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CONVECTIVE MOMENTUM TRANSPORT OBSERVED DURING THE TOGA COARE IOP: IMPLICATIONS FOR PARAMETERIZATION

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1. BACKGROUND

This work addresses the observation of collective effects of convective momentum transport (CMT) on the large-scale atmosphere over the western Pacific warm pool. CMT may have considerable impacts on the regulation and strength of Madden-Julian oscillation (MJO) and tropical circulations in general (e.g., Inness and Gregory 1997). However, the parameterization of CMT for general circulation models (GCMs) have been impeded by two difficult factors. First, the horizontal momentum of convective elements is not conserved. Second, the directions of CMT depend on the geometry and orientation of convective organizations that can not be resolved at GCM grid scales (e.g., LeMone 1983; Wu and Yanai 1994).

Based on the mass-flux approach, Shapiro and Stevens (1980) proposed a formulation for CMT parameterization that encompasses both factors:

$$\mathbf{X}_C = -M_C \frac{\partial \overline{\mathbf{v}}}{\partial p} + \delta(\mathbf{v}_D - \overline{\mathbf{v}}) + \sigma \left(\frac{1}{\rho} \nabla p^* \right), \quad (1)$$

in which $\mathbf{X}_C$ is the convection-induced acceleration of the large-scale motion, M_C the convective mass flux, δ the mass detrainment, $\overline{\mathbf{v}}$ the horizontal wind vector, $\mathbf{v}_D$ the detrained in-cloud momentum, ∇ the horizontal gradient operator, p^* the convection-induced pressure perturbation, and σ the fractional cloud coverage. In (1), M_C and δ can be estimated using the large-scale heat and moisture budgets along with a cumulus ensemble model as in Yanai et al. (1973) or from a thermodynamic parameterization such as in Arakawa and Schubert (1974). To estimate $\mathbf{v}_D$ and ∇p^*, however, is more challenging since information of subgrid-scale convective organizations is required. A lot of the consecutive efforts were devoted to solving the third term on the $r.h.s.$ of (1) (e.g., Zhang and Cho 1991; Kershaw and Gregory 1997), while only Wu and Yanai (1994) considered anisotropic convective organizations.

Another challenging aspect in the development of CMT parameterization is the lack of observations to verify the parameterization schemes and the results from cloud resolving models frequently used as substitutes for observations. During the Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA COARE) Intensive Observing Period (IOP, November 1992–February 1993), quality sounding data were obtained, which provided an excellent opportunity to study the CMT at a regional scale through the momentum budget residual, $\mathbf{X} = (X, Y)$.

2. ANALYSES AND DATA

The budget residual of the large-scale momentum equation, $\mathbf{X}$, is calculated and interpreted as the acceleration of the grid-scale (large-scale) horizontal wind due to the convergence of subgrid-scale convective and/or eddy momentum fluxes:

$$\mathbf{X} = -\nabla \cdot \overline{\mathbf{v}'\mathbf{v}'} - \frac{\partial \overline{\mathbf{v}'\omega'}}{\partial p}, \quad (2)$$

in which $\omega (= dp/dt)$ is the vertical p-velocity. The over-bar represents the running horizontal average over a large-scale area and the a prime denotes the deviation from such average. The vertical flux of horizontal momentum associated with convection ($\mathbf{F}$) is obtained by integrating $\mathbf{X}$ vertically with surface drag as the lower boundary condition.

The primary data for this study are the upper-air soundings and wind profiler data taken during the TOGA COARE IOP. A 6-hourly, $2.5°$x$2.5°$ objective analysis is produced over $130°$–$180°$ E, $20°$ S–$20°$ N, with a vertical resolution of 25 hPa from 1000 to 100 hPa. Detailed configurations of the objective analysis as well as the computations of $\mathbf{X}$ and $\mathbf{F}$ are documented in Tung and Yanai (2002). The following results and discussions are addressed for observations in the Intensive Flux Array (IFA, $152.5°$–$157.5°$ E, $5°$ S–$0°$).

