Gravitational Character of Cold Surges during Winter MONEX

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ABSTRACT

The surface pressure, temperature, dew point and wind data over the South China Sea and vicinity during Winter MONEX are examined to determine the timing of the passage of cold surges at various reporting stations. It is found that for more than half of the surge cases during Winter MONEX, a surge occurs in two stages separated by a time interval of several hours to approximately one day. The first stage is often characterized by a significant rise in pressure, while the second stage by a sharp decrease in dew point temperature. Freshening of surface winds may accompany either or both stages. The time separation between the two stages is relatively short at the upstream stations but generally long at the downstream stations. The second stage is associated with a frontal passage. On the other hand, the first stage is not clearly associated with any significant synoptic events. From its very fast propagation speed which increases with an inferred depth scale, and an increase in the local cross-isobar angle of the surface wind during passage, the first stage is identified with a synoptic-scale gravity wave type motion.

1. Introduction

During the northern winter, cold surges occur frequently over the South China Sea and bring cold continental air off the southern China coast rapidly towards the tropics (Ramage, 1971; Murakami, 1979). As the surge air penetrates into the equatorial latitudes, its temperature is usually modified significantly by the warm sea surface (Chang *et al.*, 1979) so that the surge may not remain "cold", but the freshening of the northerly winds continues and may sometimes be traced across the equator. Enhanced tropical convection immediately following (within 1–2 days) the surges over the southern China coast has been observed (Chang *et al.*, 1979; Chang and Lau, 1980, 1982). The apparaently very short time scale of the surge motion is an intriguing aspect, especially in view of the large spatial scale involved. In a theoretical investigation of the effects of cold surges, Lim and Chang (1981) proposed that the surges represent transient, gravity-wave like motions which can propagate energy into the equatorial latitudes very rapidly, and induce several types of equatorial wave-group responses.

The synoptic weather patterns associated with each cold surge always involve anticyclogenesis over southeastern China and a surface high moving southeastward off the China Coast. However, the detailed pattern may vary greatly from one case to another, and the resultant cold surge may have quite a different behavior in terms of strength, prevailing wind direction and cloud and rain distributions. Usually a cold front along the southern China coast is identified with a surge, but its relative location and relationship to the surge may vary. Clouds and precipitation may develop due to the northeasterly monsoon wind over the warm sea surface without any front. On the other hand, the cold subsiding air behind the front may be quite dry, producing clear skies and cold mornings. Thus, the local weather during surges can be either rainy, cloudy or clear, and consequently the different radiation conditions may cause different changes of the surface variables such as the temperature minimum. These variations have given rise to the various definitions of cold surges used by the Southeast Asian weather services. These definitions include a decrease of daily mean temperature or dew point, an increase in northerly, easterly or total wind, a rise in pressure or north–south pressure gradient, or a combination of several changes. The apparently different behavior of the surges at different locations also contributes to the variation in the definitions.

The purpose of this work is to study the detailed surface structure of cold surges off the southern China coast during the Winter MONEX by examining the time series of the surface reports of a number of stations in the South China Sea and vicinity. Through the use of composites, we will show that there is a systematic variation of the surge structure downstream of the coast and that most of the surge onsets at each of the stations consist of two stages separated by a period of several hours to approximately one day. Only one of the two stages can be identified as frontal passages. The other stage resembles the motion of gravity waves.

2. Data and definitions

The period of study is from 1 December 1978 to 28 February 1979, corresponding to the Winter MONEX. Fig. 1 shows the surface stations where data are used: Taipei (25°N, 121.2°E) Hong Kong (22.3°N, 114.2°E), Dongshadao (20.6°N, 116.7°E), Nanshadao (10.4°N, 114.4°E), Haikou (20°N, 110.5°E), Xishado (16.8°N, 112.2°E), Udorn (17.5°N, 102.7°E), Surin (15°N, 103.5°E), Anxuyen (9.2°N, 105.2°E) and Mandorriao (10.7°N, 122.6°E). The first four stations have hourly reports, the others have only three-hourly reports. Less than 10% of the data are missing at the first seven stations (solid circles in Fig. 1), where pressure, wind, temperature and dew point are used for detailed study. Missing data at the remaining three stations (open circles in Fig. 1) range from 15–22%. Only pressure and dew point data at these secondary stations are used to supplement the seven primary stations in a spatial analysis of the time sequence of events (Fig. 18). All other stations south of 20°N have data missing more than 25% of the time, and therefore are judged unacceptable. There are also a large number of ship reports in the South China Sea. However, due to their variable positions, a three-hourly map analysis for the entire three months would be required to extract local time series of surface variables. In view of the large number of maps (720 in total) required, and the varying, nonuniform coverage for each map time, ship reports are not used in this study.

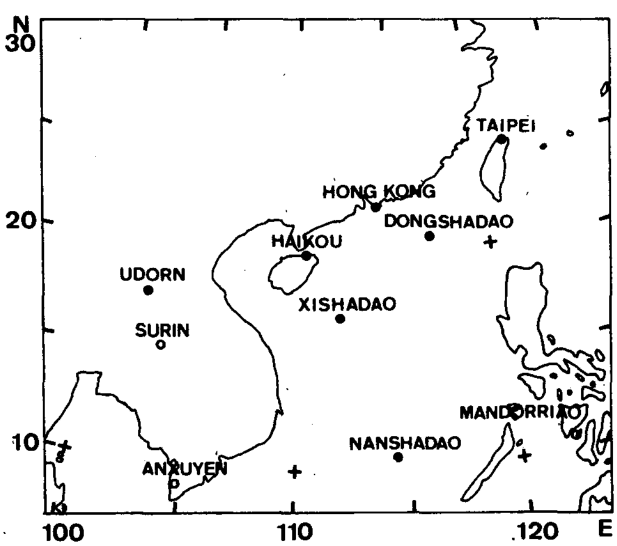

FIG. 1. Map of data stations.

In addition to the surface station reports, DMSP satellite pictures and the surface objective analysis produced by the Fleet Numerical Oceanography Center are also used for synoptic examinations to identify front locations and pressure patterns.

To remove diurnal effects, all variables were first seasonally averaged at each hour of a day and the departure values from their respective averages were used to construct time series. We then examined all the time series together with the surface synoptic charts, and found that two variables usually registered most consistently the signal of cold surges, especially at the upstream stations: a rise in pressure and a decrease in dew point, with the former usually occurring ahead of the latter. By comparing with satellite pictures and synoptic charts, we determined that the dew point decrease was normally associated with a frontal passage. On the other hand, no obvious event on the weather chart could be consistently associated with the pressure rise, except the occasional indication of a bubble high moving ahead of a front. In the ensuing discussion, we shall call the first significant pressure rise the "edge" of a surge, and call the significant dew point drop a "front" passage. A surge at a station that exhibits both shall be called a dual event, and a surge that exhibits only one of the two shall be called a single event, either edge-only or front-only.

The time series of the surface variables contain many kinds of fluctuations in addition to possible surge occurrences. To identify the edge and front passage times, synoptic charts must be examined to guarantee that only large-scale events are included. Therefore the following procedure is used. First, the beginning of a probable surge period is determined when the leading edge of a high pressure center first appears to move into southern China. Every high center approaching the southern China coast from the north is considered a possible surge producer. Next, the first pressure rise of at least 0.5 mb per six hours after the earliest possible time is chosen to be the edge passage, provided the total continuous pressure increase prior to the end of the edge event is at least 1 mb. These pressure changes appear to be quite small, but at the low latitude stations such as Nanshadao they can be quite significant. There are many occasions when a significant pressure rise occurs before the earliest possible time, which is usually the result of a ridge located over southern China that persisted from a previous surge. This "left-over" ridge is sometimes pushed southward by a new surge in the north and results in a pressure rise at the coastal stations. In a few instances, a wind increase is also observed, but if this pre-surge event occurs when the high center and front are still located over central China, it is not recognized as an edge passage.

