Chapter 5

Some Views On "Hot Towers" after 50 Years of Tropical Field Programs and Two Years of TRMM Data

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ABSTRACT

The "hot tower" hypothesis requires the existence of deep cumulonimbus clouds in the deep Tropics as essential agents, which accomplish the mass and energy transport essential for the maintenance of the general circulation. As the role of the deep convective clouds has been generally accepted, the popularity of referring to these deep "hot" towers as undilute towers also has gained acceptance. This paper examines the consequences of assuming that the deep convective clouds over tropical oceans consist of undilute ascent from the subcloud layer.

Using simple applications of parcel theory, it is concluded that observed properties of typical cumulonimbus updrafts in low- to midtroposphere over tropical oceans are inconsistent with the presence of undilute updrafts. Such undilute updrafts are far more consistent with observations in severe storms of midlatitudes. The observations over tropical oceans can be hypothetically explained by assuming large dilution of updrafts by entrainment below about 500 hPa, followed by freezing of condensate. This freezing and subsequent ascent along an ice adiabat reinvigorates the updrafts and permits them to reach the tropical tropopause with the necessary high values of moist static energy, as the hot tower hypothesis requires. The large difference observed between ocean and land clouds can be explained by assuming slightly smaller entrainment rates for clouds over land. These small entrainment differences have a very large effect on updrafts in the middle and upper troposphere and can presumably account for the large differences in convective vigor, ice scattering, and lightning flash rates that are observed. It follows that convective available potential energy (CAPE) is not a particularly good predictor of the behavior of deep convection.

Using the Tropical Rainfall Measuring Mission (TRMM) to map a proxy for the most intense storms on earth between 36°S and 36°N, they are found mostly outside the deep Tropics, with the notable exception of tropical Africa.

1. Introduction

Riehl and Malkus (1958) is one of the most quoted and influential papers in atmospheric science. The "hot tower" hypothesis is usually attributed to this paper, although those words are not used by Riehl or Malkus in any paper until several years later. What they actually wrote is that deep cumulonimbus clouds are essential to the general circulation and to the global energy balance, and that those clouds in the equatorial trough must necessarily transport moist static energy against its mean gradient above about 600 hPa. This is a conclusion that has influenced three generations of scientists and will surely stand unchallenged. Riehl and Malkus did illustrate the thermodynamic updraft path in such clouds, which was clearly intended to be pseudoadiabatic, and they indeed referred to them as "undilute" cores, later popularized as hot towers.

Why should such a universally accepted idea require renewed attention at this time? It has been known for 40 years that actual liquid water content in tropical clouds rarely exceeds 0.4 of adiabatic, although rapid coalescence growth and fallout of precipitation could perhaps have explained this fact. Recent decades of observations over tropical oceans—from 1974 in the tropical Atlantic (LeMone and Zipser 1980; Zipser and LeMone 1980), hurricanes[1] (Jorgensen et al. 1985), offshore of Taiwan (Jorgensen and LeMone 1989), offshore of tropical Australia (Lucas et al. 1994), and the warm pool of the equatorial Pacific (Wei et al. 1998; Igau et al. 1999)—have yielded data from aircraft penetrations of thousands of cumulonimbus clouds. The results reported in these papers show great consistency with one another. *Undilute updraft cores are not found.* The observed cores are of small diameter and have liquid water content and updraft velocities that are generally far smaller than would be consistent with adiabatic ascent.

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[1] Although this database included hurricanes, convection in hurricane eyewalls is an obvious special case. The cited statistics of hurricane updrafts are similar to those of typical oceanic cumulonimbi, but there is ample evidence that the hurricane boundary layer can ascend undilute in eyewalls, and this paper does not consider them further.

The more recent papers also report that measured virtual temperature excesses, although a difficult measurement, also are far less than adiabatic. Wei et al. (1998) conclude that, on average, entrainment reduced buoyancy from undilute values by 2 K while the reduction due to the observed water loading is only 0.5 K. In a truly undilute core, reduction by water loading at 700 hPa would be 2 K.

Is it possible that out of thousands of opportunities to penetrate the strongest cores available, all of them could have missed all undilute cores over a 25-yr period? Proving a negative is difficult. The purpose of this paper is to offer an alternative explanation for how vigorous oceanic cumulonimbus manage to reach the tropical tropopause, in spite of the observations that apparently indicate that undilute cores are rare to nonexistent over tropical oceans. The proposed explanation is that the dilution of the cores by entrainment in the low-to-middle troposphere can be counteracted by the combined effects of freezing of condensate, and by shifting from the condensation to the sublimation latent heating rate.

This is hardly an original or revolutionary idea. Braham's (1952) classic paper summarizing results from the Thunderstorm Project observations includes a schematic illustration (his Fig. 9) of nearly compensating effects of entrainment and ice processes. Many thermodynamic texts represent an isothermal expansion along a parcel path during the freezing process, not entirely correctly labeled as the "hail stage." This term fell into disuse, mainly because it is not possible to state with generality how much condensate freezes at what temperature. However, the fact that such freezing can reinvigorate an updraft is universally known (e.g., Riehl 1979, p. 377; Johnson and Kriete 1982; Cotton and Anthes 1989, p. 470; Ooyama 1990; Johnson et al. 1999). The basis for the idea of "dynamic seeding" (e.g., Simpson and Wiggert 1969) was to artificially initiate or hasten the freezing process. It is not necessary to reopen the debates on how often Florida or Caribbean clouds are seedable (e.g., Sax 1969). The issue here is whether cumulonimbus in the equatorial trough glaciate naturally and at what temperature. The fact is, as postulated by Riehl and Malkus (1958), that these clouds are generally embedded in extensive regions of disturbed weather, and the writer's experience is that updrafts are most often embedded in extensive upper-tropospheric clouds, with precipitating ice. Allowing for some rare exceptions, we assume herein that cumulonimbus clouds over equatorial oceans glaciate naturally between −5° and −15°C. It will become obvious that the conclusions will not change by altering these temperatures within a reasonable range.

There is a common supposition that condensation loading can account for the departure of vertical velocity from undilute values. Xu and Emanuel (1989) argue that soundings are within observational error of neutrality over tropical oceans if the reference process is the reversible adiabatic rather than the pseudoadiabatic. These arguments are elaborated in Emanuel (1994, 463–467) in which he concludes that buoyancy in a radiative–convective atmosphere should be in the range of 1–2°C. However, it will be shown that the fully loaded undilute updraft applies not to the equatorial trough but rather to midlatitude severe storms, with surprising consequences. It will also be shown that realistic cumulonimbus cores in equatorial regions can indeed have buoyancies in the predicted range of 1–2°C but that they do not begin their ascent along reversible adiabats.

