CONVECTIVE AND STRATIFORM PRECIPITATION IN THE TROPICS[1]

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ABSTRACT

Tropical precipitation systems are characterized by extensive stratiform clouds directly associated with deep convection. Ice particles grown by riming in the mid-to-upper regions of the convective cells are detrained into the stratiform cloud where they travel great horizontal distances while growing slowly by vapor deposition. These particles undergo aggregation before reaching the melting layer. The horizontal patterns of convective and stratiform precipitation are complex and vary from case to case in tropical cloud systems. However, the distinct vertical and horizontal structures of the convective and stratiform regions make them amenable to identification from space, especially if the observations can distinguish both horizontal and vertical structure.

1. INTRODUCTION

Atmospheric precipitation patterns typically exhibit complicated patterns in time and space. Consequently, sophisticated sampling and measuring techniques, such as those proposed for the Tropical Rainfall Measuring Mission (TRMM), are required to describe precipitation accurately. The purpose of this paper is to show that despite its complexity, tropical precipitation structure remains understandable and explainable in terms of rather basic precipitation mechanisms. Awareness of these physical mechanisms is important, if not essential, to the proper design of technologies for determining amounts and patterns of precipitation on a global scale. In the following sections, a conceptual model of the basic mechanisms of tropical precipitation based on recent research results is presented. This model implies that observational technologies should take careful account of the vertical as well as the horizontal structure of tropical precipitation systems.

2. BASIC PRECIPITATION MECHANISMS IN THE TROPICS

Most elementary textbooks on meteorology, as well as advanced texts in cloud physics, recognize two types of mechanisms for the growth and fallout precipitation — stratiform and convective. It has long been recognized by tropical meteorologists, such as Malkus and Riehl (1964) and Ramage (1971), that both stratiform and convective precipitation mechanisms are important in tropical precipitation. The primary precipitation producers in the tropics are large mesoscale convective systems in equatorial regions ("cloud clusters"), tropical cyclones, which produce some 25% of the rain in certain regions of the tropics (Simpson and Simpson, 1966), and orographic cloud systems. Houze and Hobbs (1982) and Leary (1984) estimate that 25-50% of cloud-cluster rainfall is stratiform. Marks (1985) and Marks and Houze (1987) find that about 60% of hurricane inner-core region rain is stratiform. Estimates do not exist for the orographic rains, but similar proportions of stratiform rain would not be surprising since tropical

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mountains probably trigger mesoscale systems rather similar to cloud clusters, but anchored to the topography.

3. A CONCEPTUAL MODEL OF PRECIPITATION MECHANISMS IN TROPICAL CLOUD CLUSTERS AND HURRICANES

In tropical cloud systems, stratiform precipitation typically occurs in direct association with deep intense convection—not as a separate phenomenon. The structure of the cloud systems is illustrated in vertical cross section in Fig. 1. The stratiform region is connected to a group of deep convective cells, which in the horizontal plane are often arranged in a line extending out of the plane of Fig. 1. Precipitation ice is generated as growing drops are carried up past the 0°C level by the convective updrafts. Thereafter the ice particles grow by riming as they accrete supercooled cloud drops forming in the updraft at mid-to-upper levels. Some of the particles growing by riming become dense *graupel* particles (terminal fall-speeds 2-6 m/s), while others, referred to as *snow* , become only moderately dense and fall more slowly (≈ 0.5-1 m/s). Substantial amounts of both graupel and snow are detrained to the environment during the lifetime of one of these cells (Fig. 2; from Ferrier and Houze — manuscript in preparation). Because of their large fall speed, the graupel particles fall quickly to the surface, within the convective region. The more slowly falling snow particles, however, are spread laterally through the stratiform cloud region by the horizontal wind as they slowly drift downward. The detrainment of the snow from the convective cells is thus the mechanism by which precipitating ice particles are introduced into the stratiform portion of the cloud system.