The time of the first significant dew point decrease of at least 2°C per six hours, with no tendency to recover for at least 12 h, is chosen to be the front passage, if it is also consistent with the synoptic analysis. If the frontal passage occurs within three hours of the edge passage, as happens from time to time at the northeastern stations, the event is defined as a front-passage surge only. In rare instances, a significant dew point decrease after the first decrease is chosen as the front pasage, if this is the only way to maintain good time continuity of front passage between different stations. In the majority of cases there is good continuity and agreement between the different stations on both the selected edge and front passages using the standard criteria. An example of the choice of edge and front times in the time series of Taipei is shown in Fig. 2.

3. Composite time series

Only data for the dual events are used in this section. This is done by compositing twice the time series of all the dual events at each station, once with respect to the time of edge passage, and once with respect to the time of frontal passage. The composited variables (with the seasonal mean diurnal cycle already removed) are plotted, relative to the values at the reference times. For all composited quantities, the standard deviations are either less than 50% of the variations from the value at the reference time, or less than 0.9 mb for pressure, 1 m s^{-1} for velocity, 1°C for temperature and 1.2°C for dew point temperature.

Table 1 lists the number of surges and dual and single events at each station. There is a higher number of edge-only events and almost no front-only events at the five southernmost stations. The total number of events also decreases towards the lower-latitude stations. This apparently reflects the fact that fewer fronts and surges are traced to lower latitudes. In general, slightly more than half of the total number of surges are dual events. Inspection of the surface analyses associated with the single-event fronts at the northeastern stations indicates that all these events are quite similar, in that the pressure gradient behind the front remains tight. This is in contrast to the dual event surges at these stations, which are, in general,

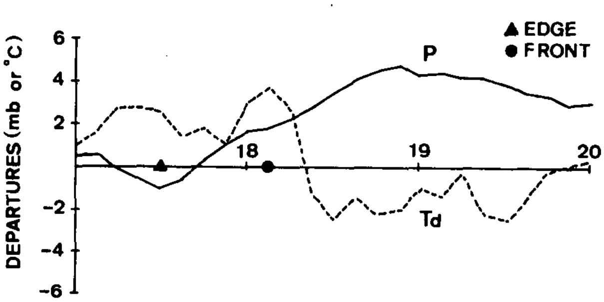

FIG. 2. Example of the choice of edge and front times from the time series of Taipei. Solid line is pressure and dashed line is dew point.

TABLE 1. Number of surges selected.

	Dual events	Edge only	Front only	Total
	Primary Stations			
Taipei	12	4	7	23
Hong Kong	12	4	5	21
Haikou	14	6	—	20
Dongshadao	13	7	2	22
Udorn	11	9	—	20
Xishadao	12	8	—	20
Nanshadao	12	6	—	18
	Secondary Stations			
Surin	3	10	2	15
Anxuyen	3	8	1	12
Mandorriao	4	6	1	11

accompanied by relatively weaker pressure gradients behind the front.

In Fig. 3 the averaged separation times between edge and front are shown at each of the stations. The stations are arranged north to south. It can be seen that there is a tendency for the separation time to increase towards the lower latitudes, although the scattering of data increases as well. A possible reason

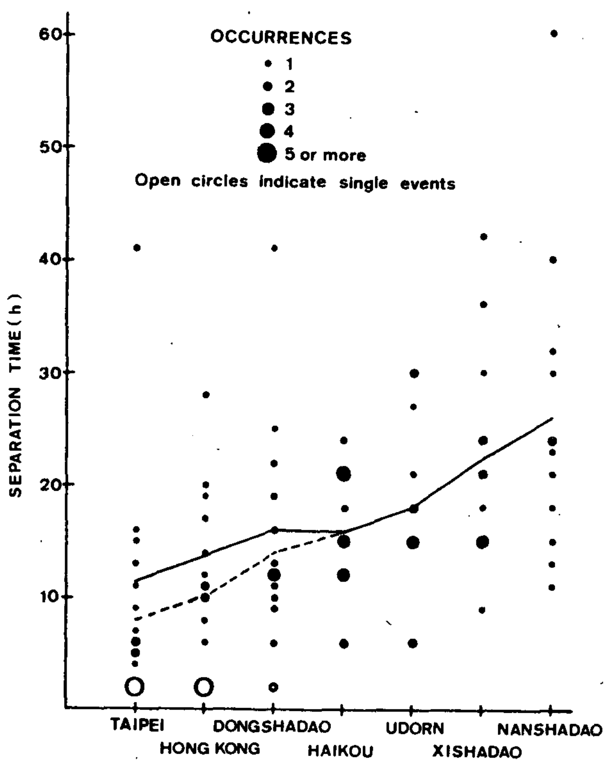

FIG. 3. Average separation time (solid line) between edge and front at each station. The dashed line represents the average separation time at each station when the front-only single-events (open circles) are included with a nominal separation of 2 h assigned to each of these events.

for this increased scattering is the smaller pressure fluctuations at the lower latitudes, which make it difficult to specify the precise timing of the events.

The composites of pressure, wind speed, temperature and dew point at the seven stations are shown in Figs. 4–10. At Taipei (Fig. 4) the edge of the surge is marked by a steadily falling pressure of 1 mb over 6 h followed by a significant pressure increase of 2.5 mb over 12 h. The front passage, on the other hand, is in the middle of a pressure rise, although the speed of rise increases after the front and the total pressure rise following the front is slightly greater than that following the edge. The wind speed reaches minimum values at both the edge and the frontal passage times, and increases afterwards. Temperature and dew point are both near maxima at the edge and front times, but the decrease in both variables is much more prominent following the front than following the edge.

At Hong Kong (Fig. 5) the changes are similar to those at Taipei, except that there is no appreciable wind increase and the temperature changes are smaller. The diagrams of Haikou (Fig. 6) again resemble those of Taipei, delineating the edge as being a local pressure minimum and the front as the starting point of a significant dew point decrease, both followed by an increase in the wind speed. At Dongshadao and Udorn (Figs. 7–8) the Hong Kong pattern is basically repeated, but at both stations the pressure increases following the edge and following the front are nearly equal. Further south at Xishadao (Fig. 9) at at Nanshadao (Fig. 10), the two island stations away from the continent, the pressure rise following the edge exceeds that following the front, while the dew point and temperature decreases remain prominent only after the front. Wind speed increases again follow both events with the front being the major event.

The composited changes of the parameters are fairly small in Figs. 4–10. This may be due to two reasons. First, the fluctuation of the time series is usually quite noisy, and the timing of the large changes customarily associated with cold surges may vary up to 12–24 h relative to the edge or front defined here. Thus the hourly structure of individual surge events may look quite different, which can make the composite time series within 12 h of the reference time relatively flat. Second, the Winter MONEX period turns out to be a weak winter monsoon season with mostly moderate to weak surges (Chang and Lau, 1982). Therefore, a composite of these mostly weak and noisy events within the short period gives only weak signals. However, the results are consistent at all seven stations, thus raising the confidence level that the data are indicative of the existence of dual events.