3. RESULTS and DISCUSSIONS

In Tung and Yanai (2002), it was found that IOP-mean deceleration and downscale kinetic energy (K) transfer occupy a deep tropospheric layer. Also, the average momentum transport is downgradient (i.e., CMT tends to smooth out vertical wind shear) as the product between $\mathbf{F}$ and large-scale vertical wind shear is examined. However, CMT during the IOP is not only highly

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variant in time but also case-dependent.

Fig. 1a shows the relative frequency (in %) of downscale K transfer in the troposphere with $E = -\bar{\mathbf{v}} \cdot \mathbf{X}$. Downscale K transfer ($E > 0$) occurs around $60-65\%$ between surface and 500 hPa, while upscale and downscale K transfers occur with nearly equal frequency in the upper troposphere between 350-200 hPa. The frequency distributions of E in the troposphere shown in Fig. 1b are in general positively skewed, as downscale K transfer occurs more frequently and with more events of larger amplitudes. Distinctly different frequency distributions of E near the surface, middle troposphere, and near the tropopause suggest possible existence of different energy cascading regimes associated with different cloud types. Fig. 1c highlights the frequency distributions at 950, 500, and 150 hPa. It clearly shows that the frequency distribution at 950 hPa is more skewed than that at 500 hPa, while the latter is more concentrated on smaller values. Finally, the frequency distribution at 150 hPa is shown with heavier tails than the others.

Furthermore, the dependence of the directions of CMT on mesoscale convective organizations documented in many previous observations (e.g., LeMone 1983) is found to be detectable at a scale comparable to the grid-size of GCMs. Upscale K transfer is found in the line-normal direction of a linear MCS (squall line). During the westerly wind phase of the two major Madden and Julian oscillation (MJO) events, X and the local time change of $\bar{u}$ are often on the same order of magnitude. It also seems that convection plays dual roles. First, as the westerlies are initiated in the lower troposphere, CMT is upgradient and helps maintain mid-level easterly shear. The upscale K transfer may help trigger the westerly wind burst (WWB). Second, in the later stage with strong lower-to-mid-level westerlies, CMT is mostly downgradient and reduces the mid-level zonal wind shear. The first role appears to be played by shallower convection and the second by very deep convection. Comparisons of the observed CMT with the Wu and Yanai (1994) parameterization are in progress.

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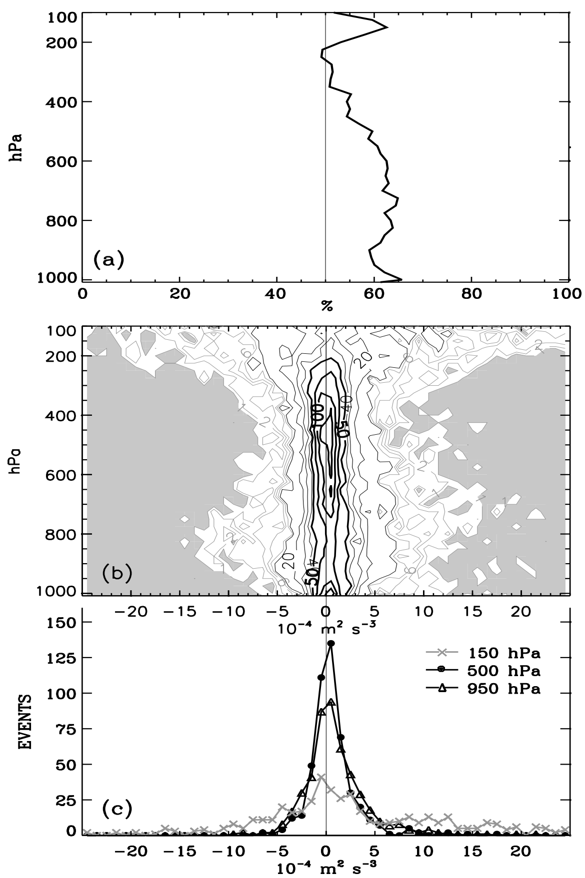

Figure 1. (a) Relative frequency of downscale K transfer ($E > 0$) in the IFA region. (b) Frequency distribution of E (10^{-4} m^{-2} s^{-3}); contour intervals are 25 above the frequency of 50, 10 between 10–50, and 2 between 2–10. The shaded field is 1. (c) Highlights of the frequency distribution in (b) at 950, 500, and 150 hPa.