2. Approach to the issue

First, the properties of truly undilute cores as they are found in real midlatitude severe storms are considered. Their large diameter is consistent with minimal entrainment, and simple parcel theory assuming adiabatic water loading is in good agreement with observations. The same assumptions for clouds over tropical oceans are shown to be inconsistent with observations. Reconciliation is proposed by exceedingly crude assumptions of the fractional entrainment rate, and by consideration of ice processes. Only by very large departures from undilute ascent are these assumed conditions brought into agreement with common observations in the deep Tropics.

The examples presented herein will unapologetically neglect the virtual temperature correction, the specific heat of condensate, and differential fall speeds of condensate. When buoyancy is integrated to calculate convective available potential energy (CAPE) between two levels, accuracy better than 10%–20% is not attempted. When calculating vertical velocity from CAPE by the parcel method, the collective effects of nonhydrostatic pressure forces, form drag, and turbulence are considered simply by taking the square root of CAPE and not the square root of 2 × CAPE (in effect, assuming that the efficiency of conversion of CAPE into vertical kinetic energy is 50%).

It is fully recognized that the hypothesis presented herein requires validation by far more sophisticated models. That is why the arguments are made for the two strongly contrasting examples of a large and powerful hailstorm, and *ordinary* oceanic equatorial trough convection. The differences between the two are so great that they can survive the neglect of many complicating factors. Later, some qualitative discussion is made in an attempt to propose differences between typical, strong tropical ocean and continental convection, but in a more speculative mode.

3. Supercell examples

Some well-documented cases can easily illustrate that large undilute cores are common in severe storms. Davies-Jones (1974) and Bluestein et al. (1988) show a number of examples of balloon ascents in storm cores, with core updraft velocities as great as 50 m s^{-1} in the

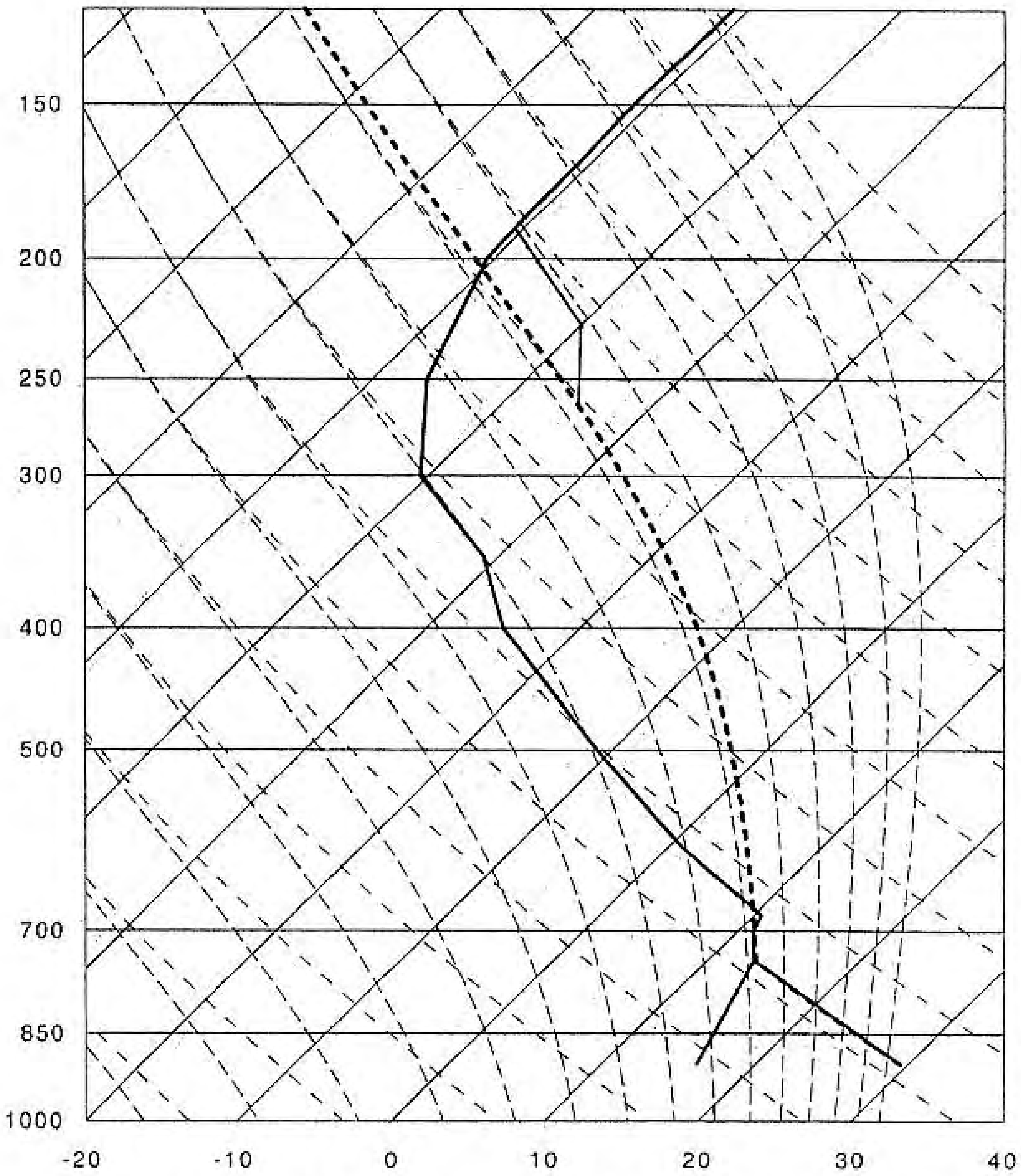


FIG. 5.1. Sounding adapted from Miller et al. (1988) representing the properties of the environment of a severe hailstorm (solid) and hypothetical pseudoadiabatic ascent from cloud base (dashed). The thin solid line near storm top shows the temperature increase from freezing of adiabatic water content between −35° and −40°C. See Fig. 5.2 and text.

midtroposphere. Bluestein et al. calculate close agreement between CAPE and updraft velocity.

The hailstorm of 2 August 1981 passed through a dense observing network, including multiple Doppler radars and a penetration by an armored, instrumented aircraft (Musil et al. 1986). The environmental conditions were derived from multiple rawinsonde ascents and cloud-base updraft properties by aircraft. Figure 5.1 shows the environmental sounding and pseudoadiabatic updraft path (Miller et al. 1988). The radar data in both papers show an updraft greater than 10 km across, and the characteristic weak-echo region. Taken together, the case for an undilute updraft is overwhelming.

