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# DIVERGENCE PROFILES IN TROPICAL MESOSCALE CONVECTIVE SYSTEMS

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## 1. INTRODUCTION

Vertical profiles of horizontal divergence have been computed from airborne Doppler radar data collected in 10 tropical oceanic mesoscale convective systems ("cloud clusters") during the Australian monsoon of 1987. The data were collected on board a NOAA WP3D aircraft during the Equatorial Mesoscale Experiment (EMEX; Houze et al 1990). These profiles are averages over areas of approximately 500 km$^2$, calculated by evaluating a line integral with Doppler data. We have examined profiles from approximately 75 of these areas, using all of the suitable EMEX Doppler data.

These profiles provide representative samples of the kinematic properties of various parts of the mesoscale precipitation features (MPFs) within the ten cloud clusters probed by the aircraft. All of these MPFs had a convective portion, often arranged into one or more linear structures, and stratiform portions associated in time or space with the convection. In some cases, convective precipitation was observed to evolve in place into stratiform precipitation. In other cases, linear regions of active convection propagated more rapidly, leaving stratiform precipitation trailing behind. In both types of situations there were transitional states, in which some cellularity was still evident in the reflectivity field, but with weaker gradients and weaker maxima. The transitional process involves the development of both a radar bright band and more horizontally homogeneous Doppler wind fields. We have combined data from areas undergoing this transition into a category we call transitional precipitation. Our sample of divergence profiles is approximately equally divided among convective, transitional and stratiform areas.

## 2. DATA AND METHODS

The EMEX Doppler radar sampling strategy was to have the P3 aircraft fly in a zigzag pattern, with straight and level flight legs about 70 km long (9 min flight time) at an angle of about 60° to each other. This geometry is shown in Figure 1. The P3 Doppler radar antenna sweeps vertically through 360° of elevation, perpendicular to the flight track, once every 6 s. Its maximum horizontal range is 40 km (dashed lines in Figure 1).

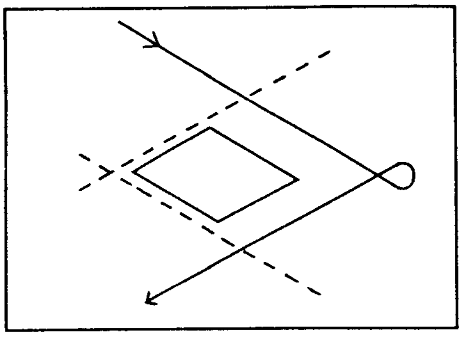


*Fig. 1. Geometry of the divergence calculation. Solid line: P3 flight path; dashed lines: Doppler range limits; box: divergence profile area boundary*

Area-average divergence in 1 km height intervals was calculated according to the divergence theorem:

$$\overline{\nabla \cdot \vec{V}_h} = \frac{1}{A}\oint \vec{V}_h \cdot \hat{n}\, dl \qquad (1)$$

where $\vec{V}_h$ is the horizontal wind, $\hat{n}$ the unit vector normal to the line integral boundary, dl a length element along the boundary, and A the area enclosed within the boundary. In this case, the area used is the parallelogram shown in the solid line in Figure 1. The sides of this parallelogram are chosen parallel to the flight tracks, and thus perpendicular to the beams of the radar, so that the horizontal component of the Doppler radial velocitiy is the component of the wind normal to the boundary of the parallelogram.

The horizontal component of the radial velocity was estimated by assuming that particle fallspeeds are a specified function of radar reflectivity, and by neglecting the mean vertical air velocity. The effect of these assumptions on the value of divergence varies with height and with the particular geometry of the parallelogram chosen. In no case were data from elevation angles over 45° used, so the effect of a constant 1 m/s error in the assumptions could contribute at most $4\times10^{-5}$ s$^{-1}$ to the divergence values at the top or bottom of a profile. The parallelograms were chosen interactively, within the constraints of the 45° elevation cutoff, the horizontal range limit, and the area of available Doppler data (precipitation area). Generally these areas were about 500 km$^2$, so the profiles should be interpreted as representing areas of linear dimension ~22 km. The results are not overly sensitive to the exact location of the parallelogram.

Data in the lowest layer, 0-1 km, sometimes show signs of possible sea clutter. The uppermost levels of the profiles are sometimes data-poor. For these reasons, values of divergence in the lowest and highest levels must be considered especially uncertain.

The mean profiles presented below were obtained by subjectively choosing a profile to represent each flight track "V", then classifying and averaging the profiles.

## 3. RESULTS

Mean divergence profiles for our sample of convective, transitional, and stratiform precipitation areas are shown in Figure 2.

### 3.1 Convective area

The convective area profile shows convergence through the lower troposphere, up to about 6 km. *In situ* wind measurements by EMEX aircraft at various levels in the lower troposphere support this finding, as they generally vary in the convergent sense across convective areas. Above 6 km, the profile shows moderate divergence to 10.5 km, where the data end. We know from satellite IR data and radar data at vertical incidence that these convective systems extend much higher, up to at least 16 km in vigorous convective areas. But the quasi-horizontal radar beams used in this study suffer attenuation and thus the divergence profiles tend to end near 10 km.

