Thermodynamic and Circulation Characteristics of Winter Monsoon Tropical Mesoscale Convection

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ABSTRACT

During the December 1978 field phase of the International Winter Monsoon Experiment (Winter MONEX), a regular diurnal cycle of deep convective activity occurred over the South China Sea immediately to the north of Borneo. The convection was initiated during the late night hours by convergence of the low-level northeast monsoon flow with the land breeze along Borneo's north coast. The precipitation feature that developed was characterized during its mature stage by a nearly continuous stratiform cloud, referred to here as a mesoscale anvil, of ~100–500 km dimension extending from the mid-troposphere (~5 km) to near the tropopause (~17 km).

Using rawinsonde data from the sounding network, thermodynamic and circulation characteristics of the convection are documented. Mesoscale upward motion is found to occur within the anvils, with a mesoscale downdraft below producing a warm, dry region over a large area just above the boundary layer. Air flow relative to the anvil on both its leading and trailing edges is inward near its base (in the mid-troposphere), and outward near its top. Mesoscale downdraft air flows out to the rear of the system. A significant cold anomaly atop the mesoscale anvils is observed with maximum amplitude ~6°C at the tropopause or in the lower stratosphere. The propensity for mesoscale anvil development over the Indonesian region and many other areas of the tropics may be partially accounted for by the deep layer of conditional instability that is observed prior to their development. This conditional instability extends not only from the surface to the midtroposphere, as is common over most of the tropics, but also, when ice processes are considered, all the way to the upper troposphere (~10 km). A cooperative instability mechanism to account for the rapid development of the mesoscale anvils in the winter MONEX region is suggested by the above observations.

1. Introduction

One of the objectives of the 1978–79 International Winter Monsoon Experiment (Winter MONEX) over Southeast Asia was to provide a documentation of the near-equatorial convective response to the winter monsoon flow and surges in this flow (cold surges) originating in the Northern Hemisphere midlatitudes. Ramage (1968), Krishnamurti *et al.* (1973) and others have pointed out the important role of convection over the Indonesian "maritime continent" region in the planetary circulation.

Several recent studies (Webster and Stephens, 1980; Houze *et al.*, 1981; Johnson and Priegnitz, 1981; Warner, 1982) have found that one of the primary components of the convective field in this region is a mesoscale (~100–500 km) precipitation system that regularly develops on a diurnal basis in the vicinity of North Borneo. With some variation in areal coverage and intensity, this convective feature was observed on nearly every day during the December 1978 field phase of Winter MONEX. Its cloud and precipitation structures were reported by Houze *et al.* (1981), and its effects on the large-scale flow were investigated by Johnson and Priegnitz (1981). More recently, Johnson (1982) attempted to deduce the vertical motion within mesoscale clouds using Winter MONEX rawinsonde data. This paper is an extension of the latter two, with the goal of better defining the thermodynamic structure and circulation features of the mesoscale cloud systems and their near environment.

The mesoscale convective systems that develop in the Winter MONEX area have a number of properties that resemble those observed in similar systems in other tropical regions. By assimilating aircraft, digitized radar and other data, Houze *et al.* (1981) have determined that in their mature and dissipating stages the mesoscale precipitation features are characterized in large part by a nearly continuous stratiform cloud of ~200 km horizontal dimension, extending from near the freezing level (~5 km or 550 mb) to the high troposphere (see their Fig. 16). This cloud system will hereafter be referred to as a mesoscale anvil following Brown (1979). Warner (1982) has carried out a detailed analysis of the mesoscale anvil on 10 December, using aircraft, satellite and ship data. We also report on findings for the 10 December case, concentrating on the anvil thermodynamic and circulation characteristics.

Johnson (1982) has inferred, using rawinsonde data in the vicinity of 11 anvil complexes, that within

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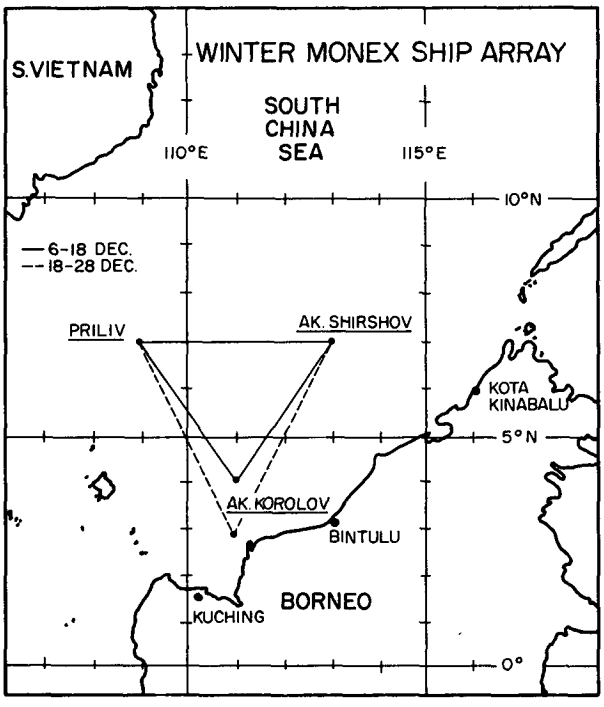

FIG. 1. The Winter MONEX ship observation network during the December 1978 Field Phase.

the clouds a mesoscale updraft occurs with an average peak vertical velocity near 10 km (250 mb) of ~12 cm s^{-1}. Beneath the mesoscale cloud systems, downward motion is observed with a peak near 3.5 km (650 mb) of ~ −3 cm s^{-1}. The estimates of Johnson (1982) for 10 December, whose limitations are discussed in Section 2, are used in a relative flow analysis for the mesoscale anvil in Section 5. As pointed out in Johnson (1982), the magnitudes of mesoscale updrafts and downdrafts found in the Winter MONEX anvils are comparable to those recently determined for a mesoscale anvil associated with a GARP Atlantic Tropical Experiment (GATE) squall line by Gamache and Houze (1982). Similar meso- to synoptic-scale cloud systems occur at midlatitudes (e.g., Maddox, 1980; Ninomiya *et al.*, 1981), and although analyses of their circulation features through the entire depth of the troposphere are limited, several that have been carried out suggest strong similarities to the tropical systems (e.g., Ogura and Liou, 1980).

At present there is incomplete understanding of key processes involved in the development of mesoscale cloud systems, both in the tropics and at midlatitudes. In Brown's (1979) numerical model of mesoscale convection, the development of a mesoscale anvil cloud occurs initially through detrainment of cloudy air into the environment. Development of mesoscale ascent within this cloud is enhanced by the establishment of a conditionally unstable lapse rate (neglecting ice processes) within it. The conditional instability is maintained by the detrainment of "high-θ_e" air in the mid-to-upper troposphere by cumulonimbus clouds, which are parameterized in the model. The role of radiative processes, not included in Brown's model, has been addressed for GATE systems by Cox and Griffith (1979) and Houze (1982), and for Winter MONEX systems by Webster and Stephens (1980). Webster and Stephens (1980) and Houze (1982) examine the relative contributions of longwave radiative destabilization of an upper tropospheric cloud layer and condensational heating in its maintenance. Results of the Webster and Stephens study suggest that radiative forcing may be more important than condensational heating for thin, non- or lightly-precipitating cloud layers, with the reverse true for deep, moderately-precipitating cloud layers. Houze, however, suggests ways in which radiative heating may still be of first-order importance in the life cycle of deep mesoscale anvil clouds. Thermodynamic observations relating to the hypotheses proposed by these authors have not yet been reported. In this paper, data pertinent to this problem, in particular, to the questions of initiation and maintenance of mesoscale anvils, will be presented.

Additionally, as best as can be determined from the available data, the airflow within Winter MONEX mesoscale cloud systems will be documented.