Miller et al. use the multiple Doppler data and a cloud model to simulate hail trajectories and hail growth, making the characteristic assumption of adiabatic cloud water content in the updraft until homogeneous freezing is assumed between −35° and −40°C. At updraft speeds averaging 20–25 m s^{-1}, air goes from cloud base to −35°C in 6–8 min, which easily explains the lack of time for particle growth by any method except accretion. The very existence of a weak-echo region validates the assumption that large graupel and hail are not entering the core of the updraft. Nelson (1983), Miller and Fankhauser (1983), and many others have justified the use of the adiabatic undilute updraft core for estimating vertical velocity and liquid water content in the weak-echo region. In the 2 August 1981 case, the penetrating aircraft measured updraft speeds as great as 50 m s^{-1} at 7 km, while the speed calculated from multiple Doppler data was 30–35 m s^{-1}.

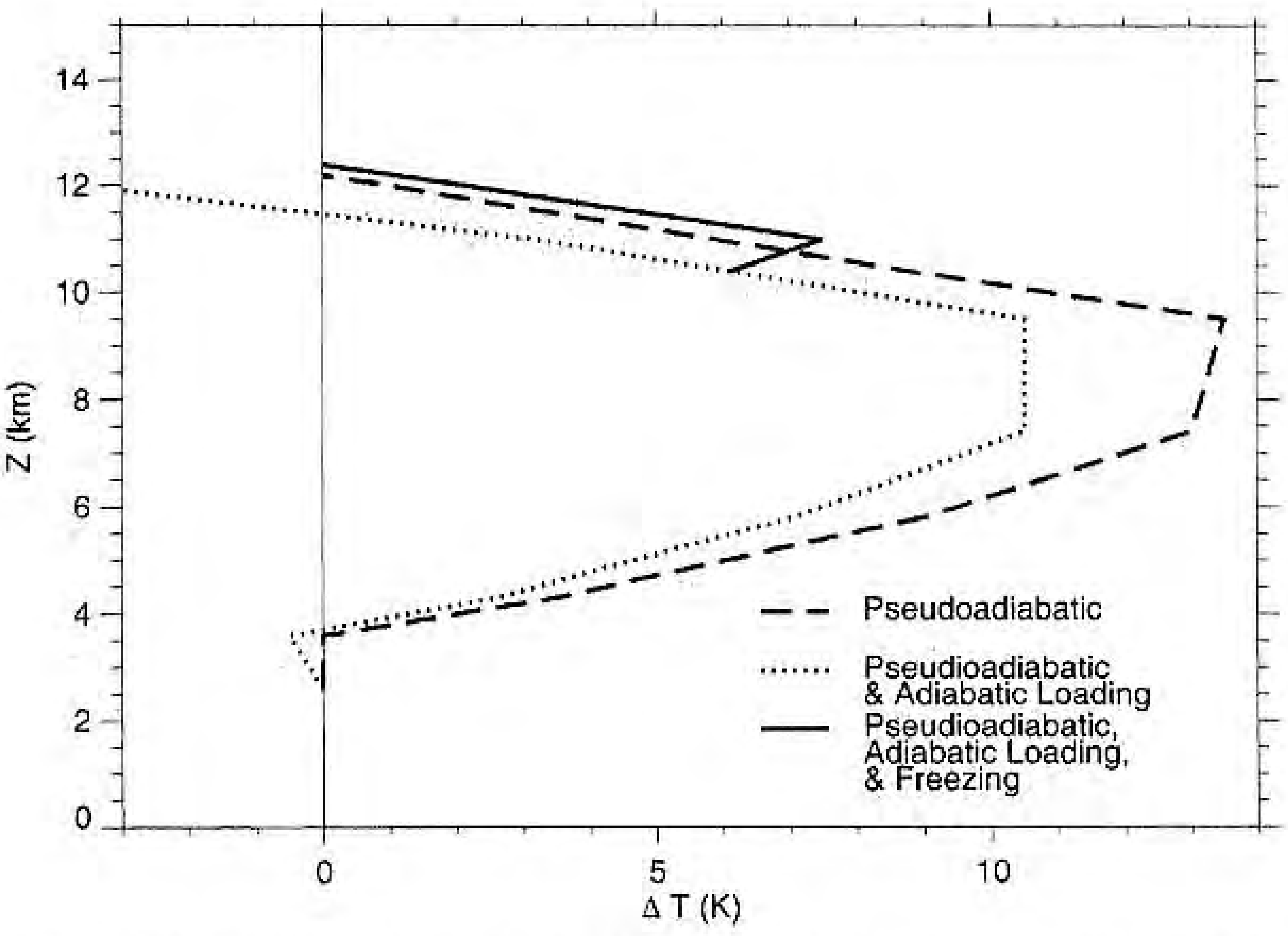


FIG. 5.2. Effective buoyancy of updraft from Fig. 5.1 according to various assumptions: standard pseudoadiabatic ascent (dashes), pseudoadiabatic ascent but adding drag from adiabatic water loading (dots), and the effect on the dotted curve of freezing the adiabatic water load (solid).

How much reduction in buoyancy is there from the adiabatic water loading? Figure 5.2 shows the buoyancy profile from the pseudoadiabatic and reversible adiabatic calculation. The condensate loading increases with height to 10 g kg^{-1} near 7.5 km, reducing the buoyancy from 13 to 10.5 K. The CAPE from the level of free convection to 7 km is reduced from 819 to 652 J kg^{-1}.

Assuming 100% efficiency of conversion from CAPE to vertical kinetic energy, the vertical velocity at 7 km would be reduced from 40 to 36 m s^{-1} by integrated water loading. Assuming 50% efficiency, the vertical velocity at 7 km would be reduced from 29 to 26 m s^{-1}. In supercell updrafts, nonhydrostatic effects could be a significant omission and their neglect could cause errors in estimated updraft speeds in either direction. Nonetheless, the range of calculated updraft speeds is in good agreement with the Doppler estimates but not quite as strong as the aircraft measurement. The overall conclusion is that the updraft core has nearly adiabatic water content (how could it not?!) and that parcel theory may somewhat underestimate peak observed velocities. When buoyancies are as great as they typically are, even adiabatic water loading, remarkably, is of secondary importance. Similar conclusions can be drawn from the Oklahoma examples of Nelson (1983) and Bluestein et al. (1988).

How much boost in buoyancy is there from freezing all condensate between −35° and −40°C? More than 4 K. This may seem large, until one views the shape of the altered buoyancy profile as a function of height (Fig. 5.2). In this particular example, the equilibrium level is raised about 800 m, and of course the large updraft would be maintained or enhanced near storm top. But the CAPE is increased relatively little, because the increased buoyancy is integrated over a small vertical distance. There is an increase of some 7 K in the potential temperature (and correspondingly to the moist static energy and equivalent potential temperature) of the outflow from the storm, from the case without freezing. Thus, the outflow is potentially warmer than either the pseudoadiabatic or reversible adiabatic value (Fig. 5.1).

