Heat and Moisture Sources and Sinks of Asian Monsoon Precipitating Systems

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Abstract

The structure and properties of heat and moisture sources and sinks of the Asian monsoon are reviewed. Results from the First GARP Global Experiment (FGGE) have yielded important information on these sources, ranging from the planetary scale down to the scale of individual convective systems. The emerging picture is one of a complex spatial and temporal distribution of heat sources over the enormous area covered by the Asian monsoon, with the detailed structure of this distribution determined in large part by a wide variety of types of precipitating systems.

Several recent experiments, the 1987 Australian Monsoon Experiment (AMEX), the 1987 Equatorial Mesoscale Experiment (EMEX), the Taiwan Area Mesoscale Experiment (TAMEX), and the 1988–1990 Down Under Doppler and Electricity Experiment (DUNDEE), have provided new knowledge concerning the nature of mesoscale convective systems within the monsoon and their contributions to monsoon heat and moisture sources and sinks. Some of the findings of these experiments confirm previous conceptual models of precipitating systems, but also provide new insight into convective processes in the Asian monsoon.

1. Introduction

The development and maintenance of the Asian winter and summer monsoon are closely regulated by the complex distribution of heat sources and sinks over Asia and the surrounding region. The summer monsoon is dependent to a large degree on sensible and latent heat sources over and in the vicinity of the Tibetan Plateau. The winter monsoon, on the other hand, is driven by deep convective heating over Indonesia and northern Australia coupled with radiative and advective heat losses over the middle and higher latitudes of east Asia. The total heat sources and sinks over the region—comprised of radiative, sensible and latent heating components—have pronounced variability on spatial and temporal scales ranging from the planetary scale, as determined by the Asian land mass, to the convective scale, as represented by the smallest elements of the monsoon precipitation systems.

The primary synoptic-scale circulation and precipitation features of the Asian winter and summer monsoons are illustrated in Fig. 1. For the Asian winter monsoon (which coincides, in part, with the Australian summer monsoon) there exist important cross-hemispheric exchanges of mass, heat and moisture in association with deep convection along and to the north of the Southern Hemisphere trough from Sumatra across Indonesia to the southwest Pacific (Fig. 1a). One of the most distinguishing aspects of the precipitation in this equatorial region, sometimes referred to as the Indonesian “maritime continent” (Ramage, 1968), is the pronounced diurnal variability of convection driven by sea and land breeze circulations over the numerous islands contained therein (e.g., Murakami, 1983; Williams and Houze, 1987; Keenan et al., 1989). The summer monsoon (Fig. 1b) has distinctly different characteristics, with the heavy precipitation shifted well off the equator, extending from the Indian subcontinent to Indochina to southern China to Japan, and the prominent diurnal variability consisting of a strong daily cycle of heating over the Tibetan Plateau. Although studies of heat sources associated with the monsoon date back many decades, a major advance in our understanding of the nature of these sources was achieved through the 1978–1979 First GARP (Global Atmospheric Research Program) Global Experiment or FGGE. Since several treatises describing results from FGGE have already been completed (Chang and Krishnamurti, 1987; Fein and Stephens, 1987), this review will focus on only a portion of those results and on more recent findings based upon post-FGGE studies and experiments that relate to monsoon heat sources.
Fig. 1. (a) Primary circulation features that affect cloudiness and precipitation in the region of the winter monsoon. Convection associated with sea and land breeze circulations exists throughout the maritime continent. Preferred coastal locations of enhanced low-level cloudiness and rainfall associated with the northeast monsoon and cold surges are indicated (stipples); cloudiness maxima over water are omitted. Hatching denotes November 1 to April 30 precipitation west of 130°E exceeding 150 cm. The 1978 Winter MONEX ship array and 1987 AMEX, 1987 EMEX and 1988–1990 DUNDEE experimental areas are shown. (b) Primary circulation features that affect cloudiness and precipitation in the region of the summer monsoon. Locations of June to September rainfall exceeding 100 cm over the land west of 100°E are indicated by hatching. Those over water areas and east of 100°E are omitted. Experimental area for the 1987 TAMEX is shown. I, II, III and IV refer to centers of 10° × 10° regions in the study of Luo and Yanai (1984).
The primary emphasis will be on the further elucidation of the nature of moist convective contributions to heat and moisture sources and sinks in the Asian monsoon. There are also potentially important impacts regarding the transports of momentum (e.g., Schneider and Lindzen, 1976; Stevens, 1979; Moncrieff, 1981; LeMone et al., 1984), but there is insufficient space to treat this subject here. The new progress discussed here will primarily relate to relatively recent field programs in the area of the Asian monsoon: Australian Monsoon Experiment (AMEX, 1987), Equatorial Mesoscale Experiment (EMEX, 1987), Taiwan Area Mesoscale Experiment (TAMEX, 1987) and Down Under Doppler and Electricity Experiment (DUNDEE, 1988–1990) [locations indicated in Figs. 1a and 1b].

Several of these recent experiments have had as an important objective the determination of the vertical distribution of heating within precipitation systems. The impact of convection on the modeled large-scale circulation appears to be critically sensitive to the positioning of the peak in the heating distribution. The theoretical basis for this sensitivity is discussed in Hartmann et al. (1984) and in the recent overview of EMEX by Webster and Houze (1991). Modeling studies of the tropical 30–60 day intraseasonal oscillation have shown an important sensitivity of the characteristics of this global-scale wave to the vertical distribution of convective heating (Takahashi, 1987; Miyahara, 1987; Sui and Lau, 1989; Lau and Peng, 1990). In particular, the phase speed of the oscillation appears to be sensitive to the vertical heating distribution. When the heating peak is in the upper troposphere, the wave appears to move too fast, whereas when the peak is in the lower troposphere, the phase speed is more in line with observations (e.g., Sui and Lau, 1989).

Because of the enormous scope of the subject of Asian monsoon heat sources in general, the topics covered in this review will be necessarily limited and many omissions will be unavoidable. It is hoped that by concentrating on information pertaining to heat and moisture sources associated with precipitating systems, reasonably adequate coverage of at least one topic can be achieved.

