

Chapter 4

From Hot Towers to TRMM: Joanne Simpson and Advances in Tropical Convection Research

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ABSTRACT

Joanne Simpson began contributing to advances in tropical convection about half a century ago. The hot tower hypothesis jointly put forth by Joanne Simpson and Herbert Riehl postulated that deep convective clouds populating the “equatorial trough zone” were responsible for transporting heat from the boundary layer to the upper troposphere. This hypothesis was the beginning of a 50-year quest to describe and understand near-equatorial deep convection. Tropical field experiments in the 1970s [Global Atmospheric Research Program Atlantic Tropical Experiment (GATE) and the Monsoon Experiment (MONEX)] in which Joanne participated documented the mesoscale structure of the convective systems, in particular the deep, stratiform, dynamically active mesoscale clouds that are connected with the hot towers. In the 1980s these new data led to better understanding of how tropical mesoscale convective systems vertically transport heat and momentum. The role of the mesoscale stratiform circulation in this transport was quantified. Tropical field work in the 1990s [especially the Coupled Ocean–Atmosphere Response Experiment (COARE), in which Joanne again participated] showed the importance of a still larger scale of convective organization, the “supercluster.” This larger scale of organization has a middle-level inflow circulation that appears to be an important transporter of momentum. The mesoscale and supercluster scale of organization in tropical convective systems are associated with the stratiform components of the cloud systems. Joint analysis of satellite and radar data from COARE show a complex, possibly chaotic relationship between cloud-top temperature and the size of a stratiform precipitation area. The Tropical Rainfall Measuring Mission (TRMM) satellite, for which Joanne served as project scientist for nearly a decade, is now providing a global census of mesoscale and supercluster-scale organization of tropical convection. The TRMM dataset should therefore provide some closure to the question of the nature of deep convection in the equatorial trough zone.

1. Introduction

Advances in understanding tropical atmospheric convection are interwoven with the career of Joanne (Malkus) Simpson. This chapter traces highlights of these advances and their connections with her career. By the early 1950s Joanne had contributed some of the first highly important observational studies of tropical convection. From early meteorological aircraft measurements she determined the basic entrainment characteristics of trade wind cumulus. In Malkus (1952) she related the tilted structure of trade cumulus to the entrainment of environmental momentum. In Malkus (1954) she examined the aircraft-measured thermodynamic properties of these clouds and concluded that while sometimes the clouds had protected inner cores with properties similar to steady-state entraining jets, the aircraft data argued primarily for the clouds being aggregates of entraining thermals in various stages of development. This latter result foreshadowed the modern view of entraining cumulus espoused by Raymond and Blyth (1986) and incorporated into the parameterization of convection in climate models by Emanuel et al.

(1994). Joanne then turned her attention to the deeper convection of the equatorial regions and joined Herbert Riehl to publish one of the landmark papers in meteorology, “On the heat balance in the equatorial trough zone” (Riehl and Malkus 1958). They postulated that undiluted updrafts in cumulonimbus maintained the mean thermodynamic stratification of the equatorial zone by transporting high moist static energy boundary layer air to the upper troposphere. Such “hot towers” would effectively bypass the middle troposphere, which is left with a generally low moist static energy. This hypothesis, which is largely accepted today, set the direction of observational research on tropical convection for the next four decades. That direction was to document and understand the phenomenology of the convective clouds containing hot towers. This paper will review briefly that research and note Joanne’s contributions along the way.

2. The 1960s: Identification of the mesoscale

The hot tower paper was not a study of convection per se. It merely hypothesized the role of convective

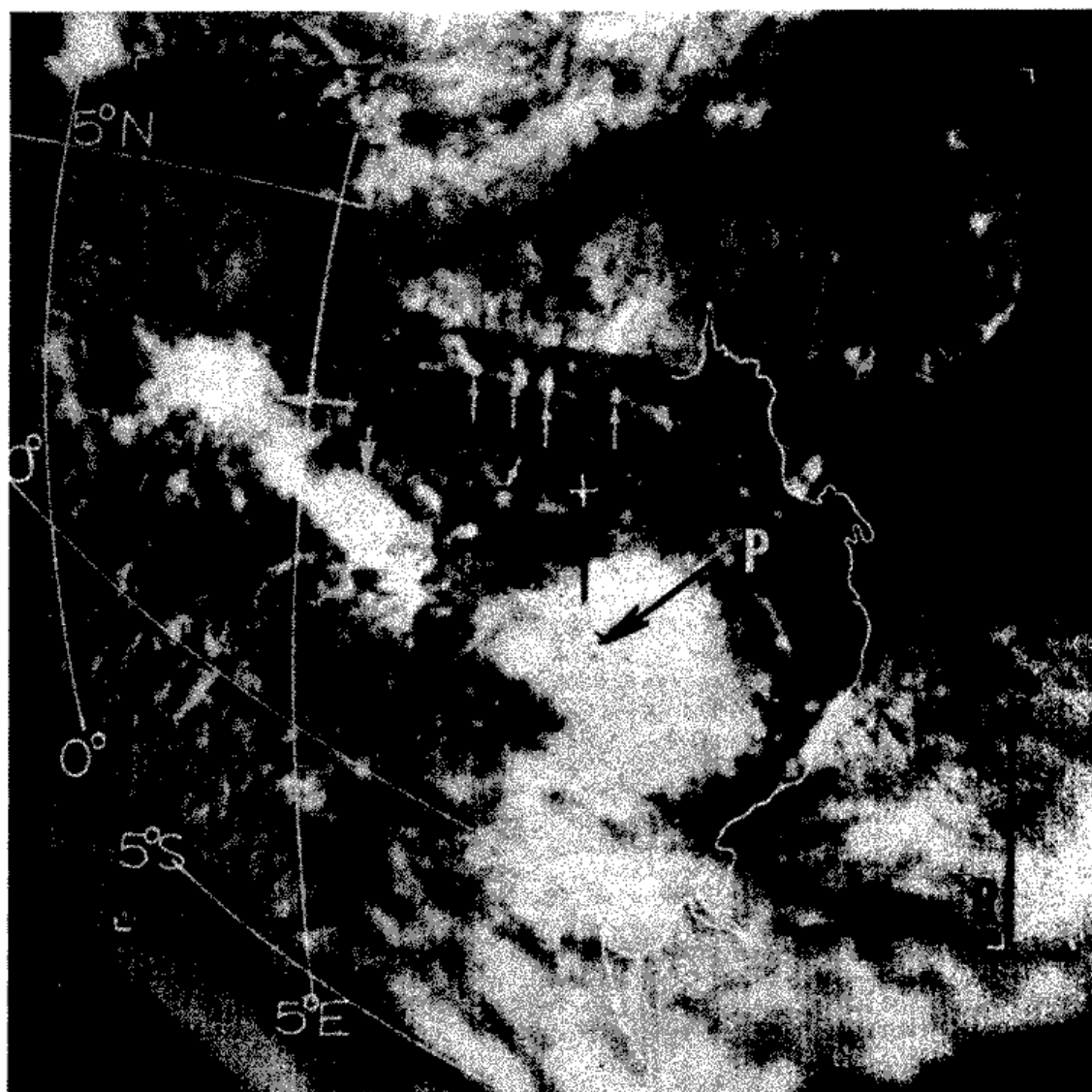


FIG. 4.1. Cumuliform clouds in the Gulf of Guinea, 0032 UTC 6 May 1964, Television Infrared Observational Satellite (TIROS) 7, pass 4761T (from Anderson et al. 1966).

clouds in maintaining the large-scale mean thermodynamic structure of the equatorial atmosphere. After the hot tower paper, Joanne continued her collaboration with Herbert Riehl by immediately setting out to test the hot tower hypothesis by making direct observations of the detailed structure of convective clouds in the equatorial zone via a series of aircraft flights over the tropical Pacific. They mapped the clouds by photographic methods and visual observation. The results published in a 229-page monograph (Malkus and Riehl 1964) were another groundbreaking contribution to tropical meteorology. This work, however, was limited by the absence of modern aircraft instrumentation, little or no satellite data, and sparse synoptic observations. Nonetheless, the cloud mapping was effective and anticipated later studies by showing that the deep tropical convection, in which hot towers occur, has a mesoscale organization. On their flights, they noticed three levels of organization: “convective, meso-, and synoptic.” The mesoscale features had characteristic horizontal scales of 15–500 km. At the end of the monograph, they stated prescient-

ly, “So far as we know, the meso-scale regimes and abrupt transitions between them have not been documented before. The main physical reasons for these transitions must be sought if attempts at theoretical modeling are to be fruitful.”