Bosart and Nielsen (1993) analyzed the interesting case of a rawinsonde balloon intercepting an outflow from a severe storm system in Louisiana. They argue that because the outflow was close to the same equivalent potential temperature as the inflow, they sampled outflow from an undilute updraft. If it was truly undilute, the argument herein would imply that the outflow should have been about 2 K higher in wet-bulb equivalent potential temperature, rather than the same value as the low-level inflow. A possible rationalization is that their inflow air may have been a degree or so lower in dewpoint, and/or that by the time the balloon sampled the outflow, some mixing had taken place that would have slightly reduced the temperature from totally undilute values.

4. Equatorial trough examples

The atmospheric structure hypothesized by Riehl and Malkus (1958) as the environment of the undilute towers is reproduced in Fig. 5.3. Its total pseudoadiabatic CAPE is 2045 J kg^{-1} and maximum buoyancy is 6 K at 400 hPa (7.56 km). The CAPE and the shape of the buoyancy profile are typical. Such soundings have been observed in the warm pool of the Pacific Ocean and shown to be representative of air entering deep convective systems (Lucas et al. 1994; LeMone et al. 1998). It does not have the slight stability near the 0°C isotherm, which is common in the warm pool region (Johnson et al. 1999); but as they have noted, this enhanced stability is more relevant to slowing ascent of cumulus congestus than of deep cumulonimbus. The assumed sounding is not quite as unstable as some Darwin, Australia soundings during the break period (Keenan and Carbone 1992) or those preceding intense thunderstorms in that region (Rutledge et al. 1992; Williams et al. 1992; Simpson et al. 1993). Later, some of the subtle but important distinctions between land and ocean convection in the equatorial trough zone will be discussed. First, the oceanic example is considered.

The pseudoadiabatic CAPE to 500 hPa is 447 J kg^{-1}. Cloud base mixing ratio is 19 g kg^{-1}, while the saturation value of the undilute parcel at 500 hPa and $T = -1$°C is 7.4 g kg^{-1}. Therefore, the fully loaded CAPE with adiabatic liquid water content, essentially the reversible adiabatic CAPE, is 179 J kg^{-1}. Making the 50% efficiency assumption, the vertical velocity of an undilute parcel at 500 hPa is 21 m s^{-1} for pseudoadiabatic and 13 m s^{-1} for reversible adiabatic ascent, respectively. Assuming clean oceanic air, fully adiabatic water loading would be very unlikely, as the average ascent rate of 6–7 m s^{-1} implies 13 min for the ascent, during which time some coalescence and fallout would occur. But any reduction in loading would increase vertical velocity still farther outside the observed range. Even the undilute reversible updraft of 13 m s^{-1} is outside the range of all known observations from the literature cited in the introduction. The reversible liquid water contents of 11 g kg^{-1} are larger than almost any known observations by a factor of 3. The thermal buoyancies of 3 K at 700 hPa and 5 K at 500 hPa for an undilute core are larger than most known observations by a factor of 2 or more (Lucas et al. 1994; Wei et al. 1998).

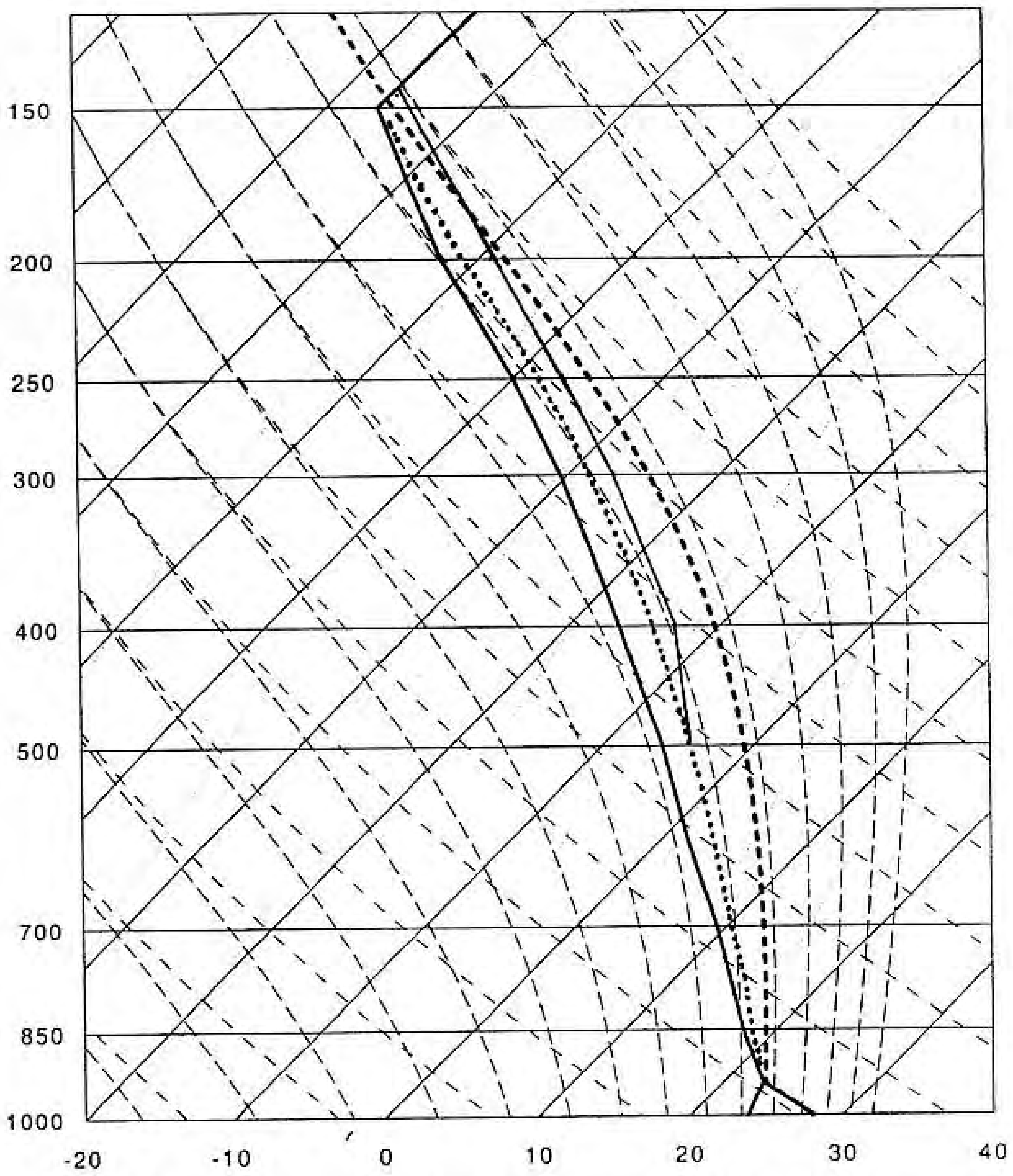


FIG. 5.3. Sounding adapted from Riehl and Malkus (1958) representing the properties of the environment in the equatorial trough zone (solid) and hypothetical pseudoadiabatic ascent from cloud base (dashed). The dotted curve represents the actual temperature of the ascent at one-third pseudoadiabatic buoyancy. The thin solid curve shows the temperature increase from that of the dotted curve from freezing one-third the adiabatic water load between 500 and 400 hPa, and subsequent ascent along the ice adiabat. See Fig. 5.4 and text.