First, the primary results of FGGE studies will be reviewed to provide a context for findings from the more recent experiments. Next, heating and moistening distributions and the character of convection within the equatorial heat source region of the Asian winter monsoon will be examined by referring to results from AMEX, EMEX and DUNDEE. Finally, the nature of the heat and moisture sources and sinks during the transition from the winter to the summer monsoon over east Asia (referred to as the Mei-Yu season over China or the Baiu over Japan) will be investigated using observations obtained in the vicinity of Taiwan during TAMEX.

2. Results from FGGE studies

a. Large-scale heat sources

As has been pointed out by Webster (1987), the essence of the broadscale monsoon circulation can be explained in its simplest terms by considering the basic processes of differential land/ocean heating, moist convection and the earth’s rotation. However, explanations for many of the detailed features of the monsoon such as the onset vortex, Somali jet, monsoon depressions, monsoon breaks, cold surge and low-frequency oscillations (e.g., see review by Krishnamurti, 1985) require a closer examination of the coupling between diabatic processes, orography and dynamics.

A review of the global and regional distributions of diabatic heating over Asia during the FGGE year has been prepared by Johnson et al. (1987). In Fig. 2 their computations of the global distributions of mass-weighted, vertically averaged diabatic heating rates are shown for the months of January, April, July and October. These values are based on vertical integrations of the isentropic mass continuity equation using ECMWF (European Centre for Medium Range Weather Forecasts) Level III analyses for 1979. During the winter and early spring of 1979 (Figs. 2a and 2b), the most prominent heating maximum extended across and to the east of the Indonesian maritime continent into the South Pacific Convergence Zone. By summer, the maximum shifted northwestern to the Indian subcontinent (Fig. 2c) and then in the fall (Fig. 2d) to the western Pacific as convection returned to the position of its wintertime near-equatorial maximum. This evolution of the diabatic heating pattern is quite typical; however, several aspects of the seasonal distributions of diabatic heating during the FGGE year were anomalous. For example, the 1979 winter pattern was characterized by two primary equatorial maxima, one in the Indian Ocean and one in the southwest Pacific (Fig. 2a), while the normal pattern exhibits a single maximum over the Indonesian maritime continent (Sumi and Murakami, 1981). Additionally, the 1979 summer monsoon was abnormally dry.

The global diabatic heating rates for the FGGE year shown in Fig. 2 are similar to those determined by a number of authors using an alternate procedure involving the first law of thermodynamics (Mason, 1984; Chen and Baker, 1986; Holopainen and Fortelius, 1986). However, differences among the various estimates exist and the accuracy of the intensity of diabatic heating is uncertain due to limitations in data and data assimilation techniques in global models (Holopainen and Fortelius, 1986). Use of satellite radiance and cloud-tracked wind data to improve determination of the divergent wind field appears to offer the most hope for improving global
diabatic heating estimates, particularly in the deep tropics (Kasahara et al., 1987; Schaack et al., 1991). Schaack et al. (1991) have found that the vertical distribution of heating in the tropics calculated from assimilated and simulated model-based global data sets to be critically sensitive to the inclusion of satellite data.

On a regional scale, several FGGE-based studies have determined the distribution of heat and moisture sources and sinks over Asia before, during and after the onset of the 1979 summer monsoon (Luo and Yanai, 1983, 1984; Nitta, 1983; Kato, 1985). These investigations have provided important information concerning the nature of moist and dry convective processes and their diurnal variations over and in the vicinity of the Tibetan Plateau during the summer monsoon.

Computations of vertical motion, the apparent heat source $Q_1$ and apparent moisture sink $Q_2$ (Yanai et al., 1973) over four $10^6 \times 10^6$ regions for a 40-day period from May 26 to July 4 1979 are shown in Fig. 3 (from Luo and Yanai, 1984). Here $Q_1$ and $Q_2$ and defined by

$$Q_1 = c_p \left( \frac{\partial T}{\partial t} + \nabla \cdot \nabla T + \left( \frac{p}{p_0} \right)^\kappa \frac{\partial \bar{q}}{\partial p} \right)$$

$$Q_2 = -L \left( \frac{\partial \bar{q}}{\partial t} + \nabla \cdot \bar{q} + \nabla \bar{q} \cdot \frac{\partial \omega}{\partial p} \right),$$

where $\kappa = R/c_p$, and $\bar{T}$, $\bar{q}$, and $\bar{\theta}$ are horizontally averaged values of temperature, specific humidity, and potential temperature.

Comparing (3) and (4), it can be seen that for precipitation systems possessing negligible eddy transports, the profiles of $Q_1 - Q_R$ and $Q_2$ should be closely matched (Luo and Yanai, 1984; Arakawa and Chen, 1987; Cheng and Yanai, 1989). When deep convection is prevalent, the peaks in $Q_1$ and $Q_2$ are separated, e.g., as in the tropical western Pacific study of Yanai et al. (1973).

It can be seen from Fig. 3 that in Luo and Yanai’s (1984) Region I, which is centered over the western
Plateau near 34°N 80°E (refer to Fig. 1b for location), there is a pattern of mean upward motion with a maximum $Q_1$ just above the surface and a negligible $Q_2$. This structure is indicative of strong sensible heat flux in this region with very little precipitation. Over the eastern Plateau (Region II, centered near 34°N 95°E) the mean vertical motion is still upward, but latent heat release is more important, contributing to nearly half of the apparent heat source. Region III, centered over the Yangzi Valley (near 28°N 115°E), exhibits large $Q_1$ and $Q_2$ which are virtually coincident in the midtroposphere, suggestive of a predominance of stratiform precipitation in that region (Luo and Yanai, 1984). Finally, Region IV, centered in the Assam-Bengal area near 25°N 85°E, shows large $Q_1$ and $Q_2$ peaks, but displaced from each other in the vertical, indicative of a prevalence of deep convection (Yanai et al., 1973). This highly variable regional structure to the monsoon heat source—and its sensitivity to moist convection and possible feedbacks between moist convection, soil moistening and the evolving circulation (e.g., Webster, 1983)—suggests that knowledge of the details of the heat sources and factors controlling their spatial and temporal variability will be important to understanding the intricacies of the monsoon circulation. Later in this paper, these results from Luo and Yanai (1984) will be related to more recent findings from the 1987 TAMEX.

