Chapter 1

A Further Look at $Q_1$ and $Q_2$ from TOGA COARE

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ABSTRACT

Two features of Yanai et al.’s profiles of $Q_1$ and $Q_2$—the commonly observed double-peak structure to $Q_2$ and an inflection in the $Q_1$ profile below the melting level—are explored using estimates of convective and stratiform rainfall partitioning based on Massachusetts Institute of Technology (MIT) radar reflectivity data collected during TOGA COARE. The MIT radar data allow the $Q_1$ and $Q_2$ profiles to be classified according to stratiform rain fraction within the radar domain and, within the limitations of the datasets, allow interpretations to be made about the relative contributions of convective and stratiform precipitation to the mean profiles. The sorting of $Q_2$ by stratiform rain fraction leads to the confirmation of previous findings that the double-peak structure in the mean profile is a result of a combination of separate contributions of convective and stratiform precipitation. The convective contribution, which has a drying peak in the lower troposphere, combines with a stratiform drying peak aloft and low-level moistening peak to yield a double-peak structure. With respect to the inflection in the $Q_1$ profile below the 0°C level, this feature appears to be a manifestation of melting. It is the significant horizontal dimension of the stratiform components of tropical convective systems that yields a small but measurable imprint on the large-scale temperature and moisture stratification upon which the computations of $Q_1$ and $Q_2$ are based. The authors conclude, then, that the rather subtle features in the $Q_1/Q_2$ profiles of Yanai et al. are directly linked to the prominence of stratiform precipitation within tropical precipitation systems.

1. Introduction

A conceptual breakthrough in understanding how tropical cloud systems interact with their environment was achieved through the landmark paper of Yanai et al. (1973), wherein the now-familiar $Q_1$ (apparent heat source) and $Q_2$ (apparent moisture sink) were defined. However, well prior to the 1973 study, Yanai (1961) introduced $Q_1$ and $Q_2$ in a paper titled “A detailed analysis of typhoon formation,” which investigated the dynamic and thermodynamic properties of the formation of Typhoon Doris (1958) in the western Pacific. Vertical profiles of $Q_1$ and $Q_2$—the first ever to be presented—were shown in Yanai (1961) for the period of the transformation of Doris from a cold-core to warm-core tropical cyclone.

Following Yanai et al. (1973), but including ice processes, we write the equations for the apparent heat source and moisture sink as follows:

$$Q_1 = \frac{\partial \bar{q}}{\partial t} + \mathbf{v} \cdot \nabla \bar{q} + \frac{\partial \bar{q}}{\partial 
abla \bar{q}}$$

$$= L_v(\bar{c} - \bar{v}) + (L_v + L_f)(\bar{d} - \bar{e})$$

$$+ L_f(\bar{j} - \bar{m}) + Q_R - \frac{\partial}{\partial p} (\bar{q}\bar{w}), \quad \text{and} \quad (1-1)$$

$$Q_2 = -L_v \left( \frac{\partial \bar{q}}{\partial t} + \mathbf{v} \cdot \nabla \bar{q} + \frac{\partial \bar{q}}{\partial p} \right)$$

$$= L_v(\bar{c} - \bar{v}) + L_0(\bar{d} - \bar{e}) + L_v \frac{\partial}{\partial p} (\bar{q}\bar{w}), \quad (1-2)$$

where $c, e, d, s, f, \text{and} \ m$ are condensation, evaporation, deposition, sublimation, freezing, and melting rates.
respectively; \( q \) is the water vapor mixing ratio; \( s = c_p T + gz \) is the dry static energy; \( Q_1 \) is the apparent heat source; \( Q_2 \) is the apparent moisture sink; \( Q_R \) is the net radiative heating rate; \( L_v \) and \( L_f \) are the latent heats of vaporization and fusion, respectively; the overbar refers to a horizontal average; and the primes denote a deviation from this average.