Therefore, it is concluded that undilute ascent in equatorial oceanic cumulonimbus is extremely rare, and if found, would constitute a special case requiring some special explanation. The conclusions of Wei et al. (1998) and many others, based upon careful analysis of penetration data, are that large dilution by entrainment is the norm, and that large conversion of cloud water to rainwater and consequent fallout from weak updrafts greatly reduces the loading. It will now be shown that despite large dilution, subcloud air can nevertheless easily ascend within cumulonimbi to the tropopause, with simple assumptions about freezing of condensate. It

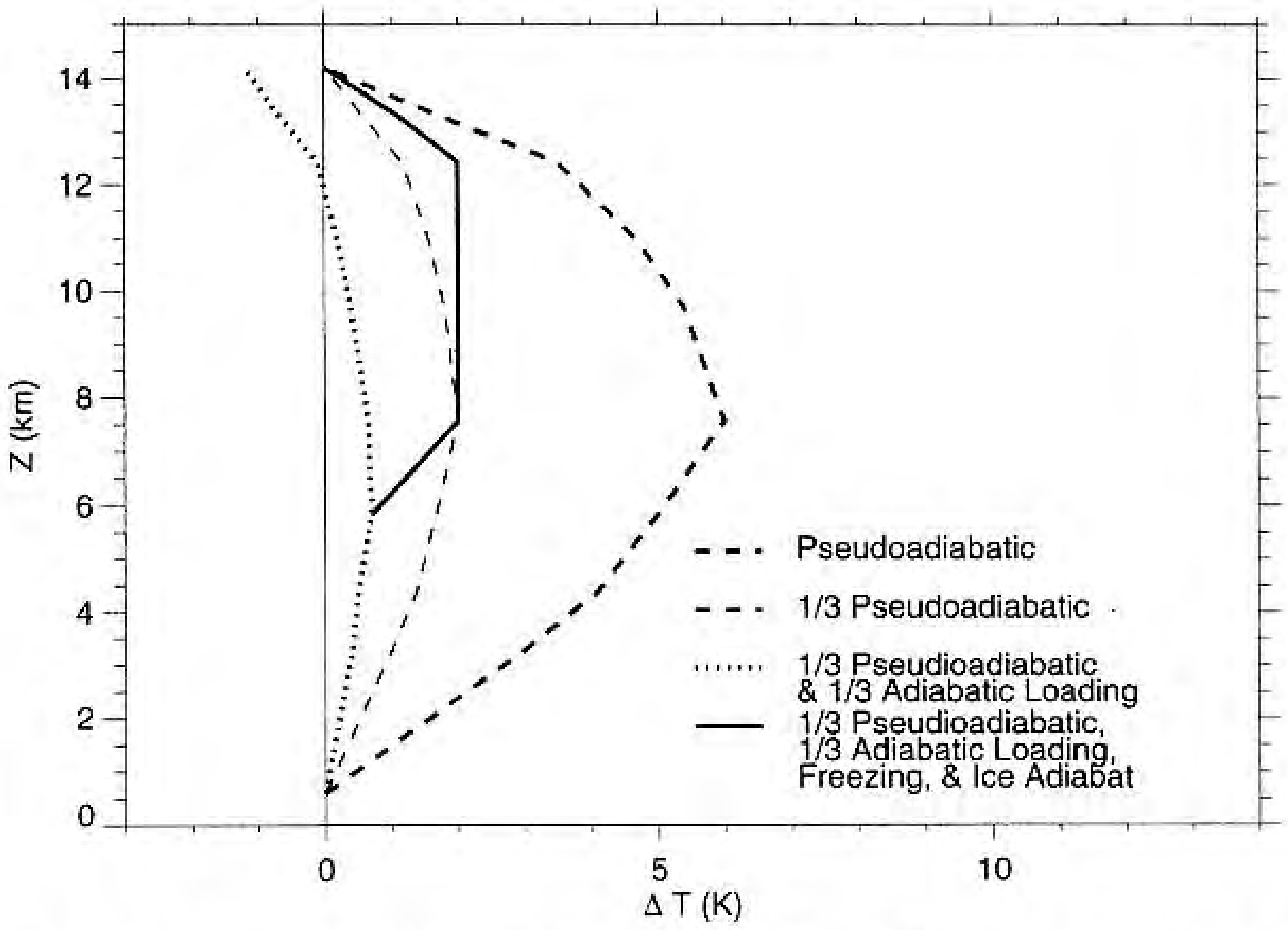


FIG. 5.4. Effective buoyancy of updraft from Fig. 5.3 according to various assumptions: standard pseudoadiabatic ascent (heavy dashes), one-third pseudoadiabatic buoyancy (light dashes), one-third pseudoadiabatic buoyancy but adding drag from one-third adiabatic water loading (dots), and the effect on the dotted curve of freezing one-third adiabatic water load and subsequently following the ice adiabat (solid).

must be emphasized that the explanation herein, while plausible, is offered as a simple hypothesis, which should not be accepted as fact without additional research.

Riehl (1979, p. 377) makes a compelling argument for the reasonableness of freezing of large amounts of condensate, and for use of the ice adiabat above 400 hPa. However, neither Riehl and Simpson (1979) nor Riehl (1979, p. 157–197) seem to question the assumption that undilute ascent is a necessity for cumulonimbus to reach the tropopause and perform their acknowledged function of energy transport.

First, consider a large (factor of 3) dilution of buoyancy from its pseudoadiabatic value by entrainment, illustrated in Fig. 5.4. By itself, this reduced buoyancy is in closer agreement with observations. Deciding on an appropriate water loading value is more difficult. The specific conceptual model of the updraft will matter. The updraft speed is now low enough to be near the fall speed of raindrops, so the drop size spectrum will matter. The simplicity of the arguments herein argues for extremely simple assumptions, so accordingly, the water loading is assumed to be a factor of 3 less than adiabatic throughout the depth of the updraft. This is on the high side of most measurements but is chosen intentionally to give a reasonably large buoyancy reduction.