Another important development during the 1960s was the launch of the first weather satellites. These pictures from space (e.g., Fig. 4.1) showed that the dominant clouds of the equatorial trough zone were mesoscale, that is, hundreds to thousands of kilometers in dimension. Since these pictures only showed the tops of the clouds, it was easy to regard them as “cirrus canopies” connecting skinny hot towers. This view was not really consistent with the visual evidence of mesoscale organization in the aircraft studies of Malkus and Riehl (1964). In an aircraft study aided by key sounding data and early satellite data, Zipser (1969) was able to postulate the basic mesoscale structure of a tropical oceanic mesoscale convective system (Fig. 4.2). The cirriform cloud top was not a thin layer interconnecting individual convective towers, as in Fig. 4.1, but rather was the top

of a deep precipitating stratiform cloud connected to a region of convective cells. Little has changed regarding Zipser's (1969) basic conceptual model. Later studies primarily have confirmed his picture, made it more quantitative, or added detail.

3. The 1970s: Documentation of the mesoscale

Despite the accumulating evidence of mesoscale organization of tropical convective systems in the 1960s, the oversimplified model of a convective population depicted in Fig. 4.3 remained popular. Ooyama (1971), Yanai et al. (1973), and Arakawa and Schubert (1974) built mathematical representations of tropical cloud ensembles on the notion that the convection was separated in scale from the larger synoptic-scale flow. A tractable mathematical approach to account for the mesoscale organization apparent in the earlier observational studies of Malkus and Riehl (1964) and Zipser (1969) awaited higher-resolution models, which became prevalent in the 1980s.

The conflict between the scale-separation theory and the potential importance of the mesoscale phenomena seen by satellite and aircraft was recognized in the planning of the Global Atmospheric Research Programme's (GARP) tropical field experiments in the 1970s. Joanne Simpson was a primary participant in the 1974 GARP Atlantic Tropical Experiment (GATE) and the 1978–9 Monsoon Experiment (MONEX). She made many aircraft flights in both of these projects and continued her efforts to map clouds photographically (Warner et al. 1980). However, GATE made use of a host of other types of measurements, which could better test the diverging conceptual models of tropical convection.

The basic design of GATE (Kuettnner and Parker 1976) was to observe details of the clouds with a fleet of instrumented aircraft and simultaneously document the synoptic-scale environment and mesoscale wind pattern with supplemental soundings launched from an armada of ships, operating in a nested array off western Africa. Additionally, the boundary layer was sampled and radiation measured, as these were essential inputs to any diagnostic application of scale-separation theory. Fortunately, the ships were also equipped with three-dimensionally scanning, quantitative precipitation radars. The motivation for the radars was primarily to measure the rain, another required input, but the radars also provided detailed observations of the mesoscale organization of the precipitating disturbance. The prevailing acceptance of the scale-separation model sometimes led to the radar observations being thought to be only of marginal necessity. Participants in GATE planning recall the frequent suggestion to use the radars to track sounding balloons. This suggestion was fortunately not followed and the radar observations, combined with the mesoscale sounding array, turned out to be key in showing that the mesoscale nature of the con-

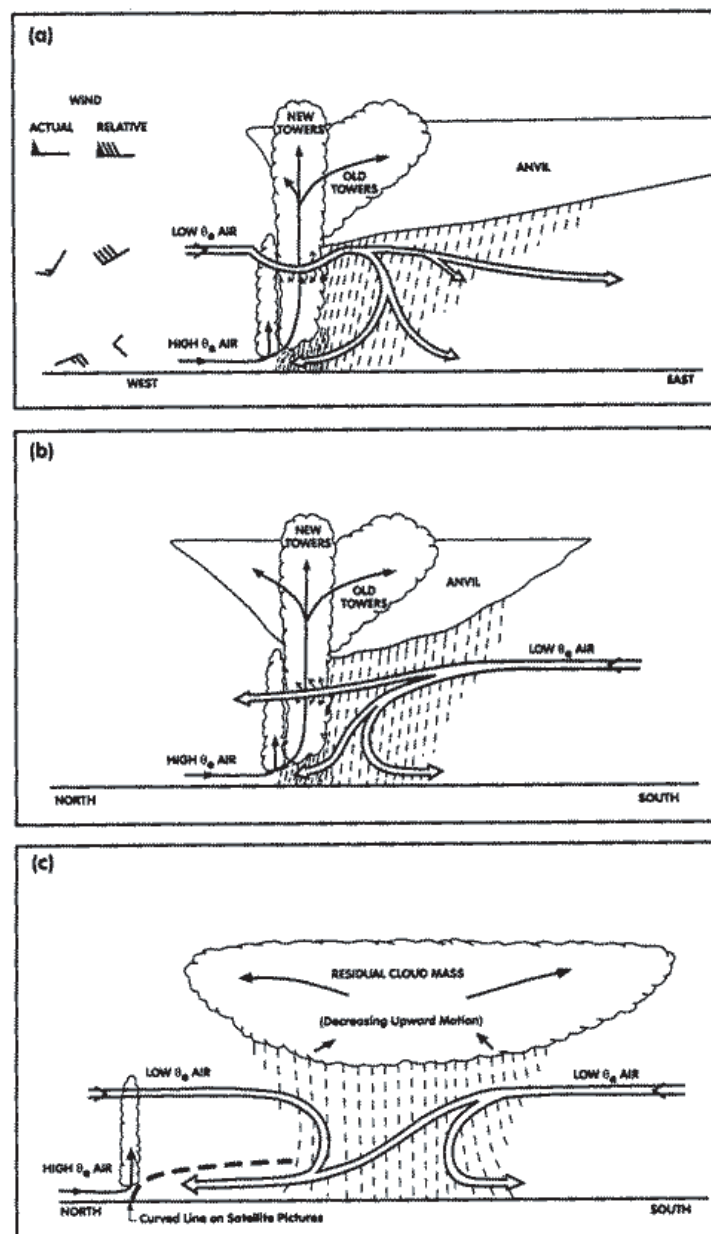


FIG. 4.2. (a) Schematic streamlines of airflow relative to a tropical oceanic convective cloud system in east–west section illustrating the mechanism of downdraft production. The low equivalent-potential-temperature (θ_e) air in the environment can pass under the anvil without necessarily intercepting convective towers, although such air that does intercept towers can be entrained by turbulent mixing into the towers and can also produce more intense and smaller-scale downdrafts than the direct large-scale production under the raining anvil. (b) Same as (a) except for north–south section. Both panels represent the intensification phase of the disturbance, with a large population of active cumulonimbus towers, either in individual clusters or in organized lines. (c) A north–south section similar to (b), but representing the dissipating phase of the disturbance, when maintenance of the downdraft is primarily by rain falling from the extensive cloud shield, although with considerable mesoscale variations in intensity not depicted in this diagram (from Zipser 1969).

vective systems was as anticipated by Malkus and Riehl (1964) and Zipser (1969).

GATE and MONEX ship and aircraft measurements made beneath the cirrus canopies showed that the rain from these clouds was dominated by cloud systems with rain areas ~ 100 km in dimension—manifestly meso-

