellite cloudiness and then averaging the values in each square for the 4-day period. The representativeness of this 4-day period is indicated by noting that the sequence of average cloudiness in Fig. 15 corresponds well both to that occurring on 10 December (Fig. 7), a day when the diurnal cloud system was particularly well-defined [see Fig. 11 of Houze *et al.* (1981)], and to the 23-day mean cloudiness pattern shown in Fig. 3 of Houze *et al.* At 0200 some cloudiness exists over interior Borneo with little over water areas. The low-level flow at Bintulu (Fig. 15a) has a slight offshore component, owing to nighttime land-breeze effects, which leads to a zone of low-level convergence paralleling the north coast [Fig. 8 of Houze *et al.* (1981)]. At 200 mb the flow is relatively uniform from the east-southeast (Fig. 15b). An area of convection develops within the low-level convergence zone near Bintulu, and by 0800 expands to cover an extensive area enveloping the southern portion of the ship array. Low-level winds near the cloudiness maximum are cyclonic and confluent: at 200 mb they are anticyclonic and diffluent. By 1400 the center of cloudiness has moved to the northwest of *Ak. Korolov* and the low-level flow over the sea near the coastline has become divergent. The strong onshore component at Bintulu is probably primarily forced by the afternoon sea breeze circulation, although some contribution from downdraft outflow associated with the mesoscale system cannot be ruled out. Flow at 200 mb at 1400 is strongly divergent in the vicinity of the cloudiness center. The analyses at 0800 and 1400 indicate that this convective system modifies the upper-tropospheric (200 mb) flow on the synoptic scale (~1000 km). The coverage of high cloudiness diminishes considerably by 2000 and winds at 200 mb show less evidence of being disturbed by convection. Low-level winds at all coastal stations are onshore at 2000 (late evening), consistent with a sea breeze circulation.

The data presented in Fig. 15 confirm the results of the companion study (Houze *et al.*, 1981), which indicates that the convective system being studied here is a result of an interaction between the Borneo nighttime land breeze circulation and the northeast monsoon flow over the South China Sea. The resulting low-level convergence contributes to a rapid growth in deep convection in a conditionally unstable environment near Bintulu during the early morning hours. The exact location of the initial convection is probably determined by the shape of the coastline, the topography of Borneo and characteristics of the synoptic-scale flow. The system subsequently grows and propagates to the west-northwest in the direction of the upper tropospheric flow and modifies the flow field at 200 mb. By evening it dissipates and the cycle is then repeated the following morning. A similar sequence of events is observed during the disturbed period and therefore is not presented here.

The composited relative humidity fields at all three ships are shown for the undisturbed period in Fig.

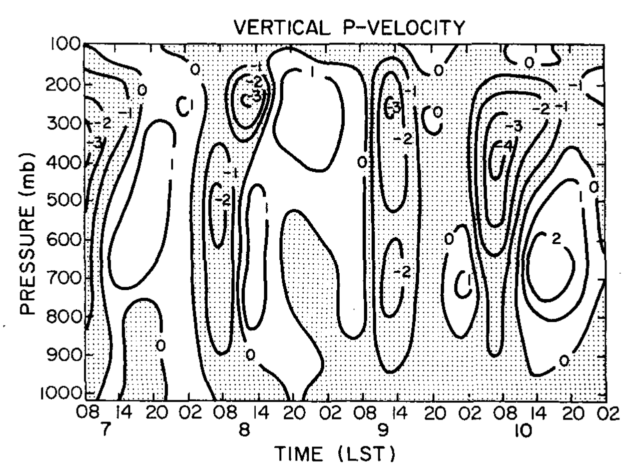


FIG. 12. Vertical p-velocity (100 mb day^{-1}) during undisturbed period.

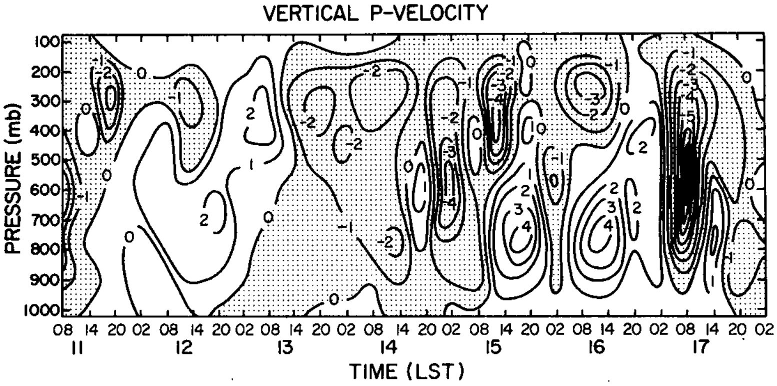


FIG. 13. As in Fig. 12 except for disturbed period.