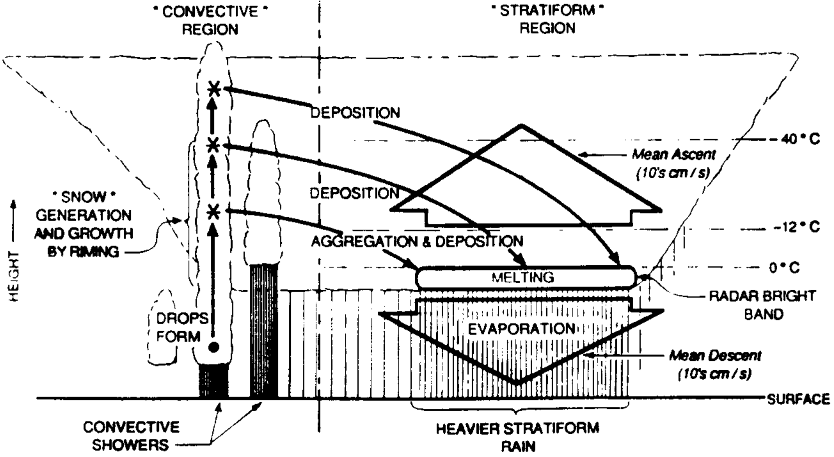

FIGURE 1. Schematic diagram of the precipitation mechanisms in a tropical cloud system. Solid arrows indicate particle trajectories.

The most intense radar bright band and the heaviest stratiform rain at the surface occur where the convectively generated snow particles reach the 0°C level, after their passage through the stratiform cloud (Smull and Houze, 1985; Rutledge and Houze, 1987). The stratiform cloud through which the snow particles pass is characterized by mean upward air motion of 10s of cm/s (Leary and Houze, 1980; Gamache and Houze, 1982, 1983,

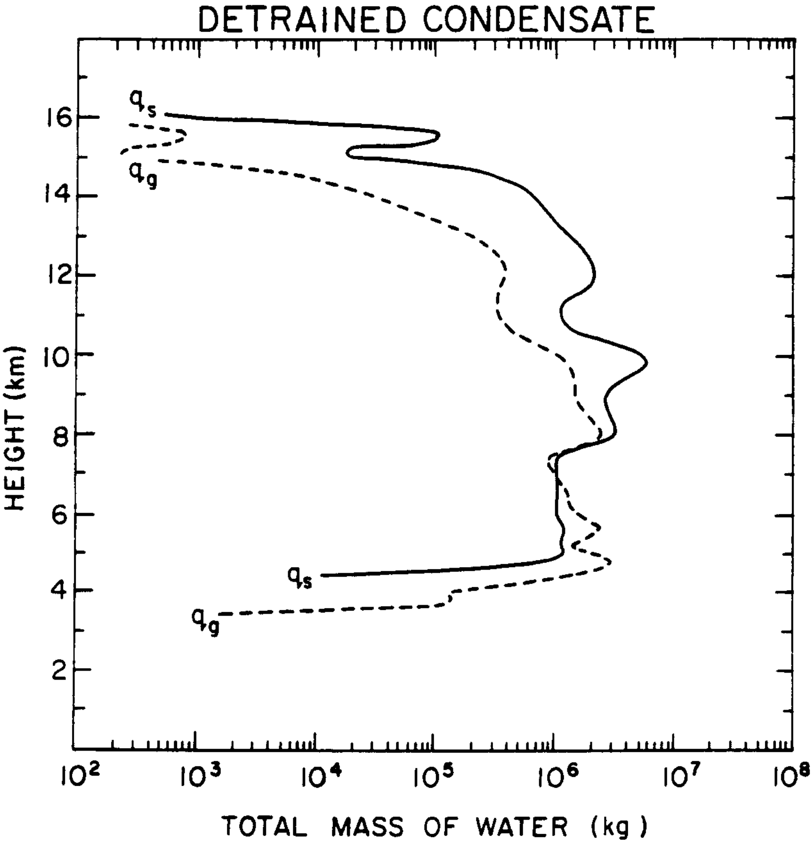

FIGURE 2. Mass of condensate detrained from a one-dimensional time-dependent model of the convective cells in the tropical oceanic squall line studied by Houze (1977). Solid line (q_s) indicates condensate in the form of snow. Dashed (q_g) indicates condensate in the form of graupel. Model calculations are from current work of Ferrier and Houze (manuscript in preparation).