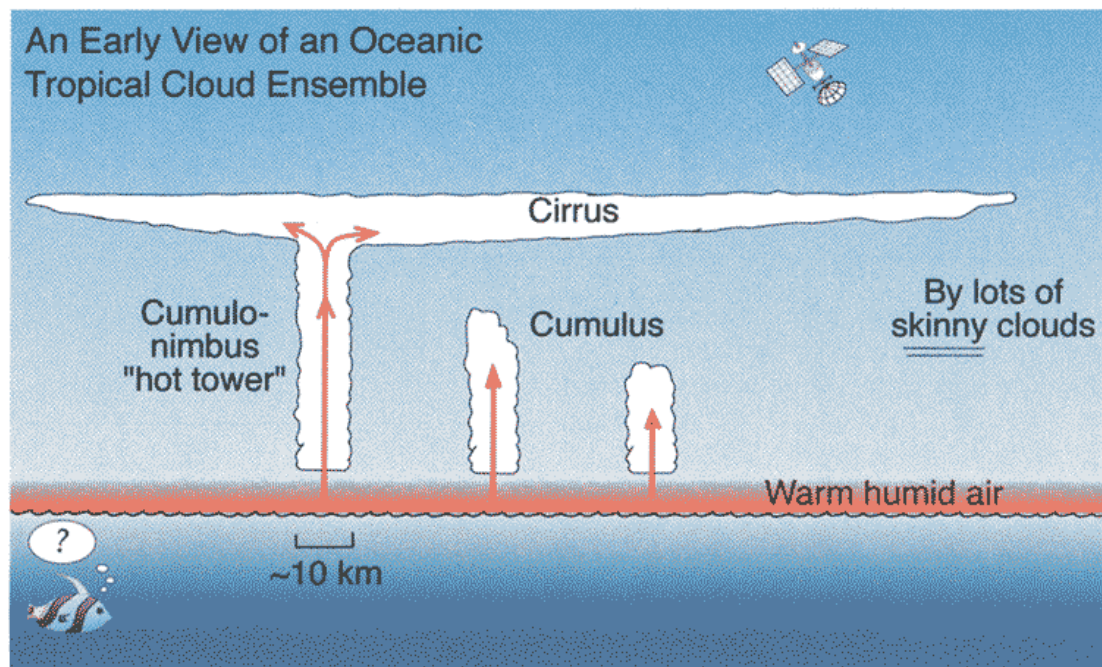


FIG. 4.3. A popular conceptual model of a tropical cloud ensemble, c. 1974.

scale. Radar observations showed that large portions of the precipitation were stratiform with pronounced melting layers (Shupiatsky et al. 1975, 1976; Houze 1977; Leary and Houze 1979), while other portions of the rain areas had embedded convective-scale cores of maximum intensity (hot towers). These radar observations substantiated the earlier visual impressions of Malkus and Riehl (1964) and Zipser (1969).

The new observations from GATE and MONEX led to a rethinking of how tropical convection vertically redistributes mass, heat, and momentum in the troposphere, and, as a result, the 1980s were a most productive period in tropical convection research.

4. The 1980s: Accounting for the mesoscale in transports of heat and momentum

Houze and Betts (1981) summarized the basic observations of convection in GATE, and Johnson and Houze (1987) summarized the MONEX observations. A major point of these summaries was the aforementioned ubiquitous occurrence of stratiform precipitation in the major rain-producing convective systems and the degree of mesoscale organization implied by this finding. Both rapidly propagating ("squall line") systems and slowly moving mesoscale convective systems exhibited stratiform precipitation regions in connection with the convection. From the Houze-Betts and Johnson-Houze summaries it was evident that a major new understanding of tropical convection would emerge from these rich datasets. A French field experiment, called Convection Tropicale Profonde (COPT-81) and conducted in the Ivory Coast (western equatorial Africa) in 1981 (Sommeria and Testud 1984) added a valuable continental dataset to the oceanic datasets of GATE and

MONEX. COPT-81 emphasized radar observations of squall-line mesoscale convective systems over land (Roux et al. 1984; Chong et al. 1987; Roux 1988; Chalon et al. 1988; Sun and Roux 1988; Chong and Hauser 1989).

One of the first important findings regarding the mesoscale organization of the convective cloud systems in GATE, MONEX, and COPT-81 was that the stratiform rain areas had their own dynamical structure, substantially different from the convective-scale dynamics of the hot towers populating the convective portion of the disturbance. The stratiform regions had convergence and vortex structure at midlevels and divergence at lower and upper levels (Figs. 4.4, 4.5; Gamache and Houze 1982, 1985; Houze and Rappaport 1984; Sun and Roux 1988; Lafore and Moncrieff 1989). As these circulation patterns became more widely known, investigators began to think about the implications of these findings for the vertical transports of momentum and heat.

LeMone (1983) analyzed the vertical redistribution of momentum by GATE mesoscale convective systems. By analyzing the GATE aircraft data, she found that a small-scale lower-tropospheric pressure minimum lay below the downshear-tilted updraft of a line of convective cells in a mesoscale convective system (Fig. 4.6). This pressure perturbation was a hydrostatic result of the warm, buoyant, sloping updraft lying overhead. LeMone further found that the pressure perturbation and associated circulation pattern of the convective system were consistent with the theoretical model of Moncrieff and Miller (1976; Fig. 4.7). Their model states that a two-dimensional steady-state convective system in an environment of specified shear similar to that of the large-scale environment in GATE must slope downshear with a low pressure perturbation underlying the sloping

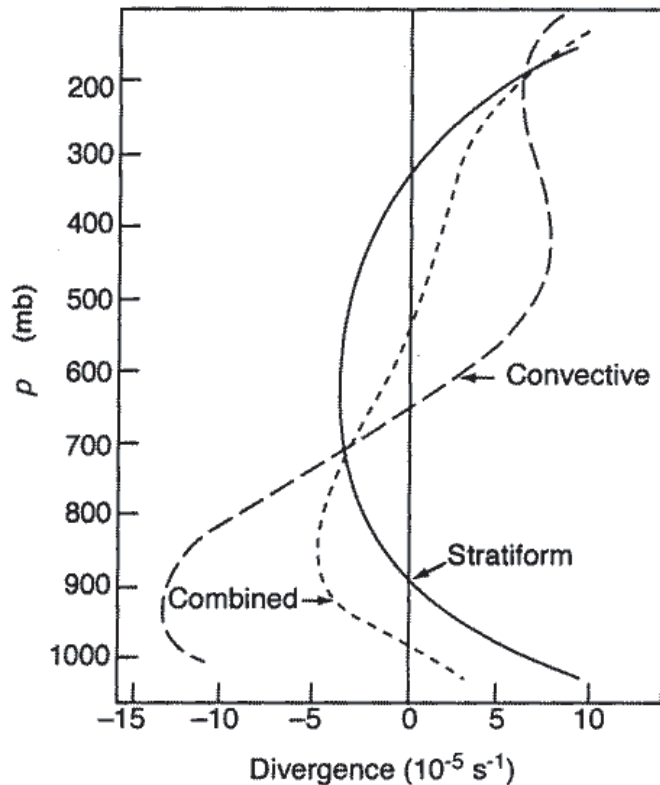


FIG. 4.4. Average divergence over the convective (long dashed), stratiform (solid), and combined (short dashed) regions of a tropical squall-line system (from Gamache and Houze 1982).

updraft. This flow configuration has a characteristic signature of vertical transport of horizontal momentum, in which cross-line momentum is removed from lower levels and added to upper levels (Fig. 4.8). The aircraft

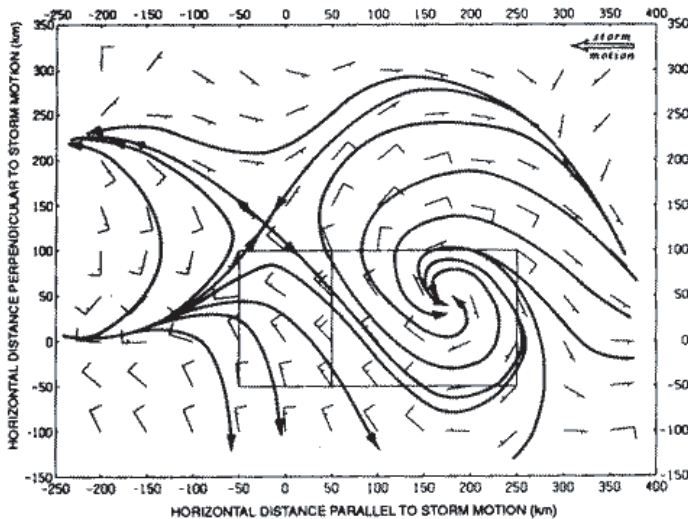


FIG. 4.5. Composite analysis of the mesoscale component of the wind at the 650-mb level of a tropical squall-line system. The smaller rectangle was the region containing the leading convective line seen on radar. The larger rectangle was the region of stratiform precipitation seen on radar. Winds were from ship-based soundings and aircraft measurements. The mesoscale component of the flow shown here was deduced by applying a mesoscale bandpass filter to the data to suppress larger- and smaller-scale wavelengths. A full wind barb represents 5 m s^{-1} . A vortex was evident toward the rear of the stratiform region (from Gamache and Houze 1985).