Yanai et al. (1973) used 1956 Marshall Islands sounding data to compute \( Q_1 \) and \( Q_2 \) and then applied a simplified cloud model to diagnose the bulk properties of cumulus ensembles, which provided substantial insight into the properties of tropical convective systems and how they impact their environment. The profiles of \( Q_1 \) and \( Q_2 \) obtained by Yanai et al. (1973) for the Marshall Islands for the period 15 April–22 July 1956 are shown in Fig. 1-1, along with radiative heating \( Q_R \) estimates from Dopplick (1972, 1979). They found a primary peak in \( Q_1 \) in the upper troposphere, whereas the principal \( Q_2 \) peak was in the lower troposphere. Yanai et al. (1973) pointed out that the separation of the \( Q_1 \) and \( Q_2 \) peaks is indicative of vigorous deep convection [i.e., strong vertical eddy fluxes of moist static energy \( h = (s + L_v q) \)]. Since the profiles are averages over a 3-month period, they represent contributions from both convective and stratiform components of precipitation systems, which have distinctly different heating and moistening profiles (Houze 1982, 1989; Johnson 1984). Just how the structure of the heating profile varies in the vertical is of considerable interest, since that determines the dynamical response of the environment to convection (Hartmann et al. 1984; Raymond and Jiang 1990; Nicholls et al. 1991; Schumacher et al. 2004).

A curious feature of the \( Q_2 \) profile is its double-peaked structure, which has also been found for the GARP Atlantic Tropical Experiment (GATE) (Esbensen et al. 1988), as well as for other experiments such as the more recent R/V Mirai Indian Ocean Cruise for the Study of the Madden–Julian oscillation (MJO) Onset (MISMO) (Katsumata et al. 2011). This feature has been attributed by Johnson (1984) and Esbensen et al. (1988) to the separate contributions of

FIG. 1-1. Apparent heat source \( Q_1 \), apparent moisture sink \( Q_2 \), and net radiative heating rate \( Q_R \) for the Marshall Islands. From Yanai et al. (1973).

FIG. 1-2. Apparent heat source \( Q_1 \) and apparent moisture sink \( Q_2 \) for MISMO in the Indian Ocean (dark curve) and TOGA COARE Intensive Flux Array (light curve). From Katsumata et al. (2011).

FIG. 1-3. TOGA COARE Intensive Flux Array quadrilateral, atmospheric sounding sites, and 4-month mean TOGA COARE rainfall (mm day\(^{-1}\)) from the Global Precipitation Climatology Project (GCPC). The circle indicates the 120-km radius radar study area. MIT radar was on board R/V Vickers.
convective and stratiform precipitation systems. Namely, condensation and deposition aloft associated with stratiform precipitation produces the upper peak while condensation in convective precipitation produces the lower peak. Placed in a time perspective, the vertical motion and hence heating and drying typically undergo an evolution (on time scales ranging from diurnal to the life cycle of tropical cloud clusters to the passage of easterly waves) from a low-level peak in the vertical motion (and heating) in the early stages to an upper-level peak in the later stages (Frank 1978; Nitta 1978; Houze 1982; Johnson and Young 1983). This evolution has since been documented on longer time scales ranging up to the 30–60-day MJO, as reviewed by Kiladis et al. (2009).

It is the purpose of this article to delve further into the relationship between the $Q_1$ and $Q_2$ profiles and convective/stratiform rain partitioning using radar and sounding data from an experiment, which is now celebrating its twenty-third anniversary—the 1992–93 Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE)—conducted in the western Pacific (Webster and Lukas 1992). However, we first note that the experiment-mean TOGA COARE $Q_1$ and $Q_2$ profiles (Johnson and Ciesielski 2000) are different from those of the Marshall Islands, GATE, and MISMO. To illustrate this difference, a comparison of the mean profiles for MISMO and TOGA COARE is shown in Fig. 1-2 (from Katsumata et al. 2011). Notably absent from the TOGA COARE results are low-level peaks in heating and drying. This behavior was also found over the northern South China Sea during the May–June 1998 South China Sea Monsoon Experiment (SCSMEX; Johnson and Ciesielski 2002). Johnson and Lin (1997) explained the unique feature of the TOGA COARE profiles as a consequence of frequent trade wind–like, nonprecipitating cumulus clouds during the quiescent and westerly wind burst phases of the MJO. These clouds were prevalent during dry midtropospheric conditions and served to moisten the lower troposphere, thereby producing prolonged periods of negative $Q_2$, as also observed during the Barbados Oceanographic and Meteorological Experiment (BOMEX; Nitta and Esbensen 1974). In contrast, during the active phase of the MJO, $Q_1$ and $Q_2$ distributions much like those of Yanai et al. (1973) were observed [Fig. 3 of Johnson and Lin (1997)].
In this chapter we will use radar data from the Massachusetts Institute of Technology (MIT) radar on board the R/V *Vickers* during TOGA COARE (Rickenbach and Rutledge 1998) to relate the heating and moistening profiles to the stratiform/convective rain fractions derived by that radar to further elucidate the factors contributing to the observed mean $Q_1$ and $Q_2$ profiles for that experiment.