2. The experiment, data and limitations of the analysis

During the December 1978 field phase of Winter MONEX, three Soviet research ships were situated in a triangular array over the South China Sea to the north of Borneo (Fig. 1). On most days from 6 to 28 December, six-hourly soundings were taken at the ship sites[1]. Six-hourly rawinsonde releases for December were scheduled at the coastal stations Kuching (96413), Bintulu (96441) and Kota Kinabalu (96471); however, they were not always achieved. The quality of the wind data from the Bintulu station (using portable upper-air equipment, type RD65 from the United States) is questionable because of a failure in the autotrack equipment early in the month. Its use in this study is limited. Hourly surface data from the ship and land stations are also employed in this study. Satellite data are from the Japanese geostationary (GMS) satellite, with IR brightness data being supplied by Donald Wylie and David Martin of the Space Sciences and Engineering Center, Madison, WI. Radar data used in this study have been obtained from the Massachusetts Institute of Technology (MIT) WR73 C-band weather radar at Bintulu and were kindly prepared for the authors by Spiros Geotis of MIT. Weather radar observations from the Soviet

[1] Data available from World Data Center A, Asheville, NC 28801.

ships did not prove to be of sufficient resolution to be as useful in the analyses reported here. Additional data used in this study were obtained from dropwindsondes launched from the National Center for Atmospheric Research (NCAR) Electra research aircraft.

The majority of the thermodynamic analyses of mesoscale anvils and their environment primarily use rawinsonde data obtained from Soviet ships. However, the cross-section analyses to be discussed use sounding data from land stations and aircraft as well. Intercomparison findings reported in FGGE Operation Report No. 7 (World Meteorological Organization, 1980) for the Winter MONEX period and in Reeves *et al.* (1976) for the Soviet sondes used in GATE indicate that 1) Dropwindsonde wind (direction/speed) and temperature errors in the South China Sea can be expected to as high as $\sim 20°/4$ m s^{-1} and $\sim 2°C$, respectively, and 2) the Soviet sondes may have a high bias in their relative humidity measurements, particularly in the upper troposphere. For the type of cross-section analyses presented in this study and the qualitative interpretations derived from them, however, these errors are considered to be tolerable.

Finally, it is noted that Soviet scientists applied corrections to the midday (1400 LST or 0600 GMT) soundings to compensate for solar-induced errors using a method based on day–night temperature differences (Dr. A. A. Zhelnin, Hydrometeorological Centre, Moscow, personal communication, 1981). GATE studies with USSR sounding data have suggested that over-corrections were made in the 1974 experiment (Reeves *et al.*, 1976); however, analysis of the data for Winter MONEX suggests the corrections have been reasonable and no further adjustments have been made.

Vertical motion for the triangle of ships has been computed using the divergence theorem with the vertical velocity balanced to zero at 87.5 mb (Johnson and Priegnitz, 1981). Johnson (1982) decomposed the fields into cloud and environment components in an attempt to deduce vertical velocities in the mesoscale anvils. Findings of these earlier investigations are incorporated into this study as part of an effort to determine air flow within the mesoscale cloud systems. When viewing the results, limitations of the analysis procedures should be kept in mind (Johnson and Priegnitz, 1981; Johnson, 1982). In particular, the accuracy of the triangle method in this region is limited, due to factors such as nonlinear variation of the flow between triangle vertices and off-centering of convection over the triangle.

Analyses to be presented later for 10 December use vertical velocities for the mesoscale anvils computed by Johnson (1982). These computations were made for 1400 LST, a time identified by Houze *et al.* (1981) and Johnson and Priegnitz (1981) as corresponding to the dissipating stage of many of the mesoscale convective systems (see Fig. 16 of Houze *et al.*, 1981). The assumption in Johnson (1982) was that during the dissipating stages of mesoscale systems the contribution to vertical motion by boundary-layer rooted convective-scale ($\sim$1–10 km) clouds is comparatively small and that the primary cloud and precipitation structure is stratiform, a picture consistent with the life cycle description given in Houze *et al.* (1981) and Leary and Houze (1979a). Computed vertical motion within the cloudy region was therefore assumed to be primarily associated with the mesoscale anvil cloud (which itself may have smaller scale motions not resolvable by the data). This assumption appears plausible, particularly when viewing sequences of satellite pictures of the mesoscale systems on different days, but cannot be proven, due to the absence of radar data in the dissipation region over the South China Sea, well distant from the North Borneo coast. Warner (1982) points out that on 10 December observations from aircraft show new cumulonimbus towers appearing on the periphery of the mesoscale anvil coincidentally with its dissipation. Consequently, vertical motion computed for the cloudy area at 1400 LST by Johnson (1982) on 10 December probably reflects contributions of both mesoscale and convective-scale motions. Nevertheless, the results of Johnson shown in Fig. 6 (10 cm s^{-1} updraft near 250 mb above a 3 cm s^{-1} downdraft near 650 mb at 1400 LST on 10 December) *suggest* that on the ship triangle scale, mesoscale anvil motions are predominantly sampled since a combined mesoscale and convective-scale vertical velocity profile should appear with a different shape if the convective-scale contribution is significant (Gamache and Houze, 1982).

To summarize, the vertical velocity for 1400 LST on 10 December taken from Johnson (1982) to be used later in this study is ascribed here to the mesoscale anvil and its associated updraft and downdraft. However, the partitioning of vertical motion into cumulonimbus and mesoscale anvil components was not possible due to lack of radar data and inadequate sounding network so that the interpretations of the motion field presented in this paper, although felt to be reasonable, cannot be proven conclusively.

3. Observed diurnal cycle of convection

Streamline analyses for 0000 GMT on 10 December over the Winter MONEX region at low levels (surface to 1000 m) and at 200 mb are shown in Fig. 2 (from Sadler, 1979). These analyses correspond to the date of the cross-sections presented later and are very similar to mean charts for the month, consistent with climatological records that show the monsoon to be a quasi-steady circulation (Ramage, 1971). On 10 December, rather uniform 5–10 m s^{-1} low-level

