Short-Term Variations of the Tropopause Height over the Winter MONEX Area

RICHARD H. JOHNSON

Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523

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ABSTRACT

An observational study of short-term (~1 week) tropical tropopause height variations has been undertaken using measurements from the December 1978 Winter Monsoon Experiment (Winter MONEX). Sounding data from three Soviet ships in the southern South China Sea and conventional rawinsonde stations in the region of the Indonesian maritime continent are used in the analysis.

During a one-week period (10–17 December), a ~1.5 km reduction in the height of the tropopause and a warming of 5–8°C in the lower stratosphere were observed over the southern South China Sea. Outside this region a systematic lowering of the tropopause was not observed. In the region of tropopause descent there was a concurrent increase in the amount of deep convective activity. Within the time period of these events, two winter monsoon cold surges (on the 10th and 15th) and a weak tropical depression (on the 14th) affected the circulation over the South China Sea.

During the period of tropopause lowering, tropospheric pressure height and surface pressure falls (having amplitudes ~20 m and 4 mb, respectively) were observed over the northern South China Sea. These observations suggest that the tropopause descent and lower-stratospheric warming may be a consequence of regional dynamical processes which are analogous to those occurring during the development of cyclones at midlatitudes. While dynamical processes seem to be a likely explanation for the observed variations, other processes related to the increased convective activity in the region may also play a role. Several such mechanisms are discussed.

1. Introduction

Deep convection in the tropics plays an important role in maintaining the high tropopause observed in the earth's equatorial regions. The long-term mean position of the tropical tropopause can be explained reasonably well in terms of a condition of radiative-convective equilibrium so long as deep convection is considered the primary convective process. Short-term variations, as, for example, observed in midlatitudes in association with baroclinic waves and, on shorter time scales, in connection with overshooting cumulonimbus tops, are less well documented in tropical regions, but may be of importance in the exchange of water vapor and trace constituents between the troposphere and stratosphere. It is the purpose of this paper to examine relatively short term (~1 week) variations in the tropical tropopause height and their relationship to deep convection using observations taken from the December 1978 field phase of the Winter Monsoon Experiment (Winter MONEX) over the Indonesian maritime continent region.

2. Background

a. Mean conditions and long-term variations

The temperature structure of the troposphere and lower stratosphere has been investigated with some success using one-dimensional radiative–convective equilibrium models. The first efforts of this nature (Manabe and Strickler, 1964; Manabe and Wetherald, 1967) attempted to include some of the effects of deep convection by adjusting tropospheric lapse rates to a standard value. The tropopause height obtained by this approach was higher than that given by a pure radiative equilibrium model (Manabe and Moller, 1961), but it was still lower than that observed. Later work by Schneider (1977) showed that effects of deep convection should be included explicitly in such calculations of tropopause height. Employing a Newtonian cooling parameterization of the radiative heating, Schneider demonstrated that the tropopause height can be expressed as being directly proportional to the mass flux in deep cumulus clouds. This concept was used by Sarachik (1978) in an equilibrium calculation of the tropical sea surface temperature based on a one-dimensional, coupled atmosphere–ocean model.

A relationship between deep cumulus activity and tropopause height has also been recently suggested by Reid and Gage (1981). These authors have reported a ~1-km annual variation in tropopause height throughout the tropics, with the highest values occurring during the Northern Hemisphere winter and early spring and the lowest during the northern summer. Reid and Gage propose that this oscillation is a consequence of an annual variation in the vertical energy transport by deep convection or hot towers (Riehl and Malkus, 1958) in response to the annual cycle in surface insolation (due to the annual variation in earth–sun distance). An alternate or additional factor that may relate to the changes in the tropopause height is the strong seasonal cycle in the intensity of the Northern Hemisphere Hadley cell, with an associated maximum lower-stratospheric cooling occurring during the northern winter when the Hadley cell upwelling is most intense (Newell et al., 1969; Reed and Vlcek, 1969; Dickinson, 1971; Manabe and Mahlman, 1976).

Several of the above studies suggest that on long time scales (~1 year) there may be a direct relationship between the intensity of deep convection and tropopause height in the tropics. Whether such a relationship exists or not, details of the mechanisms by which convection influences the tropopause height are not well known.

b. Short-term variations

Observations of short-term (~1 week or less) variations of the tropopause height in the tropics in association with deep convection are limited. It is well known that individual cumulonimbus frequently overshoot their level of zero buoyancy and penetrate a short distance into the lower stratosphere. The integrated effects of many over-shooting cumulonimbus on the tropopause, however, have not been documented. Above "mesoscale anvil" cloud systems observed during Winter MONEX near Borneo (stratiform cloud systems of ~500 km horizontal dimension and extending from the 0°C level to the upper troposphere; Houze et al., 1981; and Johnson and Priegnitz, 1981), a slight upward bulging (by about 0.5 km) of the tropopause was often observed to occur (Johnson and Kriete, 1982). In these instances significant cool anomalies were observed atop the anvils. The causes of these anomalies are still a matter of speculation.

Such short-term variations in the tropopause height may bear directly on at least two important problems: energy sources for stratospheric motions (Holton, 1972) and transport of water vapor from the troposphere to the stratosphere. Concerning the latter issue, Brewer (1949) has argued that water vapor transport must occur in the equatorial "cold trap," where upward flowing air can be freeze-dried to a sufficient extent to account for the extremely low water vapor mixing ratios observed in the lower stratosphere. The upward water vapor transport in the Hadley cell is accomplished by hot towers (Riehl and Malkus, 1958; Robinson, 1980) and their effect on the water vapor distribution of the lower stratosphere depends on the local tropopause temperature as well as the rate of injection of ice crystals into the stratosphere (Kley et al., 1979, 1982; Danielsen, 1982; Knollenberg et al., 1982; Kuhn, 1982; Holton, 1984).

Recently, some rather detailed measurements of cumulonimbus over-shooting have been obtained by high-altitude aircraft (NASA U-2) measurements near Panama (Danielsen, 1982; Kley et al., 1982; Knollenberg et al., 1982; Kuhn, 1982). One of the primary findings of the Panama study is that the observed water vapor mixing ratios just above the tropical tropopause are well below the saturation mixing ratio at the local tropopause temperature. Thus, local vertical transport through the tropopause with associated dehydration or freeze drying of the air cannot account for the extreme aridity of the lower stratospheric air in the Panama region. It has been proposed that the very dry conditions may be explained by horizontal transport from a much colder region, in particular, the area of the Indonesian maritime continent where the coldest tropical tropopause temperatures exist (Newell and Gould-Stewart, 1981; Atticks and Robinson, 1983; Danielsen, 1982; Kley et al., 1982). The tropopause in this region is coldest and highest during the Northern Hemisphere winter, the time period of winter MONEX.