2. Data and analysis procedures

a. Radar data

Radar reflectivity data from the MIT C-band Doppler radar, deployed on board the R/V *Vickers* and processed as described in Rickenbach and Rutledge (1998), are used in this study. The position of the *Vickers* within the TOGA COARE Intensive Flux Array (IFA) is shown in Fig. 1-3 along with other sounding sites in the region used in the budget analyses. Rickenbach and Rutledge (1998, see their Fig. 2) indicate the time periods of the radar and sounding operations during the 4-month TOGA COARE intensive observing period (IOP; November 1992–February 1993). Convective/stratiform rain partitioning was carried out using a slight modification of the method of Steiner et al. (1995) applied to 10-min radar reflectivity volumes. The mean stratiform rain fraction for the three cruises of the *Vickers* was determined to be 28%, which is less than the ~40% estimate for this region by Schumacher and Houze (2003) obtained from the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR). However, as we will see later, the MIT-based estimate is closer to the TRMM-based value if we remove the periods of trade wind cumulus from the average. We would expect this to be the case since the 4–5-km footprint of the PR tends to smooth out and lower the reflectivity of the precipitating cumulus (the so-called "beamfilling" problem) compared to the higher-resolution MIT shipborne radar.

b. Sounding data and averaging methodology

The 6-hourly sounding data were objectively analyzed onto a 1° × 1° grid at 25-hPa intervals from 1000 to 25 hPa over the large-scale TOGA COARE domain using procedures described in Ciesielski et al. (1997), and incorporating humidity sensor corrections as outlined in Ciesielski et al. (2003). The resulting gridded basic and derived fields were then averaged over the circular MIT radar coverage area shown in Fig. 1-3. The distribution of sounding sites in proximity to the *Vickers* is reasonably good, so analyses over this region are deemed fairly reliable, apart from other issues such as temporal data gaps and random sampling errors (Mapes et al. 2003).

3. Results for the 4-month TOGA COARE intensive observing period

A time series of $Q_1$ and $Q_2$ for the TOGA COARE IOP is shown in Fig. 1-4, along with the stratiform rainfall fraction based on MIT radar data for the three cruises of the *Vickers* and average rainfall for the MIT radar coverage area derived from the moisture budget, where the Woods Hole Oceanographic Institution Improved Meteorology (IMET) buoy is used for surface evaporation. A prominent MJO event occurred in December, characterized by a transition from shallow convection (low-level peak in $Q_2$) early in the month followed by deep convection midmonth and then stratiform precipitation (drying above moistening) at the end of the month (Lin and Johnson 1996). Consistent with this evolution is an increasing trend in the stratiform rainfall fraction through December as determined by the MIT radar.

Conspicuous in Fig. 1-4 are several ~10-day to 2-week periods of negative $Q_2$ in the lower troposphere, namely, near 750 hPa in mid-November and near 900 hPa in late December and early February. These features were described by Johnson and Lin (1997) as episodes of trade wind–like shallow cumulus existing during very
dry low- to midtroposphere conditions. The moistening in November occurred during light surface wind conditions, whereas the episodes in late December and February were during strong winds. They noted that when winds were strong during these shallow cumulus periods, there was greater moistening (negative $Q_2$) near the cloud base in association with subinversion-type (Esbensen 1978) or forced-type (Stull 1985) cumuli that were, in part, a manifestation of overshooting boundary layer eddies. When winds were light, the cumuli were slightly deeper [“inversion penetrating” after Esbensen (1978) or “active” after Stull (1985)] and the moistening peaked in the upper part of the cloud layer [similar to the Atlantic trades; Nitta and Esbensen (1974)]. Higher sea surface temperatures (by 1 K) and weaker shear observed during the November period likely contributed to the more active cumuli at that time.