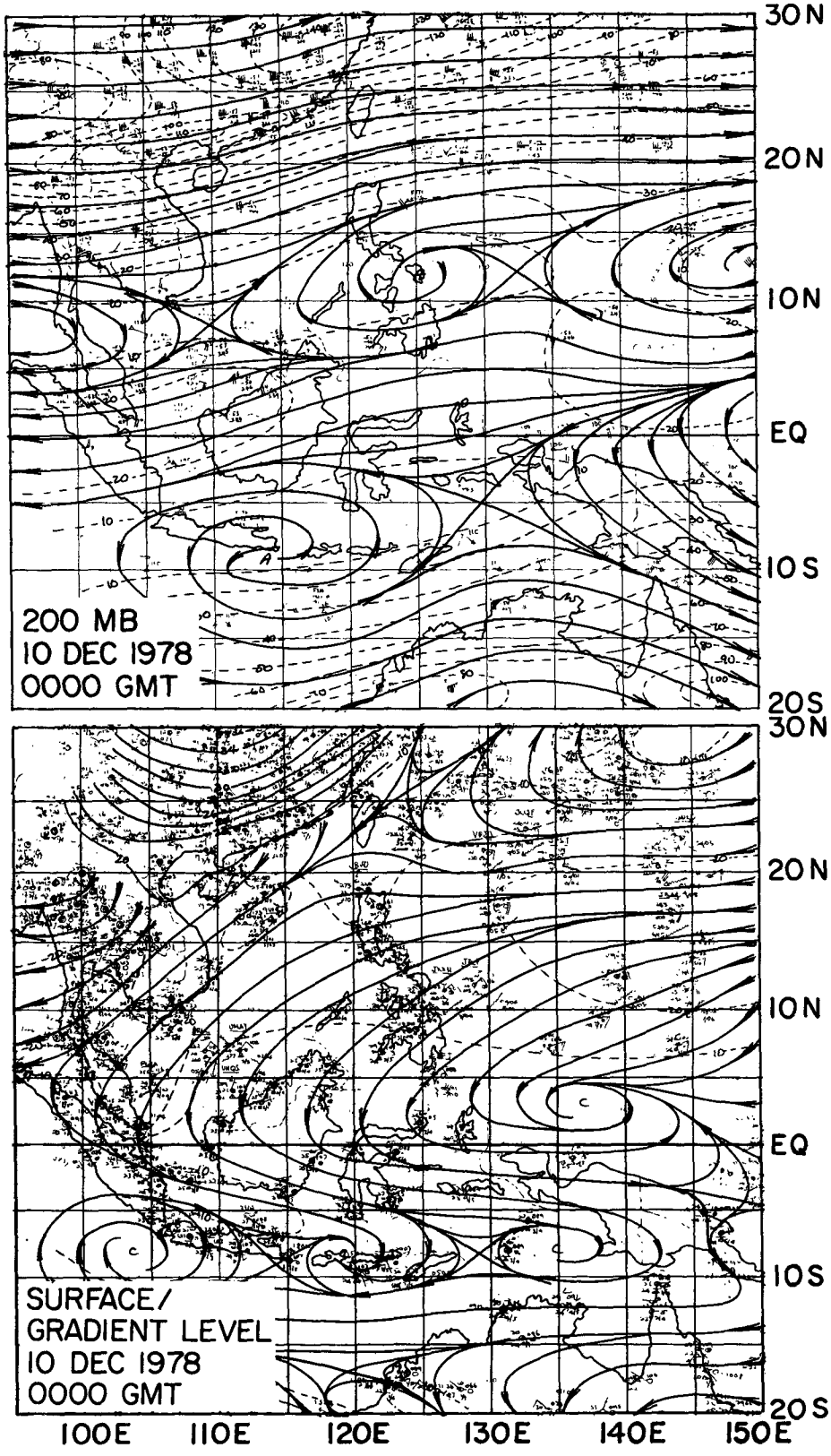

FIG. 2. Streamline analyses over the winter monsoon region at 200 mb and at low levels (surface to ~1000 m) reproduced from Sadler (1979). Dashed lines are isotachs in kt (1 kt ≈ 0.5 m s^{-1}). 0000 GMT = 0800 LST at 110°E.

northeast monsoon flow existed over the South China Sea with an anticyclone aloft at 200 mb over the central Philippines.

The diurnal regularity of convection to the north of Borneo is striking, as discussed by Houze *et al.* (1981) and Johnson and Priegnitz (1981). Convective activity offshore normally begins approximately at midnight as a group or cluster of cumulonimbus clouds slightly north of the Bintulu area. The development of these clouds is probably a consequence of low-level convergence (in a conditionally-unstable atmosphere) between the northeast monsoon flow and the nighttime land breeze off the Borneo land mass. By 0800 LST this cluster has evolved into a mesoscale (~100–500 km) upper-tropospheric stratiform cloud shield (with some cumulonimbus clouds still on the periphery) often enveloping the southern portion of the ship array. This mesoscale anvil later propagates to the west-northwest in the direction of the average mid- to upper-tropospheric flow with a maximum areal coverage over the ship triangle by 1400 LST (Johnson and Priegnitz). Continued movement to the west-northwest occurs while the convective system dissipates, with the clouds having mostly disappeared by 2000 LST.

4. Time series from *Ak. Korolov*

The almost daily occurrence of mesoscale convective systems to the north of Borneo, coupled with the positioning of research ships in their path has made possible the study of a number of convective events (Houze *et al.*, 1981; Johnson and Priegnitz, 1981; Johnson, 1982; Warner, 1982). As pointed out earlier, the convection normally passed over the southern portion of the ship array so that surface and sounding data from *Ak. Korolov* are of the greatest value for study of the structure and properties of the mesoscale clouds and their near environment. In fact, the repeatedly inclement weather accompanying the passage of convection over *Ak. Korolov* between 0800 and 1400 LST (0000 and 0600 GMT) during 6–17

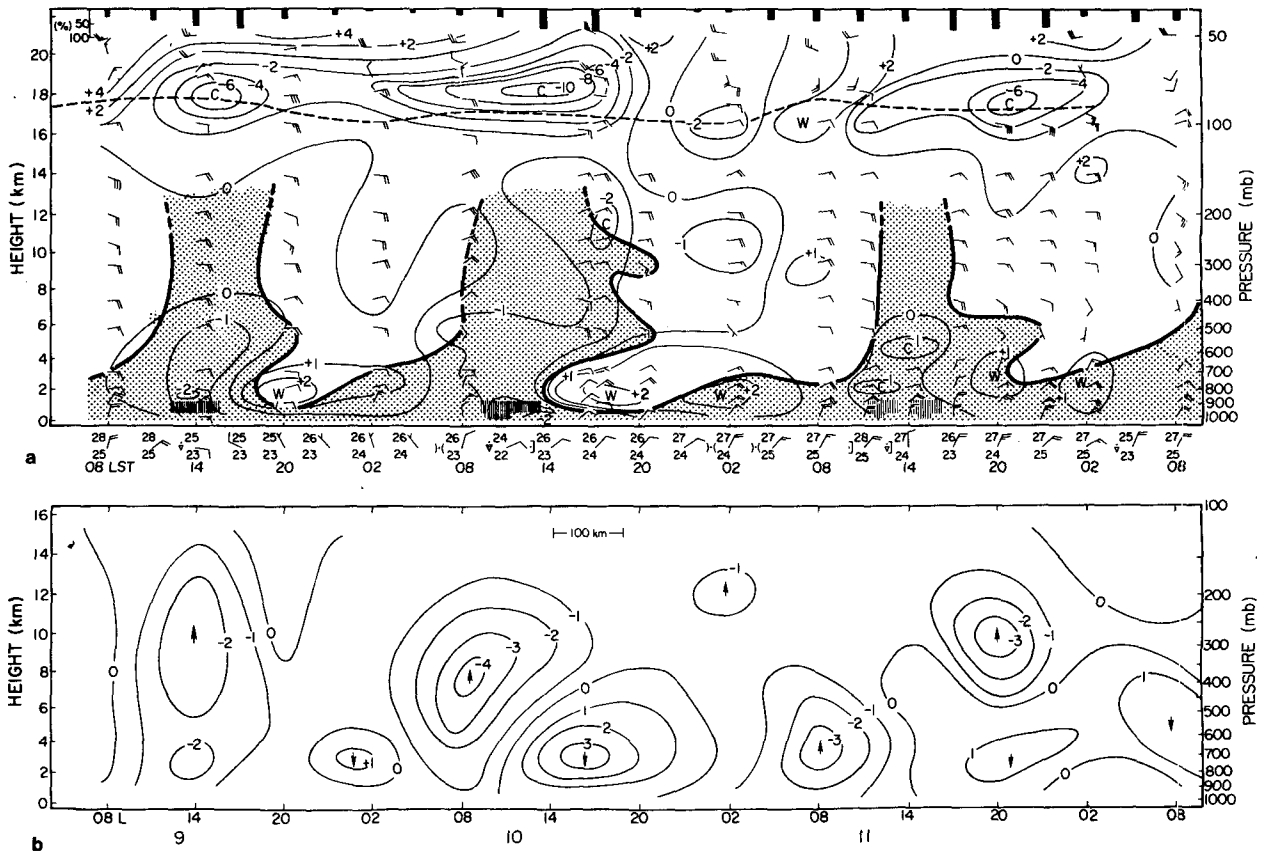

FIG. 3. (a) Rawinsonde time series at *Ak. Korolov* for the period 9–11 December 1978. Stippling denotes regions of greater than 80% relative humidity. Closely-spaced vertical lines near the surface indicate periods of rain at the ship, with longer lines representing heavy rain. Solid contours are temperature deviations (K) from the 6–28 December mean. Wind speeds are in m s^{-1} (one half barb = 2.5 m s^{-1} and one full barb 5 m s^{-1}). Horizontal dashed line near top marks the tropopause. Bars at top indicate fraction of triangle (Fig. 1) area covered by bright IR satellite cloudiness. (b) Vertical *p*-velocity in units of 100 mb day^{-1} ($\cong$1 cm s^{-1} at 950 mb and 2 cm s^{-1} at 400 mb) for the ship triangle. Distance scale indicated represents advective length scale based on ~6 m s^{-1} movement of the mesoscale anvil cloud.