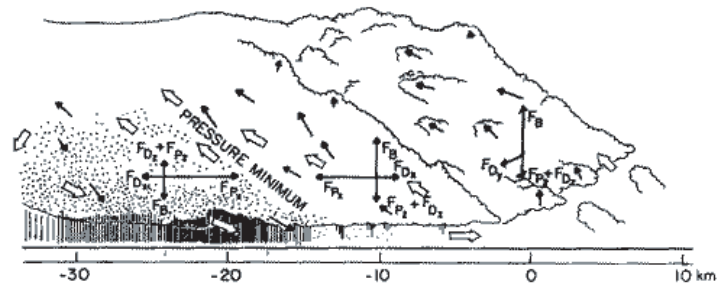


FIG. 4.6. Schematic of the processes leading to the momentum generation in the convective band. Here F_p , F_D , and F_B are forces on an air parcel owing to mesoscale pressure gradient, drag, and buoyancy, respectively. Horizontal and vertical components are indicated by subscripts x and z , respectively (from LeMone 1983).

data analyzed by LeMone (1983) implied such a transport (see her Figs. 13 and 14).

Houze (1982) analyzed the vertical redistribution of heating implied by the GATE mesoscale convective systems. Analysis of GATE, MONEX, and COPT-81 radar data showed that about 40% of the precipitation from mesoscale convective systems in these tropical regions was stratiform (Houze 1977; Cheng and Houze 1979; Gamache and Houze 1983; Leary 1984; Houze and Rappaport 1984; Churchill and Houze 1984; Houze and Wei 1987; Chong and Hauser 1989). This fact, coupled with the different dynamic structure of the stratiform region, suggested that a large proportion of the latent heat released in a convective system had a different vertical distribution than if the precipitation were of a purely convective nature. Using observations of the divergence profiles obtained by soundings and aircraft in convective and stratiform regions in GATE, Houze (1982, 1989) calculated the vertical distributions of heating in the convective and stratiform regions of a typical tropical

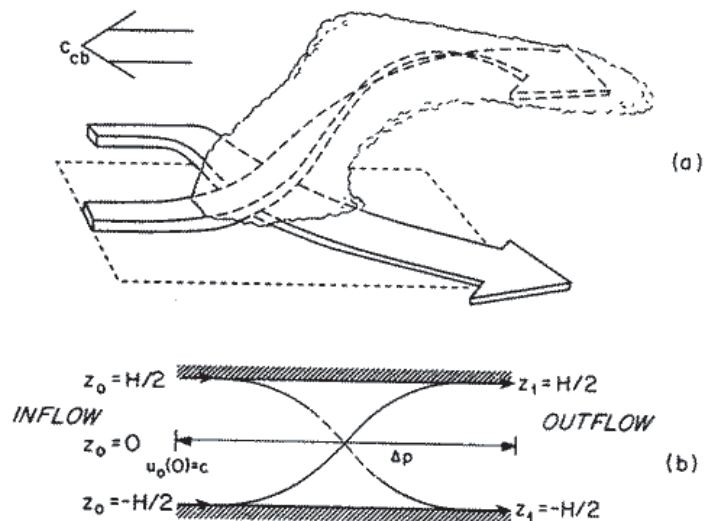


FIG. 4.7. (a) Schema of a propagating cumulonimbus; (b) limiting relative streamlines based on two-dimensional steady-state theory. On inflow, the velocity profile $U_0 = u_0 - c$, the static stability, and the parcel lapse rate are specified as a function of the inflow level z_0 , but c is calculated. Here Δp is the pressure difference across the system that must be consistent with the flow (from Moncrieff and Miller 1976).

Convective up and downdraft effects on the horizontal momentum field

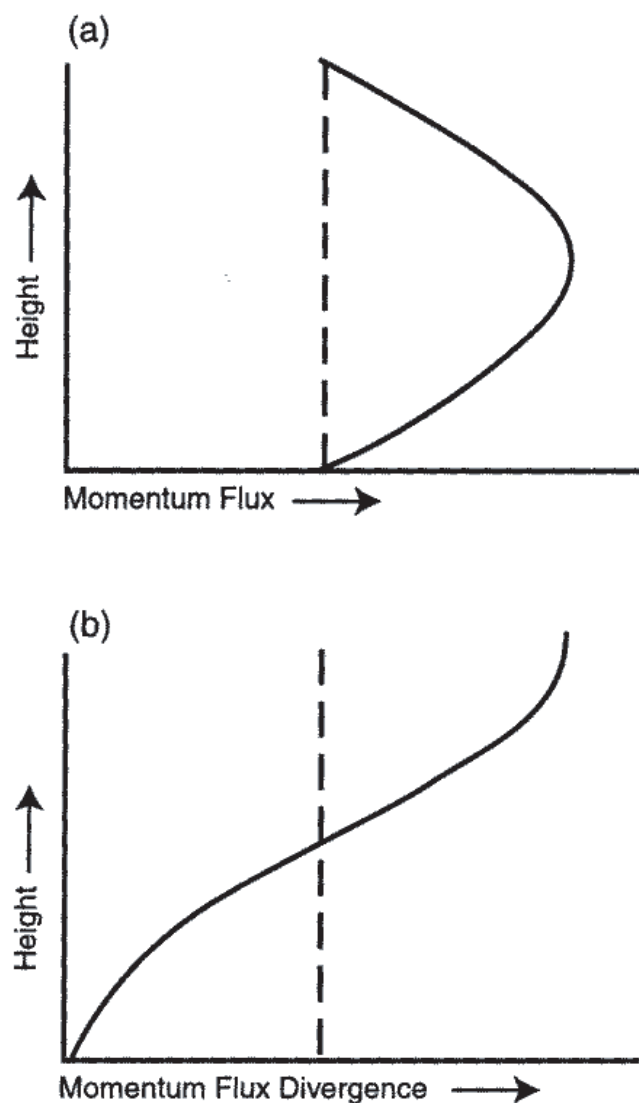


FIG. 4.8. (a) Idealized vertical flux of horizontal momentum by convective updrafts and downdrafts in a tropical oceanic organized convective system; (b) vertical divergence of the momentum flux in (a) [based on work of Moncrieff and Miller (1976) and LeMone (1983)].

mesoscale convective system, with precipitation 40% stratiform. Figure 4.9 sketches the shapes of profiles that he found to be characteristic of each type of region. The heating profile in the convective region forms a half sine wave, while that of the stratiform region forms a full sine wave. The tops of the profiles are at the tropopause. The lower panels show the profile of the vertical divergence of heating (which of course just mirrors the mass divergence profile) in each type of region. The convective region has a two-layer profile (convergence at low levels, divergence at upper levels), while the

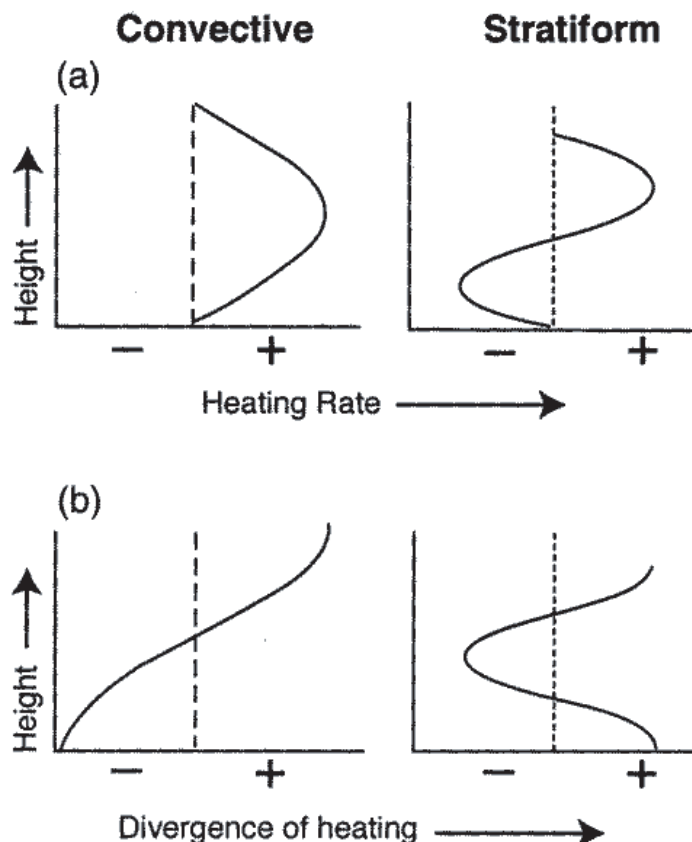


FIG. 4.9. (a) Idealized vertical flux of sensible heat in the convective and stratiform regions of a tropical mesoscale convective system; (b) vertical divergence of the fluxes in (a) [based on work of Houze (1982, 1989)].

stratiform region has a three-layer profile, with convergence in middle levels sandwiched between divergence at low levels and aloft. The large-scale (i.e., balanced) flow responds directly to the profile of vertical divergence of heating, which is a source of large-scale potential vorticity (Haynes and MacIntyre 1987). To the extent that precipitating mesoscale convective systems constitute the large-scale heat source in the Tropics, the large-scale circulation must be largely a response to the convective and stratiform heating profiles. Mapes (1993) and Mapes and Houze (1995) later elaborated on this point. Hartmann et al. (1984) obtained a much more realistic Walker cell circulation over the tropical Pacific when they assumed a large-scale heating profile characteristic of mesoscale convective systems with strong stratiform components.