1985; Johnson, 1982; Houze and Rappaport, 1984; Churchill and Houze, 1984b; Chong et al., 1987). In this environment of widespread but moderate vertical motion, the snow particles grow by vapor deposition but not by riming. These snow particles are typically of very irregular shape; however, sometimes their crystalline habits can be discerned in particle images sampled by aircraft. Figure 3, from Houze and Churchill (1987), shows ice particle types observed by aircraft in tropical stratiform regions at flight-level temperatures of + 5 to -25°C. Pristine crystal shapes, including needles, columns, plates and dendrites, were observed in maximum concentration about a kilometer below the altitude where their growth habit was determined. These shapes are a clear indication of growth by vapor deposition. The larger dendritic crystals apparently aggregated to form large snowflakes that were in maximum concentration about 1 km above the 0°C level. Such aggregation is a further characteristic of the stratiform precipitation process.

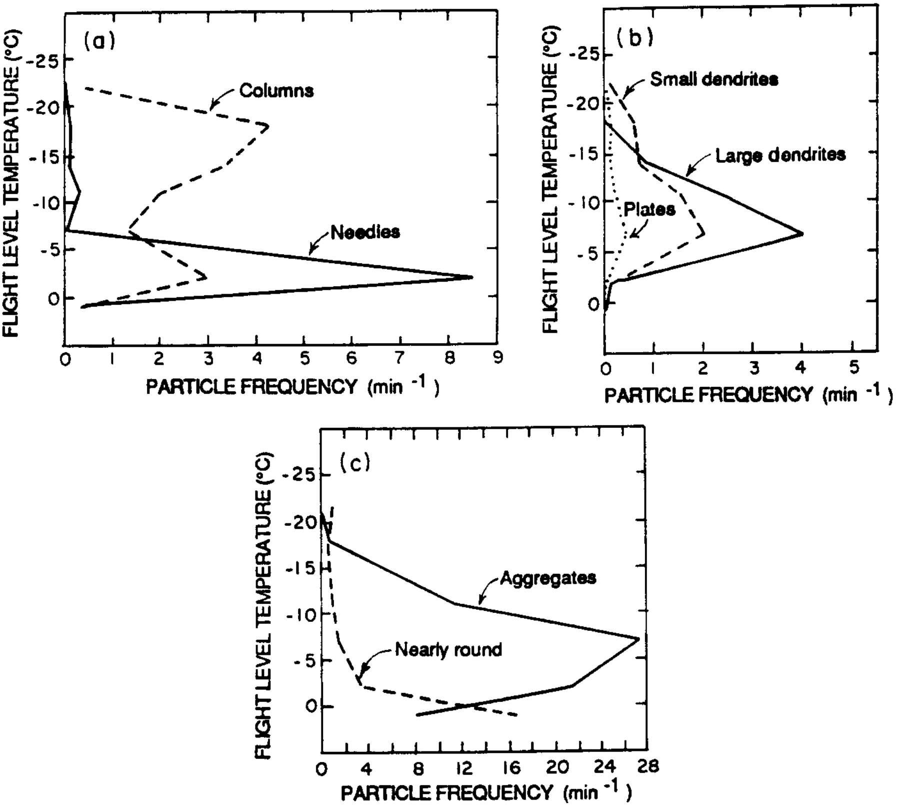

FIGURE 3. Vertical distribution of observed frequencies of ice-phase hydrometeors in the rain areas of the Bay of Bengal depression of 3-8 July 1979. For each particle type the number of hydrometeors observed for each minute of in-cloud flight time are plotted against the flight-level temperatures at which they were observed. (a) Columns and needles. (b) Small dendrites, large dendrites and plates. (c) Aggregates of ice particles and nearly round particles. From Houze and Churchill (1987).

From diagnostic modelling of the water budget and microphysical processes in a stratiform region similar to those in tropical rain systems, Rutledge and Houze (1987) found that both the influx of snow into the stratiform region from the convective cells and the growth of the snow as it passed through the region of the mesoscale updraft contributed strongly to the stratiform precipitation process. Without the lateral influx of snow, their model stratiform cloud was incapable of producing significant rain. On the other hand without the mesoscale ascent within the stratiform cloud, only about one-fourth as much stratiform rain reached the surface. Thus a kind of feeder-seeder process is at work; the deep convective cells feed snow particles into the stratiform cloud, where mean ascent provides moisture for vigorous depositional growth of the snow particles.