December often prevented or delayed launches of the 0000 and 0600 GMT soundings. This situation led to the repositioning of the ship 1° to the south on 18 December, away from the path of the convection, where it remained for the remainder of the month (Fig. 1).

A vertical time section illustrating the passage of three convective systems on 9–11 December over *Ak. Korolov* is shown in Fig. 3. During this period, a transition from undisturbed conditions to a moderate cold surge over the South China Sea occurred (Johnson and Priegnitz, 1981). The sequence in Fig. 3 typifies those for other days during 6–17 December, but the analyses at these other times are somewhat more confused due to slight differences in the track of the mesoscale convection and a significant overall increase in convection after the 11th. The time series for 9–11 December is also presented because it is centered on the 10 December case, for which space cross-section analyses are examined later. An isolated mesoscale anvil is particularly well-developed on this day and has received attention in other studies (Houze *et al.*, 1981; Warner, 1982). Based on satellite tracking, Johnson and Priegnitz (1981) determined that, on the average, mesoscale anvils moved in a west-northwest direction at ~ 6 m s^{-1}. An advective distance scale based on this speed is presented in the figure. The plotted winds indicate the somewhat irregular spacing of the soundings caused, in part, by the precipitation events.

In the lower portion of the upper diagram, the rainfall episodes based on hourly surface data are indicated by vertical lines, with longer lines representing heavy rain. Only three-hourly surface data are plotted in the figure. Each cloud system can be approximately visualized as being enclosed within the 80% relative humidity (stippled) region. As each system passed the ship, squally weather, i.e., heavy rain, a surface wind shift and sudden cooling (~ 2°C) normally occurred at its leading edge. The cooling in the rain area in the lower troposphere is evident in the analysis of temperature deviations (°C) from the 6–28 December mean (solid labeled contours in upper diagram of Fig. 3). To the rear of the rain area, in each case, is a region of warming in the lower troposphere of up to 2°C, with maxima near 800 mb (see also Webster and Stephens, 1980). Drying (relative humidities less than 80% and nearly as low as 60% at 900 mb at 1400 LST on the 10th, as shown in Fig. 5 later) is seen to accompany the low-level warming. Based on the surface ship reports, the low-level drying and warming does not extend to the surface and only light rain, if any, reaches the surface in this region.

These lower tropospheric features very closely resemble those reported for mesoscale convection associated with tropical squall lines in the eastern Pacific (Zipser, 1969), and eastern Atlantic (Houze, 1977; Zipser, 1977). Studies in these other regions as well as the numerical modeling work of Brown (1979) indicate that the warming and drying are associated with mesoscale downdrafts beneath the anvil clouds. An analysis of vertical motion for the triangle of ships (*Ak. Korolov* is the southern vertex) reveals that indeed mesoscale subsidence in the lower troposphere is occurring on 10 and 11 December in the regions of warming and drying (lower portion of Fig. 3). That this triangle-computed vertical velocity may reflect motions on the scale of the mesoscale cloud is substantiated by the subjectively-determined large fraction of the triangle area covered by bright IR satellite cloudiness (clouds appearing virtually white on infrared satellite photographs) at the times of passage of the weather systems (bars at the top of Fig. 3).

In the upper troposphere, upward motion associated with the cloud systems is evident with peak vertical velocities near 300 mb. There are some differences in the patterns each day, but as noted by Johnson and Priegnitz (1981) and Johnson (1982), a basic picture emerges: a mesoscale updraft in the mesoscale anvil and mesoscale downdraft below, consistent with the schematic models for tropical squall lines proposed by Zipser (1969, 1977) and Houze (1977), the modeling results of Brown (1979) and the GATE squall-line composite study of Gamache and Houze (1982). The inability to obtain an identical vertical motion structure with the passage of each system is probably more related to the lack of centering of the convection over the ship triangle and errors introduced in the triangle computations of vertical motion, than to any true differences in the motion field that may exist between systems. The analysis for 10 December is most consistent with the modeled and observed structures for GATE systems mentioned above and consequently, further analysis of these data in the form of space cross-sections is given later.

The largest temperature fluctuations accompanying the mesoscale anvils are in the very high troposphere and lower stratosphere (Fig. 3). Deviations having amplitude ~ 6°C are seen with the minima located at or slightly above the tropopause (dashed line) near 18 km. Superimposed on the diurnal fluctuations for this three-day period is a longer period negative anomaly which is a reflection of warmer conditions at these levels later in the month.

Conceivably, concern might be raised that the cold anomalies are a manifestation of errors introduced by the passage of sondes through clouds and precipitation, e.g., the occurrence of riming and subsequent sublimation on the instrument. However, the saturation vapor pressure at the very cold tropopause temperatures observed is too low to permit sublimation rates large enough to account for the anomalies.

Observations of cold anomalies at the top of mesoscale anvils in tropical regions are limited. Some evidence of their collective effect on larger scales is

possibly seen in GATE tropical wave disturbance composite data (Reed, 1978). Reed cites overshooting by cumulonimbus towers as a possible cause for the observed cool anomalies in the convectively-active trough region of the composite waves, although a collection of mesoscale anvils in a large-scale region with cold anomalies above each like those illustrated in Fig. 3 (whose cold structure may not be a result of overshooting) may equally well account for the observed large-scale cooling.

There have also been reports of such features above midlatitude mesoscale convective systems (e.g., Fritsch and Maddox, 1981; Ninomiya *et al.*, 1981). At midlatitudes, some investigations into the physical mechanisms which cause the cold anomalies have been made (Fritsch and Brown, 1981). Fritsch and Brown, in a numerical modeling study, conclude that cumulonimbus overshooting may play a role, but is *not* a *necessary* condition for near-tropopause cooling to exist. It has been found by these authors that with or without cumulonimbus overshooting, *forced mesoscale ascent* near the tropopause can lead to cooling there. Further studies appear to be necessary to sort out the relative importance of different scales of vertical motion processes in cooling, atop mesoscale convective systems.

Yet another process which may account to a large degree for the observations shown in Fig. 3 is cloud-top radiative cooling (Albrecht and Cox, 1975; Cox and Griffith, 1979; Griffith *et al.*, 1980; Webster and Stephens, 1980). The magnitude of the cloud-top cooling seen during the passage of the Winter MONEX mesoscale anvils is consistent with the radiative cooling rates computed by Cox and Griffith (1979) and Griffith *et al.* (1980) for GATE mesoscale cloud clusters and by Webster and Stephens (1980) for the Winter MONEX mesoscale cloud systems. In these studies, the cooling is attributed to longwave radiation to space from the tops of the high-level cloud layer. This argument seems plausible, but two complicating factors in the Winter MONEX observations need explanation.

First, Griffith *et al.* (1980) find the maximum radiative cooling rates to occur in the upper portion of the high cloud layers with very little cooling above the clouds themselves. As best as can be determined, however, the observed cooling maxima in the Winter MONEX region occur ~1–2 km above the mesoscale anvil top. Using aircraft photogrammetry, Warner (1981, 1982) has determined an average mesoscale anvil top height of 12.5 km (~200 mb) for 10 December. Indirect estimates from Japanese GMS IR data indicate that, at their highest, the tops of these extensive cloud shields are between 150 and 100 mb (~14 and ~17 km), with occasionally a few embedded isolated tops extending above 100 mb (Webster and Stephens, 1980; Warner, 1982, Fig. 13). It must be recognized, however, that cloud top estimates from IR satellite data, for reasons ranging from resolution limitations to cloud mixing effects, may give a quite ambiguous determination of cloud-top height (e.g., Adler and Markus, 1982). All available data from aircraft and radar in the experiment indicate that the maximum tops of cumulonimbus clouds, which contain much stronger updrafts than the mesoscale anvils, are no higher than 100 mb (Warner, 1982), although it is possible that a few penetrated 100 mb and simply were not sampled. This information strongly suggests that the maximum cooling is concentrated at or above the extensive mesoscale anvil top, not within the cloud itself.