16. In general, results for the disturbed period are qualitatively the same and therefore are not presented. The most significant diurnal variations in the upper troposphere occur at the *Priliv* and *Ak. Korolov*. A pronounced increase in relative humidity occurs above 600 mb at *Ak. Korolov* at 0800–1400 LST and above 300 mb at *Priliv* near 2000. These variations are consistent with the observed passage of the mesoscale convective system across the southern portion of the ship array (Figs. 7, 8 and 15). Both relative humidity and satellite data suggest that there is a considerable reduction in the thickness of the mesoscale anvil cloud as it propagates to the northwest of *Ak. Korolov*. Little diurnal variation in the upper troposphere occurs at *Ak. Shirshov*. Evidence presented earlier of the existence of relatively dry air in mesoscale downdrafts [at *Ak. Korolov* on the 10th (Fig. 14)] is only weakly apparent in the diurnal composite. The difficulty of obtaining a similar structure on each day clearly represents a sampling problem, but it is felt that most mesoscale downdraft systems in this region are characterized by a relatively dry lower troposphere to some degree as observed in other tropical regions (e.g., Zipser, 1969, 1977).

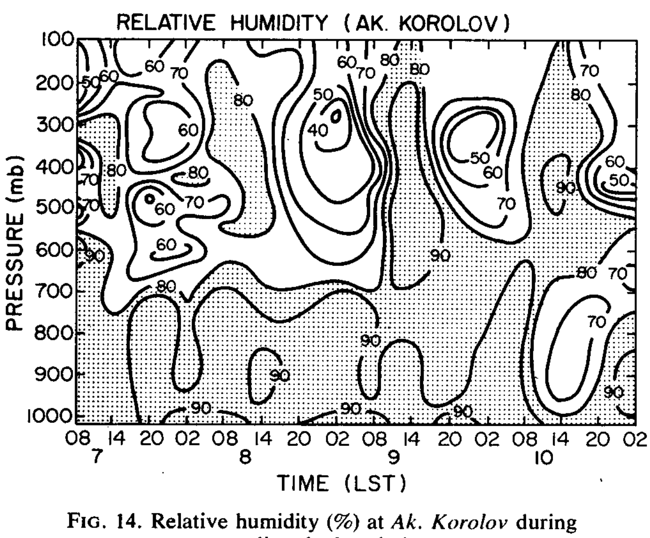
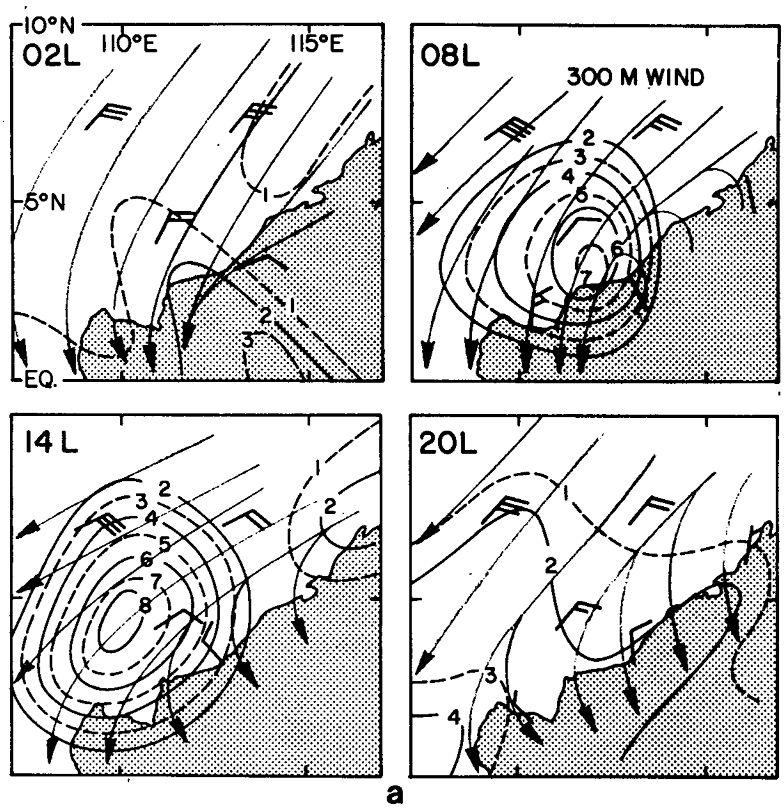


FIG. 14. Relative humidity (%) at *Ak. Korolov* during undisturbed period.