4. HORIZONTAL DISTRIBUTIONS OF CONVECTIVE AND STRATIFORM PRECIPITATION IN CLOUD CLUSTERS AND HURRICANES

The conceptual model in Fig. 1 envisages the vertical structure of a tropical cloud system. The convective cells and attendant stratiform structure depicted there occur in various horizontal patterns. The horizontal arrangement of stratiform and convective rain has proven to be a very useful indicator of the mesocale structure and organization of both cloud clusters (Houze and Betts, 1981; Johnson and Houze, 1987) and hurricanes (Jorgensen, 1984; Marks and Houze, 1987).

In cloud clusters, the stratiform and convective precipitation occur in a wide variety of patterns. Sometimes, the convection is arranged horizontally in a propagating arc-shaped line, with the stratiform cloud and precipitation trailing behind (Zipser, 1969, 1977; Houze, 1977; and others). In other clusters, the convection may be in less rapidly moving lines (Leary and Houze, 1979; Barnes and Sieckman, 1985) or groups of cells tied to some topographic feature such as a coastline (Churchill and Houze, 1984a).

In hurricanes, convective-stratiform structure is seen in the outer extremities of the storm, where convective cells can be located on the upwind end of a spiral band, while ice particles detrained from the cells are carried downwind into a stratiform region of the band (Atlas et al., 1963). In the inner-core region of the hurricane, which is dominated by the circular eyewall, radial cross sections typically show stratiform precipitation structure in an annular region just outside the eyewall convection (Marks and Houze, 1987).

In all these cases, the stratiform region occurs adjacent to the convection with the heaviest stratiform rain in a location consistent with the trajectories of the snow particles relative to the cells, as shown in Fig. 1. Sometimes the ice particles from the convective cells are carried great distances by the horizontal wind. For example, in the inner-core region of the hurricane, the trajectories of ice particles ejected from a spot within the eyewall swirl around the storm up to 1 1/2 times before they reach the melting layer (see Fig. 4; from Marks and Houze, 1987).

Several additional factors can contribute to making the horizontal pattern of stratiform and convective precipitation in a cloud cluster or hurricane complex: (1) Since the ice particles generated in convective regions take a long time to fall out, the convection may actually disappear before the detrained ice particles reach the melting level and fall out as stratiform rain. Thus, an instantaneous pattern of precipitation in a cloud cluster or hurricane may contain either stratiform precipitation associated with earlier convection, which is no longer present, or active convection may be present whose detrained snow has not yet had time to influence a stratiform precipitation region. (2) A cloud cluster may contain several groups or lines of convection each affecting different stratiform regions (e.g., Leary and Houze, 1979). (3) Several precipitation features, each consisting of some convection and some stratiform precipitation, may overlap, intersect or merge.

5. DETERMINATION OF CONVECTIVE AND STRATIFORM COMPONENTS OF TROPICAL RAINFALL FROM SPACE

The complexities of the horizontal precipitation patterns in cloud clusters and hurricanes lead to the necessity of careful sampling of rainfall from space in a program such as TRMM. However, the discussion in Sec. 5 indicates that these complexities appear primarily to be superpositions and arrangements of the basic convective and stratiform precipitation mechanisms depicted in Fig. 1. This result implies that, despite the