b. Mesoscale heat sources

Moving down to the mesoscale, FGGE observations have also provided new information concerning the geographical distribution of convective systems and the vertical distribution of heating and moistening within convection in the Asian monsoon. Some of these findings have been reviewed by Johnson and Houze (1987), Houze (1989) and more recently by Rutledge (1991). Modeling studies of large-scale tropical circulations, including low-frequency oscillations, have shown an important sensitivity of the modeled circulations to the assumed vertical distribution of heating (e.g., Hartmann et al., 1984; DeMaria, 1985; Lau and Peng, 1990). Our understanding of this vertical distribution for all geographical areas and conditions is limited; however, it appears that mesoscale convective systems contribute importantly to it and evidence is accumulating to indicate that there exist more similarities than differences in the structure and properties of mesoscale convective systems throughout the tropics and in the summertime midlatitudes (Houze and Hobbs, 1982; Johnson
Fig. 4. Schematic of a tropical cloud cluster mature stage in which a cloud shield has developed and covers area $A_c$, convective cells are located in area $A_h$, stratiform precipitation is falling from a middle-level cloud base within area $A_s$, and area $A_o$ is covered by upper-level cloud overhang. Mesoscale updraft and downdraft along vertical cross-section $BB'$ are shown by wide, open arrows; condensation (COND.) in the mesoscale updraft, evaporation (EVAP.) in the mesoscale downdraft, and the melting layer in the stratiform precipitation region are indicated. Shortwave (SW) and longwave (LW) radiation (RAD.) are denoted by wavy arrows. Area $A$ is a large-scale region containing the cloud cluster, and $A_e$ is a cloud-free environmental area surrounding the cluster. (From Houze, 1982.)

An important advance in understanding the heating distributions within tropical cloud clusters was achieved by the introduction of a conceptual model for the life cycle of a tropical mesoscale convective system by Houze (1982). This model was based primarily on findings from the 1974 GARP Atlantic Tropical Experiment (GATE) and the 1978–1979 Monsoon Experiment (MONEX). Diabatic processes occurring during the mature stage of Houze’s idealized cloud cluster are presented in Fig. 4. At this stage of development, both cumulonimbus and stratiform precipitation coexist, the latter covering a considerably larger area than the former. Within the stratiform region, mesoscale ascent is generally found in the upper troposphere and descent in the lower. While a uniform mesoscale updraft is indicated in Fig. 4, several recent studies have discovered a fine-scale, convective-cell substructure to the stratiform region, suggesting that at times the mean mesoscale ascent may actually be a consequence of many smaller-scale drafts (Leary and Rappaport, 1987; Keenan and Rutledge, 1991; Mapes and Houze, 1991). As depicted in Fig. 4, the existence of an extended upper-level anvil cloud around the convective system may lead to important contributions by radiative heating to the total cloud cluster heating. Condensation, melting and evaporation occur in both regions, but their vertical distributions are considerably different.

Heating rates for this idealized cloud cluster are shown in Figs. 5 and 6. The total heating, consisting of radiative heating (based on daytime average values from Webster and Stephens, 1980) and latent heating within both the convective and stratiform regions, is shown by the solid curve in Fig. 5. Heating within the cumulonimbus towers alone is indicated by the dashed curve. The convective heating has a peak in the midtroposphere (near 6 km), whereas the total cluster heating peak is shifted upwards, to 8–10 km, with the total heating at low levels being rather small. The upward shift of the total heating peak is a consequence of depositional...
and/or condensational heating in the stratiform region, which has a peak in the middle to upper troposphere (Fig. 6), and a net radiative heating in the anvil for this daytime situation.\footnote{The radiative heating contribution depends on the depth of the radiatively active anvil and the time of day. If optically thin, then an average heating over the depth of the anvil occurs day or night (e.g., Ackerman et al., 1988). If optically thick, then a net cooling at cloud top (particularly strong at night) and a net warming at anvil base occur (e.g., Webster and Stephens, 1980).} At low levels the reduction in the total heating over that in the convective region is a consequence of cooling by evaporation and melting in the stratiform region (illustrated in Fig. 6).

The heat source for the stratiform region determined by Houze (1982), has been independently confirmed by Johnson and Young (1983) using rawinsonde data from the Winter Monsoon Experiment (Winter MONEX). They used sounding data from the Winter MONEX Soviet ship triangle (Fig. 1a) to compute $Q_1$ and $Q_2$ for seven separate cloud clusters off the north coast of Borneo at times during which it was determined that primarily stratiform rainfall existed over the triangle. The comparison of the heating rates from the two studies shown in Fig. 6 shows good agreement and lends credence to the conceptual model advanced by Houze (1982). While general agreement has now emerged concerning the vertical profile of heating in the stratiform region of cloud clusters (heating in the middle to upper troposphere and cooling in the lower troposphere below the 0°C level), there is much less certainty regarding the vertical profile in the convective region. Houze (1989) has recently discussed this issue and pointed out that various studies have placed the cumulonimbus heating peak anywhere from the lower to middle troposphere. It may be the case that there is a natural variability in the convective heating profiles from one type of organized convective system and/or large-scale environment to another which makes generalizations concerning the structure of this component of the total heating rather difficult.