5. The 1990s: Superclusters and chaos

Early satellite pictures, like that in Fig. 4.1, indicated the mesoscale size of tropical convective systems dominating the equatorial regions, especially over the vast oceanic regions. As satellite sampling became more comprehensive, it became possible to characterize the cloud population of tropical regions statistically. One of the centers of tropical convection is the "warm pool" of the western Pacific and Indian Oceans. This region

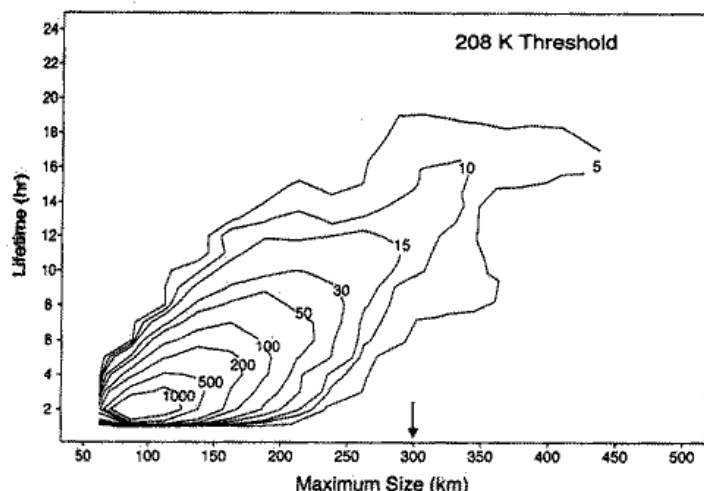


FIG. 4.10. Frequency of occurrence of convective systems tracked by an automatic tracking algorithm (per 25-km size interval per hour) as a function of the maximum size (abscissa) reached by a convective system during its lifetime (from the start to end of its life cycle) for all of the trackable clusters that occurred over the warm pool during COARE (from Chen and Houze 1997).

was the focus of COARE in 1992–93 (Webster and Lukas 1992; Godfrey et al. 1998). Joanne Simpson was a major participant in the aircraft program of COARE, especially with the National Aeronautics and Space Administration (NASA) DC-8.

Tracking methods applied to geosynchronous satellite data (e.g., Williams and Houze 1987) can indicate the lifetime and maximum size attained by mesoscale convective systems defined by a given threshold infrared temperature. The Williams–Houze method mimics the way an analyst would follow patterns in a series of satellite images by accounting for mergers and splits as the system goes through its life cycle. Chen et al. (1996) and Chen and Houze (1997) used the Williams–Houze method to determine statistics of the convection in COARE. Figure 4.10 shows their results for mesoscale convective systems defined by an infrared threshold of 208 K. The plot shows the frequency of occurrence by system lifetime and maximum size. Larger systems tend to last longer, but there is a lot of spread in the distribution. Systems reaching 300 km or more in maximum dimension (i.e., more than about 1 000 000 km² in area) last anywhere from 5 to 20 h. The longer lasting ones are what Nakazawa (1988) began to call “superclusters.” Chen et al. (1996) called the systems > 300 km in dimension “superconvective systems,” regardless of whether they were short or long lived. A lot of COARE research in the 1990s focused on these larger mesoscale convective systems.

Kingsmill and Houze (1999a,b) examined airborne dual-Doppler radar data collected on research flights on 25 different days of COARE. Many of these flights were in superconvective systems. Some flights were in convective regions and consistently showed deep updrafts consisting of sloping layers of air rising over advancing cold pools in circulations resembling those theorized by

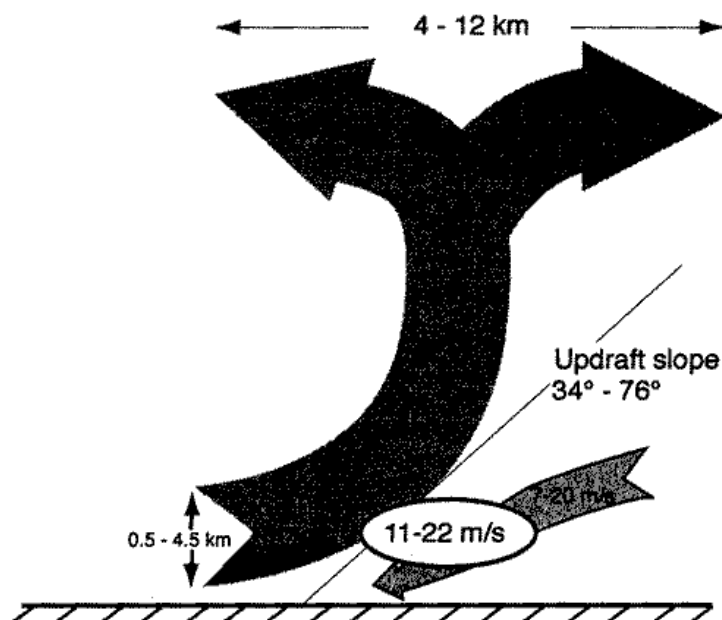


FIG. 4.11. Schematic of airflow in the convective regions of mesoscale convective systems observed by airborne Doppler radar in COARE. The numbers (from bottom to top) indicate the observed ranges of values for the depth of the inflow layer, horizontal relative velocity of inflow and outflow air currents, the slope of the updraft, and the width of the divergent region aloft. The horizontal directional differences of the low-level updraft inflow and midlevel downdraft inflow were often significantly different from 180° [based on figures and tables of Kingsmill and Houze (1999a)].

Moncrieff and Miller (1976; Fig. 4.7). Figure 4.11 is a schematic composite of the structure seen by Kingsmill and Houze (1999a,b). These updrafts comprised the hot towers predicted by Riehl and Malkus (1958). However, they were not simply narrow vertical pipes carrying air from the boundary layer to the tropopause, as suggested by Fig. 4.3. The air entering the updraft came from a layer much deeper than the boundary layer. Typically, this layer was one to a few kilometers deep, and the air flowed rearward in a deep layer, extending from the middle through the upper troposphere.

Other flights were in the stratiform regions of superconvective systems, and the data from these flights invariably showed an extensive midlevel inflow, which lay just at the base of the precipitation anvil and sloped downward through the precipitation melting layer in the heart of the cloud system (Fig. 4.12). The midlevel inflow seen in these cases was similar to midlevel inflows in most mesoscale convective systems, except for the extreme horizontal extent. The direction of the midlevel inflow was related closely to the direction of large-scale environmental flow at midlevels.

Moncrieff and Klinker (1997) inferred the existence of superconvective systems with midlevel inflow entering from a direction determined by the large-scale environmental flow at midlevels (700–850 mb) when they used forecasts and analysis from an operational global numerical weather prediction model to study an especially active convective period in the COARE region (Fig. 4.13; note the horizontal scale of the disturbance

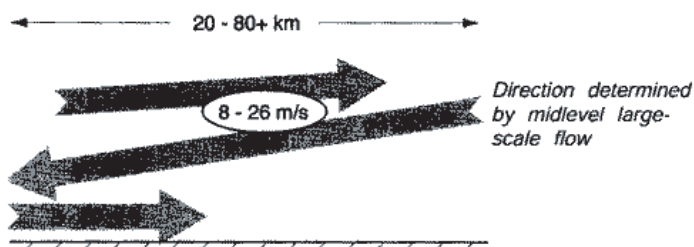


FIG. 4.12. Schematic of airflow in the stratiform regions of mesoscale convective systems observed by airborne Doppler radar in COARE. The numbers (from bottom to top) indicate the observed ranges of values for the horizontal relative wind velocity at low levels, the horizontal scale of the midlevel inflow, the horizontal relative velocity of the midlevel inflow and outflow air currents, the differential horizontal velocity between the middle and upper level, and the velocity at upper levels [based on figures and tables of Kingsmill and Houze (1999a)].

they describe, and the direction of the midlevel inflow). They found that these broad midlevel inflows of environmental air fed the mesoscale downdraft of the superconvective system. They further determined that the downward transport of momentum by these midlevel inflow mesoscale downdraft circulations played a strong role in balancing the large-scale momentum budget (see their Fig. 8b).