4. Relating $Q_1$ and $Q_2$ to stratiform rain fraction

The frequent occurrence of trade wind regimes over the warm pool during TOGA COARE can be attributed to “dry intrusions” that were observed in association with the MJO (Parsons et al. 1994; Numaguti et al. 1995; Yoneyama and Fujitani 1995; Mapes and Zuidema 1996), which helped to inhibit the growth of convection (e.g., Redelsperger et al. 2002). Johnson and Lin (1997) focused on $Q_1$ and $Q_2$ during these trade wind–like periods by averaging the profiles for times when precipitation was less than 3.5 mm day$^{-1}$, the average surface evaporation rate during TOGA COARE. Alternatively, to explore the characteristics of deep convection during TOGA COARE, we remove the effects of these periods by including only those times when the precipitation exceeded 3.5 mm day$^{-1}$. The resulting $Q_1/Q_2$ profiles are shown in Fig. 1-5. They now look much like those of Yanai et al. (1973) (see Fig. 1-1), namely, possessing a double-peak structure to $Q_2$ (though with several additional peaks) and an inflection in the $Q_1$ profile near 650 hPa.$^1$ Therefore, to interpret the Yanai

$^1$ Both the Marshall Islands and the western Pacific $Q_1$ profiles also show peaks near 150 hPa. These peaks may not represent any physical processes, rather they may be artifacts of applying the boundary condition $\omega = 0$ at the tropopause or 100 hPa such that some upward motion acting on weak stability above the lapse-rate minimum (Fueglistaler et al. 2009) produces a local heating maximum.
et al. (1973) profiles in light of the TOGA COARE results, we subsequently restrict analyses to the dates and times that make up Fig. 1-5 (184 total 6-h periods). In support of this procedure, we note that an inflection in the $Q_1$ profile was also found by Schumacher et al. (2007) for the heavy-rain threshold cases of SCSMEX and the 1999 Kwajalein Experiment (KWAJEX).

The $Q_1$ and $Q_2$ profiles as a function of stratiform rain fraction (SRF) are shown in Fig. 1-6. As SRF increases, there is a transition from vertically separated, single peaks in heating and drying in the low- to midtroposphere to nearly coincident peaks at higher levels, consistent with an evolution in the precipitation from mostly convective to mainly stratiform in character (Luo and Yanai 1984). The evolution for $Q_2$ is more complex than that for $Q_1$, with multiple drying peaks aloft above a moistening peak in the lower troposphere. The low-level drying peaks between 700 and 800 hPa for SRF > 40% likely reflect the effects of convection coexisting with stratiform precipitation (Leary and Houze 1979).

Another way of viewing this transition is by comparing profiles for different values of SRF (Fig. 1-7). In this plot SRF values shown are averages for the following SRF bins: <20%, 20%–30%, 30%–40%, 40%–50%, 50%–60%, and >60%. Values for $Q_2$ are plotted only for <20%, 30%–40%, and 50%–60% for the sake of clarity. Curves have been smoothed in the vertical with a 1–2–1 filter.

Because of the abundant precipitation over the warm pool, melting leaves a measurable and persistent effect on the static stability. Melting takes place over a relatively shallow layer [−300–400 m deep; Willis and Heymsfield (1989)] below the 0°C level. Freezing of
hydrometeors occurs at levels above 0°C, but over a deeper layer; nevertheless, the combined effects of freezing above melting serves to increase the static stability at the 0°C level and also from $L_v(T - T_m)$ in (1-1), the vertical gradient in $Q_1$ there. However, when computing $Q_1$ from sounding data, it is the lhs of (1-1) that is calculated and, since the vertical advection term $\frac{\partial s}{\partial p}$ is usually the dominant term in that calculation, the impact of freezing and melting perturbs $\frac{\partial s}{\partial p}$ and hence the $Q_1$ profile. To illustrate this effect, a time series of static stability, represented as $\frac{dT}{dz}$ in Fig. 1-8, shows a persistent stable layer in proximity to 0°C. This stable layer is strongest during periods of heaviest rainfall, so its linkage to melting is perceptible. Also seen in Fig. 1-8

![Graph showing static stability $dT/dz$ over TOGA COARE MIT](image)

**Fig. 1-8.** (top) TOGA COARE intensive observing period time series of static stability $dT/dz$ (K km$^{-1}$) (dashed line indicates the 0°C level), (middle) time series of stratiform rain fraction, and (bottom) moisture-budget-derived rainfall. All fields are for MIT radar area.