While the observational platforms of Winter MONEX permitted the determination of heat and moisture sources and sinks for some winter monsoon convective systems (Johnson and Young, 1983; Johnson, 1984), the placement of the Summer MONEX ship arrays did not turn out to be optimal for similar computations for the summer monsoon. The only study that this author is aware of that examines heat and moisture budgets on the scale of individual convective systems is that of Nitta (1980). Using rawinsonde data from a network of four Soviet ships in the Bay of Bengal for a 3-day period (21–23 July 1979), Nitta found mean $Q_1$ and $Q_2$ profiles closely resembling the $Q_1$ profile shown in Fig. 6. This finding, including the nearly coincident profiles of $Q_1$ and $Q_2$, suggests a prevalence of upper-level stratiform cloud systems over the Bay of Bengal for the period of Nitta’s study. A frequent occurrence of stratiform precipitation over the Bay of Bengal has been reported in the Summer MONEX observational studies of Warner and Grumm (1984), Houze and Churchill (1987) and Gamache (1990), which may support Nitta’s (1980) results. However, much more study of the structure of summer monsoon convective systems is needed and, owing to the limited scope of Summer MONEX, will have to await the outcome of future field experiments.

c. Radiative effects

Radiative heating represents a potentially important contributor to the total diabatic heat source associated with moist convection, on scales ranging from the planetary scale to the scale of individual cloud clusters. The north Borneo mesoscale convective systems (Webster and Stephens, 1980; Houze et al., 1981; Johnson and Priegnitz, 1981) and others within the monsoon region (Williams and Houze,
produce extensive-upper tropospheric cloud shields that persist for extended periods of time. The solar and infrared radiative heating components active in such systems are illustrated in Fig. 4 (from Houze, 1982). It has been proposed that differential radiative heating, both in the horizontal and vertical, in the region of these clouds can significantly affect the evolution of the clusters. Gray and Jacobson (1977), Cox and Griffith (1979) and McBride and Gray (1980) have hypothesized that changes in the horizontal variation of radiative divergence in the vicinity of cloud clusters from day to night can lead to a mass circulation that enhances cloud development at night. This possibly important role of radiative effects in the dynamics of cloud cluster has been supported by modeling studies of Cohen and Frank (1987), Dudhia (1989) and Churchill and Houze (1991).

Webster and Stephens (1990) have proposed that the longwave cooling off the tops of deep upper tropospheric stratiform clouds and longwave warming near their base could lead to a destabilization, thereby promoting the development and longevity of the cloud layer. A modeling study by Churchill and Houze (1991) tends to support this idea, although they find that the depth of the radiatively driven, convective overturning is too small to substantially change the hydrometeor field and the water budget of the stratiform cloud system. Randall et al. (1991) have shown using a general circulation model that the diurnal cycle of shortwave heating leads to a diurnal cycle of precipitation, apart from any land effects, with an early morning maximum in rainfall. Given such effects, along with the pronounced sea and land breezes over numerous islands of the maritime continent and the strong sensible heating over the Tibetan Plateau, it is clear that a marked diurnal modulation of the Asian monsoon diabatic heat source should exist, although it is yet to be fully understood.

3. Post-FGGE field experiments

For later reference, heating and moistening profiles from several tropical experiments will be presented first. In Fig. 7a (adapted from Johnson, 1984) the apparent heat source $Q_1$ normalized by the observed precipitation rate ($Q_1$) is shown for five studies ranging from the western Pacific region (Reed and Recker, 1971; Nitta, 1972; Yanai et al., 1973) to Florida (Johnson, 1976) to the eastern Atlantic GATE region (Thompson et al., 1979). All of these profiles represent the composite heating resulting from a number of convective events at various stages of their life cycles. The western Pacific and Florida cases have heating peaks in the midtroposphere between 400 and 500 mb. The eastern Atlantic heating peak is at a distinctly lower level, perhaps as a result of different cloud populations and/or lower sea surface temperatures in the GATE region. A comparison of $Q_2$ profiles for the various regions is presented in Fig. 7b. One of the noteworthy features of these profiles (except for the eastern Atlantic case) is a double-peak structure, one
peak in the midtroposphere and another in the lower troposphere. This structure has been attributed by Johnson (1984) and Esbensen et al. (1988) to the drying effects of two distinct precipitation features: the deep convective towers, providing the lower-level peak, and the stratiform region, providing the upper-level peak. This hypothesis is supported by some degree by the results of a 24-h GATE cloud ensemble simulation by Soong and Tao (1980). Recently, however, Dudhia and Moncrieff (1987), Lafore et al. (1988) and Chong and Hauser (1990) have shown that the vertical eddy transport of water vapor can also play an important role in determining details of the $Q_2$ profiles and in some instances can actually be the predominant factor in determining this double-peak structure.

a. Australian Monsoon Experiment (AMEX) results

From mid-January to mid-February 1987, Phase II of AMEX was conducted over northern Australia (Fig. 1a) to study the structure and properties of the Australian monsoon and the nature of convective systems within it. The overall scope and objectives of AMEX are reviewed by Holland et al. (1986) and McBride and Holland (1989). Frank and McBride (1989) and McBride et al. (1989) have conducted heat and moisture budget studies from 13 January to 14 February using 6-hourly sounding data from a network of stations around the perimeter of the Gulf of Carpentaria (Fig. 8). The major convective episodes studied tended to be confined within the Gulf. Composites of the heating profiles (essentially $Q_1$, but omitting the typically small storage term) for four convective systems over three stages in their composite life cycle are shown in Fig. 9 (from Frank and McBride, 1989). The stages illustrated are the growth, maximum intensity and early decay periods in the life cycle. Results for the GATE cloud cluster composite of Frank (1978) are also shown for comparison. Frank and McBride note that while the GATE and AMEX profiles peak at similar levels (near 550 mb) at the time of maximum intensity, the GATE profile exhibits a change with time [peak heating in the lower troposphere in the early stages

Fig. 8. The network of 6-hourly radiosonde stations surrounding the Gulf of Carpentaria during AMEX Phase II, 1987. (From McBride et al. 1989.)

