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INFLOW AND OUTFLOW CHARACTERISTICS OF CONVECTION IN TOGA COARE

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1. INTRODUCTION

Tropical convective clouds redistribute heat, moisture and momentum throughout the atmosphere, they impact upper oceanic circulations and fluxes across the ocean-atmosphere interface, and they alter the flow fields and thermodynamic stratification within the atmosphere such that they affect subsequent convective activity. General circulation models and coupled ocean-atmosphere models, such as those used to represent the El-Nino / Southern Oscillation, must parameterize all these cloud-scale processes. This study assesses the validity of the conceptual models used in parameterization theories by focusing on the kinematic properties of air parcels flowing into and out of 25 cloud systems sampled by combinations of the two NOAA WP-3D aircraft and the NCAR Electra aircraft during TOGA COARE. The kinematic structures of the convection are analyzed by examining both the high-resolution (75-150 m) tail Doppler radar data from each aircraft (~27,000 vertical cross sections viewed in all) and the lower-resolution (1000-1500 m) three-dimensional wind fields derived from the tail-Doppler radar data (~150 separate 3-D volumes derived). A more detailed analysis incorporating thermodynamic observations is in Kingsmill and Houze (1997).

2. RESULTS

Updraft inflows and downdraft outflows were the airflow features most commonly observed in convective cells. They were positioned adjacent to each other at gust front interfaces that sloped at various angles and directions (Kingsmill and Houze 1995). Descending mid-level inflows were the most common airflow features observed in stratiform precipitation regions. They usually manifested themselves at the base of an anvil but often extended toward the interior of the precipitation system (Kingsmill and Houze 1995).

We examined all of the tail Doppler radar data from the 25 aircraft missions to locate the signatures of updraft inflows, downdraft outflows, stratiform inflows, and other associated circulation features. To tabulate the results of this extensive analysis systematically and quantitatively, we devised simplified models of the inflow and outflow structures in convective cells and stratiform precipitation (Figs. 1 and 2, respectively). The parameters defined in the conceptual models indicate both the geometry and the strength of the inflow and outflow patterns recognizable in tail radar cross sections. By inspection of the tail radar cross sections, and the associated 3-D wind field analyses, we determined and recorded the values of all the parameters defined in Figs. 1 and 2 for 27 distinct updraft-downdraft pairs and 22 different stratiform inflow/outflow structures observed by the tail Doppler radars. Although the conceptual models in Figs. 1 and 2 represents the airflow in a gust-front-relative or system-relative sense, we could only determine the flow parameters in an earth-relative sense because we generally could not determine gust front or system propagation speeds from the aircraft observations. Also, the earth-relative speeds are more relevant to fluxes at the ocean surface and to the large-scale momentum budget.

The primary results of this statistical study are summarized below:

- Upstream of the gust front, the center height (Z_{UI}) of the updraft inflow (V_{UI}) varied from 0.5 to 4.5 km. These results suggest that a considerable amount of air from above the boundary layer enters the convection.
- Maximum values of horizontal wind speed in downdraft outflows (MAX $|V_{DO}|$) were greater than MAX $|V_{UI}|$ for all but three updraft-downdraft pairs. Downdraft outflows thus systematically produce larger air-sea fluxes of sensible and latent heat than do updraft inflows.
- The direction of V_{DO} is better correlated with the direction of large-scale winds at 850 mb compared to 500 mb. This suggests that downdraft outflows at the ocean surface evidently consist of air brought down from the lower tropospheric environment
- Stratiform inflows (V_{SI}) most frequently originated at about 7 km (Z_{ORIG}) and descended about 3 km (Z_{TERM}), although a few extended down to the surface.
- The direction of V_{SI} is best related to the large-scale winds at 400-500 mb. These levels correspond well with the 4-7 km layer where most stratiform inflows were observed. However, this relationship is skewed in a way that suggests the large-scale winds at these levels turned clockwise (in most cases cyclonically) as they entered the stratiform inflows.
- The directions of V_{UI} and V_{DO} are offset from each other at 45-90° angles. Similarly, the directions of V_{SI} and stratiform outflows (V_{SUO} and V_{SLO}) are offset from each other at 45-135° angles. These results suggest that convective cells and stratiform precipitation regions are usually characterized by a

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three-dimensional mesoscale flow structure. In contrast, the directions of $\mathbf{V}_{UI}$ and $\mathbf{V}_{SI}$ are offset from each other at either 0° or 180° angles, suggesting that they have a two-dimensional, rather than three-dimensional, relationship to each other.