From the above considerations, it appears to be particularly worthwhile to investigate in some detail the relationship between deep convection and tropopause height using data from Winter MONEX. Some analyses on short time scales (approximately hours to days) have already been completed (Johnson and Kriete, 1982). It is the purpose of this study to extend that earlier work to longer time and space scales over the Indonesian maritime continent.

3. Data analysis procedures

The period of this study has been chosen to coincide with the time period of the positioning of three Soviet research vessels in a triangular array off the north coast of Borneo (6–28 December 1978; Fig. 1). Six-hourly soundings are generally available from these ships and this high time resolution has permitted rather detailed study of the effects of individual mesoscale convective systems on the tropopause (Johnson and Kriete, 1982). In the present study one sounding per day (at 0000 GMT when available) is used to examine longer-period (approximately a week) variations near the tropopause level.

In addition to the Winter MONEX ship soundings, rawinsonde observations have also been obtained from the land and island stations indicated in Fig. 1.[1] Data are particularly sparse over the Indonesian maritime continent where only a few stations exist and several of those that report do so very irregularly (e.g., 97014, 97180, 97724). The data sparsity in this region leads to serious difficulties in the analyses there.

Tropopause levels were generally recorded with each sounding; however, in a few instances they were not reported or were obviously in error, in which case additions or corrections were made. The standard con-

[1] Observations from the First GARP Global Experiment (FGGE) data archive provided by the National Center for Atmospheric Research, Boulder, CO.

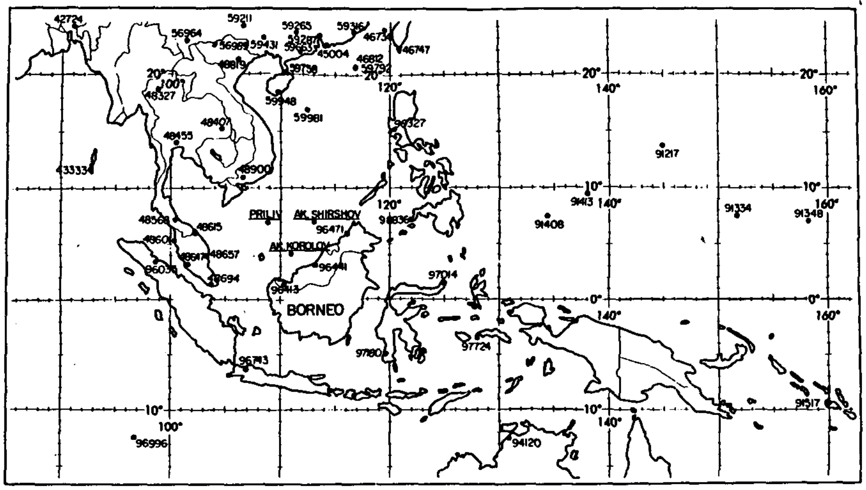

FIG. 1. Sounding stations used in this study during 6–28 December portion of field phase of Winter MONEX. The Soviet ship *Ak. Korolov* moved 1° south of plotted position on 18 December.

vention (WMO, 1960) was used to define tropopause height, and this level normally corresponds to the level of the minimum temperature.

Satellite data were obtained from the Japanese Geostationary Meteorological Satellite (GMS-1).

4. Large-scale mean conditions

While the primary focus of this study will be on the variations of tropopause height in the Winter MONEX intensive observing area over the South China Sea, it is important to first examine the large-scale conditions over the entire region during the period of study.

In Fig. 2 the flow at the tropopause level (~90 mb or 17 km) is depicted at 0000 GMT on 15 December, about the middle of the period of study. A large anticyclone is present over the western Pacific with a ridge axis between 10° and 15°N. The flow at this level on this date closely resembles that observed at other times during the month and is also very similar to the average 200-mb flow for the entire winter (Sadler, 1979; Sumi and Murakami, 1981).

The average tropopause height for the 23-day period is shown in Fig. 3. Interestingly, the highest tropopause positions during this period are not found near the equator, but, rather, are displaced northward along a roughly east–west axis near 20°N. This axis is slightly north of the anticyclonic ridge axis (Fig. 2). Since deep convection does not exist in the region of the highest tropopause whereas it does occur over the entire maritime continent area during the period, the concept of a direct relationship between tropopause height and deep cumulus mass flux (e.g., Schneider, 1977) seems, at first glance, to be violated. However, viewed on a

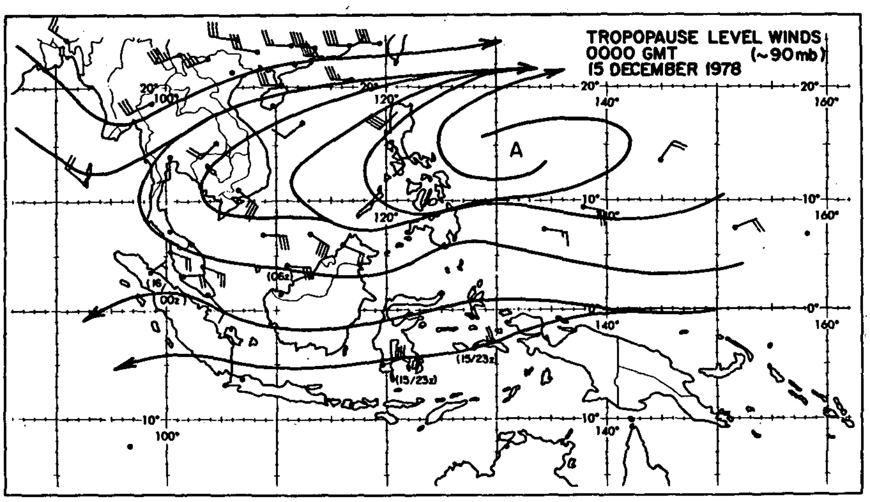

FIG. 2. Tropopause level winds (at ~90 mb or ~17 km) on 15 December 1978. Observations are at 0000 GMT unless otherwise indicated.