![Graph showing stratiform rain fraction and rainfall](image)

**Fig. 1-9.** Static stability $dT/dz$ (K km$^{-1}$) as a function of stratiform rain fraction for the MIT radar coverage area during TOGA COARE for times when moisture-budget-derived rainfall over that area exceeded 3.5 mm day$^{-1}$. 
is a persistent, though fluctuating in intensity, trade wind stable layer, which tends to be strongest during periods of light rainfall and negative low-level $Q_2$ (Fig. 1-4).

To further elucidate the relationship between the melting stable layer and stratiform precipitation, $dT/dz$ is plotted as a function of SRF in Fig. 1-9. As the SRF increases, the strength of the melting stable layer increases, as one would expect considering the associated larger horizontal areas covered by precipitation when the SRF is high. On the other hand, the trade wind stable layer weakens as SRF increases, consistent with the idea that this layer occurs episodically over the warm pool (Johnson and Lin 1997) and is present primarily outside the active phase of the MJO when the SRF is low. In addition, there is a noticeable descent of the height of the trade stable layer as SRF increases. This behavior may be related to the finding of Johnson and Lin (1997) that during light-rain (and light wind) periods of the MJO with small SRF, there is a greater proportion of active trade cumulus (Esbensen 1978; Stull 1985), which rise to higher elevations than during the westerly wind burst phase with high SRF, when “forced” cumuli that are extensions of boundary layer turbulence predominate.

Because the stratiform precipitation systems cover large areas, their impact on the temperature field is significant. This effect is seen in Fig. 1-10, where for SRF > 50%, a shallow cool anomaly is present in a layer below the melting level, accompanied by a deeper moist layer aloft. For the largest values of SRF, there are both warm and dry anomalies centered just below 800 hPa. These features are manifestations of “onion soundings,” often observed in association with the stratiform precipitation regions of tropical squall lines or cloud clusters (Zipser 1977). This structure can also be seen in Fig. 1-11, a plot of the mean relative humidity for SRF > 60% and < 20%. For large values of SRF, moist conditions exist above 0°C, indicative of stratiform anvil clouds aloft, with dry conditions below. In contrast, the mostly convective situations (SRF < 20%) are characterized by a relatively dry mid- to upper troposphere but slightly moister conditions below 3 km. The two contrasting profiles in Fig. 1-11 are consistent with the bimodal relative humidity behavior for TOGA COARE reported by Brown and Zhang (1997). For the lowest values of SRF (Fig. 1-10), dry conditions are observed in the midtroposphere, which act to suppress cloud development.
Also observed for large SRF values (Fig. 1-10) is a layer of cooling near the tropopause (~150 hPa), a feature commonly observed atop mesoscale convective systems in the tropics (Johnson and Kreite 1982; Holloway and Neelin 2007). In addition, a cool anomaly is observed near the surface for increasing values of SRF, indicative of extensive modification of the boundary layer by downdrafts as the stratiform rain amounts and associated area coverage increases (Zipser 1977; Fitzjarrald and Garstang 1981).