3. IMPLICATIONS

The observations suggest that the conceptual models used in parameterization theories are valid but oversimplified. From the standpoint of heat transport, the conceptual models (e.g., Emanuel et al. 1994) overestimate the depth of downdrafts and underestimate the origination height of updrafts. From the standpoint of momentum transport, the conceptual models (e.g., Moncrieff 1992) include the correct airflow components but fail to account for aspects of their three-dimensional complexity. Fortunately, though, the two most important circulation features, the convective updraft inflow and the mid-level stratiform inflow current, tend to exhibit two-dimensionality in relation to each other, which suggest that the two-dimensional momentum transport parameterizations may have some credence in the complex population of warm-pool convection.

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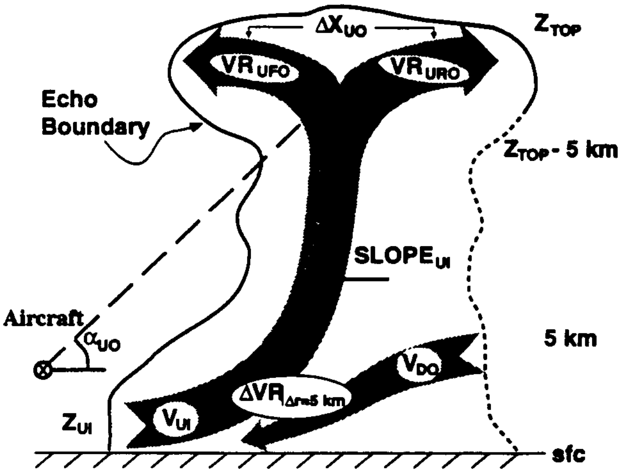

Figure 1. Conceptual model of airflow in convective updrafts and downdrafts. The parameters are Z_{UI} (center height of the updraft inflow), V_{UI} (horizontal wind speed and direction of the updraft inflow), V_{DO} (horizontal wind speed and direction of downdraft outflow), $\Delta VR|_{\Delta r=5km}$ (radial shear of radial velocity over a 5 km distance), $SLOPE_{UI}$ (slope of the updraft inflow), VR_{UFO} (radial velocity of the updraft outflow exiting on the forward side of the cell), VR_{URO} (radial velocity of the updraft outflow exiting on the rear side of the cell), ΔX_{UO} (horizontal distance separating VR_{UFO} and VR_{URO}), α_{UO} (elevation angle from the aircraft to the location of updraft outflow), and Z_{TOP} (echo top). The short dashed portion of the echo boundary represents the fact that the convective cells sometimes are connected to larger regions of stratiform precipitation.

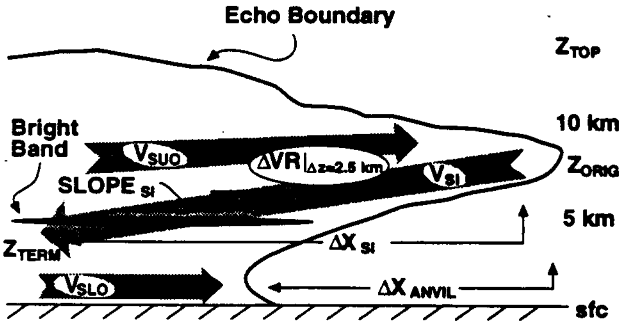

Figure 2. Conceptual model of airflow in stratiform precipitation regions. The parameters are V_{SI} (horizontal wind speed and direction of the stratiform inflow), V_{SUO} (horizontal wind speed and direction of the upper stratiform outflow), V_{SLO} (horizontal wind speed and direction of the lower stratiform outflow), $\Delta VR|_{\Delta z=2.5km}$ (vertical shear of radial velocity over a 2.5 km distance), Z_{ORIG} (origination height of the stratiform inflow), Z_{TERM} (termination height of the stratiform inflow), ΔX_{SI} (horizontal extent of the stratiform inflow), $SLOPE_{SI}$ (slope of the stratiform inflow), ΔX_{ANVIL} (horizontal extent of anvil), and Z_{TOP} (echo top).