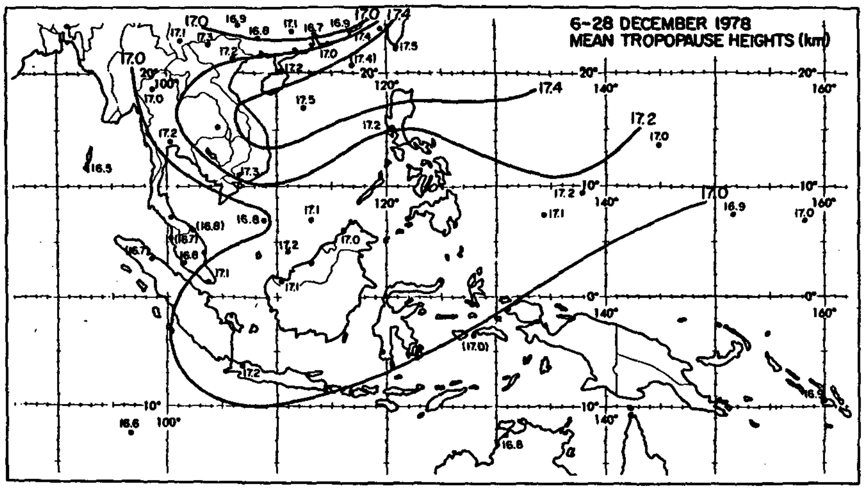

FIG. 3. Mean tropopause height (km), 6–28 December 1978. Numbers in parentheses are station averages with a few days of missing data.

global scale, the tropopause is indeed highest in the tropics where deep convection predominates and the shifting of the maximum heights to a position away from the equator is probably a consequence of large-scale dynamical processes and/or the modulating effects of the convection itself (in a manner to be discussed later).

The lowest tropopause temperatures during this period are in the equatorial belt with values near −85°C over the maritime continent (Fig. 4). There is some indication of slightly warmer conditions over the maritime continent than the area immediately surrounding it (also evident in Fig. 2 of Newell and Gould-Stewart, 1981). A possible explanation for this feature will be given later based on the results of this study. The much warmer conditions observed just off mainland China in the vicinity of Taiwan are not readily explainable.

5. Observations at ship array near Borneo

In Johnson and Kriete (1982) it was shown that with the passage of mesoscale convective systems at the southernmost ship in the triangular array off the north coast of Borneo (*Ak. Korolov*), a cooling of 4–6°C in the high troposphere and lower stratosphere above the convection was often observed. Associated with the cooling was a slight lifting (~0.5 km) of the tropopause. The causes of this cooling are uncertain. Johnson and Kriete suggest that cumulonimbus overshooting, mesoscale lifting or radiative cooling (or combinations of these processes) may be possible explanations.

A longer period variation in tropopause heights and temperatures is also observed at *Ak. Korolov*. This variation can be seen from soundings plotted at 24-h intervals (Fig. 5). Over this 3-week period in December

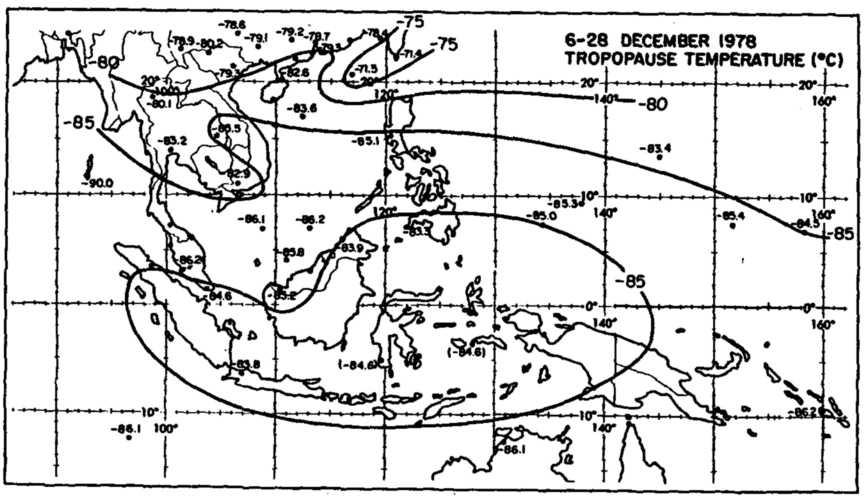

FIG. 4. Average tropopause temperature (°C), 6–28 December 1978. Numbers in parentheses indicate incomplete record.

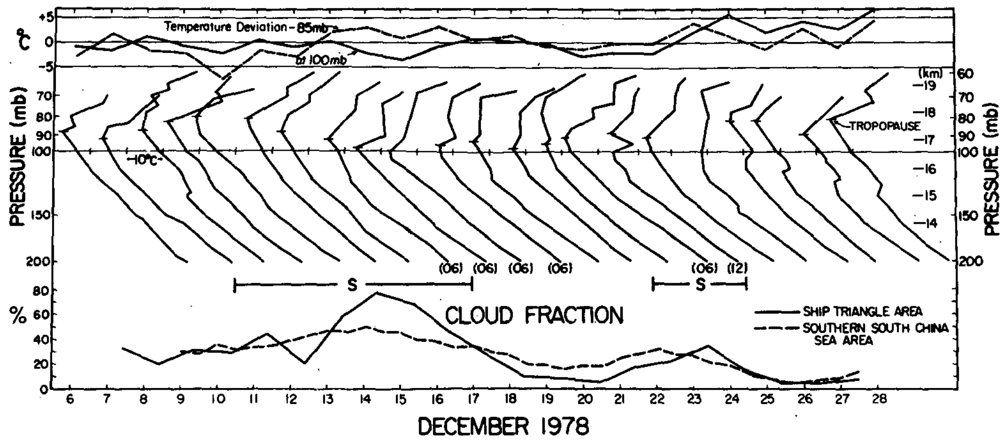

FIG. 5. Time series of soundings in the vicinity of the tropopause at *Ak. Korolov*. Soundings are at 0000 GMT unless otherwise indicated. Each sounding curve (except those on the twenty-fourth and twenty-sixth) crosses the 100-mb level with a temperature between −80 and −90°C. Temperature deviations from the 23-day mean at 85 and 100 mb at top. Cloud fraction (percent area coverage of bright infrared satellite cloudiness) for the ship triangle area (Johnson and Priegnitz, 1981) and a larger area (approximately five times as large) over the southern South China Sea encompassing the triangle area (from Houze et al., 1981) at bottom. Periods of surface wind speed > 10 m s^{-1} at the Soviet ships are marked by *S* (surge periods).