Preliminary radiative transfer calculations by Professor S. K. Cox (personal communication, 1982) indicate that the only plausible radiative explanation for the observed cooling is one that requires an injection into the lower stratosphere of a small amount of ice. Using the broadband infrared radiative transfer model described in Griffith *et al.* (1980), Cox has determined that the establishment of a ~1 km thick ice cloud layer in the lower stratosphere near the level of maximum cold anomalies in Fig. 3 (~80 mb) having an ice water content of 0.05 g m^{-3}, with the thin layer residing above a deep cloud layer whose top is at 150 mb, can produce a cooling rate integrated over the thin ice layer of the same magnitude as the observed cooling. Of course, weak circulations may develop in the lower stratosphere to compensate the radiative effects, and the sensible cooling that is observed may be somewhat different than that given by radiative forcing alone since it represents the net effect of all processes that occur. The few overshooting convective towers that occur may account for the injection of the ice, which should have a long residence time at these cold levels where the saturation water vapor pressure is very low.

Again, the above hypothesis is only one of several possible, and the role of radiative cooling relative to adiabatic expansion cooling by overshooting towers and mesoscale ascent is yet undetermined. Direct aircraft measurements of the complete field of cloud top heights and ice concentrations near the tropopause were not available during Winter MONEX, preventing a more precise investigation of the role of radiative and vertical motion processes.

The second complication on the radiative question is the fact that strong cloud-top cooling is evident around mid-day (Fig. 3), at which time shortwave heating near cloud top should largely offset longwave cooling (Webster and Stephens, 1980). Of course, it is possible that the observed cooling may reflect a recovery from a much stronger cooling that occurred earlier during the development of the mesoscale anvil before sunrise in combination with advective changes. The extent of the cooling prior to the arrival of the cloud system at *Ak. Korolov* cannot be determined from the available data.

The character of this cloud-top cooling as viewed on a tephigram is illustrated in Fig. 4 for 10 December at *Ak. Korolov*. On this day, as on many others, the mesoscale anvil cloud developed between 0200 and 0800 LST off the Borneo coast and extended out to *Ak. Korolov* by 0800 LST. Particularly noteworthy is the significant cooling, ~5°C in 6 h, near the tropopause. The strongest high-level cooling is at 1600 LST, and at the same time warming in the lower troposphere atop the boundary layer is evident.

The study of Webster and Stephens also finds that considerable longwave warming should occur near the bases of the anvil clouds (600 to 500 mb or 4–5 km). They remark that, based on the work of Leary and Houze (1979b), cooling rates associated with hydrometeor melting may frequently be sufficient to largely offset the radiative warming near cloud base. The observations in Fig. 3 show very little evidence of a warming near cloud base; in fact, a slight cooling of ~1°C appears to be present.

In summary, the largest temperature fluctuations accompanying the passage of mesoscale convective systems over the southern South China Sea occur near the tropopause or in the lower stratosphere. Fluctuations of secondary magnitude occur in the lower troposphere, associated with rainfall evaporation and mesoscale downdrafts. Although a radiative explanation for the high-level fluctuations based on longwave cooling from the mesoscale anvil cloud top may appear plausible, it does not give a maximum cooling at levels as high as those observed. An alternative radiative explanation involves the injection into the lower stratosphere of a small amount of ice, presumably by overshooting cumulonimbus clouds. The relative contributions of radiative processes, cumulonimbus overshooting and forced mesoscale ascent to the production of cold anomalies atop mesoscale anvil systems is not yet known and further study is required.

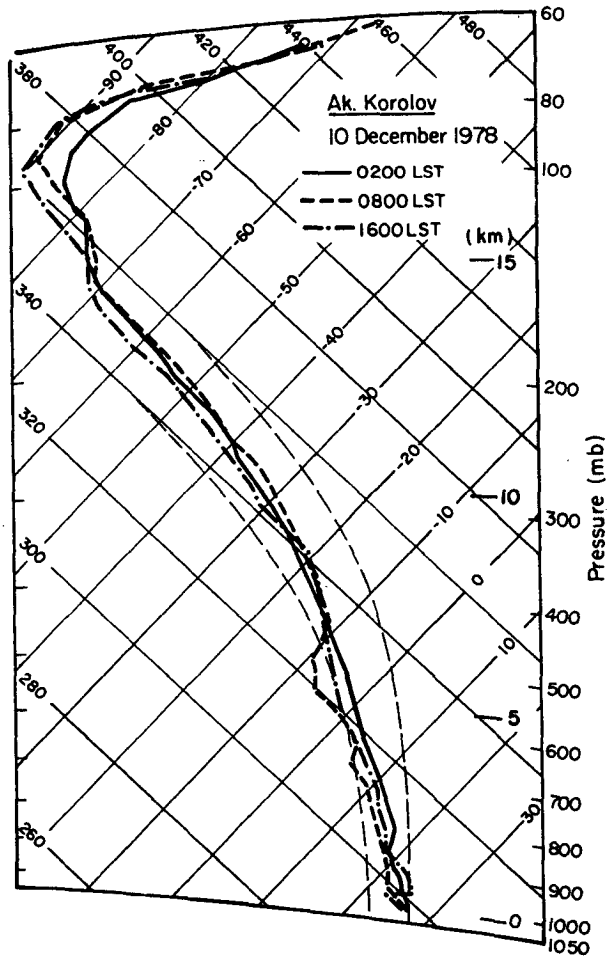

FIG. 4. Tephigram plot of temperature soundings at *Ak. Korolov* prior to and during the passage of mesoscale anvil system on 10 December. Thin dashed lines are pseudoadiabats.

5. Cross-section analysis of mesoscale convection for 10 December

A particularly well-developed, isolated mesoscale anvil system passed through the southern portion of the ship array on 10 December (Houze *et al.*, 1981; Johnson and Priegnitz, 1981; Warner, 1982). It developed as a cluster of cumulonimbi immediately after midnight off the north Borneo coast near Bintulu (Fig. 1), grew to mesoscale dimension by 0800 LST and, based on tracking by satellite, propagated during the early afternoon to the west-northwest at ~6 m s^{-1} across the southern portion of the ship array, later dissipating over the South China Sea. In this section, rawinsonde, dropwindsonde, radar and satellite data will be used in an effort to depict the evolution of the mesoscale cloud system.

Four cross-sections on 10 December at six-hour intervals have been constructed along the approximately straight line formed by two ships *Priliv* and *Ak. Korolov*, and the land station Bintulu (Fig. 5). Data from the MIT radar at Bintulu are shown as reflectivities and satellite IR estimates of cloud top are indicated. The field of relative humidity has been analyzed (solid curves) to assist in defining the location of the mesoscale cloud system. Wind components (m s^{-1}) in the direction of motion of the convective system or in the plane of the section (approximately perpendicular to the Borneo coastline) are shown by dashed lines in Fig. 5. Shaded regions represent flow toward Borneo. Dropwindsonde data from the *Electra* research aircraft have been used in the analysis from ~400 mb to the surface at the positions indicated. When viewing the sections, keep in mind that the convective system moves approximately in the plane of the figure from right to left at ~6 m s^{-1}.