In summary, the dual-event pattern can be detected at all the stations. The edge, in addition to being the time of the first pressure rise in a probable surge period, also tends to coincide with a pressure minimum. The front, on the other hand, usually occurs at a higher pressure. Furthermore, the post-frontal rise is usually larger than the post-edge rise at the upstream stations, and smaller at the southern stations away from the continent. By our definition, the front is clearly marked by a significant decrease in

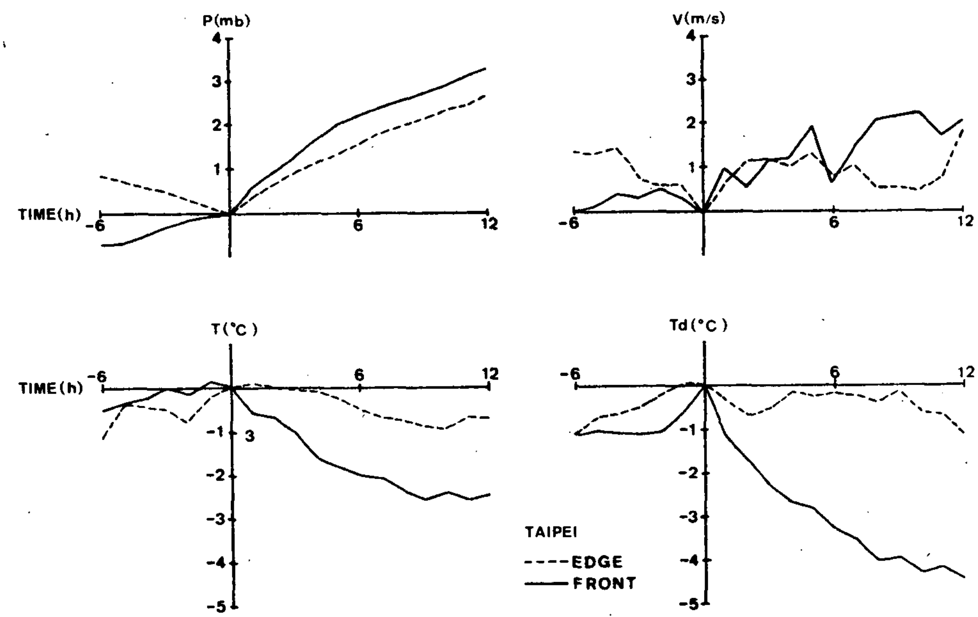

FIG. 4. Composite time series for all the dual events at Taipei. Solid lines are for front and dashed lines are for edge.

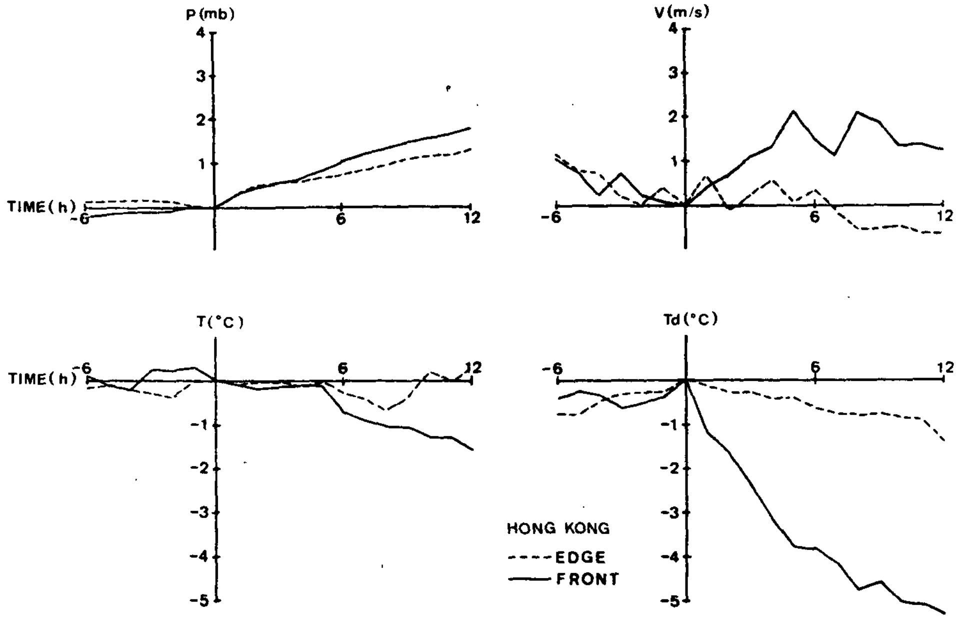

FIG. 5. As in Fig. 4, except for Hong Kong.

the dew point, and it is also accompanied by a temperature drop. The edge also shows similar tendencies but the decreases are much weaker. Freshening up of the wind speed follows both events, with the front passage producing larger acceleration than the edge passage.

4. The case of 29 January–1 February 1979

To study the separation of the edge and front events in more detail, the strongest surge case during the Winter MONEX period is chosen for a synoptic examination. According to the criteria of pressure rise and dew point drop, the strongest surge occurred near the end of January 1979. Fig. 11 shows the 24-hourly surface pressure analysis for 29 January–1 February 1979, and Figs. 12–15 show the time series of pressure, wind speed, temperature and dew point at the seven stations. At each station the time series are plotted by setting the value at edge passage to zero. Note that in these figures the ordinate increments represent twice those of Figs. 4–10. An edge line is

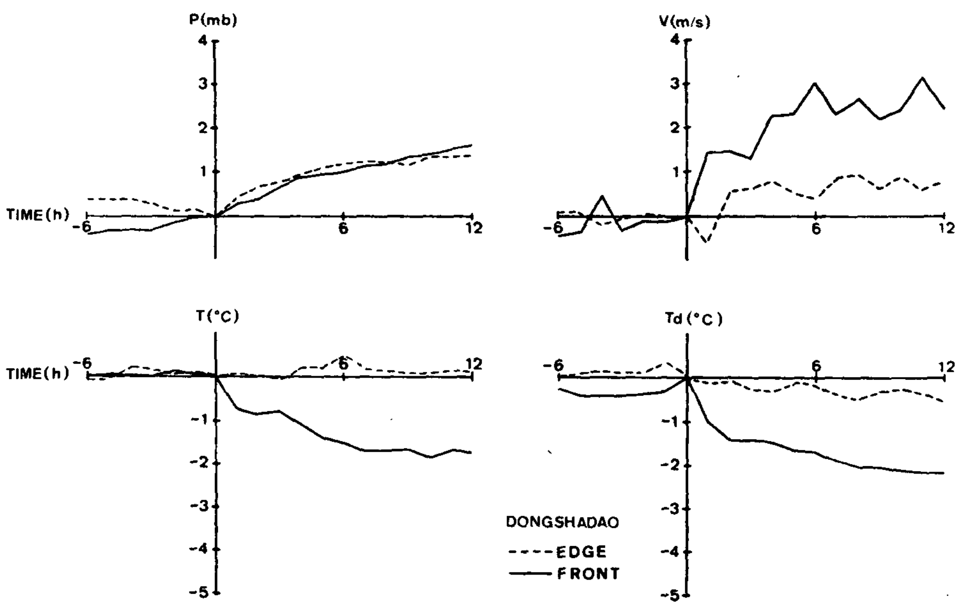

FIG. 6. As in Fig. 4, except for Dongshadao.

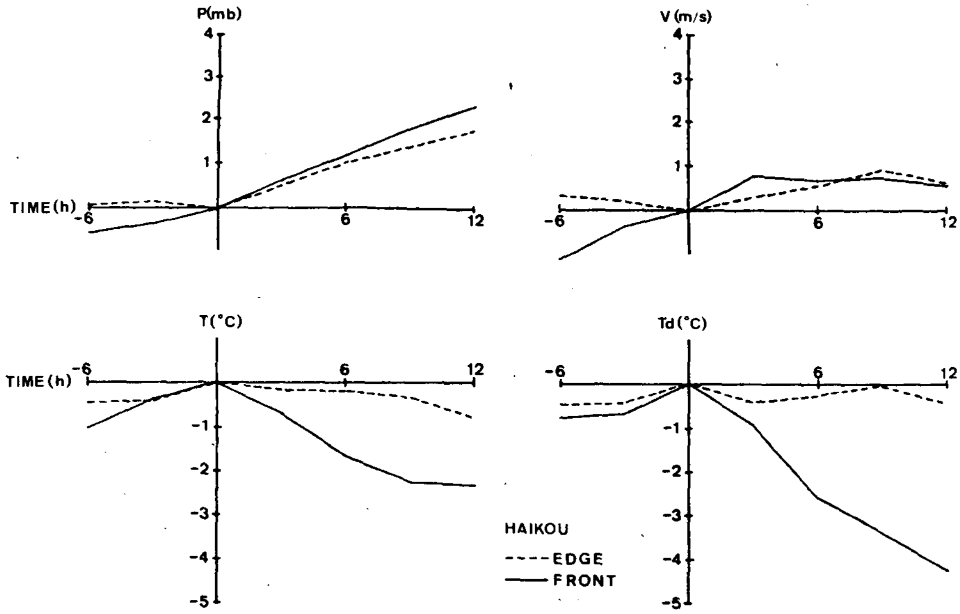

FIG. 7. As in Fig. 4, except for Haikou.

also subjectively analyzed in each of the charts of Fig. 11, which is based on the time series of Figs. 12–15.