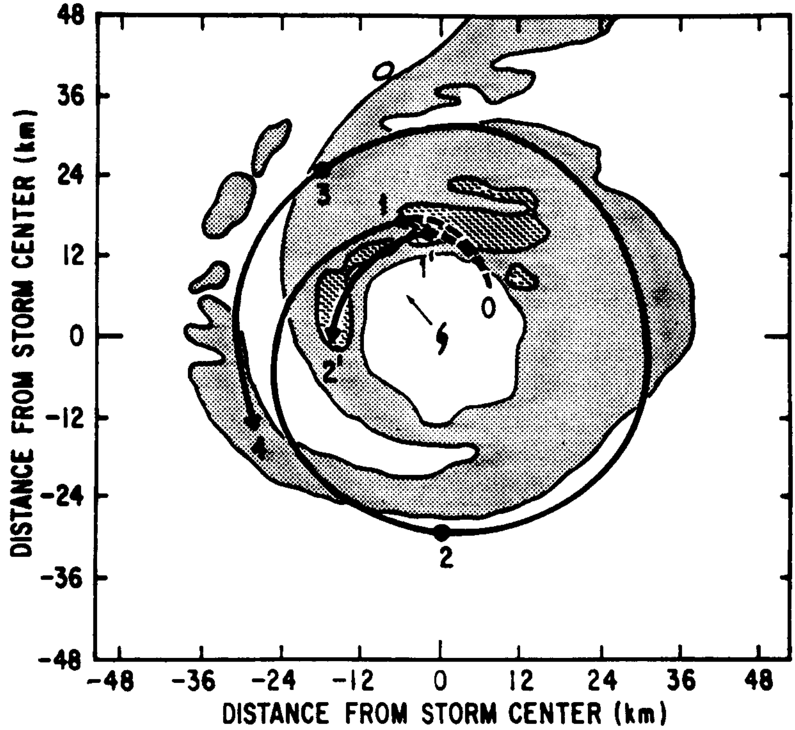

FIGURE 4. Plan view of the low-level reflectivity field in the inner core of Hurricane Alicia. Superimposed are horizontal projections of calculated trajectories of precipitation particles falling from 12 to 1 km altitude. Reflectivity contours are for 20 and 35 dBZ. Storm center and direction of motion are also shown. From Marks and Houze (1987).

complexity of the horizontal structure of tropical rain patterns, the building blocks of the patterns remain relatively simple. A primary objective of TRMM should therefore be to distinguish the basic convective and stratiform components of tropical precipitation.

Attempts are presently being made to resolve stratiform and convective components of tropical cloud clusters from conventional satellite measurements. Adler and Negri (1987) have developed an algorithm for distinguishing convective and stratiform regions by using infrared images from geosynchronous satellites. Their technique initially identifies all relative minima in the cloud-top temperature field as potential convective centers. These points are then tested against empirically derived criteria designed to screen out minima associated with minor irregularities in the background cirrus shield. A temperature threshold for the stratiform areas is determined from the statistics of the cloud-top temperatures in the region surrounding the convective centers. Application of a slightly modified version of the Adler-Negri algorithm to data from Winter MONEX has been used to estimate the convective and stratiform areas of cloud clusters over the South China Sea (Goldenberg and Houze — work in progress). The results (see Fig. 5) are encouraging in that they agree well with estimates of the stratiform areas obtained from radar data by Churchill and Houze (1984a).