As seen in Fig. 5, reflectivity data from the MIT radar at Bintulu indicates coverage of the cloud sys-

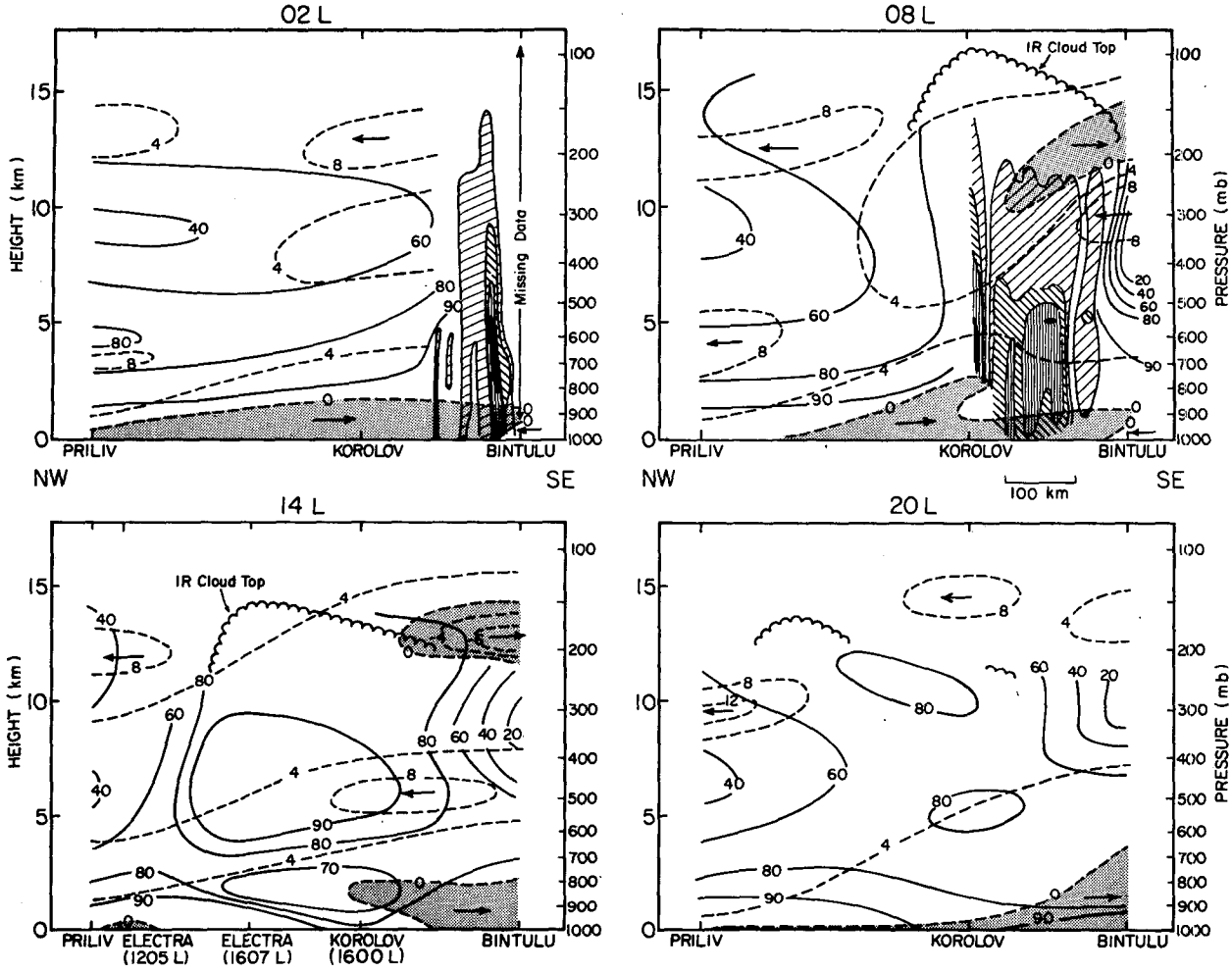

FIG. 5. NW–SE vertical cross-sections from *Priliv* to Bintulu at six-hourly intervals for 10 December. The MIT WR73 C-band weather radar was based at Bintulu. The outside radar contour is for the minimum detectable echo with the inner contours for 27, 33 and 39 dB(Z). Solid labeled contours indicate relative humidity (%) and dashed contours represent the wind component (m s^{-1}) in the plane of the section. Light shaded regions indicate flow from left to right toward the Borneo coast. Estimates of cloud top based on IR satellite data are shown.

tem only for the first two periods, 0200 and 0800 LST, since the convection moves beyond the range of the radar by 1400 LST. The convective-scale or cumulonimbus character of the convection at 0200 LST is apparent with high reflectivities extending to the upper troposphere. These clouds originate in a localized region of convergence along the coastline as low-level onshore flow (shaded region) meets the Borneo nighttime land breeze (Houze *et al.*, 1981; Johnson and Priegnitz, 1981). By 0800 LST the convection expands to cover a ~400 km region as viewed by satellite with deep cumulonimbus activity still evident at the limiting range of the Bintulu radar.[2] However, in the intervening region nearer to the coastline, a quite different pattern appears, namely, a zone of mostly horizontally-stratified precipitation. A rapid drop-off in reflectivity above the freezing level (~550 mb) over a ~100–200 km region is seen with a "bright band" (Leary and Houze, 1979a,b) structure present over part of this area. The radar observations for 10 December have been discussed in detail by Houze *et al.* (1981).

Surface data from *Ak. Korolov* show a sudden increase in winds and heavy rain beginning between 0900 and 1000 LST and continuing until 1100 LST. Light precipitation follows for the next several hours ending at 1400 LST (Fig. 3). During this period, the mesoscale anvil passes over *Ak. Korolov* and its presence along with a dry mesoscale downdraft (cf. Fig. 3) in the lower troposphere is evident at 1400 LST (Fig. 5). The analyses at 0800 and 1400 LST show the flow to strongly diverge away from the anvil top

[2] In a recent, more detailed analysis Colleen Leary (personal communication, 1982) has found that the distant cumulonimbus echo at 0800 LST in Fig. 5 extends at least to ~15–16 km altitude.

near 200 mb and converge near the anvil base in the mid-troposphere. This pattern of divergence and convergence is also seen in a vertical section (not shown) perpendicular to the one in Fig. 5 (through *Ak. Shirshov*, *Ak. Korolov* and Kuching). As noted in Johnson and Priegnitz (1981) as well as many other studies, these circulations are necessary if a mesoscale updraft superimposed on a mesoscale downdraft is to occur. Low-level divergence is present over the region in the afternoon and early evening as the Borneo sea breeze fully develops.

Assuming a 6 m s^{-1} movement and using the estimated mesoscale anvil vertical velocity computations of Johnson (1982), streamlines depicting the *relative* flow field for the mesoscale anvil have been determined (Fig. 6). At 1400 LST the anvil appears to be largely decoupled from the boundary layer with inward, upward and outward motion in the cloud itself and downward motion below the cloud out the rear of the system. The subjective analysis in the region between the two Electra dropwindsonde reports is not completely reliable and there may, in fact, still be some remaining cumulonimbus convection on the leading edge of the cloud system (Warner, 1982). In fact, later, at ~1600 LST, considerable redevelopment of cumulonimbus convection occurs within the ship triangle area (Warner). Keeping these limitations of the analysis in mind, we remark that the circulation associated with anvil cloud itself closely resembles that inferred for tropical squall lines in the eastern Pacific by Zipser (1969) and in GATE by Houze (1977) and Zipser (1977) and is consistent with the schematic for these Winter MONEX systems presented by Houze *et al.* (1981, Fig. 16). The relative flow field, including inflow in the mid-troposphere to the rear of the anvil, is strikingly similar to that found recently by Gamache and Houze (1982) in a composite analysis of a GATE squall line. It appears as though, despite their geographical differences, tropical squalls and associated mesoscale anvils in both tropical regions have very similar structural and dynamic characteristics.

6. Thermodynamic properties of the environment bearing on mesoscale anvil development

Mechanisms which account for the rather rapid transformation of groups or clusters of cumulonimbus clouds into mesoscale anvil systems, such as those observed in the tropical Winter MONEX region (Houze *et al.*, 1981) or at midlatitudes (Maddox, 1980), are not well understood. As noted earlier, the development of mesoscale anvils in Brown's (1979) model was strongly enhanced by the establishment of a conditionally-unstable lapse rate in the upper troposphere through detrainment of high-θ_e air by embedded or neighboring cumulonimbus clouds.