Fig. 9. Apparent heat source ($Q_1$) ($^\circ$C day$^{-1}$) for AMEX and GATE composite cloud cluster (a) growing stages, (b) maximum intensity stages [Frank's (1978) Stage 3 (dashed) and Stage 4 (solid)] and (c) early decay stages. (From Frank and McBride, 1989.)
stratiform cloud systems appear to be a very frequent occurrence over the ocean.

b. Equatorial Mesoscale Experiment (EMEX) results

Concurrently with AMEX, a second, primarily aircraft-oriented experiment—EMEX—was conducted during January and February 1987 over and in the vicinity of the Arafura Sea to the north of Australia (Fig. 1a). An overview of EMEX has been recently prepared by Webster and Houze (1991). The primary objectives of EMEX were to determine (1) the vertical distribution of heating in cloud clusters of the Australian monsoon and (2) the mechanisms responsible for the convective and stratiform components of the cloud systems.

A number of EMEX studies are yet forthcoming, so only preliminary results are discussed here. The principal measurements involved the use of the United States NOAA WP3D aircraft with an airborne Doppler radar. A key strategy was to have the P3 aircraft fly in a zigzag pattern so that horizontal divergence from the Doppler data could be calculated within parallelograms having sides (~70 km in length) parallel to the flight track and encom-
passing specific precipitation target areas. The flight missions were conducted within the monsoon westerlies over the sea off the north coast of Australia between 125° and 140°E (Fig. 1a). This location is within and to the west of the budget study area of AMEX (Fig. 8).

An interesting finding from the EMEX aircraft studies (Mapes and Houze, 1991) is that the mesoscale convective systems in this region contained both areas of deep convection and stratiform precipitation, as has been observed elsewhere in the tropics, such as in the eastern Atlantic GATE area (Houze, 1977; Zipser, 1977; Leary and Houze, 1979). In a study of ten EMEX mesoscale convective systems, Mapes and Houze found that the stratiform precipitation areas usually evolved in place from deep convective cells and the overall evolution of the system depended importantly on the triggering of new convection by convergence along the edges of the downdraft cold pool in the boundary layer.

Vertical profiles of divergence have been calculated with the airborne Doppler data by Mapes and Houze (1990) for three classifications of precipitation structures: convective region, stratiform region and transitional region (separating the convective and stratiform regions). The mean profiles from approximately 20 cases in each category are shown in Fig. 11. In the convective region (Fig. 11a) convergence was observed from the surface to about 6 km, with divergence above. These results are consistent with those for the AMEX cloud cluster growing stage of Frank and McBride (1989), wherein they found $\omega$ increasing upward to a peak near 5 km [their Fig. 5b]. The profiles in the transitional and stratiform regions (Figs. 11b and 11c) are distinctly different, with convergence in the midtroposphere and divergence near the surface. The findings for these regions are in agreement with those of Houze (1982) and Johnson and Young (1983) shown in Fig. 6 for the stratiform region (evident by noting that to a reasonable approximation $Q_z \propto -\omega$).

One important EMEX scientific objective was the determination of the effects of mesoscale convective systems on the atmospheric radiative budget. This subject has been studied by Wong et al. (1991) using a numerically simulated cloud cluster coupled with a two-stream radiation model applied to EMEX data. The life cycle of an EMEX squall-line system has been simulated by Wong et al. using the Colorado State University Regional Atmospheric Modeling System (Tripoli and Cotton, 1982). The resulting cloud and precipitation distributions were then used to determine their impact on the radiative heating field.

Results from Wong et al. (1991) 3 h into their simulation (at 0815 LST) are shown in Fig. 12. The field of total hydrometeor mixing ratio (Fig. 12a) indicates that the system is characterized by a leading convective line and trailing stratiform precipitation region. Shown in Fig. 12b are the net radiative budgets (infrared plus solar heating) across the system at the same time. In terms of absolute magnitude, the largest modulation of the radiative field by the cloud cluster is of the net flux at the surface, where there is up to a 500 W m$^{-2}$ reduction, primarily as a result of solar extinction by the cloud layer. However, in the atmosphere there is a pronounced modulation of the net radiative flux, principally due to infrared effects, with a variation from a net radiative cooling in the clear sky outside the system to a net tropospheric heating inside the system (equivalent to a 1.7 K day$^{-1}$ relative warming of the entire

![Fig. 11. Mean profiles of divergence (10$^{-4}$ s$^{-1}$) for (a) 19 convective areas, (b) 21 transitional areas and (c) 20 stratiform areas based on EMEX airborne Doppler data. The dashed line shows extrapolated values necessary to make the profiles mass balanced. (From Mapes and Houze, 1990.)](image-url)
tropospheric column within the storm). As noted by Wong et al. (1991), such effects could have a significant impact on the dynamics of individual cloud clusters by enhancing their mass circulation and, as well, may have important implications for potential greenhouse warming effects of tropical convective systems (Stephens and Greenwald, 1991).

c. Down Under Doppler and Electricity Experiment (DUNDEE) results

As discussed earlier, the Indonesian maritime continent serves as the climatological heat source for the Asian winter monsoon. The most prominent feature of the convection in this region is its pronounced diurnal variability, characterized by daytime convection over land and nighttime convection over the adjacent ocean areas (Murakami, 1983; Williams and Houze, 1987; Keenan et al., 1989). In large part, the past experiments such as MONEX, AMEX and EMEX have concentrated on the study of convection over water, either over the ocean or just off the shore of land masses. DUNDEE, conducted in the vicinity of Darwin, Australia, (Fig. 1a) during November–February, 1988–1989 and 1989–1990, has offered the first opportunity to study the detailed characteristics of monsoon convection using a surface-based, dual Doppler radar network providing coverage over both land and ocean in the region of the maritime continent.

An overview of DUNDEE has been recently prepared by Rutledge et al. (1992). While one of the principal objectives of DUNDEE was to study the electrical properties of tropical monsoon convection, a number of aspects of the precipitation and kinematic structures of mesoscale convective systems were determined. In Fig. 13a (from Rutledge et al.,

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![Figure 12](image-url)
Fig. 13. Vertical cross-sections of radar reflectivity in dBZ for (a) the DUNDEE monsoon case of 30 November 1988 extending out over the open ocean to the northwest of the TOGA radar and (b) the break-period convective event of 10 January 1989 over land to the west of the MIT radar. (From Rutledge et al., 1992.)