The surface analysis of 29 January gives the first indication of a "bubble" of the high pressure system over China moving southward ahead of the front. The breakthrough occurred in the northeast corner of the South China Sea. The analysis, 24 h later, shows much faster southward progression of the edge, which passed through all seven primary stations compared to the slower speed of the frontal movement. The 31 January analysis shows an increase in speed of the front. By 1 February, the front began to dissipate after passing through Nanshadao.

The pressure series (Fig. 12) shows how strongly the various stations were affected by this part of the surge. A pressure rise of nearly 8 mb occurred at Taipei within 24 h of the edge passage. As the edge first started affecting the northeastern part of the South China Sea, it passed Dongshadao after Taipei,

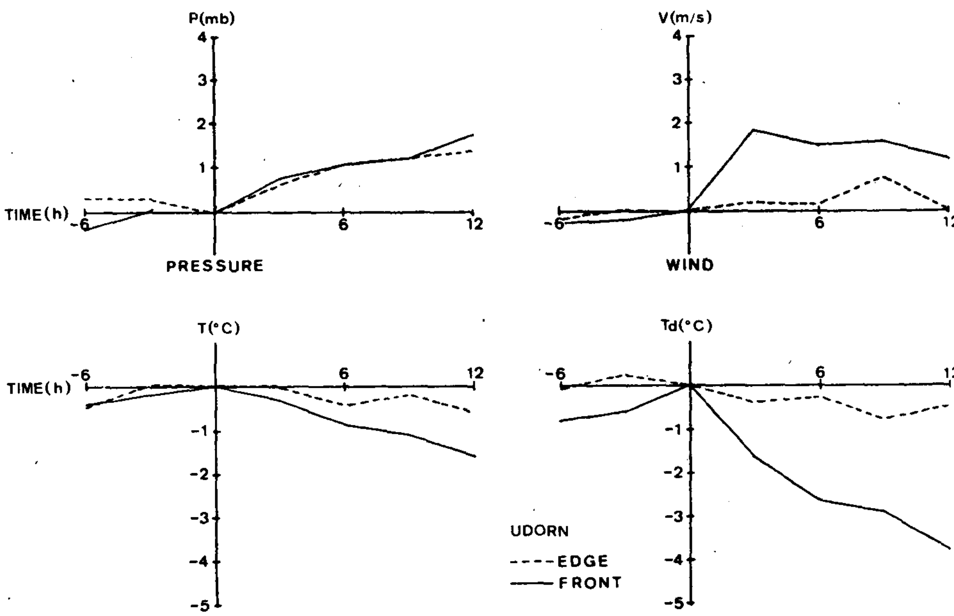

FIG. 8. As in Fig. 4, except for Udorn.

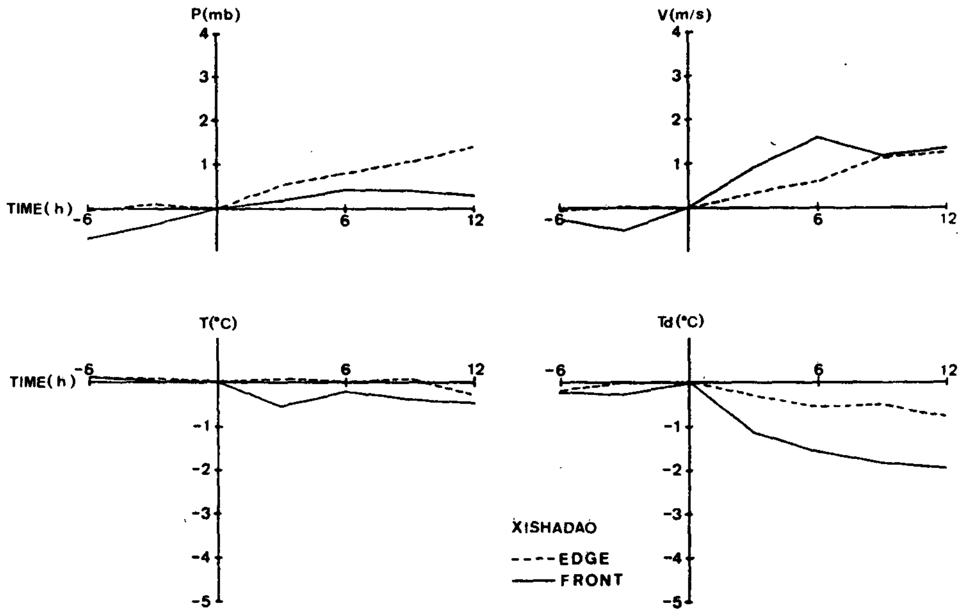

FIG. 9. As in Fig. 4, except for Xishadao.

and passed Hong Kong a few hours later. The edge then passed rapidly through Haikou and Xishadao, Udorn and Nanshadao, with a propagation speed of $\sim$40 m s^{-1}. This fast speed cannot be accounted for by upper air advection as the strongest surge winds at the 700–800 mb levels usually do not exceed 25 m s^{-1}.

The frontal passage at each of these seven stations differed considerably from the edge sequence. The front was first noted at Haikou, rather than Taipei—a result of a strong push southwestward of the bubble high over westcentral China (see the 31 January map in Fig. 11). The passage at Hong Kong followed soon afterward, while the passage at Taipei and Dongsha-

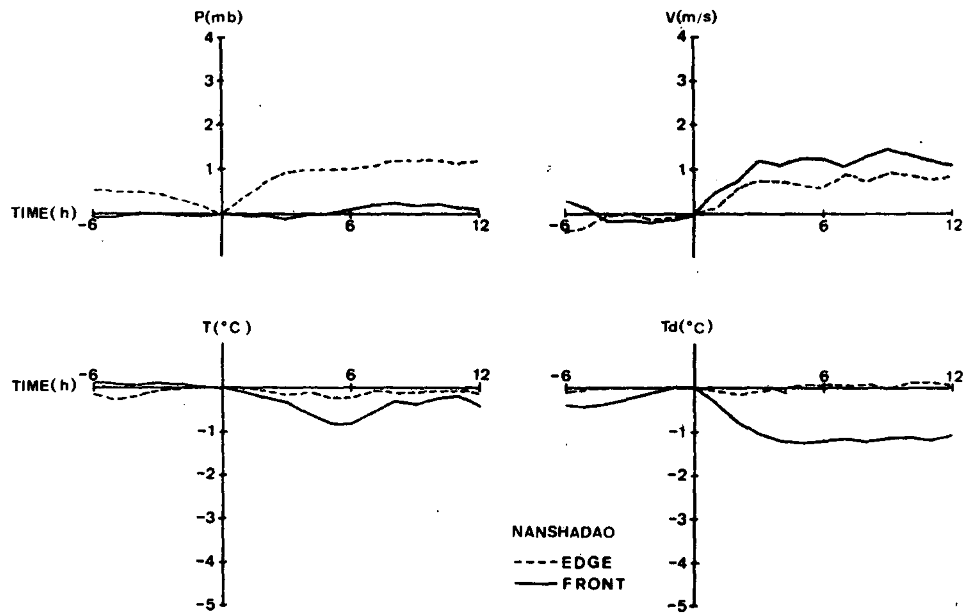

FIG. 10. As in Fig. 4, except for Nanshadao.