In the computation of \( Q_2 \) from large-scale fields, the dominant term is \( \overline{\omega} q_p / \partial p \). The individual contributions to this term are plotted as a function of SRF in Fig. 1-12. There is a clear upward shift in the vertical motion peak (Fig. 1-12, top) as SRF increases. The average SRF for the cases considered here (those for rainfall exceeding 3.5 mm day\(^{-1} \)) is 36%, somewhat higher than the 28% for the entire MIT radar period. Viewing the \( \overline{\omega} \) variation and noting that half the rain is above SRF = 36% and half below, it is readily apparent that the double-peak structure to \( Q_2 \) arises from the individual convective and stratiform contributions. The time series of \( dq/dp \) (Fig. 1-12, middle) shows a trend toward a local maximum near the melting layer as SRF increases, reflecting the increasing presence of stratiform clouds with bases near that level (Johnson et al. 1996). To confirm that the term involving \( \overline{\omega} q_p / \partial p \) is the principal contributor to \( Q_2 \), the SRF-sorted behavior of this term is shown in Fig. 1-12 (bottom). Overall, the broad pattern and evolution of this term is similar to that of \( Q_2 \) (Fig. 1-6, bottom), showing distinctly different vertical structures for small and large values of SRF. The greater vertical structure in \( Q_2 \) is likely a result of horizontal advection of dry air in thin layers, often occurring near the melting level, which Mapes and Zuidema (1996) and Johnson et al. (1996) found to be prevalent over the western Pacific warm pool during TOGA COARE.

5. Summary and conclusions

It has been over four decades since the landmark paper of Yanai et al. (1973) diagnosing apparent heat sources \( Q_1 \) and moisture sinks \( Q_2 \), as well as convective transports based on a simplified cloud model, using Marshall Islands data. In subsequent years, numerous field campaigns in the tropics and midlatitudes have been conducted computing \( Q_1 \) and \( Q_2 \), with results similar to those of Yanai et al. In this chapter we explore aspects of those heating and moistening profiles using estimates of convective and stratiform rainfall partitioning based on MIT radar reflectivity data from the R/V *Vickers* during TOGA COARE (Rickenbach and Rutledge 1998). Particular attention is given to (i) the commonly observed double-peak structure to \( Q_2 \) and (ii) an inflection in the \( Q_1 \) profile below the melting level, and the relationship of these features to the convective cloud populations.

The MIT radar data allow the \( Q_2 \) from large-scale fields, the double-peak structure to \( Q_2 \) and (ii) an inflection in the \( Q_1 \) profile below the melting level, and the relationship of these features to the convective cloud populations. The MIT radar data allow the \( Q_2 \) from large-scale fields, the double-peak structure to \( Q_2 \) and (ii) an inflection in the \( Q_1 \) profile below the melting level, and the relationship of these features to the convective cloud populations. The MIT radar data allow the \( Q_1 \) and \( Q_2 \) profiles to be classified according to stratiform rain fraction and, within the limitations of the datasets, interpretations to be made about the relative contributions of convective and stratiform precipitation to the mean profiles. Radar data from the three cruises of the *Vickers* are used along with gridded fields constructed from the TOGA COARE sounding array and averaged over the MIT radar coverage area. To remove periods when trade wind–like cumulus were present during TOGA COARE, times were selected for analysis when the average rainfall rate over the MIT area exceed 3.5 mm day\(^{-1} \). This criterion resulted in 184 total 6-hourly periods, for which the average stratiform rain fraction was 36%.

The sorting of \( Q_2 \) by stratiform rain fraction leads to the conclusion that its double-peak structure is a result of the separate contributions of convective and stratiform precipitation, as suggested by Johnson (1984), Esbensen et al. (1988), and others. The convective contribution gives a lower drying peak, which when combined with the stratiform contribution of a drying peak aloft (along with moistening at low levels), yields the double-peak structure. With respect to the inflection
in the $Q_1$ profile below 600 hPa or 4 km, this feature appears to be a manifestation of cooling by melting just below the 0°C level, which has a prominent impact due to the broad areal coverage of stratiform precipitation.

We conclude, then, that the rather subtle features in the $Q_1/Q_2$ profiles of Yanai et al. (1973) are directly linked to effects of stratiform precipitation systems, years ago identified by Zipser (1969, 1977) and Houze (1977) as integral components of tropical convection. These systems cover large areas and leave behind perturbations to the temperature and moisture stratification in the tropics, which are readily detectable using sounding data. With the recent completion of the Dynamics of the Madden–Julian Oscillation (DYNAMO) field campaign in the Indian Ocean (October 2011–March 2012), the opportunity exists to further extend this analysis to another tropical ocean basin.

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