In 1992, a vertical cross-section of the radar reflectivity from the United States TOGA Doppler radar is shown for an active period of the Australian summer monsoon on 30 November 1988. The cross-section extends out over the open ocean off the north coast of Australia. The pattern of convection in this case consists of a deep convective region near the radar with tops to nearly 17 km accompanied by an extensive region of stratiform precipitation. [Rutledge et al. note that some attenuation occurred in this instance where the radar beam passed through the convective region, thereby unrealistically limiting the vertical extent of the stratiform region.] This reflectivity pattern closely resembles that observed in other tropical oceanic regions such as GATE (Leary and Houze, 1979). Rutledge et al. (1992) indicate that during this active monsoon period the convective available potential energy (CAPE) was relatively low (~500–1000 J kg⁻¹) and distinctly different from the high values of CAPE observed during the monsoon break periods.

A characteristic vertical cross-section of reflectivity for a convective event during the monsoon break period is shown in Fig. 13b (for 10 January 1989). These data (from the Massachusetts Institute of Technology Doppler radar) are from over land and have a vertical structure that stands in contrast with convection during the active monsoon. A very deep core of high reflectivities is seen extending into the upper troposphere, much like that observed in mid-latitude severe thunderstorms (Donaldson, 1961). The storm environment in this case had a much higher value of CAPE (~2000 J kg⁻¹) and vertical velocities were estimated from high-elevation-angle single-Doppler measurements to be as high as 30–35 m s⁻¹. Clearly, with these two contrasting active and break monsoon reflectivity profiles and convective structures (also seen at times other than those shown here), considerably different heating profiles on different horizontal scales can be expected.

The Rutledge et al. (1992) results from DUNDEE therefore suggest that within the Australian monsoon two primary modes of convection exist over land areas, one characteristic of tropical maritime convection (during the active monsoon) and another of continental convection (during the break monsoon). There are also variations within these two basic classifications (Keenan and Carbone, 1989). The overall heat sources generated by these two types of convection likely have important differences, whose dynamical effects may provide a feedback mechanism influencing the evolution of the active and break periods of the monsoon itself. It may be that there are similar active-to-break variations in the structure of summer monsoon convection over the Indian subcontinent; however, radar measurements are not available to confirm such variations in detail.

There are several additional findings from DUNDEE that are worthy of mention. The first concerns the character of the vertical motion within the stratiform region. Keenan and Rutledge (1991) studied the structure and kinematics of one of the DUNDEE oceanic monsoon systems as it moved inland over Darwin on 12 January 1990. Although the general structure of the system was similar to others in the tropics, with a stratiform region trailing a line of convection, the upward vertical motion in the stratiform region was not a smooth, broad region of ascent (as depicted in Fig. 4). Rather, there existed a series of weak convective-scale updrafts and downdrafts with peak magnitudes ~1 m s⁻¹. Several other studies have also reported a considerable degree of convective-scale structure within the stratiform precipitation regions of mesoscale convective systems (Leary and Rappaport, 1987; Mapes and Houze, 1991). Referring to (3) and (4), it can be seen that given the same net condensation (or deposition) in the stratiform region, the heat and moisture sources (Q₁ and Q₂) contributed by the stratiform precipitation system may depend upon whether or not convective-scale motions exist. Thus, eddy transports within the “stratiform” regions of mesoscale convective systems and their impact on Q₁ and Q₂ may not always be negligible, as has often been assumed.

Secondly, the DUNDEE results indicate that
there may be significant land vs. ocean differences in heating profiles within the maritime continent. Such a conclusion has already been suggested by the AMEX study of vertical motion by Keenan et al. (1989). It might be generally expected that over islands where sea breeze and topographic effects can be important, more vigorous convection may occur than that over the adjacent ocean. It is then possible that there may be a diurnal cycle in the heating profile over the maritime continent, as has been detected over the Tibetan Plateau (Nitta, 1983), but in this case in association with the sea and land breezes over the numerous tropical islands. Some of the results regarding sea breeze convection from TAMEX (presented in the next subsection), although very preliminary, may shed some light on the question of the diurnal variation of heating over islands within the tropics.

d. Taiwan Area Mesoscale Experiment (TAMEX) results

TAMEX was conducted during May and June 1987 in the vicinity of Taiwan (Fig. 1b) with the objective of investigating the processes that produce heavy rain over Taiwan during the Mei–Yu season (Kuo and Chen, 1990). As discussed earlier, Luo and Yanai (1983, 1984) computed precipitation, vertical motion, heating (Q1) and moistening (Q2) distributions over the Yangtze and southern China regions (including the Taiwan area) for the FGGE year. They showed through an analysis of the Q1 and Q2 profiles that much of the Mei–Yu rainfall is produced through large-scale or stratiform precipitation processes. It is of interest to know to what extent their conclusions can apply to precipitation systems occurring locally over the Taiwan area (which is contained within Luo and Yanai’s (1984) Region III centered over the Yangtze valley; Fig. 1b).

In order to determine the general character of the cloud systems producing rainfall over Taiwan, Johnson and Bresch (1991) computed the vertical motion, heating and moistening distributions within these systems using six-hourly sounding data from the TAMEX Special Observing Period (SOP; mid-May to mid-June). Vertical motion was calculated over a \( \sim 3 \times 10^4 \) km\(^2\) area encompassing most of the mountainous island of Taiwan using a procedure described by Nitta (1983). The computed fields were then related to the precipitation structure of the cloud systems as determined by TAMEX research radars.