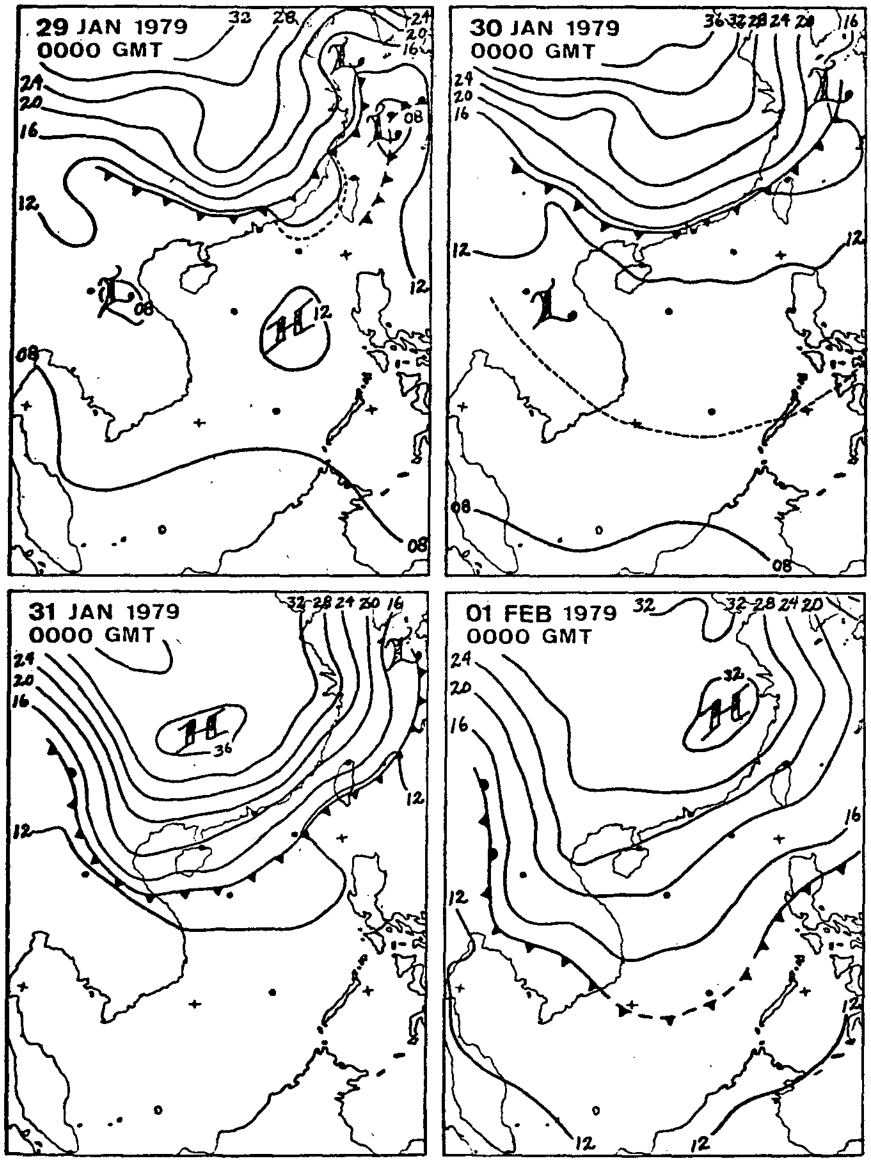

FIG. 11. Surface analysis for 29 January–1 February 1979. Isobars are (p − 1000) mb.

daò lagged that at Haikou by several hours. Passage at Xishadao and Udorn were next, followed eventually by Nanshadao. The averaged frontal movement speed is ~ 10 m s^{-1}. There was a good indication at all stations of a significant pressure rise after the front, except for Nanshadao, where the rise was rather moderate, apparently because the front was rapidly losing strength.

Of particular interest is the double dip in pressure associated with the edge and frontal passages at the northeastern stations of Taipei, Dongshadao and Hong Kong. The other stations do not show the second dip associated with the front, as was found to be the case with many of the other surges. But they still show an increased frontal pressure rise, even without the drop preceding it.

The wind speed series (Fig. 13) shows how much variability can be in both space and time between stations. Taipei experienced the greatest increase following the edge, with a wind direction shift from the west, immediately before the edge, to easterly several hours later. The next major shift occurred at the frontal passage, with the wind direction changing from east–southeast to northeast accompanied by a sharp, though short-lived, speed increase.

The Dongshadao time series shows a strong wind

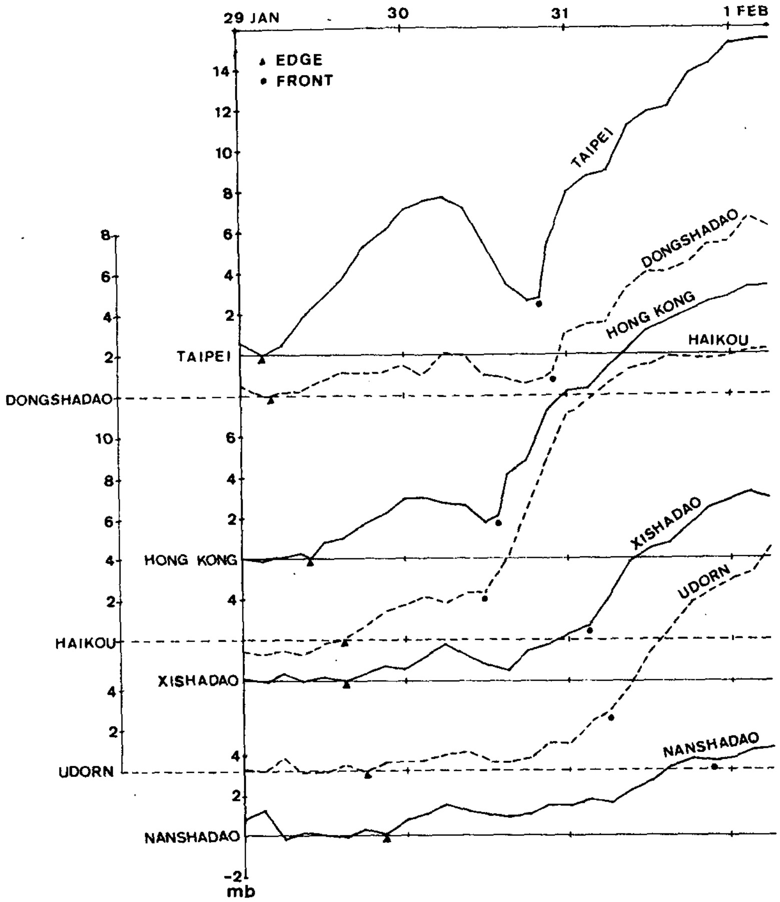

FIG. 12. Pressure time series, 29 January–1 February 1979.

increase with both events. Prior to the edge passage, the wind was calm. A significant increase by ~6–7 m s^{-1} occurred within a day after the edge passage. The wind then veered from northeast just after the edge to the southeast preceding the front. With, the frontal passage, the wind shifted to the north–northeast and increased by another 8–9 m s^{-1}.

The Hong Kong wind increased sporadically after the edge passage and after the front passage, with a direction shift from east to north–northeast occurring right at the front. The Haikou series shows several peaks, with a minor one occurring just before the edge, when the wind was from the south–southeast. It shifted to the north–northeast and increased substantially with the edge passage. Strangely, the front passage occurred during a peak wind period, though it was accompanied by a slight wind shift to the north.

The largest wind at Xishadao occurred with the front, rather than with the edge as at Taipei. A minor wind shift (south–southeast to east–southeast) did occur with the edge passage, but the largest shift (to the north–northeast) occurred with the strong winds of the front. The wind at Udorn was nearly calm for several days prior to the front, but increased sharply and became easterly with the frontal passage. Nanshadao's wind followed the Udorn–Xishadao pattern with little change following the edge and a much larger one associated with the front passage.