1978, an oscillation in the tropopause height occurs having an amplitude of about 1.5 km. The highest levels occur near the first and again at the end of the period. In the lower portion of Fig. 5 the fraction of two areas covered by upper-level cloud, determined from satellite infrared imagery, are illustrated: 1) the ship triangle area (solid curve) and 2) a larger (~5 times as large) area along Borneo's north coast enclosing the ship triangle (dashed curve, from Houze et al., 1981). Also indicated are two cold surge periods over the South China Sea.

The period 11–17 December has been noted by Houze et al. (1981) and Johnson and Priegnitz (1981) to be a time of significantly-increased deep convective activity over the southern South China Sea as a result of surges peaking on the eleventh and fifteenth (Fig. 5) and a tropical wave disturbance entering the region on the fourteenth. The increase in deep convection associated with the weaker surge on the twenty-third was considerably less. From Fig. 5 it is seen that the major reduction in the tropopause height occurs during the period of increased deep convective activity. Possible explanations for these observations will be presented shortly.

Also shown in Fig. 5 are temperature deviations from the 23-day means at 100 and 85 mb. As the tropopause descends, warming is observed in the lower stratosphere and cooling in the high troposphere. These changes are better illustrated in Fig. 6, which contains the temperature soundings at 0000 GMT on the tenth and 0600 GMT on the fifteenth (a sounding at 0000 GMT on the fifteenth was not taken). During this 5-day period, considerable warming occurs between 100 and 70 mb (an average of ~5°C) and a slight cooling between 100 and 125 mb (~1°C). The tropospheric lapse rate adjusts toward a dry adiabat by the fifteenth, probably as a consequence of an increase in deep convective mixing. The changes illustrated in Fig. 6 are very similar to those observed in comparison plots of soundings at other times near both ends of this period as well as at the other two ships.

To demonstrate that the behavior of the tropopause at *Ak. Korolov* is not an isolated occurrence, time series of tropopause heights have also been determined at the other two Soviet ship positions over the South China Sea (*Priliv* and *Ak. Shirshov*) and are shown in Fig. 7. The variations at *Ak. Korolov* are clearly seen to be also present at the other two locations. The changes in

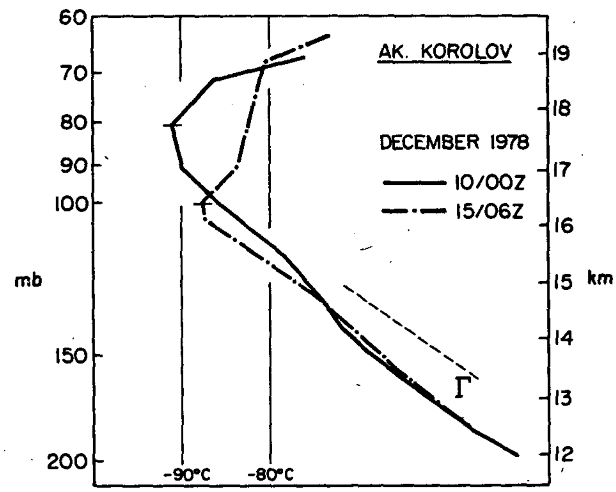

FIG. 6. Soundings at *Ak. Korolov* at 0000 GMT 10 December, and 0600 GMT 15 December. Dry adiabat is marked by gamma. Tick marks indicate tropopause.

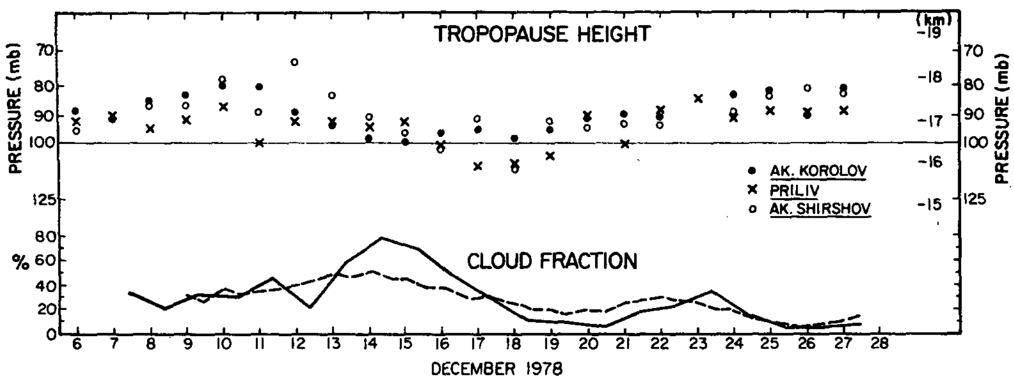

FIG. 7. Time series of tropopause heights at *Ak. Korolov, Priliv* and *Ak. Shirshov*. Cloud fraction as in Fig. 5.

temperature structure at the other two ships are similar to those shown in Fig. 6.

In addition to the changes described above, systematic variations in surface pressure and tropospheric pressure heights were observed at the Soviet ship positions. Time series of average temperature, height and surface pressure deviations for the ship array are shown in Fig. 8. It is evident that during the period of tropopause descent, height falls occurred in the area reaching an amplitude of ~20 m through most of the troposphere by the fifteenth and sixteenth. The height falls are largely a consequence of lower-tropospheric cooling. Surface pressure fell during this period by about 4 mb. The period of height falls and reduced pressure coincide with the propagation of a decaying tropical depression into the region on the fourteenth and the arrival cold surges on the tenth and fifteenth.

Surface pressure and height falls were not observed with the cold surge on the twenty-third. Neither was there any apparent systematic lowering of the tropopause at this time.

6. Temporal variations on a larger scale

To examine tropopause height variations on a scale larger than the ship triangle area, analyses like those shown earlier for the ships have been repeated for each of the stations in Fig. 1 for which sufficient data exist. The procedure has been to determine daily departures of the tropopause height at each station from the 6–28 December mean. These values are presented adjacent to infrared satellite images for the period 10–20 December in Fig. 9.