With thermal buoyancy and water loading both reduced by factors of 3, effective CAPE between cloud base and 500 hPa is about 60 J kg^{-1}, reducing the updraft to under 8 m s^{-1}, again assuming 50% efficiency of conversion. This is still on the high side of the range of observations, about halfway between the highest 10th percentile for tropical oceans and the highest 10th percentile for the Thunderstorm Project observations over land (Lucas et al. 1994). Repeating the calculation for the 700-hPa level, the updraft is about 4 m s^{-1}, about the same as the highest 10th percentile over oceans.

Next, consider this hypothetical 8 m s^{-1} updraft at 500 hPa, containing 3.9 g kg^{-1} condensate. The environment temperature is −6°C, and the assumed updraft temperature has been reduced to −4.3°C from its pseudoadiabatic value of −1°C. Common research aircraft experience flying in disturbances over tropical oceans is that neither cloud water nor rainwater in updrafts of modest strength will remain unfrozen for more than a few minutes, even at temperatures as warm as −5°C, and certainly not by −10° or −15°C (e.g., Black and Hallett 1986; Willis and Hallett 1991). It is probably a conservative assumption that updrafts such as this one will freeze condensate between −4° and −15°C which, in this case, is between 500 and 400 hPa. The latent heat of sublimation rather than condensation is assumed from −15°C to cloud top. The solid line in Fig. 5.4 gives the resulting parcel path.

The details of the events in the lower part of the troposphere are complex and surely require cloud resolving models for understanding. However, Fig. 5.4 is clear in demonstrating the following: if the updraft can survive to about −5°C to loft several grams per Kilograms of condensate at more than a few meters per second, the buoyancy gain from freezing and subsequent shift to the ice adiabat is considerable. A large increase in updraft velocity results from integrating this enhanced buoyancy over a large vertical distance. In the example shown, water-loaded CAPE between 500 and 150 hPa is about 610 J kg^{-1}, which would increase the vertical velocity (again at 50% efficiency) by almost 25 m s^{-1} between 500 and 150 hPa.

Thus, one arrives at a schematic model of the vertical distribution of buoyancy in strong tropical oceanic cumulonimbus (Fig. 5.4), consistent with weak updrafts in the lower half of the troposphere and quite strong updrafts above midtroposphere. Such a model explains many of the observations. For example, vertically pointing wind profiler observations (e.g., Balsley et al. 1988) and observations from the airborne ER-2 Doppler radar looking downward from 20 km (Heymsfield et al. 1996; G. M. Heymsfield 1998 and 1999, personal communication) occasionally show updrafts in the 10–20-m s^{-1} range in the upper troposphere, but hardly ever in the lowtroposphere to midtroposphere. Ebert and Holland (1992) illustrate a case of extremely cold temperatures above a tropical cyclone that imply upper-tropospheric updrafts in the 20–m s^{-1} range with soundings similar to Fig. 5.3. While direct observations are scarce, the author's experience in the field includes encounters with a few updrafts of about 20 m s^{-1} in the upper troposphere over tropical oceans, for example, during the birth of Oliver (Simpson et al. 1997), but never in lowtroposphere to midtroposphere.

The hypothetical parcel paths are also shown on the thermodynamic diagram (Fig. 5.3). The essential point to note is that the equivalent potential temperature (and therefore also the moist static energy) of the outflow is nearly identical to that of the totally unrealistic pseudoadiabatic ascent. The moist static energy lost by entrainment and mixing below 500 hPa has been gained through the ice processes. This near equality is probably coincidental. Unfortunately, it has often been used (misused) to imply that undilute ascent is a common occurrence.

5. Differences between oceans and continents near the equator

The example above applies mainly to the cumulonimbus clouds of the oceanic equatorial trough zone. The observational database is much more solid over the ocean than over continents. More importantly, evidence is increasing that storms over tropical continents are much stronger than those over tropical oceans. The increased hazard of penetration is an important reason for the near absence of in-cloud data in strong continental storms.

Orville and Henderson (1986), Goodman and Christian (1993), and Goodman et al. (2000) used satellite observations of lightning to show that "lightning loves land." Rutledge et al. (1992) and Williams et al. (1992) showed that the continental regimes near Darwin, Australia, produced more intense storms than did the oceanic regimes. Zipser (1994), Zipser and Lutz (1994), and Petersen and Rutledge (1998) showed that the rain-to-lightning ratio is far greater over oceans, and that the reasons are related to the weaker updrafts over oceans, in agreement with findings in Lucas et al. (1994). Mohr and Zipser (1996) and Mohr et al. (1999) used passive microwave satellite data to show that the ice scattering signatures over land were consistently stronger than those over oceans. (The justification for using low brightness temperatures in the 37- and 85-GHz passive microwave channels is outlined in the next section.)

Joanne Simpson's leadership role in making the Tropical Rainfall Measuring Mission (TRMM) satellite a reality is well known (Simpson et al. 1988, 1996; Kummerow et al. 1998). It is fitting that we are now able to use the data from TRMM to address some of the quantitative issues about the characteristics of tropical convection in different regions directly. One step in that direction is to use not just passive microwave data, an indirect indicator of convective vigor, but the TRMM radar, which gives a direct measure of the height by large hydrometeors.

Nesbitt et al. (2000) made a systematic comparison of TRMM radar and passive microwave estimators of convective strength for two tropical Pacific Ocean regions and for two continental regions (tropical Africa and the Amazon basin) for a 3-month period. Not surprisingly, the results, especially their Figs. 5, 8, and 9, confirm earlier indications that by each measure, convection over the two oceanic regions is weaker than over either of the two land regions, but with storms over equatorial Africa much stronger than those over the Amazon (see also McCollum et al. 2000). They also used the lightning imaging sensor on TRMM to demonstrate that the flash rate over the two land regions was greater than that over the two ocean regions by two orders of magnitude.

The question arises whether these admittedly stronger storms over land might have true undilute cores. That is always a possibility for the very strongest storms (more on this soon). However, it is argued here that a modest change in the assumed updraft strength in the midtroposphere can account for a major change in the properties of that storm. Zipser and Lutz (1994) point out that most raindrops can fall through a 5-m s^{-1} updraft but not through a 10-m s^{-1} updraft. The faster the updraft, other things being equal, the greater the supercooled liquid water content should be. Thus, a 10-m s^{-1} updraft would have more condensate freezing, greater graupel riming rates, greater heights attained by strong radar echoes, and greater ice scattering signatures at 37 and 85 GHz. Many authors have pointed out that the noninductive ice–ice collision process requires substantial supercooled liquid water content, graupel, and small ice particles. Modeling studies by Baker et al. (1995, 1999) find great sensitivity of flash rate to updraft velocity, such that the difference between 5 and 10 m s^{-1} may translate into a huge difference in flash rate. Following this reasoning, we explore how small changes in the assumed parcel path in Figs. 5.3 and 5.4 might have major effects.