The temperature and dew-point time series (Figs. 14–15) at most stations are remarkably similar. Significant temperature and dew-point decreases occurred with the edge passage at Taipei, and were followed by fairly strong increases just prior to the front. Sharp falls then occurred with the front passage. This pattern can be seen at almost all of the other stations except at some southern stations where there was no increase between the two events. The exception is the temperature at Nanshadao. But even here the effect of the front is evident, if one compares the large temperature rise during the three afternoons preceding the front (which perhaps indicate a larger diurnal cycle amplitude during this time than the seasonal average), with the absence of a temperature rise after its passage.

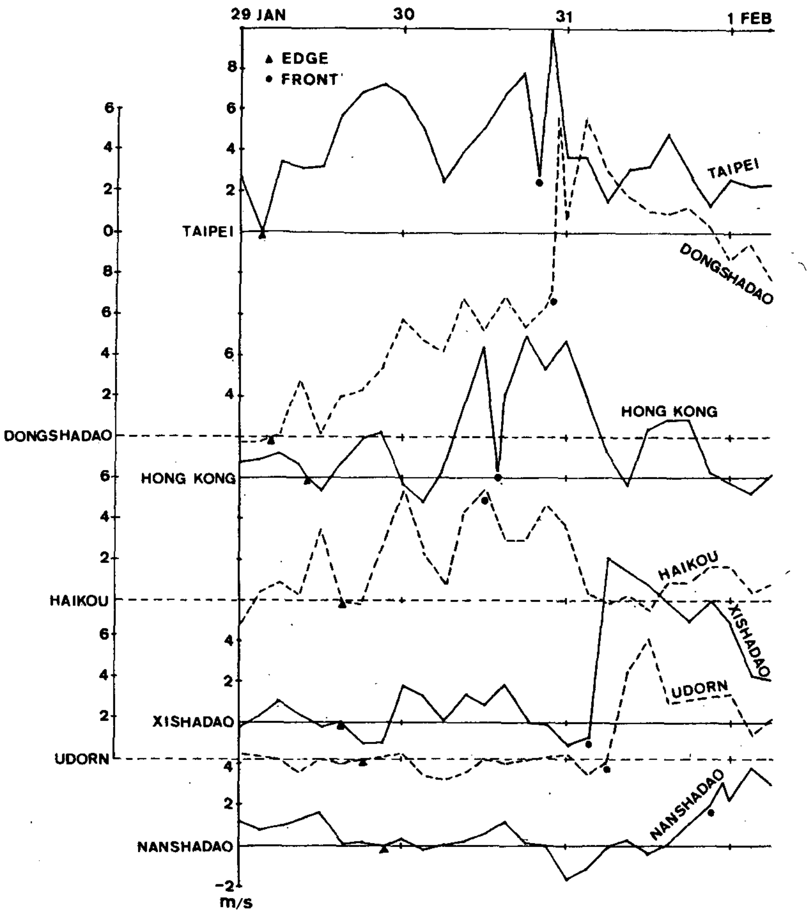

FIG. 13. As in Fig. 12, except for wind speed.

5. Discussion and concluding remarks

The foregoing analysis indicates that the second stage of a two-event surge is due to a frontal passage. The first stage, the edge, is also somewhat characteristic of fronts with increases in pressure and wind speed following its passage, except that its intensity is usually weaker especially in temperature and dew point decreases. A natural question is: What is the physical process of the edge passage? From the increased separation time at the lower latitude stations, it appears that the edges move southward at a faster speed than the fronts. The theoretical study by Lim and Chang (1981) suggests that the equatorward movement of a pressure surge may be viewed as a transient motion under an adjustment of the pressure-wind imbalance; therefore the characteristic scale of propagation speed is that of the gravity waves rather than the advection velocity. This interpretation appears plausible in view of the faster speed of the edge movement.

To look further into the possibility that edges are gravity–wave like motions, a diagram of separation time versus surge intensity is constructed (Fig. 16). Here the intensity is defined as $I \equiv \Delta p - \Delta T_d$, where Δp is the maximum positive pressure departure in mb and ΔT_d the maximum negative dew point departure in °C, both from their respective seasonally-averaged diurnal profiles, over a surge period. Although somewhat arbitrary, this parameter gives an indication of the surge strength. Because the intensity index generally decreases towards lower latitudes and away from the continent, the indices at each station are normalized with respect to the indices at Taipei by multiplying a weight of $\bar{I}_T/\bar{I}_S$, where $\bar{I}_T$ is the averaged I at Taipei and $\bar{I}_S$ is the averaged I at the particular station. This is done at the five stations in the northern and central South China Sea. Udorn and Nanshadao are not included because of their remote downstream locations, and the apparently different geographical characteristics which render the use of the normalized I-index inappropriate. The plot in Fig. 16 is fairly scattered. Nevertheless, one can see a grouping of the weaker surges in the 5–20 h

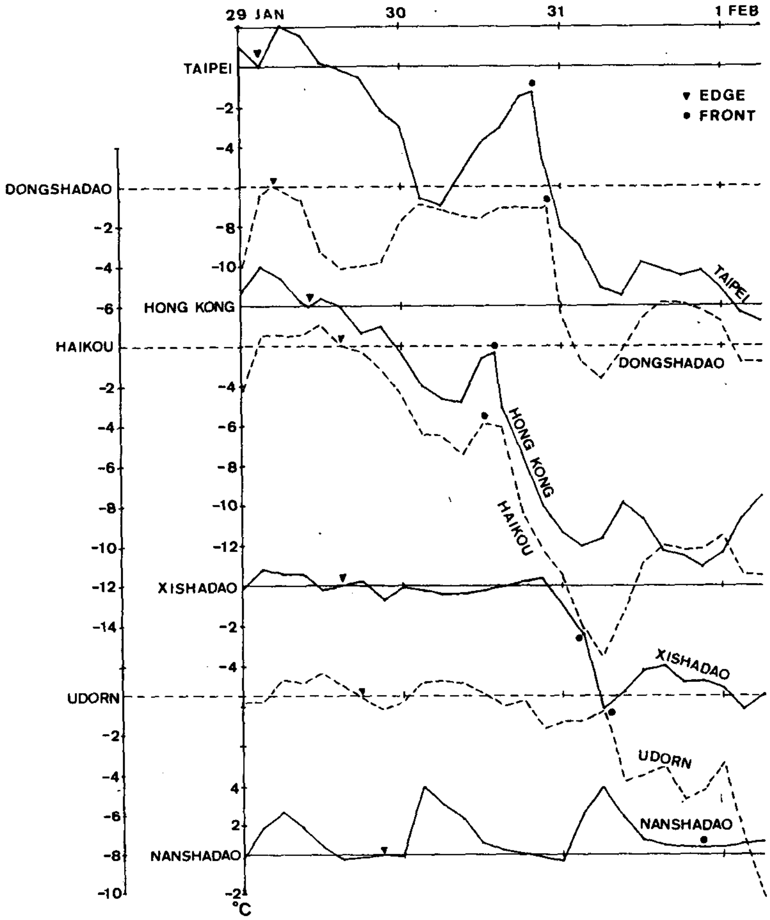

FIG. 14. As in Fig. 12, except for temperature.

range of separation time and a tendency for the stronger surges to be associated with the larger separation times. This seems to indicate that the movement of the edge away from the front is faster for the stronger surges. Since stronger surges are likely to be deeper over the northern South China Sea so that the subsiding cold continental air may penetrate further into the equatorial latitudes, it may be reasoned that these surges propagate like gravity waves with the larger depth scales propagating at faster speeds.