Again, analyses of the sparse rawinsonde data are difficult; nevertheless, several important features emerge. First, there is an enhancement in cloudiness over the southern South China Sea after the tenth (cf. Figs. 5 and 7), reaching a peak on the fourteenth and fifteenth and then diminishing. The westward progression of a tropical depression across the Philippine Islands into the South China Sea can be seen to occur from the eleventh to the fourteenth. The gradual descent of the tropopause at the ships coincident with this increase in convective activity (Figs. 5 and 7) extends over a much larger area than the ship array itself. It appears to include much of the southern South China Sea within and downwind (with reference to tropopause level winds; Fig. 2) of the area of enhanced cloudiness. The region of depressed tropopause levels persists until the eighteenth.

The surface pressure falls in the ship array illustrated in Fig. 8 also extend beyond the area of the ships. Large-scale views of the surface pressure on the fifteenth and changes from the tenth to the fifteenth are shown in Fig. 10. A region of low pressure is observed on the 15th over the southern South China Sea and southern Philippine Islands (Fig. 10a). The five-day pressure change pattern shows a region of 4 to 5 mb falls extending in a northeast–southwest direction from the ship array north of Borneo to the northern Philippine

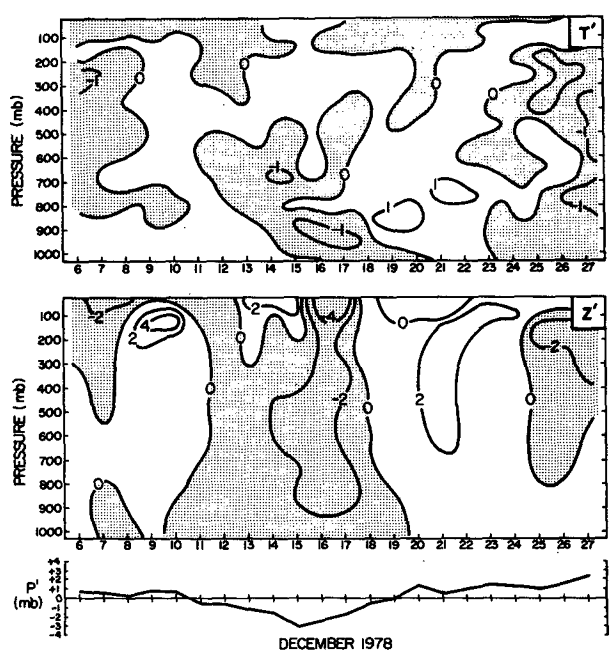

FIG. 8. Time series of ship array temperature, geopotential height and pressure deviations from 6–28 December means: T' (°C), z' (decameters), p' (mb).

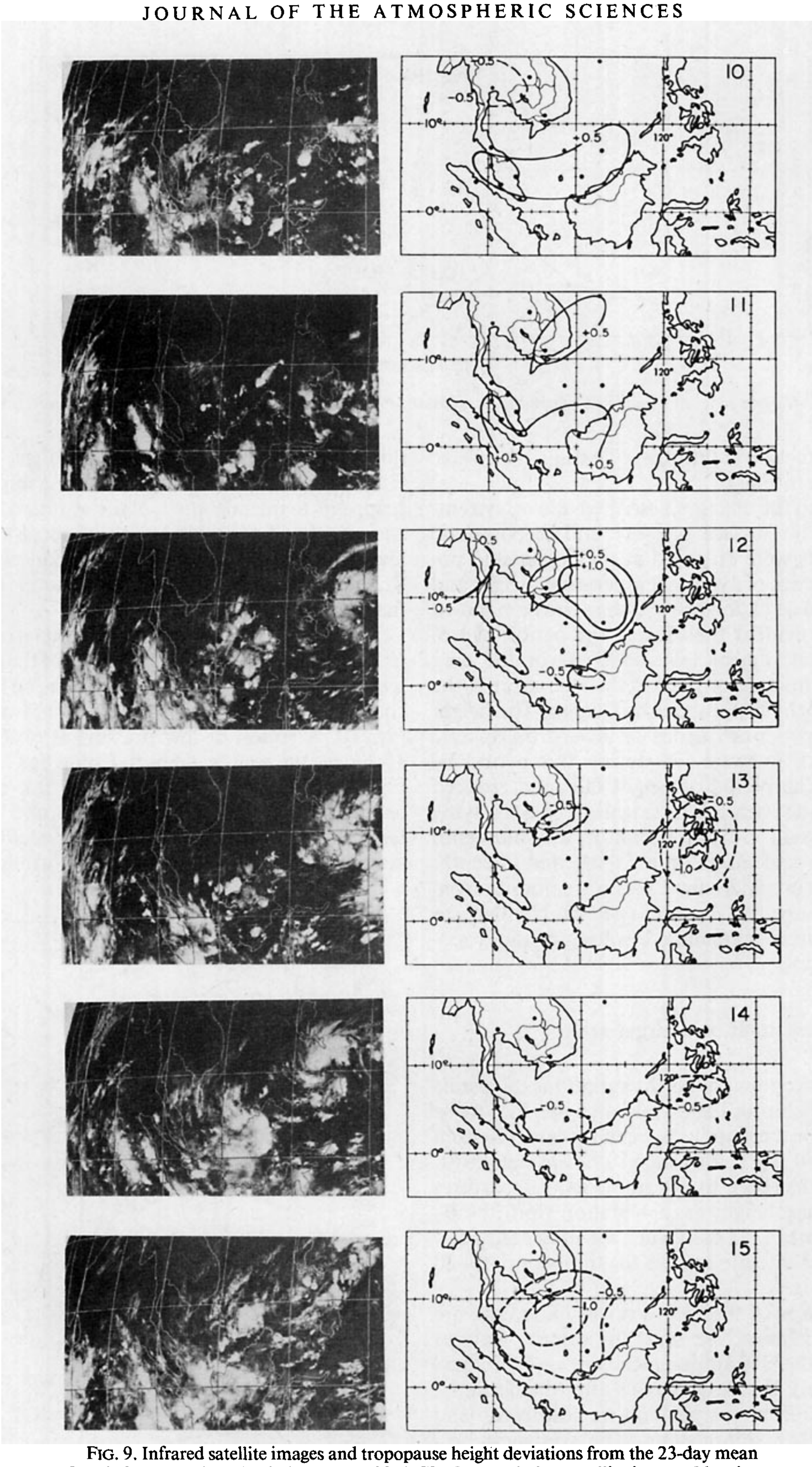

FIG. 9. Infrared satellite images and tropopause height deviations from the 23-day mean for 10–20 December. Deviations are at 0000 GMT on each day, satellite images 6 h prior to that time. Numbers in parentheses are deviations from means computed with a few missing observations during the period. Areas with deviations in excess of 0.5 km are contoured. (Increases are solid curves, decreases dashed.)