The diurnal variation of divergence and vertical velocity for the undisturbed and disturbed periods is shown in Figs. 17 and 18, respectively. Immediately apparent is a qualitatively similar behavior in the computed fields during both periods. The similarities include (all at 1400, the approximate time of maximum high-cloud coverage in the ship triangle) (i) divergence maxima at 175 mb; (ii) convergence maxima near 400–500 mb; (iii) upward motion maxima near 250–300 mb; and (iv) downward motion maxima near 700 mb. As noted previously, these features are consistent with the circulation characteristics determined for mesoscale anvil clouds in other tropical regions. The primary features at 1400 are a mesoscale downdraft below the melting level (~550 mb) and a mesoscale updraft above. The mid-tropospheric convergence is viewed as a circulation forced by the vertically diverging mesoscale draft system, which, in turn, is forced primarily by cloud microphysical processes. The extent to which the larger scale flow may interact with the mid-level convergence to dynamically reinforce the mesoscale updrafts and downdrafts is not known, but at least it is clear that mid-tropospheric convergence does not initiate these draft systems since it normally does not exist prior to the occurrence of the convection (Figs. 10 and 11).

It is important to note here that the compositing technique has considerably reduced the amplitude of the extrema in the composites for the disturbed period due to the slight phase-shifting of the oscillation that occurred from one day to the next (Figs. 11 and 13). Inspection of these figures shows, however, that when averaged over the 24 h period the upper tropospheric divergence and vertical velocity maxima are greater during the disturbed than the undisturbed period, consistent with an overall increase in convective activity during 11–17 December.



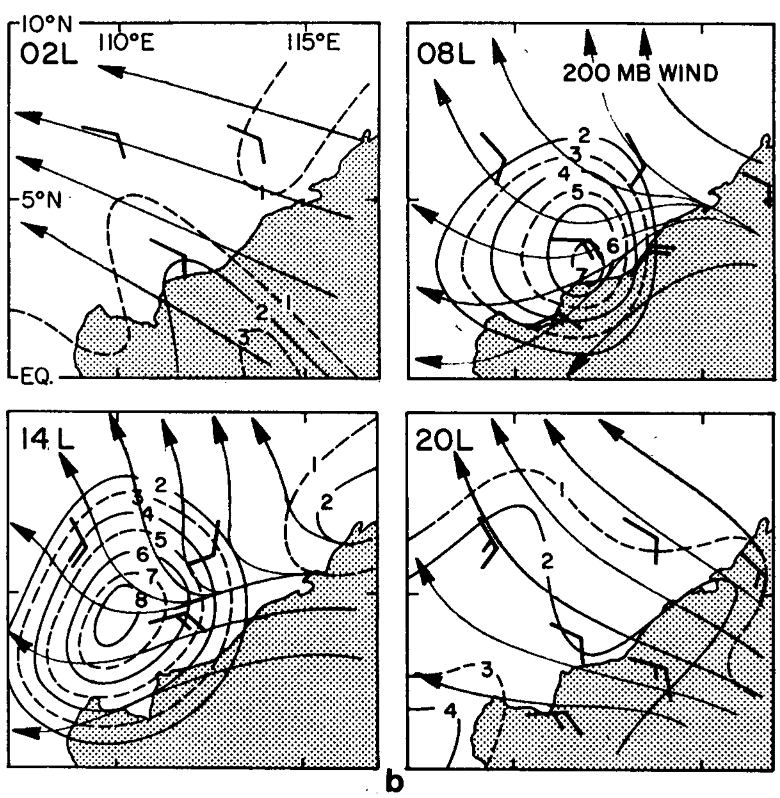


FIG. 15. Average bright satellite infrared cloudiness in tenths during undisturbed period (7–10 December) and streamline analyses for the low-level or 300 m flow (a) and the upper level or 200 mb flow (b).