A comparison can be made between the times of edge and front passages at all the stations by tracing each individual edge and front. However, the movement of the edges and fronts are sometimes obscured by other synoptic systems in the South China Sea region. Some examples of these systems include the development of a Taiwan Low in the vicinity of Taiwan, the passing of a tropical disturbance in the central southern South China Sea, or a heat low over southwestern China or the northern Indochina Peninsula. In the following discussion we shall call such cases the obstructed cases, and those edges and fronts moving continuously without such interferences the unobstructed cases. Fig. 17 shows the average lag times relative to Hong Kong for edge and front passages at all the stations, both for all obstructed and unobstructed cases. Both dual- and single-event surges are included in the calculation. It is seen that the average surge passes through Hong Kong prior to all other stations, although there are a number of individual cases where a surge affects Taipei or Haikou first. It is also seen that for all stations except Taipei, it takes two to four times as long for the front to move through as it does for the edge.

Based on the information provided by Fig. 17, schematic diagrams for the unobstructed movement of an edge and that of a front are depicted in Figs. 18 a and b, respectively. Both figures are based on an average of 18 passages at the seven primary stations and, as indicated in the diagrams, the unobstructed surges represent an overriding majority of all the cases. Data from the three secondary stations are also

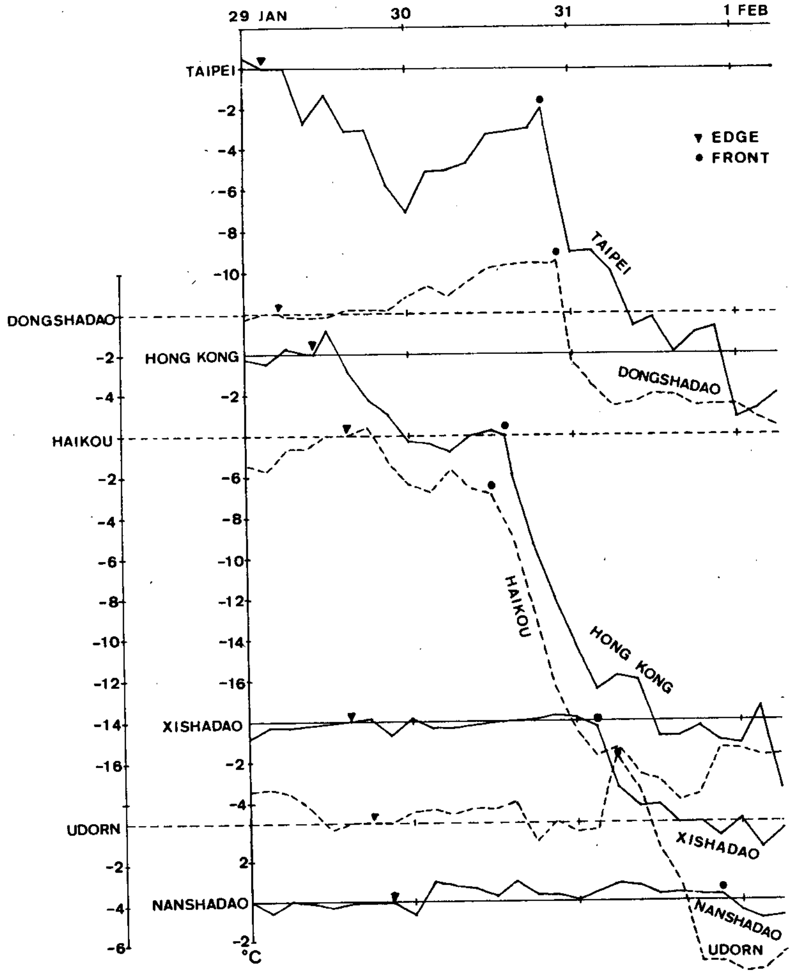

FIG. 15. As in Fig. 12, except for dew point.

used to provide guidance in the data void regions. Here we see that the front is progressing southward at a relatively steady speed of ~11 m s^{-1} (standard deviation 3.2 m s^{-1}) as it slowly weakens in the central South China Sea, while the fast-moving edge seems to accelerate downstream with a 40 m s^{-1} (standard deviation 12.1 m s^{-1}) speed in the northern and central South China Sea.

The contrast in the speed of movement between the front and the edge is certainly very distinct. The propagation speed of the front is comparable to the advective velocity, but the propagation speed of the edge is several times the advective velocity, which again suggests the gravity wave nature of the edge.

Another interesting feature of the edge which is indicative of its gravity wave characteristics may be found by examining the cross-isobar angle of the surface winds. This is done at Dongshadao, where the effect of high terrain is smallest among the stations, and the data base is still adequate for reliable isobar analysis. Fig. 19 shows the composited cross-isobar angle at this station as a function of time relative to the front and edge passages. As can be seen 12 h before the edge, and 12 h after the front, the average crossing angle is 23–25°. This is relatively geostrophic, considering the effect of friction. Between the edge and frontal passages (with an average separation time of ~16 h), the crossing angle of 29° is also relatively small. At the edge and front passage times, this angle increases to near 40°, with the angle at edge passage slightly larger. The increased cross-isobar angle for the moving front is expected because the front is pushed by the steep pressure gradients behind it. On the other hand, the increase in the angle at the edge passage is not associated with any front; therefore it appears to provide a further indication of the existence of gravity-wave type motions.

In summary, we have shown that more than half

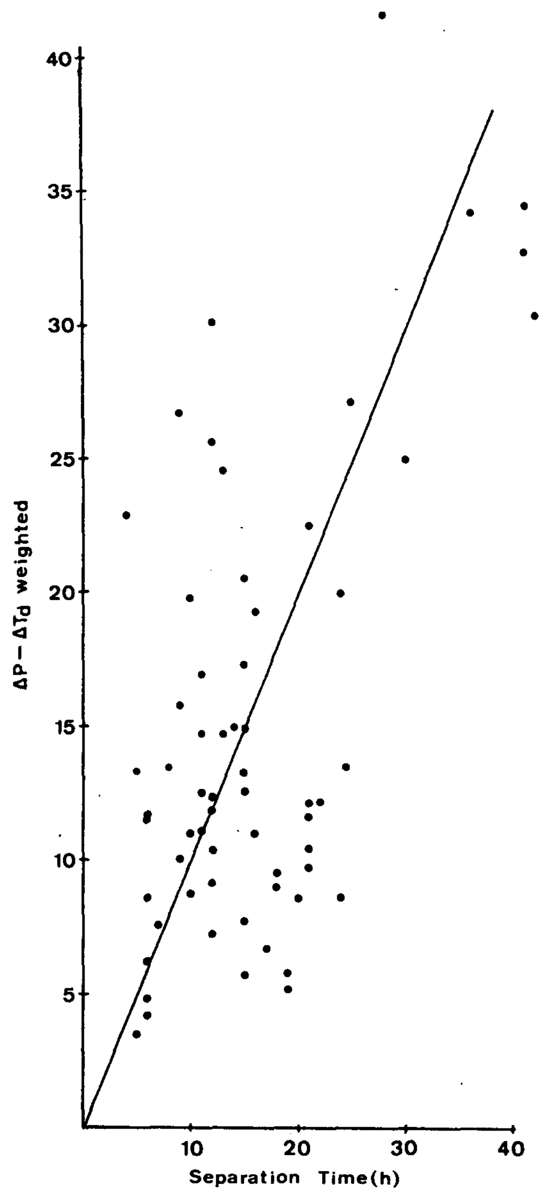

FIG. 16. Intensity of individual surges versus separation time for five northern and central South China Sea stations.