Consider first a slightly greater entrainment rate below 500 hPa than assumed for Figs. 5.3 and 5.4, that might be more characteristic of oceanic clouds. As already shown, the parcel buoyancy in Fig. 5.4 is consistent with an 8-m s^{-1} updraft at 500 hPa. A slightly greater dilution would reduce this toward 5 m s^{-1}. The time for the updraft to reach 500 hPa would increase, the fraction of condensate falling out would increase, and the updraft boost from condensate freezing would decrease. A slight decrease in vigor would, in fact, be more consistent with the typical properties of tropical oceanic cumulonimbus clouds without materially changing their ability to reach the upper troposphere and contribute their still ample moist static energy as required (Riehl and Malkus 1958).

Consider now a slightly smaller entrainment rate in the broader updraft cores that appear to be more characteristic of continental clouds. This slightly smaller dilution would easily increase updraft strength to 10 or 12 m s^{-1}. The time for the updraft to reach 500 hPa would decrease, the fraction of condensate falling out would decrease, and the supercooled cloud liquid water content would increase. The updraft boost from freezing of condensate would increase and the updraft speed in the upper troposphere (already nearly 25 m s^{-1}) could reach very large values. Thus, it is not necessary to assume undilute ascent from cloud base to explain extremely vigorous cumulonimbus clouds, with high lightning flash rates, large optical depth of graupel, and correspondingly low brightness temperatures at 37 and 85 GHz, as observed over tropical continents.

If it is true that highly diluted updrafts with small differences in entrainment rates result in updrafts of 5 m s^{-1} versus 10–12 m s^{-1} at 500 hPa, this corresponds to the difference observed between oceanic convection and "ordinary" continental convection summarized by Lucas et al. (1994). A sensitivity study using a one-dimensional model with entrainment and microphysics that supports this speculation was carried out by Ferrier and Houze (1989). They show that small changes in either entrainment or in low-level forcing result in large changes in updraft velocity. These and many other studies summarized in Blyth (1993) and Houze (1993) tend to show that the specific mechanism of entrainment is less important than the fractional dilution with outside air, which is a strong inverse function of updraft radius.

Why should updrafts over land have smaller entrainment? Lucas et al. (1994) have already speculated that these differences could be caused by larger diameter updrafts over land, related to the deeper mixed layers. See also Lucas et al. (1996), offering additional possibilities that the slightly greater convective inhibition often observed over land may result in larger updrafts from cloud base as would be required to overcome the inhibition (i.e., larger forcing). The oft-repeated contention that CAPE is greater over land than over water does not survive close scrutiny (Lucas et al. 1994), but the "shape of the CAPE" is very important, often fatter over land than over tropical oceans. More importantly, the main purpose of this paper is to demonstrate that CAPE *per se* is overrated as a predictor of the behavior of convection when entrainment, water loading, forcing, and the vertical distribution of buoyancy are taken into account. This is a point well made by Blanchard (1998) in the context of forecasting severe weather.

Following the reasoning in this section, it is concluded that strong continental convection often begins as moderately entraining updrafts in the low troposphere to midtroposphere, but that updraft speeds increase greatly in the upper troposphere, not infrequently exceeding 25–35 m s^{-1}. This behavior has been observed and modeled in the famous "Hectors," the cumulonimbus found on many days during November and December over the Tiwi Islands north of Darwin, Australia (Simpson et al. 1993).

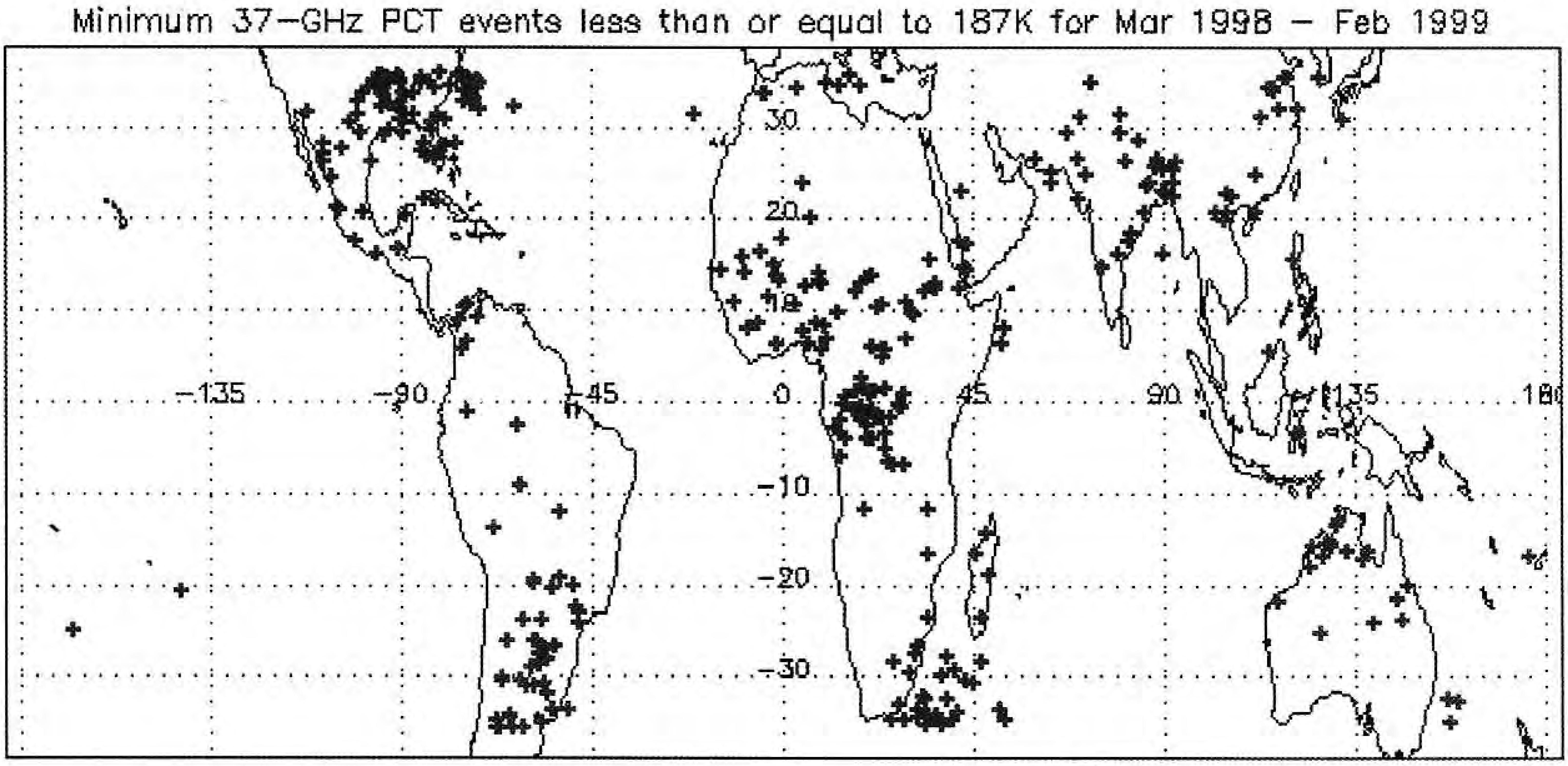
6. Equatorial trough versus subtropical convection according to TRMM