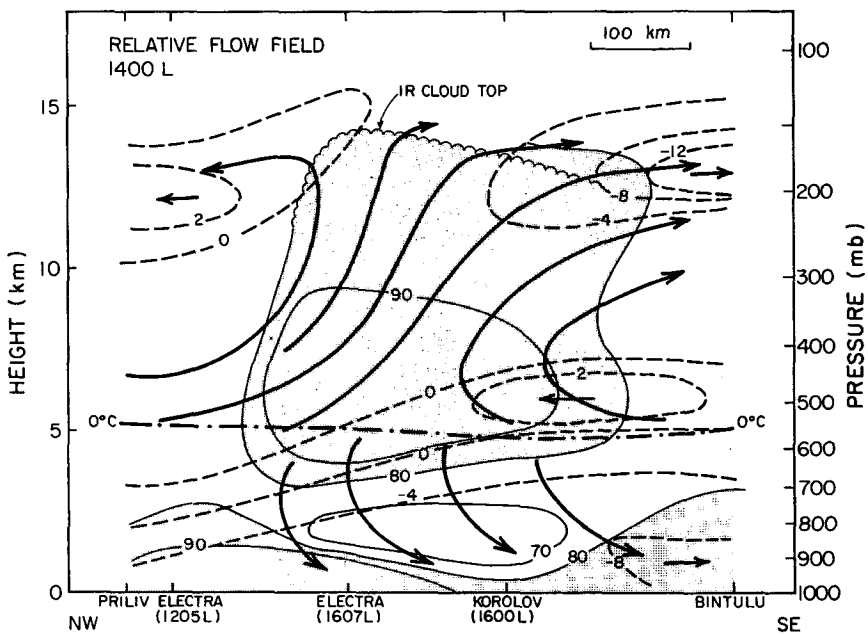

FIG. 6. NW–SE cross-section of mesoscale anvil system at 1400 LST. Streamlines, which indicate the flow relative to the anvil cloud, have been determined by assuming a 6 m s^{-1} movement from right to left, and using the vertical velocity for the anvil system at this time computed in Johnson (1982). Solid contours indicate relative humidity with shading for values greater than 80%. The horizontal component of the wind (m s^{-1}) in the plane of the section is shown by dashed lines. Data from Electra dropwindsondes extend from ~450 mb to the surface.

As is well known (Holton, 1979), the lower troposphere over most of the tropics is conditionally unstable. The Winter MONEX region is no exception, as is illustrated in Fig. 7 ($\partial\theta_{es}/\partial z < 0$ implies conditional instability, where θ_{es} is the saturation equivalent potential temperature). The Fig. 7 soundings for the 9–11 December period at *Ak. Korolov* represent late night (0200 LST) and afternoon (1400–1700 LST) conditions prior to and during or subsequent to the passage of mesoscale anvil systems at the ship. Conditional instability over most of the depth of the lower troposphere (below ~600 mb) is present for the 9–11 December period and is evident in mean soundings (not shown) for the entire field phase period. On the 11th at 0200 LST conditional instability extends all the way to ~300 mb (~9 km). This situation is rare and does not show in the mean soundings for the period.

From Fig. 7, neglecting ice processes, the upper troposphere from ~5 to 10 km is weakly to moderately stable to moist ascent (with the exception of 0200 LST on the 11th). The afternoon profiles (1400–1700 LST), characteristic of conditions within or just following the passage of mesoscale anvils (ship triangle at these times is 61, 76 and 59% covered by bright IR cloudiness on 9, 10 and 11 December, respectively), show more stability in the upper troposphere than the profiles at 0200 LST, which are generally characteristic of the atmosphere prior to mesoscale anvil development (IR cloud coverage 0,0 and 9%, on 9, 10, 11 December, respectively). The observations thus suggest that the upper troposphere is stabilized by the mesoscale convective activity. On the few days during December that did not have a mesoscale convective system pass over *Ak. Korolov*, stabilization as shown in Fig. 7 did not occur over the same time interval. Since θ_{es} at each level is a function of temperature only, the profiles in Fig. 7 show that this stabilization can, to some degree, be accounted for by cooling below ~500 mb (~6 km). This cooling can be attributed to the evaporation of precipitation and, additionally, just below the freezing level (~550 mb or 5 km), to the melting of hydrometeors. Cooling due to melting can often be seen in soundings through tropical rain systems (as discussed by Riehl, 1979) and has been quantitatively analyzed in GATE precipitation events by Leary and Houze (1979b). The stabilization can also be partly attributed in some instances to warming in the upper troposphere (Fig. 7), which may be a result of condensational heating and freezing within the mesoscale anvils and associated sinking in their environment.

If effects of freezing are included in the upper troposphere, i.e., an ice adiabatic process is considered (e.g., Riehl, 1979, p. 377), nearly neutral (to moist ascent) or conditionally-unstable conditions can be

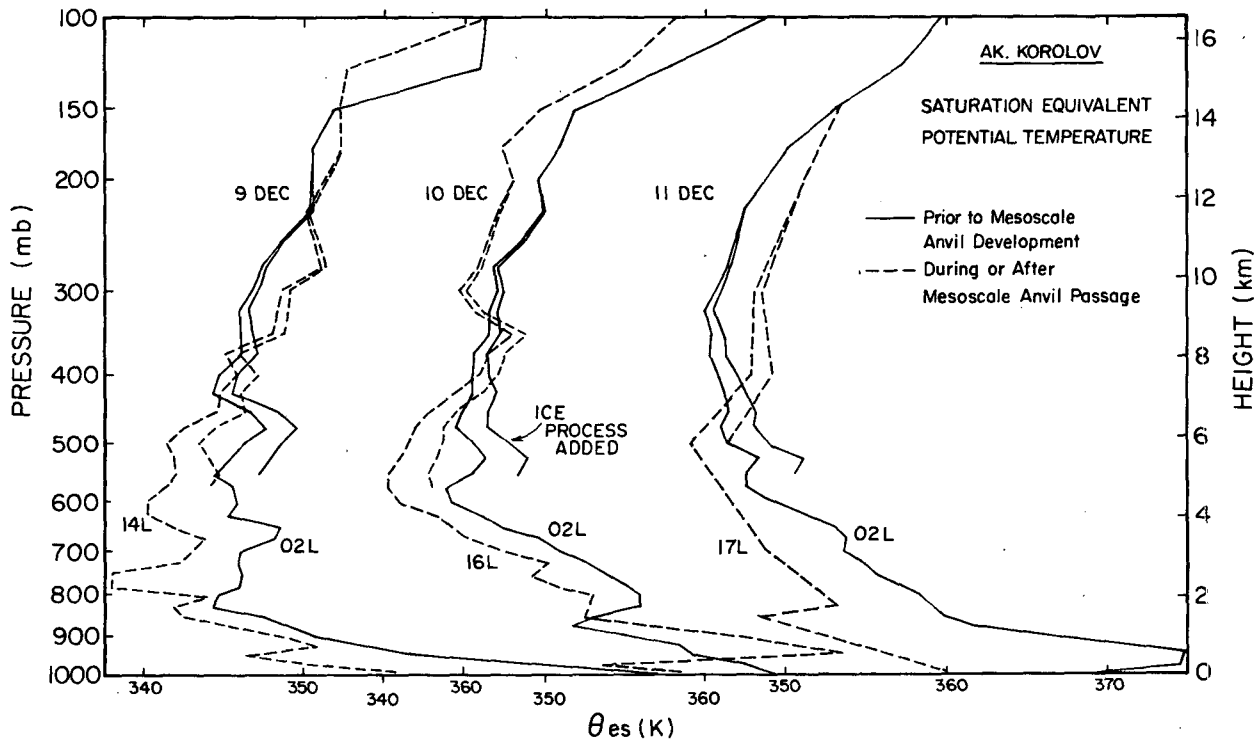

FIG. 7. Soundings of saturation equivalent potential temperature θ_{es} at *Ak. Korolov* for 9, 10 and 11 December depicting the thermodynamic state prior to (0200 LST) and during or subsequent to (1400–1700 LST) mesoscale anvil development. Curves originating in the mid-troposphere include the effects of ice processes.