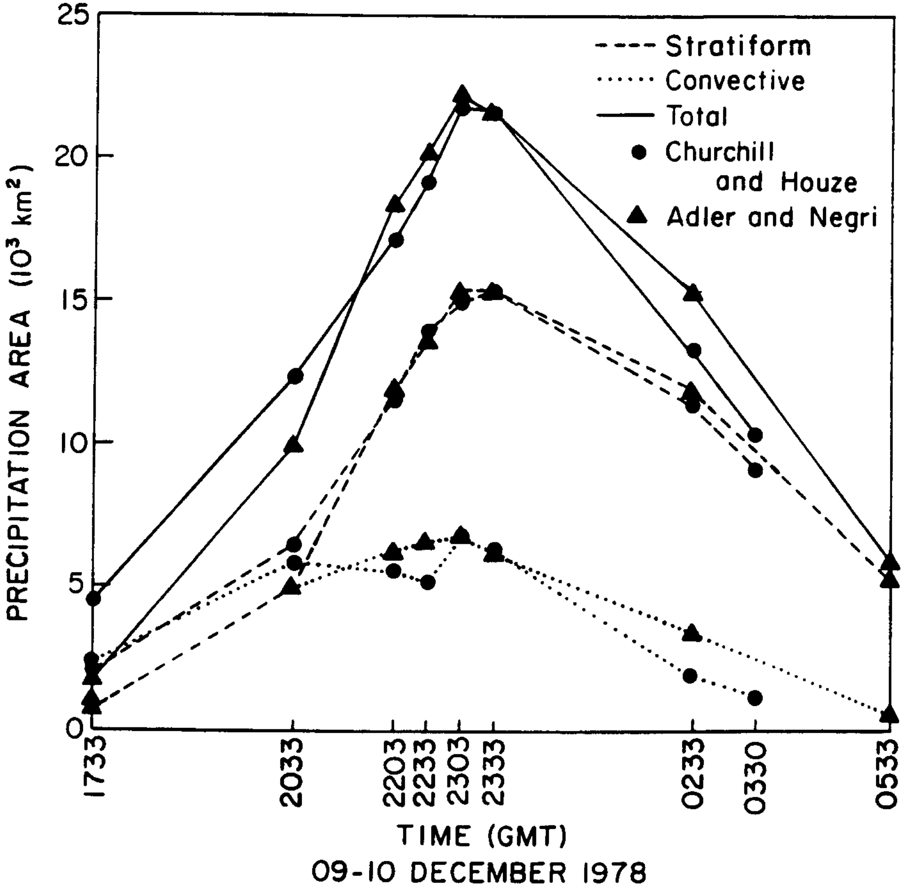

FIGURE 5. Estimates of the total, stratiform and convective precipitation areas for Churchill and Houze's (1984a) Winter MONEX cloud cluster "B". One set of curves was determined from radar data by Churchill and Houze. The other set was determined from infrared satellite data by Goldenberg and Houze (work in progress) using a modified version of the technique of Adler and Negri (1987).

While useful, this type of technique is limited in that it is based entirely on horizontal pattern recognition. A particular difficulty is that, while the method is able to recognize the existence of convective regions, a somewhat arbitrary assumption must be made regarding the horizontal size of the convective region surrounding a center. Consequently, satellite-derived results such as those in Fig. 5 have considerable uncertainty as a result of this assumption. From Fig. 1, it is evident that the stratiform and convective processes are most clearly distinguished by their differing vertical structure. It is therefore important for future measurements, such as those in TRMM, to have good observational capability in the vertical as well as the horizontal. In this case, it will be possible to use both vertical structure and horizontal variability to distinguish convective and stratiform regions in tropical precipitation, thereby removing much of the present uncertainty.

6. CONCLUSIONS

Although the horizontal patterns of precipitation in tropical cyclones and cloud clusters can be quite complex, they are made up of basic stratiform and convective components characterized by quite different and distinct precipitation mechanisms, which have been summarized in Fig. 1. Because of these different physical mechanisms, it is important that in an effort, such as TRMM, in which tropical precipitation is to be mapped globally, that the stratiform and convective components as well as the total amounts of rain be determined. If these components are clearly identified over the whole tropics, several important scientific results will accrue:

- The microphysical mechanisms of precipitation throughout the tropics will be known in addition to total rain amounts.
- The mesoscale internal organization of tropical cloud systems, which is often well indicated by the relative juxtaposition of convective and stratiform areas, will be sampled throughout the tropics, thus allowing a thorough census of squall-line and other types of cloud cluster types.
- The vertical distribution of diabatic heating associated with tropical cloud systems can be more accurately calculated. In the stratiform regions, the cooling that occurs in connection with melting and evaporation at low-to-mid levels strongly affect the vertical heating profile (Houze, 1982). Accurate determination of the relative amounts of stratiform and convective precipitation will allow these important stratiform effects to be included properly in the determination of the vertical distribution of heating in the tropics.

Current methods used to identify convective and stratiform precipitation regions in the tropics from detailed horizontal patterns are useful, but are limited by various arbitrary assumptions. Because stratiform and convective regions in tropical cloud systems can be distinguished physically by their vertical structure (as idealized in Fig. 1), identification of them will be improved by measurements that have the capability to distinguish the characteristic vertical structures of the convective and stratiform regions. This conclusion emphasizes the importance of measuring the vertical as well as the horizontal structure of tropical precipitation in TRMM.

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