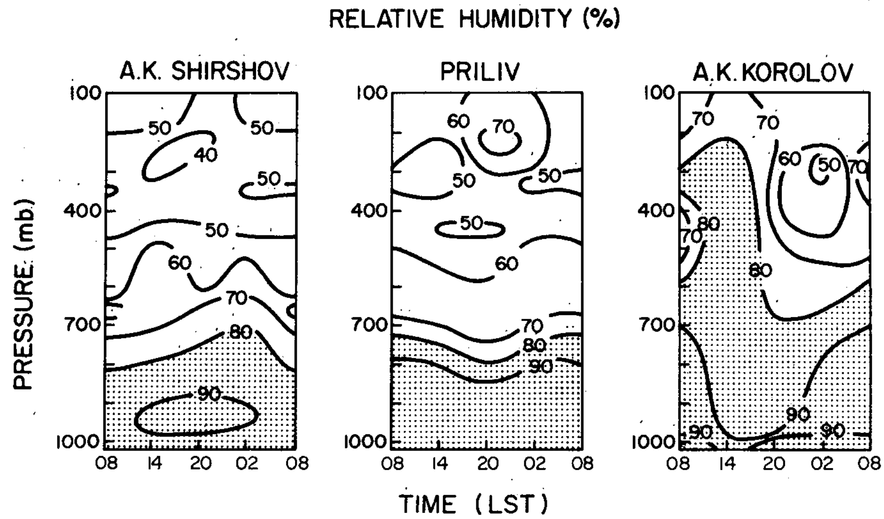


FIG. 16. Composite relative humidity (%) for undisturbed period.

Since the diurnal patterns are similar during both undisturbed and disturbed periods, we can conclude that the diurnal forcing of convection involving land-sea breeze circulations along the north coast of Borneo is so strong that it prevails even in the presence of significant synoptic-scale forcing. It appears that longer period forcing such as cold surges or tropical waves has the primary effect of increasing the overall level of convective activity; with the amplitude of the diurnal oscillation in cloudiness over the southern South China Sea modified only slightly. A similar conclusion is drawn in the companion study of Houze *et al.* (1981). Evidence presented in Fig. 4 suggests that the enhancement of convection by cold surges may be attributable to increased low-level convergence accompanying the surges. A similar mechanism may operate in the case of the synoptic-scale waves; however, it is difficult to isolate the effects of the few waves that occurred during the period, particularly when the strongest entered the South China Sea at approximately the same time as the cold surge on the 15th.

An implication of results of both studies is that the mass circulation in equatorial monsoon convective systems is not simply a population of "hot towers" or cumulonimbi (Riehl and Malkus, 1958).

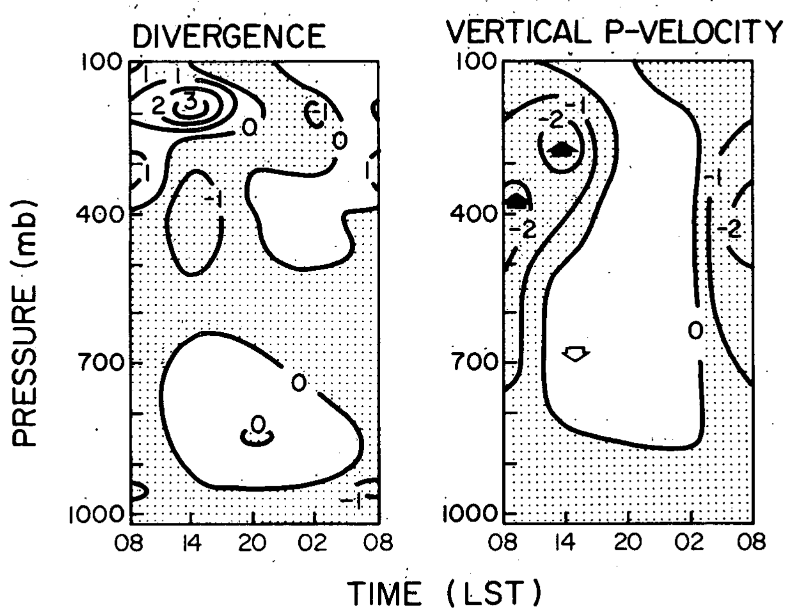


FIG. 17. Composite divergence (10^{-5} s^{-1}) and vertical p-velocity (100 mb day^{-1}) for undisturbed period.