To illustrate the wide range of precipitation-producing mechanisms during the Mei–Yu, results from the event of a cold front passage on 17–18 May 1987 will be presented. The first rainfall over Taiwan in connection with this system was associated with a N-S pre-frontal squall line that approached Taiwan from the west around 0000 L on the 17th at \( \sim 16 \) m s\(^{-1}\). The structure of this squall line has been documented by Wang et al. (1990) using a dual-Doppler radar network along the north coast of Taiwan. The storm contained a leading convective line and trailing stratiform precipitation region, much like squall lines observed elsewhere in the tropics and midlatitudes (e.g., Houze et al., 1989). Over the next seven hours precipitation moved inland with widespread light rain occurring over the coastal regions and deep convection over the central mountains. Approximately 4 h later around 1200 L stratiform precipitation enveloped much of the region following cold frontal passage. On the 18th, post-frontal stratiform precipitation occurred over much of the island.

Fig. 14. TAMEX apparent heat source Q1 and apparent moisture sink Q2 \( (\degree C \text{ h}^{-1}) \) at 0200 L (solid) and 0800 L (dashed) on 17 May 1987. (From Johnson and Bresch, 1991.)

Q1 and Q2 profiles at 0200 and 0800 L on the 17th are shown in Fig. 14. Q1 has primary peaks near 550 mb whereas Q2 exhibits two peaks, one at upper levels (broadly between 400 and 550 mb) and the other at low levels near 700 mb. The separation between the Q1 and lower Q2 peaks is an indicator of deep convection (Luo and Yanai, 1984). But also present in this situation is an upper level Q2 peak roughly coincident with that of Q1, suggestive of a contribution from stratiform precipitation. Indeed in this case a mixture of convective structures is observed ranging from cellular convection to stratiform precipitation, the latter being associated with a squall line and then, later, frontal overrunning and orographic effects. Johnson and Young (1983) have noted that Q1 and Q2 for mesoscale anvils associated with tropical squall systems have nearly coincident peaks in the upper troposphere. The squall line trailing stratiform cloud may have contributed to the upper-level peaks in this case.

Interestingly, a midtropospheric minimum in Q2 (near 625 mb) is present at both times at approximately the same level as those for the western Pa-
Fig. 15. As in Fig. 14, except for 18 May.

Specific and Florida cases (Fig. 7b) and the AMEX cases (Fig. 10). Considering these similar results from diverse regions, this feature of the Q2 profile clearly appears to be not just a localized phenomenon. With the mixture of deep convective and stratiform precipitation present in this 16–17 May TAMEX event, it is not clear, however, which of the two mechanisms discussed earlier (or perhaps a combination of both) may have contributed to the double-peak Q2 structure in this case.

Presented in Fig. 15 are the Q1 and Q2 profiles at 0200 and 0800 L on the 18th. The pattern is distinctly different from that 24 h earlier with heating and drying in the midtroposphere (above 800 mb) and cooling and moistening below. This structure is consistent with the existence of stratiform precipitation where the stratiform cloud layer exists in the midtroposphere and rainfall evaporation dominates in the lowest levels. It is similar to that determined for tropical mesoscale stratiform cloud systems (e.g., Houze, 1982; Johnson and Young, 1983), except that the peaks at both upper and lower levels are shiftward downward in this case. The lower maxima are consistent with the presence of frontal and/or orographically generated stratiform precipitation in contrast with the deep tropics where detrainment from deep cumulonimbus plays an essential role.

Summarizing these findings (and others reported in Johnson and Bresch, 1991), it appears that heavy precipitation over Taiwan during the Mei–Yu consists of both convective and stratiform components. During periods of deep convection, deep upward motion is present and a separation of Q1 and Q2 peaks is observed (noted as a signature of deep convection by Luo and Yanai, 1984). A double peak structure to Q2 is observed at times of deep convection, as has been seen elsewhere (Johnson, 1984; Dudhia and Moncrieff, 1987; Esbensen et al., 1988; Lafore et al., 1988; Chong and Hauser, 1990). When stratiform precipitation is present, the Q1 and Q2 peaks are nearly coincident. These findings generally support those of Luo and Yanai (1984) indicating a predominance of stratiform rainfall over the entire southern China and Yangtze regions (including Taiwan) during the Mei–Yu; however, they also suggest that in at least a portion of this region the precipitation may consist of a mixture of deep convection and stratiform components. It appears that similar conclusions can be drawn regarding precipitation during the Baiu over Japan (e.g., see review by Ninomiya and Murakami, 1987).

Furthermore, the instances of stratiform precipitation in the Taiwan area (contributing to moderate-to-heavy rain) are characterized by coincident Q1 and Q2 peaks in the middle to lower troposphere (600 to 800 mb) as opposed to the occurrence of nearly coincident Q1 and Q2 peaks in Luo and Yanai (1984) at a somewhat higher level (near 400 to 500 mb). The lower peaks in the Taiwan area are consistent with the existence of shallow cold frontal lifting in stable air (where gravity current dynamics appear to be relevant; Trier et al., 1989) and stable orographic lifting. In contrast, the higher peaks farther north over southern China and the Yangtze region (Luo and Yanai, 1984) may indicate the effects of large-scale ascent in baroclinic systems. Thus, it appears that in the Taiwan area heavy rain in stable situations may depend critically on low-level forcing mechanisms.

Heating and moistening distributions are next examined during a portion of a three-day period (24–26 May) when synoptic-scale influences were minimal. On these days, skies were generally clear in the morning, followed by afternoon thunderstorms over the interior as a result of sea breeze circulations. Such conditions were difficult to find during TAMEX as disturbed weather associated with the Mei–Yu frequently affected the Taiwan area.

The diurnal cycle of Q1 and Q2 on May 24 is illustrated in Fig. 16 (from Johnson and Bresch, 1991).
Heating and drying developed at low levels several hours after sunrise (0800 L) in association with developing convection and extended throughout the entire troposphere in the afternoon (1400 L). The maximum heating occurred at very high levels (between 200 and 250 mb) and there was a distinct separation between the $Q_1$ and $Q_2$ peaks, indicative of deep convection. At 2000 L, the heating weakened at upper levels and converted to cooling below mountain crest. Similarly, drying aloft and moistening below is seen in the $Q_2$ profile. The structure of the $Q_1$ and $Q_2$ profiles at 2000 L is characteristic of that observed within the stratiform regions of mesoscale convective systems (Houze, 1982; Johnson and Young, 1983). The latter studies have related the heating at high levels to condensation and freezing in stratiform cloud aloft and the cooling below to precipitation evaporation and melting.