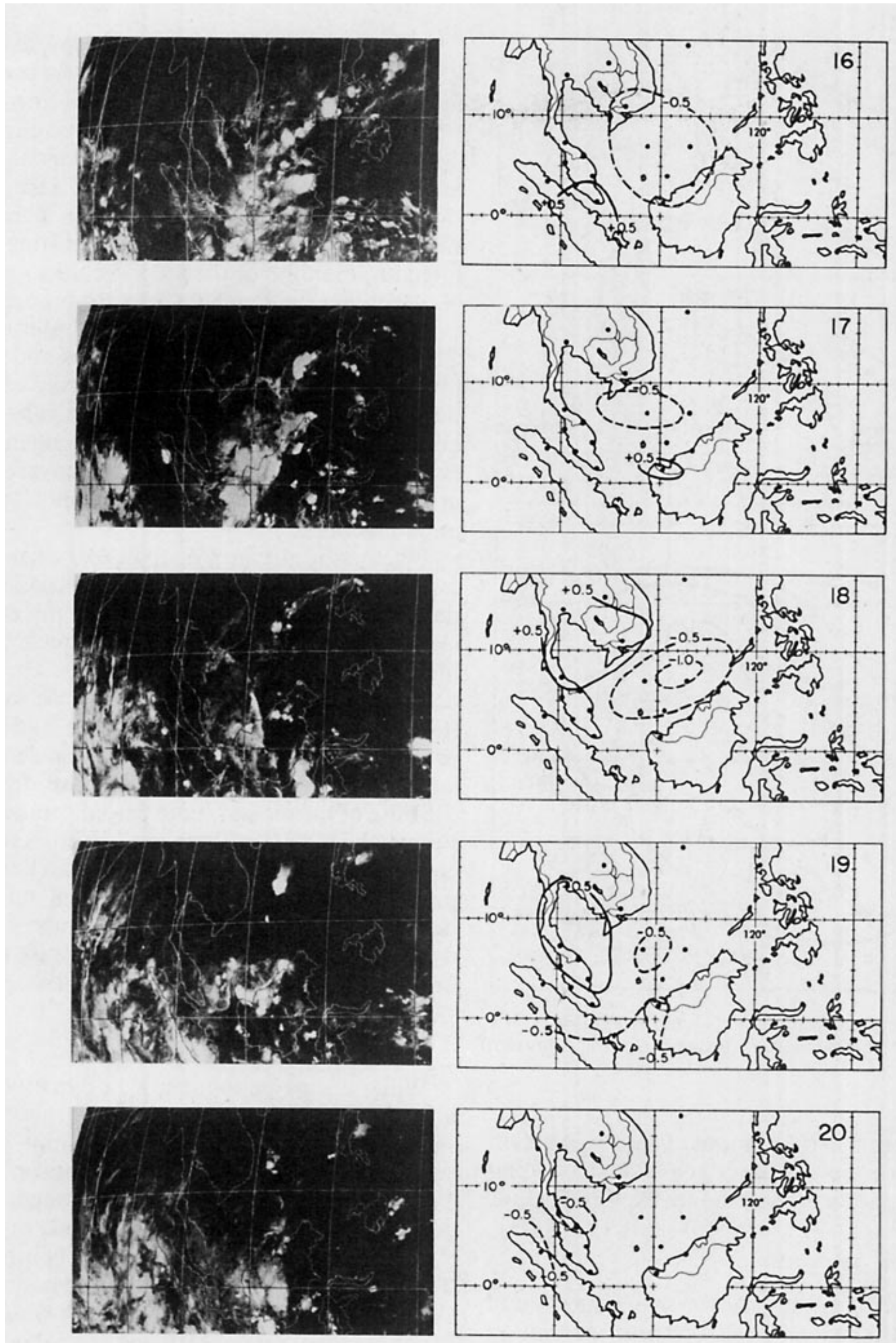

FIG. 9. (*Continued*)

Islands (Fig. 10b). Comparison of the field of tropopause height deviations for the fifteenth (Fig. 9) and the surface pressure patterns (Fig. 10) shows some overlap in the positions of the extrema, although there is a greater northward and eastward extension of the surface pressure centers.

7. Possible explanations for tropopause variations

The findings from this Winter MONEX observational period indicate an inverse relationship between the intensity of deep convective activity and tropopause height over the southern South China Sea for the period 10–15 December 1978. During this period there is a ~0.5–1.5 km reduction in the tropopause height and a lower-stratospheric warming up to 8°C just above the tropopause. At the same time, surface-pressure and tropospheric-pressure heights are observed to fall over a large portion of the southern South China Sea. While these pressure falls are occurring (likely in response to two cold surges and a tropical depression), there is a