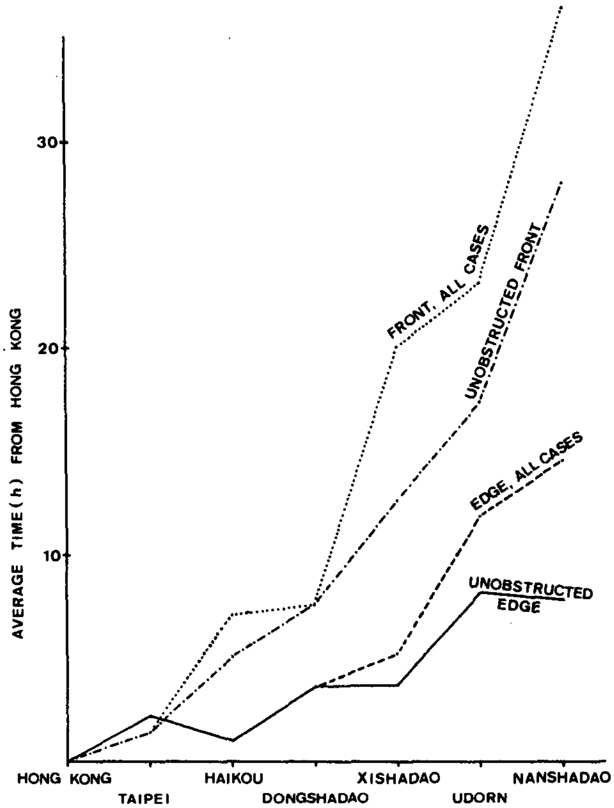

FIG. 17. Average time lag of edge and front passage at a station after passing Hong Kong.

of all the surge cases during the Winter MONEX occurred in two stages, with the first stage best characterized by the first significant rise in the surface pressure and the second stage by a sharp decrease in the surface dew point. Following both stages, the surface wind usually freshens and often with a northerly acceleration. Synoptic weather charts and satellite pictures confirm that the second stage is associated with a cold front passage, with an averaged southward movement velocity of ~ 11 m s^{-1} in the South China Sea. The first stage, on the other hand, is difficult to trace on the synoptic charts and moves southward with an averaged speed of 40 m s^{-1}. The characteristics of the propagation speed and its relationship to the surge intensity, and the time change in cross-isobar angle of the surface wind all suggest that this first stage may be a manifestation of gravity waves. This interpretation is consistent with the theoretical work by Lim and Chang (1981), who showed that gravity–wave type transient motions of the wind–mass adjustment processes would result in a surge response in the tropics which resembles the observed pattern.

The possibility of gravity-wave excitation during synoptic scale cyclogenesis has been reported by many investigations (e.g., Bosart and Cussen, 1973; Uccellini, 1975). The observed gravity-wave type motions in these studies, however, are all of the meso- or smaller scale. The spatial scale of the surge edges reported here is much larger, even though their time scale is relatively short compared to the usual time scale of the synoptic-scale motions.

A natural extension of this study is to examine the structure of the monsoon surges further downstream. Because fronts usually stall and dissipate over the South China Sea, surges reaching very low latitudes

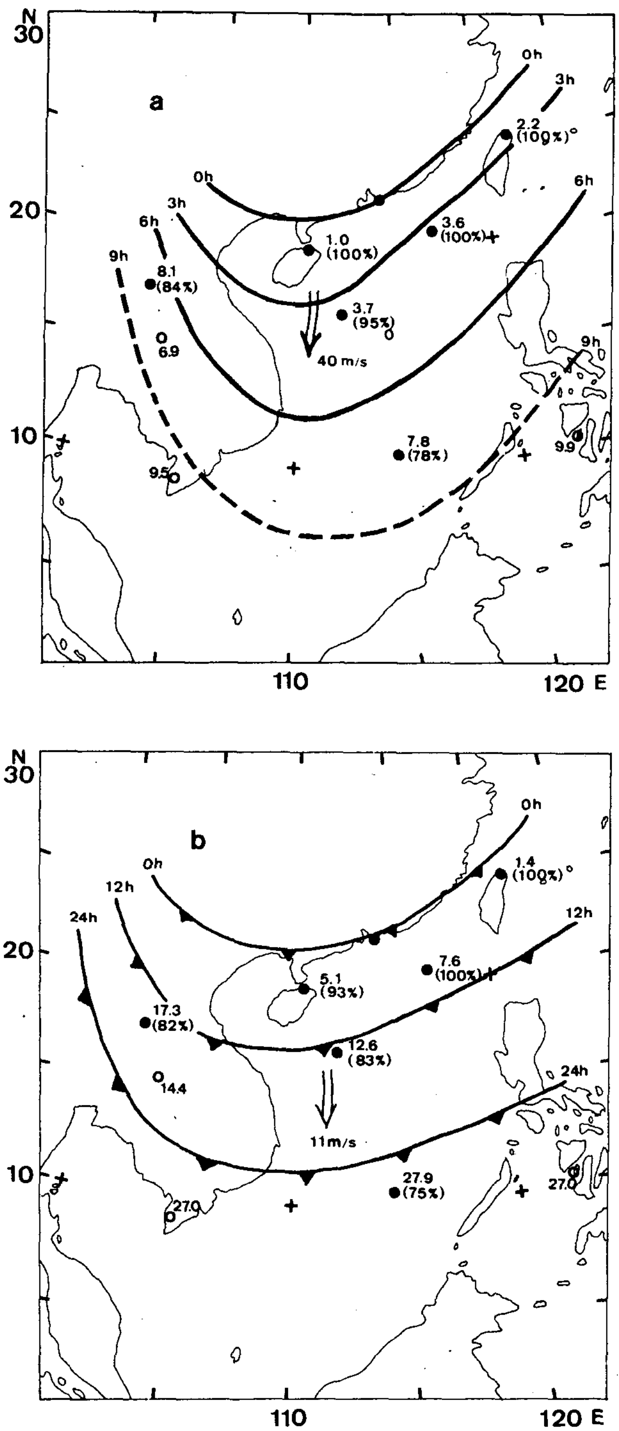

FIG. 18. Schematic diagram for the progression of (a) unobstructed edge, (b) unobstructed front.

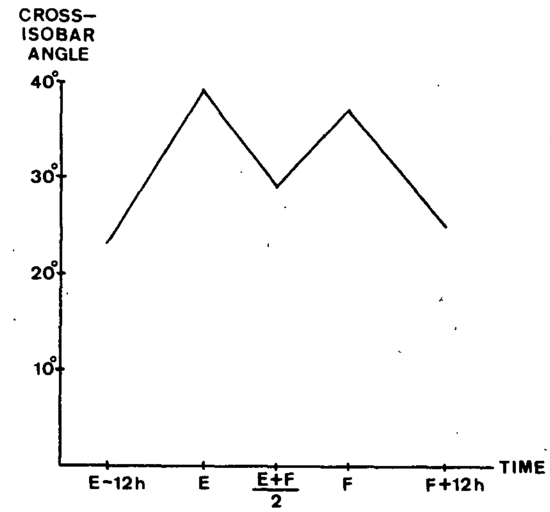

FIG. 19. Composite cross-isobar angle of surface winds as a function of time with respect to the edge and front at Dongshadao.

should be of the edge type only. Therefore it would be interesting to trace the surge edges towards the equator or even into the Southern Hemisphere. In particular, it would be interesting to see if weather changes, such as the frequent sporadic occurence of heavy rainfall over the Malaysian Peninsula and Borneo during winter are related to the surge edges. However, the smallness of the pressure and temperature fluctuations in the equatorial latitudes and the frequent interference from activities of tropical disturbances (Chang *et al.*, 1979) would make it more difficult to isolate the surge signals and timings accurately. Compounding this problem is the large data-void region in most of the central and southern South China Sea. In fact, the present study has been made possible by the specially enhanced surface observations at several of the South China Sea stations (Nanshadao in particular), and the generally improved data quality during Winter MONEX. Extensive efforts of analyzing the ship reports may be necessary in future studies. Another possible future investigation is to study the vertical structure of the surges using upper air data in the lower troposphere. This can only be done near the South China coast and Taiwan where radiosonde reports are available. However, the normally once- or twice-daily reports will make it even more difficult to trace the sequence of events there, as the average separation time between the two stages is less than 12 h. Finally, the Winter MONEX period was a season of rather weak winter monsoon in East Asia. Therefore, a similar study during more normal or intense seasons may provide a more definitive picture of the surge structure.

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