There is already ample evidence that the convective systems of the equatorial trough zone, although heavily raining and unquestionably vital because of their collective role in the general circulation, are not as strong as many of the severe storms of higher latitudes. Mohr and Zipser (1996) defined mesoscale convective systems as "intense" according to numbers of pixels with 85-GHz polarization corrected temperature (PCT; see Spencer et al. 1989) less than threshold values, signifying large optical depth of ice scattering by dense ice particles (i.e., graupel or hail). The equatorial trough zone had few of these with the sole exception of continental Africa. Notably, there were few intense systems in tropical South America or the Indonesian (maritime continent) region. With some differences, the distribution of intense systems in Mohr and Zipser resembled those of large mesoscale convective complexes mapped by Laing and Fritsch (1997).

The physical significance of the ice scattering signature is that it is directly related to the ice water path with few approximations. As Vivekanandan et al. (1991) stated, ". . . the ice layer remains relatively unobscured from a spaceborne radiometer at 37 GHz and 85 GHz, perhaps presenting an ice-phase characterization as a more inherently retrievable property than the rain phase." They show that low brightness temperatures (T_b) at these frequencies are quantitatively related to ice density and size. While relationships are not unique, they provide strong justification for considering that very low T_b means large depth of high-density ice particles. The implication is that strong updrafts are required for large depths of graupel or hail, and therefore that low T_b can be used as a proxy for convective intensity. (This would seem to be a more direct proxy than cold IR cloud-top temperatures.)

This paper argues that true undilute updrafts from below cloud base are likely in certain severe storms but rarely in equatorial latitudes. Undilute updrafts starting with large water vapor content (such as the tropical ocean sounding) would certainly contain very large graupel or hail. Rather than use the 85-GHz channel, the 37-GHz (8-mm wavelength) channel is even more sensitive to large graupel and hail. We examined all orbits for a full year of TRMM data (March 1998–February 1999) and searched for the minimum PCT at 37 GHz in each and every precipitation feature that was observed. Then we simply plotted the locations of all systems containing at least one pixel colder than an arbitrary T_b, selected such that this T_b is only achieved on average of once per day. That 37-GHz T_b is 187 K, and the resulting distribution is shown in Fig. 5.5. With the notable exception of equatorial Africa (again!), the equatorial trough zone is hardly represented at all, especially the oceans.

Figure 5.5 is interpretable as a map of the most intense convective storms viewed by TRMM (36°N–36°S), and it includes a few surprising features. The total dominance of Africa over the maritime continent and tropical South America is surprising, although the lightning data and Nesbitt et al.'s (2000) data presage these results. The extension of subtropical maxima offshore of the U.S. east coast, the South African east coast, and offshore of southeast Australia is also surprising. The storms in the Mediterranean Sea are surprising; they appear only in autumn and may be related to cold air



Minimum 37–GHz PCT events less than or equal to 187K for Mar 1998 – Feb 1999

FIG. 5.5. The precipitation features observed by TRMM during one year with the coldest 37-GHz PCT (strongest ice scattering signature; see text). At 8-mm wavelength, colder PCT is proposed as a measure for largest optical depth of large graupel and/or hail, and as a crude proxy for updraft strength.

over warm water. However, the severe storm areas of the southern United States, subtropical South America, and India–Bangladesh appear in the locations and seasons expected.

If nearly undilute towers existed in the Tropics, it is concluded based on the above arguments that they would have updrafts from 10 to 20 m s^{-1} at -5°C with 7–12 g kg^{-1} of condensate. Before this condensate load could significantly slow the updraft, freezing would generate an additional 2–3-K buoyancy and invigorate the updrafts to 30–40 m s^{-1}. Assuming only that such clouds would have regions, perhaps between updrafts and downdrafts, where the combination of large supercooled liquid water content, large graupel content, and large numbers of small ice particles coexist, vigorous charge separation would be likely. The large depth of graupel and small hail would give very low brightness temperatures at 85 and 37 GHz.

The TRMM observations, of which Fig. 5.5 is but one small example, strongly suggest that this rarely, if ever, happens over tropical oceans, but elsewhere, especially in subtropical regions well known for severe weather. Such powerful storms appear mainly over Africa in the deep Tropics. McCollum et al. (2000) note that remote sensing techniques are overestimating rain in Africa, and speculate on reasons for the low precipitation efficiency of African storms. That paper, Mohr et al. (1999), and others are pointing the way for using TRMM and other satellite data to survey and compare the properties of storms over the globe. Among the most important of these properties is the degree of dilution of updrafts, their vertical velocity, and the intensity of storms. This paper hypothesizes that the most intense storms (and undilute updrafts) are rarely found over tropical oceans, proposes some reasons for this, and suggests that careful exploitation of data from TRMM can broaden our understanding of the nature and distribution of intense convection around the world.

7. Conclusions

Observations of the properties of extreme midlatitude severe storms are consistent with the presence of undilute updrafts.

Observations of the properties of typical cumulonimbus clouds over tropical oceans are inconsistent with the presence of undilute updrafts.

The common observations over tropical oceans can hypothetically be explained by assuming large dilution of updrafts by entrainment below about 500 hPa, followed by freezing of condensate. This freezing and subsequent ascent along an ice adiabat reinvigorates the updrafts and permits them to reach the tropical tropopause with the necessarily high values of moist static energy, as the hot tower hypothesis requires. It is recognized that the explanation offered herein is speculative and probably controversial.

More speculatively, the large difference observed between typical ocean and land clouds can be explained by assuming slightly smaller entrainment rates for clouds over land. These small entrainment differences have a very large effect on updrafts in middle and upper troposphere and can presumably account for the large differences in convective vigor and ice scattering that are observed.

Also speculatively, small differences in entrainment rate can lead to differences in updraft strength in midtroposphere (5 m s^{-1} vs 10–12 m s^{-1}) that are typically observed between land and ocean, and in turn can lead to the very large differences in lightning flash rates that are observed.

CAPE is a measure of maximum *potential* vertical velocity. Without taking account of the vertical distribution of buoyancy, entrainment, water loading, and the degree of forcing, it is *not* by itself a good predictor of the intensity or vertical velocity in convective clouds.

Using TRMM to map a proxy for the most intense storms on earth between 36°S and 36°N, they are found mostly outside the deep Tropics, with the notable exception of tropical Africa.

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