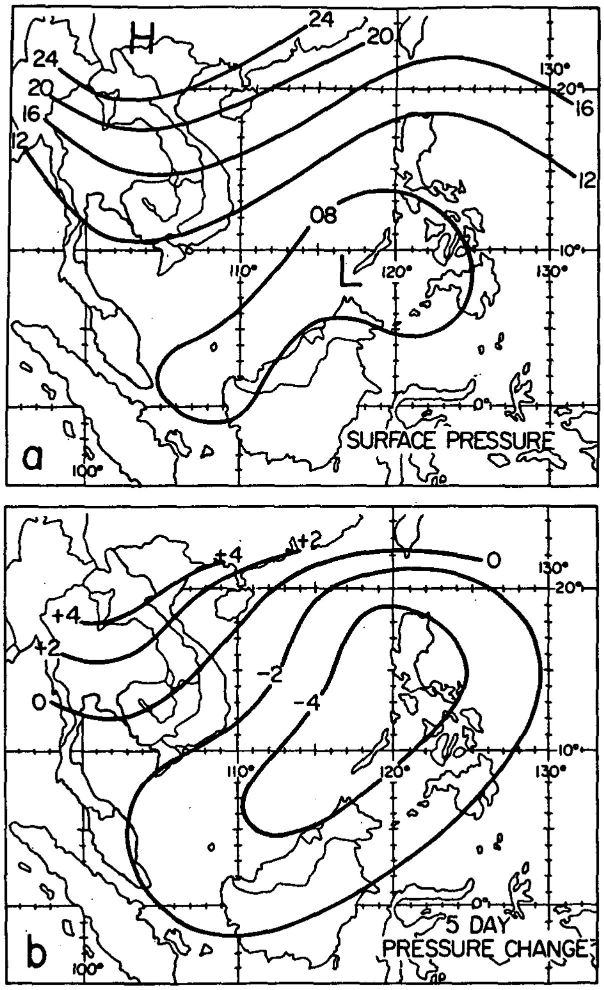

FIG. 10. Surface pressure (mb; 08 = 1008 mb) at (a) 0000 GMT 15 December and (b) five-day (10–15 December) surface pressure change in mb.

considerable increase in the amount of deep convection over the southern South China Sea. Possible explanations for this observed behavior are explored below.

a. Dynamical mechanisms

At midlatitudes it is well known that a substantial reduction in the tropopause height occurs in association with cyclones and upper-level lows or troughs. The descent may occur in baroclinic waves as part of the process of frontogenesis (i.e., tropopause folding; Reed and Sanders, 1953) or through an adjustment toward hydrostatic equilibrium in connection with the strong deformation of upper cold troughs (e.g., Palmén and Newton, 1969). The latter process often leads to the development of "false tropopauses" in the mid- to upper troposphere which, while representing discontinuities of first order, do not actually mark the division between tropospheric and stratospheric air. Similar processes may be occurring in the tropics, but they are not well documented.

In the Winter MONEX case the flow at upper levels is generally anticyclonic throughout the period (similar to that shown in Fig. 2). However, in the low to mid-troposphere (below 500 mb) a cyclonic circulation was observed crossing the Philippine Islands on the fourteenth, accompanying the passage of a tropical depression (Fig. 9 and Chang et al., 1981). This circulation weakened after entering the South China Sea on the fifteenth, the time of the second cold surge. Chang et al. (1979) have noted that westward-propagating waves from the western Pacific may, upon entering the South China Sea, interact with cold surges and produce an intensification of organized deep convection to the north of Borneo. The intensification is likely a consequence of enhanced low-level convergence near the Borneo coast. The peaking of cloud cover over the ship array on the fourteenth to fifteenth may represent such an interaction.

Whether or not the tropopause descent was directly related to the cold surges and weakening tropical depression is not entirely clear, but the evidence presented here suggests that these dynamical features may indeed have been important factors. The tropopause descent may be a hydrostatic response to the cooling (Fig. 8), possibly associated with the cold surges, and/or a dynamical response to the tropical depression. The lack of pressure falls and tropopause descent during the time of the second surge period centered about the twenty-third—when there is a slight increase in deep convection—further supports the idea that dynamical processes exert the primary control on tropopause height on this time scale. Work is in progress to see if dynamical arguments for the tropopause lowering can be substantiated on a quantitative basis.

b. Convective effects

While it may be the case that dynamical processes are the primary contributors to tropopause height modulations, it is important to examine possible convective effects. We have seen (Johnson and Kriete, 1982) that there is a slight upward bulging of the tropopause immediately above individual mesoscale convective systems over the southern South China Sea. The cumulative effects of many such systems on the large-scale environment in which they are embedded is not obvious. Here we suggest several possible mechanisms which might act to lower the tropopause.

1) SUBSIDENCE INDUCED BY OVERSHOOTING CUMULONIMBUS TOWERS

Recent measurements from high-altitude aircraft (NASA U-2) flights near Panama have shown that tropical cumulonimbus have turrets that overshoot the tropopause by 2–3 km and mix with the warm lower-stratospheric air (Danielsen, 1982). Evidence is presented by Danielsen to suggest that when the turrets collapse, they encounter new ascending currents and diverge horizontally just above the tropopause, forming an anvil of ice crystals. Danielsen proposes that radiative destabilization within the anvil causes growth and removal of ice crystals from the lower stratosphere, thereby accounting for a stratospheric dehydration.

Importantly for this study, these observations imply that there is a net upward mass transport across the tropopause within the clouds, requiring a compensating subsidence in the cloud environment in the lower stratosphere. The mixing of the turrets with lower-stratospheric air makes the ascent irreversible and the degree of this mixing determines the extent to which the environment is forced to subside. The subsidence, as weak as it might be, can contribute to strong warming in the highly stable lower stratosphere. A net warming at the tropopause level may be achieved if the mixing is highly intermittent and the turrets come into radiative equilibrium with their environment faster (approximately hours) than the large-scale mixing time scale (approximately days).

It is useful to view these changes in thermodynamic structure in terms of dry static energy ($s = c_pT + gz$) profiles (Fig. 11). Following the period of disturbed convective activity, there is a distinct change in the structure of s to one more closely resembling a well-mixed boundary layer. In partial analogy to the mixed layer, it might be argued that the intensified convective mixing has produced nearly adiabatic conditions below the tropopause and increased the stability above (by overshooting towers).

2) Radiative effects

The effects of increased cloud cover on the field of radiative heating near the tropopause are difficult to determine precisely; nevertheless, there is evidence to indicate that the anvil clouds produced by deep convection contribute to a net radiative cooling near their tops, rather than a warming (Griffith et al., 1980;

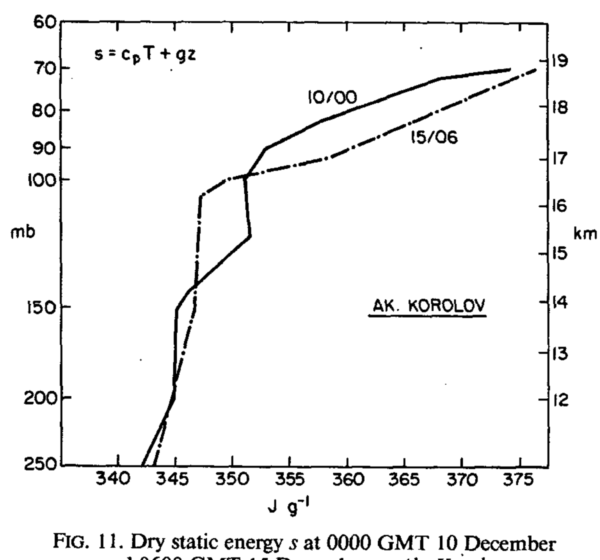

FIG. 11. Dry static energy s at 0000 GMT 10 December and 0600 GMT 15 December at *Ak. Korolov*.