Using Doppler radar data from both ship and aircraft in superconvective systems in COARE, Houze et al. (2000) found evidence in the observations to confirm that the midlevel inflows of the superconvective systems transported momentum downward over large regions. They examined superconvective systems in different parts of the Kelvin–Rossby wave structure that dominated the wind pattern over the COARE region during December–February of the project (Fig. 4.14). They found that as the downdrafts associated with the extensive midlevel inflow circulations transported momentum downward, they enhanced the low-level westerly winds in the region of the westerly jet between the two large-scale gyres (a positive feedback). In the region of westerly onset (east of the gyres), the midlevel inflow circulations transported environmental easterly wind downward and thus reduced the incipient low-level westerlies (a negative feedback). This result, together with the Moncrieff and Klinker (1997) analysis, indicates the potentially large importance of the superconvective systems and of the mesoscale (as opposed to embedded convective scale) circulations in the large-scale momentum budget.

6. The year 2000 and beyond: Mapping convection in the equatorial trough zone with the TRMM satellite

The 1990s brought an increased awareness of the importance of circulations in superconvective systems, which adds to the knowledge of the importance of hot towers (Riehl and Malkus 1958) and mesoscale circulations in ordinary mesoscale convective systems (Zip-

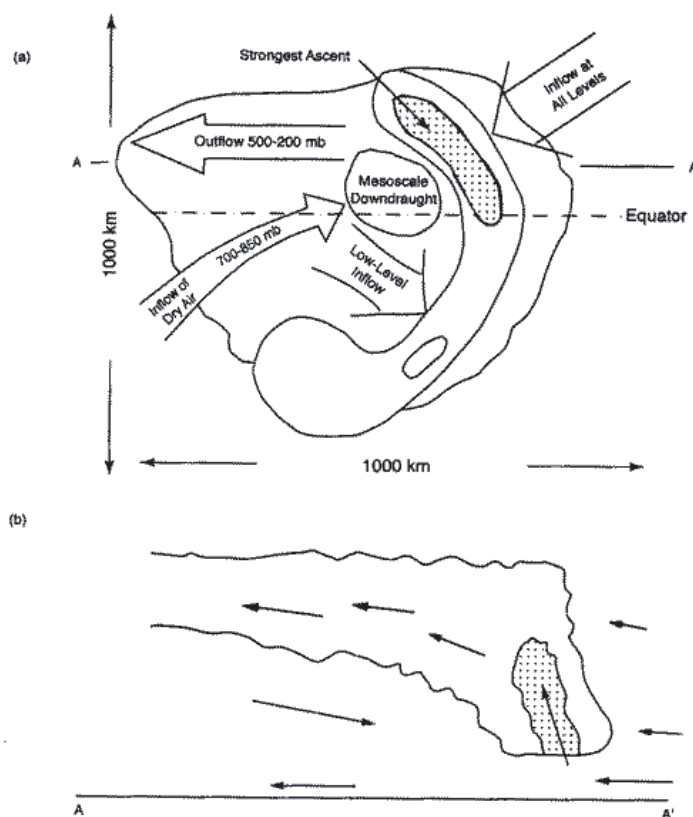


FIG. 4.13. Conceptual model of supercluster: (a) plan view, (b) zonal cross section through the line AA' in (a) (from Moncrieff and Klinker 1997).

ser 1969). An important question remaining is the relative importance of the convective, mesoscale, and superconvective scales over the whole equatorial trough zone. Just how variable is convection in the Tropics? Is it predictable?

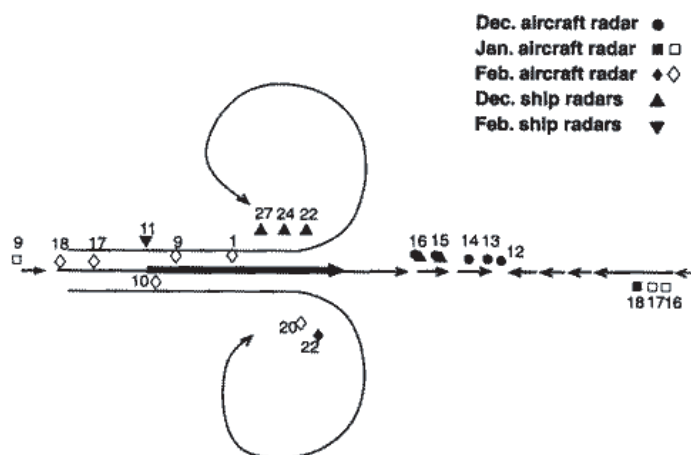


FIG. 4.14. Locations, in relation to the archetypical atmospheric Kelvin–Rossby wave, of ship and aircraft radar data obtained on different days during COARE. The idealized streamlines are drawn as they would appear on a map of the winds at the 850-mb level. The bold streamline indicates where the winds were strongest. Solid symbols indicate observations of superconvective systems. Open symbols indicate mesoscale convective systems <300 km in dimension. The solid symbols represent superconvective systems, which exceeded 300 km in horizontal scale. Numbers indicate the day of the month (from Houze et al. 2000).

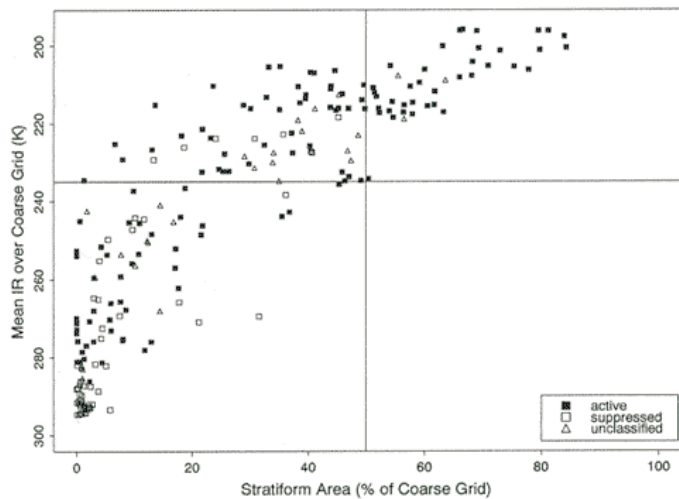


FIG. 4.15. Stratiform precipitation area determined by aircraft radar vs mean infrared temperature observed by satellite over the ~ 200 -km scale region containing the radar observations. Data were from all the aircraft missions of COARE and thus represent convection over the western Pacific oceanic warm pool (from Yuter and Houze 1998).

The only instrument platform capable of making a census of convective phenomena throughout the equatorial regions is the meteorological satellite. Yuter and Houze (1998) analyzed COARE aircraft radar data taken concurrent with satellite infrared images. Since COARE was four months in duration, it provided an opportunity to analyze the joint variation of satellite and radar data over a specific region of the equatorial zone. Yuter and Houze (1998) applied an algorithm to aircraft radar data (lower fuselage data from the two P3 aircraft) to distinguish between the convective and stratiform components of the precipitation observed over a 200-km diameter area centered on the aircraft. The size of the stratiform precipitation area, observed by aircraft, is an

index of the mesoscale organization of the cloud system seen by the satellite. Figure 4.15 shows the relationship between the mean satellite-observed infrared temperature over the 200-km diameter region of radar observation. Each point represents one snapshot of concurrent satellite and radar data. The data showed a systematic relationship between the two variables, but not a strong correlation. Yuter and Houze (1998) likened this behavior to that of a phase space in a chaotic system (Lorenz 1993). Some combinations of variables just did not occur; specifically, large stratiform rain areas ($>50\%$ of the 200-km diameter sampled region around the aircraft) did not occur if the mean infrared temperature over the 200-km sampled region was greater than about 220 K. Smaller stratiform regions ($<50\%$ of the 200-km diameter sampled region around the aircraft) occurred with almost any mean cloud-top temperature over the sampled area, though the probability decreased with decreasing cloud-top temperature. A chaotic behavior in general would raise questions about the predictability of tropical mesoscale and superconvective systems.