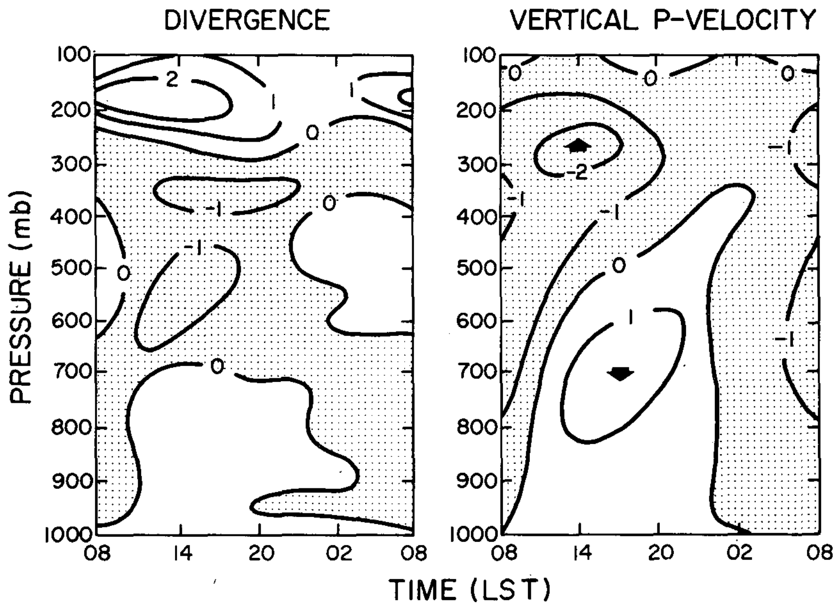


FIG. 18. As in Fig. 17 except for disturbed period.

Clearly, convective-scale drafts in monsoon disturbances exist and are important; however, considerable evidence has been presented to indicate that mesoscale convective circulations also are prevalent in the monsoon region. Future energy budget studies of the tropical monsoon region must consider the contributions of convective-scale *and* mesoscale updrafts and downdrafts to the total energy transport process (Riehl and Simpson, 1979).

6. Summary and discussion

This observational study has had two primary objectives: 1) documentation of the response of deep convection in the near-equatorial winter monsoon region to both long (synoptic) and short (diurnal) period forcing, and 2) a determination of the characteristic thermodynamic and mass circulation features associated with deep convection in this region. The analysis is derived primarily from rawinsonde observations taken from three Soviet research vessels situated off the north coast of Borneo from 6 to 28 December 1978 during the Winter Monsoon Experiment (WMONEX). Six-hourly soundings were released throughout this period and from these, diurnal and longer period variations in meteorological variables have been determined.

An important finding of this study is the observation that deep convective activity over the region of the southern South China Sea and north Borneo during the winter monsoon undergoes a pronounced diurnal oscillation on a day-to-day basis; however, the areal extent of convection within the diurnally oscillating system is modulated by surges in the northeast winter monsoon and tropical waves. When synoptic-scale forcing occurs, deep convective activity becomes more extensive, yet a diurnal cycle of convection to the north of Borneo persists. These conclusions are supported by satellite data, rawinsonde thermodynamic data and vertical motion computations based on the Soviet triangle of ships, and agree with those reported by Houze *et al.* (1981) in a radar study of convection in this region.

Second, it is found that the most dominant mode of convection over the southern South China Sea during this winter monsoon period is that of a mesoscale rather than convective-scale dimension, with distinct mesoscale circulation features. A mesoscale convective system regularly develops along the north Borneo coast in the early morning and later propagates to the northwest across the southern portion of the ship array (see also Houze *et al.*, 1981). The air flow in such systems is characterized by mesoscale upward motion above ~500 mb and mesoscale downward motion below, consistent with that observed in mesoscale convective systems in other tropical ocean regions (e.g., Zipser, 1969; Leary and Houze, 1979b). Actual vertical velocities within the mesoscale drafts could not be determined because the cloud system occupied at most only 60–75% of the WMONEX ship triangle area. However, considering that vertical motions in the environment of clouds are normally relatively weak, the deduced triangle-scale circulations are felt to qualitatively represent those of the mesoscale systems rather well. At 200 mb the convective systems have a significant effect on the flow on the synoptic scale (~1000 km).

Though characteristics of convection over the southern South China Sea have been fairly well defined in this paper, an extension of the implied convective behavior and circulations for this region to the entire near-equatorial winter monsoon region is not justified. The entire Indonesian maritime continent region is very complex topographically and WMONEX observations throughout this area were very limited. Satellite data and radar data from Bintulu (Houze *et al.*, 1981) suggest that convection over land also undergoes a diurnal cycle, but is only weakly modulated by monsoon surges. The vertical circulations within the convective systems over land and within systems over water elsewhere in the Indonesian region cannot be determined from WMONEX data, but we suspect, primarily based on satellite data, that in many areas they are similar to those observed within the mesoscale convective system off the north coast of Borneo. A more extensive observational program would be necessary to answer the question of the nature and characteristics of the entire tropical convective response in this region to monsoon forcing. Nevertheless, considering the extremely large dimension of the South China Sea–north Borneo convective system under study (Short and Wallace, 1980) and its location near the position of maximum velocity potential at 200 mb for the northern winter (Krishnamurti *et al.*, 1973; Chang and Lau, 1980), it is felt that deep convection in this region plays an important role in the Hadley and/or east-west circulations of this region, and therefore documentation of its thermodynamic and kinematic properties is important.

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