Webster and Stephens, 1980; Danielsen, 1982; Knollenberg et al., 1982; Kuhn, 1982). Thus, it is difficult to conceive of cloud-top radiative effects, as described by the above authors, as an explanation for the lower-stratospheric warming.

Another possible radiative mechanism might exist in connection with modulations in cloud activity near the tropopause. To illustrate this concept, we first consider the analogy of a well-mixed boundary layer to the tropical troposphere (Sarachik, 1978), though the mixing is highly intermittent, and obtain a prediction equation for the tropopause height z_T based on a zero-order jump model (Lilly, 1968):

$$\frac{\partial z_T}{\partial t} = \bar{w} - \frac{(\overline{w's'})_{zT-}}{\Delta s} + \frac{1}{\rho \Delta s} \Delta F_R, \qquad (1)$$

where w = vertical velocity, $(\overline{w's'})_{zT-}$ is the heat flux at the base of a transition layer (of infinitesimal depth within the context of the jump model) separating the troposphere from the stratosphere, Δs the jump in dry static energy across the transition layer, $\Delta F_R = F_{R+} - F_{R-}$ the jump in the net radiative flux F_R (W m^{-2}) across that layer and ρ is density; overbar refers to an average over the entire area.

Equation (1) is a useful prediction equation when the mixing elements are numerous and the base and top of the transition layer are well defined by considering averages in time or space over a statistically representative population of eddies. For the problem at hand, however, the eddies are highly intermittent. Consequently, we alternatively apply the heat budget to the nonturbulent cloud environment, which covers most of the area, to get a similar expression:

$$\frac{\partial z_T}{\partial t} = \tilde{w} + \frac{1}{\rho \Delta s} \Delta \tilde{F}_R, \qquad (2)$$

where tilde refers to cloud environment values.

From (2), the tropopause can be seen to descend if there is subsidence ($\tilde{w} < 0$) and/or $\Delta \tilde{F}_R < 0$. The latter condition implies a net radiative heating in the transition layer.

There are at least several possible ways in which radiative heating in the transition region may occur as a consequence of the increase in deep convective activity. One possibility is that the increased albedo due to increased cloud cover will enhance the ozone heating in the lower stratosphere. Lacis and Hansen (1974) have shown that an increase in the ground albedo from zero to one can lead to a corresponding 1°C day^{-1} increase in the ozone heating at 20 km. The cloud cover changes in the Winter MONEX region do not suggest such a large albedo change; nevertheless, some heating may occur from this process.

In addition, there exists the possibility that subsidence in the environment of the overshooting turrets may contribute to a downward transport of ozone-rich air from the lower-stratosphere, thereby leading to an enhancement of the ozone heating rate. That such a downward transport can occur at midlatitude in association with vertical motions accompanying baroclinic waves has been demonstrated by Reed (1950). Without measurements of the degree of downward mixing or transport which occurs, the extent to which this process may account for the observed heating is difficult to determine.

8. Discussion

Sounding data from the southern South China Sea and its vicinity obtained during Winter MONEX (December 1978) have revealed an unexpected relationship between the tropopause height and deep convective activity on a ~1-week time scale. Rather than rise during a period of increased deep convective activity, the tropopause in the region of the convection is observed to descend by ~1.5 km with an associated 5–10°C warming in the lower stratosphere.

The increased deep convection occurred in association with two winter monsoon cold surges (on 10 and 15 December) and a weak tropical depression that crossed the Philippine Islands on the fourteenth. During the period of these circulation features, a 4–5 mb reduction in surface pressure and ~20 m decrease in tropospheric pressure heights were observed over the eastern and southern portions of the South China Sea. It is possible that dynamical processes associated with these events may have led to the tropopause descent, perhaps through a hydrostatic response to slight cooling associated with the cold surges (with the effect somehow localized over the southern South China Sea) and/or a dynamical response to the lower-tropospheric circulation associated with the tropical depression. Since dynamical processes at midlatitudes have been clearly connected with tropopause descent, a dynamical explanation for the Winter MONEX observations appears to be a logical choice, although we have not yet put dynamical arguments on a quantitative basis. This work needs to be done.

It seems premature, however, to disallow the possibility that the convection itself influences the tropopause level regionally and on a ~1-week time scale. Of course, the influence could conceivably go either way and, in fact, may be weak relative to dynamical effects. There are at least two mechanisms worth considering, however, by which convection could act to lower the tropopause. One possibility is that cumulonimbus turrets overshoot irreversibly into the lower stratosphere, thereby inducing a slow subsidence and warming in the environment of the cloud systems. A net warming may occur if the mixing is highly intermittent and the turrets come into radiative equilibrium with their environment faster than the large-scale mixing time scale. Secondly, radiative effects may also play a role through an increase in the ozone heating due to (i) an increased albedo in the disturbed area and/or (ii) a downward transport of ozone in the cloud environment.

If deep convective activity is correlated with lower-tropopause heights (by whatever mechanism) over a large-scale area and on a one-week time scale, then the findings of this study may have broader implications. For example, our results appear to be consistent with the observations of Newell and Gould-Stewart (1981) of a local maximum in January tropical tropopause temperatures at the equator over the Indonesian maritime continent. This local maximum is centered on the equatorial January maximum in cloudiness (Sadler, 1977) and, presumably, deep convection. Finally, it may also be noted that at most of the stations included in the tropical tropopause study of Reid and Gage (1981), the minimum tropopause height occurs during the seasonal period of maximum precipitation (or deep convection) at the stations. Thus, the modulating effects of deep convection (or dynamical processes manifested by an increase in deep convective activity) on tropopause height may be also evident on seasonal time scales.

This study is intended to only be a preliminary examination of short-term (~1 week) effects of deep convection on the tropical tropopause. Further observational work is clearly needed as well as more detailed explanations for this observed behavior.

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