seen in each of the soundings to extend to approximately 10 km or 250 mb, not just to the mid-troposphere. Importantly, the point is being made here that nearly the entire troposphere, prior to the development of mesoscale anvil clouds, is conditionally unstable. The rapid growth of extensive anvil clouds might be encouraged when conditional instability extends to the mid- to upper troposphere, as it does here. This statement might be particularly true if mid-tropospheric convergence, often seen accompanying mature mesoscale anvils (Johnson and Priegnitz, 1981; Gamache and Houze, 1982), develops concurrently with the embryo anvil growth, thereby possibly forcing new convective-scale cells in a nearly-saturated mid-to-upper troposphere. *Such a process might be referred to as a type of cooperative instability mechanism whereby cloud processes (melting and evaporation at low levels and condensation and freezing at upper levels) drive a larger-than-cloud-scale circulation (mid-tropospheric convergence forced by vertically-diverging airstreams) which, in turn, feeds back to enhance cloud growth.*

Our findings suggest that the effects of freezing on mesoscale anvil development are important and probably should be included in future models of their growth. The relative roles played by radiation, latent heat and dynamical processes in the formative and intensifying stages (Leary and Houze, 1979a) need further study. Houze (1982), following the work of Webster and Stephens (1980), has already made initial attempts to arrive at realistic estimates of relative roles of processes involved in the maintenance of mature mesoscale anvils.

The existence of neutral to weakly conditionally-unstable (to ice adiabatic ascent) soundings through a deep layer of the upper troposphere of this region can be partly attributed to the very high and cold tropopauses that are observed. The December average tropopause height and temperature are 90 mb (~17 km) and −90°C, respectively. The temperature soundings in Fig. 4 are typical examples. Similar temperature structures over Indonesia have been reported by Stepanova (1959) and over the tropical western and eastern Pacific by Jordan (1960). Soundings from GATE suggest similar conditions are prevalent in the eastern Atlantic, although the tropopause is ~2 km lower and ~10°C warmer than in the Winter MONEX area. These conditions may assist the development of similar mesoscale anvil cloud and rain systems in these areas (e.g., Zipser, 1969; Houze, 1977; Zipser, 1977; Riehl, 1979), although other factors must surely play important roles.

7. Summary and conclusions

An analysis of the thermodynamic and airflow characteristics of Winter MONEX mesoscale convective systems has been carried out. In the region over the South China Sea slightly to the north of Borneo, a considerable number of mesoscale anvil cloud systems (Houze *et al.*, 1981; Johnson and Priegnitz, 1981) developed and passed through an array of three Soviet research vessels during the experiment. Sounding data from these ships, land stations and aircraft have been used to determine some important features of these cloud systems.

The main findings of this study are:

1) The strikingly regular diurnal development of mesoscale convection along the north coast of Borneo as a result of the interaction of the northeast monsoon flow with the Borneo land breeze (Houze *et al.*, 1981; Johnson and Priegnitz, 1981) has been further documented. Based on rawinsonde time series and cross-sections it has been determined that these systems resemble in many respects squall lines observed in other tropical oceanic regions (e.g., those found in the eastern Pacific and Atlantic: Zipser, 1969, 1977; Houze, 1977; Gamache and Houze, 1982). These Winter MONEX convective systems, during their mature stages, are characterized by lines of cumulonimbus clouds along their leading edges and trailing mesoscale (~200–500 km horizontal dimension) anvils based near the freezing level (5 km) extending to near the tropopause. Mesoscale lifting occurs in the anvil clouds with a mesoscale downdraft below producing a warm, dry region over a large area just above the boundary layer. Air flow relative to the anvil on both its leading and trailing edges is inward near its base (in the mid-troposphere) and outward near its top (Fig. 6). Mesoscale downdraft air flows out to the rear of the system. These circulation features are consistent with those found in a composite study of a GATE squall line by Gamache and Houze (1982).

2) Significant cold anomalies (amplitude ~ 6°C) atop the mesoscale anvils are observed with a peak cooling at the tropopause or in the lower stratosphere. The maximum cooling is observed accompanying the passage of the anvils at *Ak. Korolov* (Fig. 3) in the early afternoon. All available data strongly suggest that the maxima are situated *above* the tops of the mesoscale anvil clouds.

3) The upper troposphere in the Winter MONEX area prior to the development of mesoscale anvil clouds is nearly conditionally unstable, if ice processes are considered. As a consequence, it can be said that, at this time, nearly the entire troposphere to ~10 km or 250 mb is in some sense conditionally unstable. This thermodynamic stratification may assist the rather rapid development of mesoscale anvil clouds from initial groups or clusters of cumulonimbus clouds, particularly if mid-tropospheric convergence accompanies the embryo anvil growth.

4) Ship soundings show evidence of considerable stabilization in the upper troposphere during and subsequent to the anvil passage. Possible causes of the

stabilization include cooling by melting hydrometeors near cloud base and warming at higher levels due to condensation, freezing or cloud environment sinking.

The main purpose of this paper has been to document the thermodynamic and air flow characteristics of tropical mesoscale convective systems in the Winter MONEX region in such a way that some light may be shed on their initiation and maintenance. The fact that they start as cumulonimbus elements forced by localized convergence associated with the land breeze at night along the north coast of Borneo seems quite clear (Houze *et al.*, 1981; Johnson and Priegnitz, 1981). However, the mechanisms leading to the transformation of the cumulonimbus clouds to an extensive mesoscale anvil cloud system in a matter of a few hours are not so clear. To some extent, of course, the initial growth and expansion of the mesoscale anvil is accomplished by the incorporation of cloud and precipitation debris from dissipating cumulonimbi into a larger-scale rain system (Leary and Houze, 1979a). It is suggested in this study that the rapid growth of mesoscale anvils may also be assisted by the conditional instability of the cloud environment and mid-tropospheric convergence forced by cloud microphysical processes (melting and evaporation below the anvil base with freezing and condensation above); however, certainly not all questions pertaining to their growth have been answered. In particular, the possible role of radiative destabilization of upper-tropospheric cloud layers in mesoscale anvil development (Cox and Griffith, 1979; Webster and Stephens, 1980; Houze, 1982) needs to be addressed in greater detail. The relative roles played by radiative, thermodynamical, dynamical and microphysical process in mesoscale anvil cloud evolution will not be precisely known until more refined observational, analytical and numerical studies are carried out.

Questions on radiative processes have been raised by the observations reported in this study of cold anomalies above Winter MONEX mesoscale anvils. Since these anomalies appear to be centered ~1–2 km above mesoscale anvil top, cloud-top longwave radiative cooling, which is a maximum within the cloud just below cloud top (Griffith *et al.*, 1980; Webster and Stephens, 1980), does not appear to be capable of explaining them. Some preliminary radiative transfer calculations (S. K. Cox, personal communication, 1982) suggest that the only radiative explanation for the cooling in the lower stratosphere is one that requires the injection of a small amount of ice into this region by the convection below. The occasional cumulonimbus clouds which overshoot into the stratosphere may account for this injection. Satellite IR data cannot be used unambiguously to confirm or reject this hypothesis, nor to obtain a precise estimate of mesoscale anvil cloud top. Coupled with this uncertainty are two possible dynamical mechanisms which may contribute to the anvil-top cold anomalies: 1) overshooting by individual cumulonimbus clouds and 2) forced mesoscale ascent near the tropopause (Fritsch and Brown, 1982). Direct measurements by aircraft, bearing on these questions (as accomplished only partially during GATE; Griffith *et al.*, 1980), would be extremely valuable.

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