As Tropical Rainfall Measuring Mission (TRMM) project scientist for a decade of her career, Joanne Simpson led the effort to put the satellite in space that may resolve such questions. The TRMM spacecraft has a meteorological radar onboard and thus provides the opportunity to determine the statistics of mesoscale and superconvective organization over the equatorial trough zone about which she and Herbert Riehl speculated in 1958. One of the TRMM products computed and archived every day is the spatial distribution of convective and stratiform precipitation shown by the TRMM Precipitation Radar (PR). The algorithm used to separate the echo into convective and stratiform components is that of Awaka et al. (1997). Figure 4.16 shows an ex-

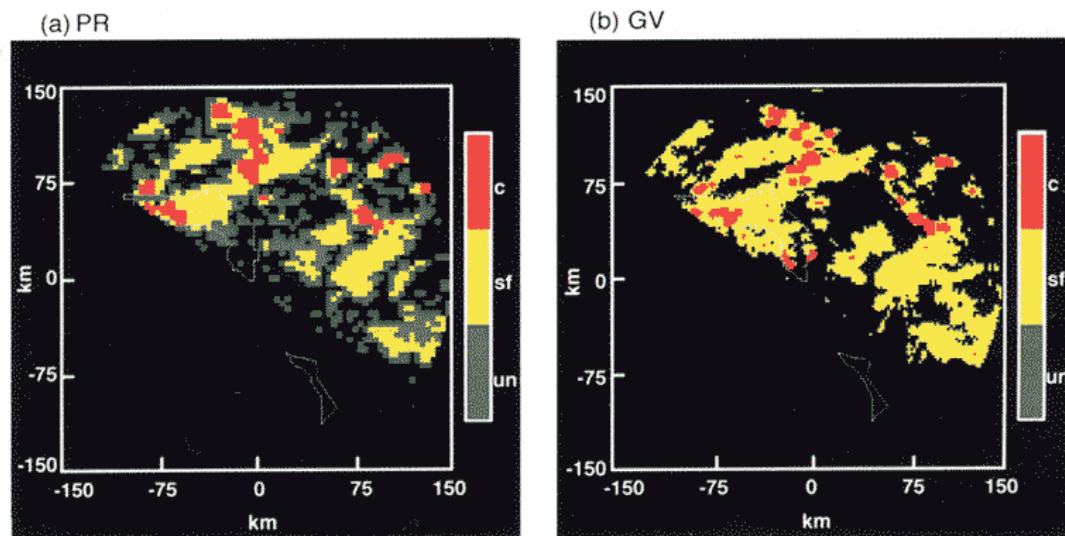


FIG. 4.16. Precipitation patterns indicated by (a) the PR on the TRMM satellite and (b) the Kwajalein TRMM ground-validation (GV) radar. Both radar echo patterns have been separated into convective (red) and stratiform (yellow) components. Undecided echo categories for the PR are indicated in green. The Kwajalein Atoll is indicated in white. Data are for 0251 UTC 25 Nov 1998, orbit 5712.

ample of the convective-stratiform pattern over the Kwajalein atoll. The Kwajalein ground-validation radar (www.atmos.washington.edu/gcg/MG/KWAJ/) pattern for the same time is shown for comparison. The results from the satellite and ground-based radars are clearly consistent.

The TRMM satellite appears to be capable of estimating close to the full amount of stratiform component of precipitation (Schumacher and Houze 2000). However, because the sensitivity of the PR is relatively low (minimum detectable reflectivity ~ 17 dBZ) the total area covered by stratiform precipitation may not always be evident. However, the passive microwave data from TRMM can be helpful in filling out the pattern, so that it will be possible to determine statistics on the scales of stratiform precipitation areas in relation to cloud-top temperature (as in Fig. 4.15) for wide regions of the Tropics. It will be possible then to relate these statistics to terrestrial characteristics such as sea surface temperature, land versus ocean, and orography, as well as to features of the large-scale atmospheric circulation.

7. Final comments

Advances in tropical convection have pursued an understanding of the nature of the convective systems in which the "hot towers" hypothesized by Riehl and Malkus (1958) carry high moist static energy from the atmospheric boundary layer to the tropopause. In the first observational expedition to investigate these phenomena, Malkus and Riehl (1964) noticed that tropical convection was not just a matter of convective and synoptic scales, but that a "mesoscale" organization of the convection existed with horizontal dimensions ~ 15 – 500 km. Over the next 30 years ever more sophisticated field experiments (in most of which Joanne participated) have elaborated on this mesoscale theme. Zipser (1969) described the mesoscale circulation in and below the massive, deep nimbostratus layer that identifies tropical mesoscale convective systems in satellite cloud-top images. GATE showed that $\sim 40\%$ of rain in the oceanic equatorial zone fell from these nimbostratus "anvils" connected with the hot towers and that the anvil cloud layer was dynamically active (Houze 1977; Gamache and Houze 1982). Further analysis of data from GATE and MONEX showed how the mesoscale organization affects transports of momentum (LeMone 1983) and heat (Houze 1982). COARE focused attention on larger mesoscale phenomena, namely, superclusters (Nakazawa 1988) or more generically "superconvective systems" (Chen et al. 1996). Moncrieff and Klinker (1997) have used large-scale modeling and Houze et al. (2000) have used COARE ship and aircraft radar data to show that the superconvective systems are significant transporters of momentum through the action of organized midlevel inflows connected with large stratiform precipitation regions.

It remains to be determined the global impact of these

mesoscale aspects of tropical convection. Joint variability of satellite-observed cloud-top temperature and the occurrence of stratiform precipitation (an index of mesoscale organization) suggest a complex relation between satellite-observed cloud-top imagery and radar-observed stratiform precipitation coverage (Fig. 4.15). The TRMM satellite offers the best way to explore this relationship over the next several years. The precipitation radar onboard the satellite is able to identify stratiform precipitation areas, within the limits of the radar's sensitivity. Outside these limits the passive microwave radiometers on the spacecraft can fill out the picture. Thus, Joanne Simpson's career in tropical convection comes full circle. In 1958 she helped to identify the active convection in the equatorial trough zone as the phenomenon on which to concentrate observational attention. Exactly four decades later, the TRMM satellite was flying and providing the means to make a global census of tropical convection and its mesoscale organization.

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REFERENCES

- Anderson, R. K., E. W. Ferguson, and V. J. Oliver, 1966: The use of satellite pictures in weather analysis and forecasting. WMO Tech. Note 75, 184 pp.
- Arakawa, A., and W. H. Schubert, 1974: Interaction of a cumulus ensemble with the large-scale environment: part I. *J. Atmos. Sci.*, **31**, 674–701.
- Awaka, J., T. Iguchi, H. Kumagai, and K. Okamoto, 1997: Rain type classification algorithm for TRMM Precipitation Radar. *Proc. Int. Geoscience and Remote Sensing Symp.*, Singapore, IEEE, 1633–1635.
- Chalon, J.-P., G. Jaubert, F. Roux, and J.-P. Lafore, 1988: The west African squall line observed on 23 June 1981: Mesoscale structure and transports. *J. Atmos. Sci.*, **45**, 2744–2763.
- Chen, S. S., and R. A. Houze Jr., 1997: Diurnal variation and life-cycle of deep convective systems over the tropical Pacific warm pool. *Quart. J. Roy. Meteor. Soc.*, **123**, 357–388.
- , —, and B. E. Mapes, 1996: Multiscale variability of deep convection in relation to large-scale circulation in TOGA COARE. *J. Atmos. Sci.*, **53**, 1380–1409.
- Cheng, C.-P., and R. A. Houze Jr., 1979: The distribution of convective and mesoscale precipitation in GATE radar echo patterns. *Mon. Wea. Rev.*, **107**, 1370–1381.
- Chong, M., and D. Hauser, 1989: A tropical squall line observed during the COPT 81 experiment in West Africa. Part II: Water budget. *Mon. Wea. Rev.*, **117**, 728–744.
- , P. Amayenc, G. Scialom, and J. Testud, 1987: A tropical squall line observed during the COPT 81 experiment in West Africa. Part I: Kinematic structure inferred from dual-Doppler radar data. *Mon. Wea. Rev.*, **115**, 670–694.
- Churchill, D. D., and R. A. Houze Jr., 1984: Development and structure of winter monsoon cloud clusters on 10 December 1978. *J. Atmos. Sci.*, **41**, 933–960.
- Emanuel, K. A., J. D. Neelin, and C. S. Bretherton, 1994: On large-scale circulations in convecting atmospheres. *Quart. J. Roy. Meteor. Soc.*, **120**, 1111–1143.
- Gamache, J. F., and R. A. Houze Jr., 1982: Mesoscale air motions associated with a tropical squall line. *Mon. Wea. Rev.*, **110**, 118–135.