Finally, at 0200 L on the 25th, $Q_1$ converted to cooling above 700 mb. This deep layer of cooling at night is often present at other times and typically extends to near the surface (although not in this case). It is presumed to be a consequence of evaporation of precipitation and cloud debris from the convection that occurred earlier in the afternoon and evening over the island. This conclusion is supported by the negative $Q_2$ (moistening) observed from 250 to 600 mb. [The drying below 600 mb, however, has no obvious explanation.] Radiative cooling might also contribute to the negative $Q_1$, but the cooling is too large and over too deep a layer to be attributed solely to radiative effects (Webster and Stephens, 1980).

The extremely high level of heating at 1400 L in Fig. 16 was also observed on several other days during TAMEX. This result may suggest that the peak in heating over tropical islands is shifted upward from that over the adjacent oceans. A similar possibility was suggested earlier for the Indonesian maritime continent. These results concerning the diurnal cycle are very preliminary, however, and further study is needed before any definitive conclusions can be drawn.

4. Summary and conclusions

Over the past decade there has been considerable progress in the determination of the detailed characteristics of the heat and moisture sources and sinks of the Asian monsoon. Studies based on FGGE and its regional experiments Winter and Summer MONEX have enabled documentation of monsoon heat sources on a variety of scales ranging from the planetary to the synoptic to the mesoscale. In this paper some of the FGGE results have been reviewed to provide a background for discussion of findings from several more recent experiments: the 1987 Australian Monsoon Experiment (AMEX); the 1987 Equatorial Mesoscale Experiment (EMEX); the 1988–1990 Down Under Doppler and Electricity Experiment (DUNDEE) and the 1987 Taiwan Area Mesoscale Experiment (TAMEX).

Results from AMEX, EMEX, DUNDEE and TAMEX reveal the existence of mesoscale convective systems having cloud and precipitation structures similar to those observed elsewhere in the tropics. A structure commonly observed is one consisting of deep convective towers with attendant stratiform precipitation, such as has been well documented in GATE (Houze, 1977; Zipser, 1977; Leary and Houze, 1979). Despite this similarity with GATE, however, the mean heating profiles deduced from AMEX and inferred from EMEX observations are different from those of GATE. They are more like those determined for the western Pacific Marshall Islands region (e.g., Yanai et al., 1973), where there is a peak in the heating in the midtroposphere. The peak in the mean heating for the GATE region is in the lower troposphere. Thus, while it appears that certain patterns of convective organization in the tropics (and even midlatitudes) appear to be universal, it is unsafe to assume that the mean heating distributions will be the same. Moreover, some of the DUNDEE results (Keenan and Rutledge, 1991) suggest that further refinements of conceptual models of tropical cloud clusters may be in order, by pointing to the existence of considerable convective-scale motions embedded with the stratiform precipitation regions of such systems.

Modeling studies applied to EMEX data indicate that modulations of infrared and solar radiation by tropical cloud clusters are significant. It appears that horizontally varying radiative heating in tropical mesoscale convective systems may markedly influence their dynamics and also serve to promote their longevity; however, the interaction between radiative and moist convective processes has not yet been thoroughly treated in models.

Doppler radar studies from TAMEX during the transition from the winter to summer monsoon indicate a variety of precipitation structures in the vicinity of Taiwan, ranging from pre-frontal deep convection to post-frontal overrunning and orographic precipitation. The heat and moisture sources and sinks deduced from TAMEX soundings yield vertical profiles consistent with the radar-observed precipitation. The findings support those of Luo and Yanai (1984) indicating a frequent occurrence of stratiform precipitation during the Mei-Yu, but also suggest the existence of a wide range of precipitation types during this season, from deep convection to stratiform precipitation.

AMEX and TAMEX also have provided further
evidence of the apparently persistent feature of a double-peak structure to the apparent moisture sink $Q_2$ in the tropics and subtropics. The mechanism for this phenomenon may be the coexistence of convective and stratiform rainfall or strong eddy transports of water vapor in the lower troposphere by deep convection or a combination of both processes. A midtropospheric minimum in relative humidity is associated with this feature. Further studies to understand the possible causes of this minimum are needed, both for explaining the nature of monsoon moisture sources and also for understanding the controls on upper-tropospheric water vapor, which is an important factor in regulating the earth’s climate.

It is quite clear that while much has been learned concerning Asian monsoon heat and moisture sources and sinks from FGGE and subsequent experiments, many questions remain to be answered. Particularly lacking is information concerning the detailed precipitation characteristics of monsoon convection over land areas, e.g., over the Indian subcontinent, China, southeast Asia and the Indonesian maritime continent. Such measurements are difficult, but are needed to better define the nature of these sources. Radiative effects are also not yet fully understood. It is recommended that future field experiments give important attention to these issues.

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アジアモンスーン降水系の熱と水蒸気のソースとシンク

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アジアモンスーンの熱と水蒸気のソースとシンクの構造・特性についてレビューした。First GARP Global Experiment (FGGE) の結果は、プラネタリースケールから個々の対流系のスケールまでの熱・水蒸気源の重要な情報をもたらした。その結果アジアモンスーンの影響下にある広大な地域での、広範な種類の降水系によってもたらされている空間的・時間的に複雑な熱源分布が明らかになりつつある。

最近の実験、1987年の Australian Monsoon Experiment (AMEX)、1987年の Equatorial Mesoscale Experiment (EMEX)、Taiwan Area Mesoscale Experiment (TAMEX)、1988-90年の Down Under Doppler and Electricity Experiment (DUNDEE)、はモンスーン域のメソスケール対流系の特性とそれらのモンスーンの熱・水蒸気源への寄与に関する新しい知識を提供した。これらの実験結果のいくつかはこれまでに出されている降水系の概念モデルを裏付けるものであるが、同時にアジアモンスーンにおける対流過程への新しい見方も提供している。