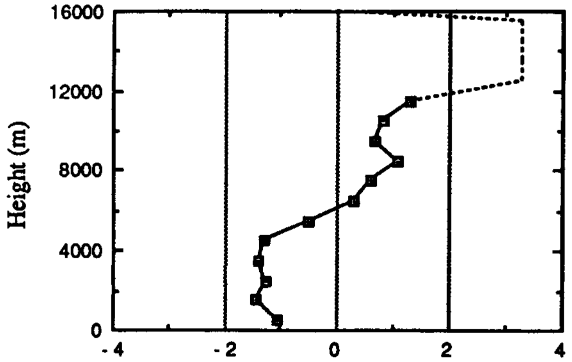
### 3.2 Transitional area

The transitional area profile shows a shallow layer of divergence near the surface. This low level outflow is consistent with observations from the NCAR Electra aircraft in the lower troposphere (not shown) that as the convective areas age, the downdraft to updraft mass flux ratio increases. Above 4 km, the profile shows deep convergence increasing with height up to the top of the data at 10.5 km. This remarkable feature may be related to the divergence in the upper levels of the convective profile, as discussed in section 4.

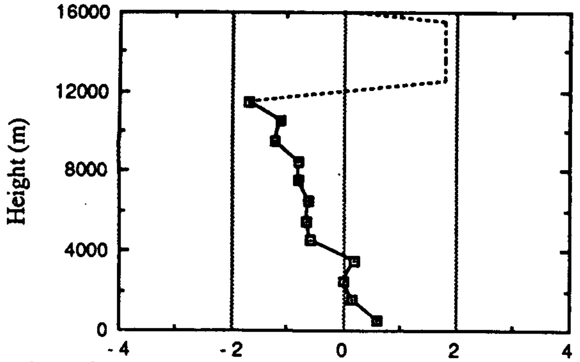
### 3.3 Stratiform area

In the stratiform area profile, the divergence in the lower troposphere is deeper and stronger, suggesting the increased importance of the mesoscale downdraft. Above that, midlevel convergence is seen, weakening up to the top of the data at 9.5 km.

*a) Convective*



*b) Transitional*



*c) Stratiform*

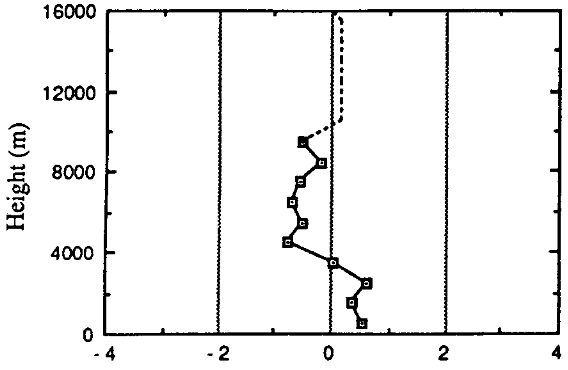


*Fig. 2. Mean profiles of divergence (units $10^{-4}$ $s^{-1}$). a) 19 convective areas. b) 21 transitional areas. c) 20 stratiform areas. The dashed line shows extrapolated values necessary to make the profiles mass balanced.*

This convergence layer is somewhat deeper than past studies have found. In part this may reflect the difficulties of classification. While many individual profiles show the convergence going over to divergence above 7 or 8 km, others show convergence above that, often as a separate maximum. Most of our "stratiform" areas (mean area 605 $km^2$) are not truly homogeneous. The line between transitional and stratiform is a fuzzy one, and as noted above, transitional profiles show strong convergence at upper levels. Also, precipitating anvils are known visually to have an ascending cloud base as they dissipate, so that late-stage stratiform precipitation might have elevated maxima of upward mass flux and convergence. Lumping all types of precipitation without obvious cellular structure together as "stratiform" may blur important distinctions.

## 4. THE TRANSITION PROCESS

The stratiform precipitation in MPFs, although associated with its own active mesoscale circulations, owes its existence to convection. Modeling studies have shown that both ice particles from deep convection and the condensation occurring in the mesoscale updraft are necessary to reproduce observed amounts of stratiform rain (e.g. Rutlege 1986). But the actual physical processes in this scale interaction, whereby small-scale convective activity fills a mesoscale area of the upper troposphere with moist potentially warm air suitable for a mesoscale updraft, remain unclear. The interaction cannot be explained in terms of parcels detraining from giant cumulus clouds at their level of neutral buoyancy. The ~25-km-resolution, averaged view of the transitional process provided by the profiles in Fig. 2 raises a number of new questions. What is the meaning of the deep convergence in the transitional profile? Integration upward from the surface, as can be seen by inspection of Fig. 2b, shows that it must feed into an upward mass flux maximum in the high troposphere. Environmental air at those levels would have to be strongly forced to ascend; more likely the air converging into this upper-level upward mass current is composed of buoyant air diverging out of previous/adjacent convective areas at that level. In this view, the transitional profile represents essentially a continuation of the convective process, and the question shifts to why divergence is observed to start in convective areas at 6 km altitude.

In the P3 Doppler data at vertical incidence, we have often observed downdrafts in the high troposphere in convective areas. Some of the divergence in the 6-10 km levels of the convective profile may be contributed by the bases of these downdrafts. In addition, perturbation pressure forces which resist buoyant ascent may also cause updraft air to spread out horizontally before reaching its nominal level of neutral buoyancy. Research into these questions is continuing.

## 5. ACKNOWLEDGEMENTS

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## 6. REFERENCES

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