- , and —, 1983: Water budget of a mesoscale convective system in the tropics. *J. Atmos. Sci.*, **40**, 1835–1850.
- , and —, 1985: Further analysis of the composite wind and thermodynamic structure of the 12 September GATE squall line. *Mon. Wea. Rev.*, **113**, 1241–1259.
- Godfrey, J. S., R. A. Houze Jr., R. H. Johnson, R. Lukas, J.-L. Redelsperger, A. Sumi, and R. Weller, 1998: COARE: An interim report. *J. Geophys. Res.*, **103**, 14 395–14 450.
- Hartmann, D. L., H. H. Hendon, and R. A. Houze Jr., 1984: Some implications of the mesoscale circulations in tropical cloud clusters for large-scale dynamics and climate. *J. Atmos. Sci.*, **41**, 113–121.
- Haynes, P. H., and M. E. MacIntyre, 1987: On the evolution of vorticity and potential vorticity in the presence of diabatic heating and frictional or other forces. *J. Atmos. Sci.*, **44**, 828–841.
- Houze, R. A., Jr., 1977: Structure and dynamics of a tropical squall-line system. *Mon. Wea. Rev.*, **105**, 1540–1567.
- , 1982: Cloud clusters and large-scale vertical motions in the tropics. *J. Meteor. Soc. Japan*, **60**, 396–410.
- , 1989: Observed structure of mesoscale convective systems and implications for large-scale heating. *Quart. J. Roy. Meteor. Soc.*, **115**, 425–461.
- , and A. K. Betts, 1981: Convection in GATE. *Rev. Geophys. Space Phys.*, **19**, 541–576.
- , and E. N. Rappaport, 1984: Air motions and precipitation structure of an early summer squall line over the eastern tropical Atlantic. *J. Atmos. Sci.*, **41**, 553–574.
- , and T. Wei, 1987: The GATE squall line of 9–10 August 1974. *Adv. Atmos. Sci.*, **4**, 85–92.
- , S. S. Chen, D. E. Kingsmill, Y. Serra, and S. E. Yuter, 2000: Convection over the Pacific warm pool in relation to the atmospheric Kelvin–Rossby wave. *J. Atmos. Sci.*, **57**, 3058–3089.
- Johnson, R. H., and R. A. Houze Jr., 1987: Precipitating cloud systems of the Asian monsoon. *Monsoon Meteorology*, C. P. Chang and T. N. Krishnamurti, Eds., Clarendon Press, 298–353.
- Kingsmill, D. E., and R. A. Houze Jr., 1999a: Kinematic characteristics of air flowing into and out of precipitating convection over the west Pacific warm pool: An airborne Doppler radar survey. *Quart. J. Roy. Meteor. Soc.*, **125**, 1165–1207.
- , and —, 1999b: Thermodynamic characteristics of precipitating convection over the west Pacific warm pool. *Quart. J. Roy. Meteor. Soc.*, **125**, 1209–1229.
- Kuettner, J. P., and D. E. Parker, 1976: GATE: Report on the field phase. *Bull. Amer. Meteor. Soc.*, **57**, 11–27.
- Lafore, J. P., and M. W. Moncrieff, 1989: A numerical investigation of the organization and interaction of the convective and stratiform regions of tropical squall lines. *J. Atmos. Sci.*, **46**, 521–544.
- Leary, C. A., 1984: Precipitation structure of the cloud clusters in a tropical easterly wave. *Mon. Wea. Rev.*, **112**, 313–325.
- , and R. A. Houze Jr., 1979: The structure and evolution of convection in a tropical cloud cluster. *J. Atmos. Sci.*, **36**, 437–457.
- LeMone, M. A., 1983: Momentum transport by a line of cumulonimbus. *J. Atmos. Sci.*, **40**, 1815–1834.
- Lorenz, E. N., 1993: *The Essence of Chaos*. University of Washington Press, 227 pp.
- Malkus, J. S., 1952: The slopes of cumulus clouds in relation to external wind shear. *Quart. J. Roy. Meteor. Soc.*, **78**, 530–542.
- , 1954: Some results of a trade-cumulus cloud investigation. *J. Meteor.*, **11**, 222–237.
- , and H. Riehl, 1964: *Cloud Structure and Distributions over the Tropical Pacific Ocean*. University of California Press, Berkeley, 229 pp.
- Mapes, B. E., 1993: Gregarious tropical convection. *J. Atmos. Sci.*, **50**, 2026–2037.
- , and R. A. Houze Jr., 1995: Diabatic divergence profiles in western Pacific mesoscale convective systems. *J. Atmos. Sci.*, **52**, 1807–1828.
- Moncrieff, M. W., and M. J. Miller, 1976: The dynamics and simulation of tropical cumulonimbus and squall lines. *Quart. J. Roy. Meteor. Soc.*, **102**, 373–394.
- , and E. Klinker, 1997: Organized convective systems in the tropical western Pacific as a process in general circulation models: A TOGA COARE case study. *Quart. J. Roy. Meteor. Soc.*, **123**, 805–827.
- Nakazawa, T., 1988: Tropical super clusters within intraseasonal variations over the western Pacific. *J. Meteor. Soc. Japan*, **66**, 823–839.
- Ooyama, K., 1971: A theory on parameterization of cumulus convection. *J. Meteor. Soc. Japan*, **49**, 744–756.
- Raymond, D. J., and A. M. Blyth, 1986: A stochastic mixing model for nonprecipitating cumulus clouds. *J. Atmos. Sci.*, **43**, 2708–2718.
- Riehl, H., and J. S. Malkus, 1958: On the heat balance in the equatorial trough zone. *Geophysica*, **6**, 503–538.
- Roux, F., 1988: The west African squall line observed on 23 June 1981 during COPT 81: Kinematics and thermodynamics of the convective region. *J. Atmos. Sci.*, **45**, 406–426.
- , J. Testud, M. Payen, and B. Pinty, 1984: West African squall-line thermodynamic structure retrieved from dual-Doppler radar observations. *J. Atmos. Sci.*, **41**, 3104–3121.
- Schumacher, C., and R. A. Houze Jr., 2000: Comparison of radar data from the TRMM satellite and Kwajalein oceanic validation site. *J. Appl. Meteor.*, **39**, 2151–2164.
- Shupiatzky, A. B., A. I. Korotov, V. D. Menshenin, R. S. Pastushkov, and M. Jovasevic, 1975: Radar investigations of evolution of clouds in the eastern Atlantic. GATE Rep. 14, vol. 2, International Council of Scientific Unions/World Meteorological Organization.
- , —, and R. S. Pastushkov, 1976: Radar investigations of the evolution of clouds in the East Atlantic. *TROPEX-74*, XXX, Ed., Vol. 1, *Atmosphere* (in Russian), Gidrometeoizdat, Leningrad, USSR, 508–514.
- Sommeria, G., and J. Testud, 1984: COPT81: A field experiment designed for the study of dynamics and electrical activity of deep convection in continental tropical regions. *Bull. Amer. Meteor. Soc.*, **65**, 4–10.
- Sun, J., and F. Roux, 1988: Thermodynamic structure of the trailing-stratiform regions of two west African squall lines. *Ann. Geophys.*, **6**, 659–670.
- Warner, C., J. Simpson, G. van Helvoirt, D. W. Martin, D. Suchman, and G. L. Austin, 1980: Deep convection on day 261 of GATE. *Mon. Wea. Rev.*, **108**, 169–194.
- Webster, P. J., and R. Lukas, 1992: TOGA COARE: The coupled ocean–atmosphere response experiment. *Bull. Amer. Meteor. Soc.*, **73**, 1377–1416.
- Williams, M., and R. A. Houze Jr., 1987: Satellite-observed characteristics of winter monsoon cloud clusters. *Mon. Wea. Rev.*, **115**, 505–519.
- Yanai, M., S. Esbensen, and J. H. Chu, 1973: Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *J. Atmos. Sci.*, **30**, 611–627.
- Yuter, S. E., and R. A. Houze Jr., 1998: The natural variability of precipitating clouds over the western Pacific warm pool. *Quart. J. Roy. Meteor. Soc.*, **124**, 53–99.
- Zipser, E. J., 1969: The role of organized unsaturated convective downdrafts in the structure and rapid decay of an equatorial disturbance. *J. Appl. Meteor.*, **8**, 799–814.