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Radar Analysis of a Tropical Oceanic Squall Line: Momentum Budgets and Sensitivity of Vertical Structure to Thermodynamic Characteristics in the Environment

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SUMMARY

A momentum analysis of a tropical oceanic squall line system is described using dual-Doppler radar data, as sampled by ship-borne radar platforms during TOGA COARE. The influence of the squall-type Mesoscale Convective System on the surrounding environment is examined through retrieved momentum transports and budget terms. The system evolved over a 2.5 hour period, initially possessing an orientation perpendicular to the low-level (1000-800 mb) wind shear but later developed an orientation parallel to the mid-level shear (800-400 mb). Analysis of the system showed that the squall line evolved in distinct stages during the sampling period: an intensifying period (stage 1); a nearly steady-state period (stage 2); and a dissipating period (stage 3).

The momentum budget terms revealed a complex evolution that was by no means steady state over the duration of the sampling period. In general, the largest momentum fluxes occurred in stage 1 and the smallest in stage 3. The zonal and meridional momentum fluxes were of similar magnitude throughout most of the sampling period, suggesting that the momentum transports were three-dimensional despite the quasi two-dimensional appearance of the squall line. Tendencies in the zonal and meridional winds showed that the MCS produced an overall increase (decrease) in the low-level meridional (zonal) wind shear during the sampling period.

A one-dimensional cloud model is used to examine the sensitivity of cloud vertical structure in the ship-sampled convective system to differences in environmental temperature and moisture profiles. This is accomplished by comparing sounding data collected in the environment of the ship-sampled system with sounding data in the environment of a more intense convective system sampled by aircraft on the same day, but several hundred kilometers away. The model results suggest that, although the ship-sampled MCS had higher CAPE, the presence of a slightly drier layer in the lower troposphere (850-740 mb) likely played a significant role in reducing the intensity of the ship-sampled system relative to the aircraft-sampled system. Composites of momentum transports from both the ship and aircraft systems showed large differences in vertical structure and magnitude, emphasizing the sensitivity of convective system characteristics to small changes in environmental parameters.

KEYWORDS: Radar observations Momentum transports Tropical convection

1. INTRODUCTION

Many previous studies have shown that cumulus convection can have a significant impact on the surrounding environment through momentum transports. Houze (1973) demonstrated that cumulus-scale transports of horizontal momentum were of similar magnitude to the mean meridional flux of angular momentum, at least at certain times, in both mid-latitude and tropical locations. Stevens (1979) found that convective activity produced a significant contribution to the observed synoptic-scale momentum budget of a tropical easterly wave. Similar results were obtained by Sui and Yanai (1986) using a vorticity budget analysis. In the west Pacific warm pool region, Houze et al. (2000) showed that the momentum transports of superconvective systems (defined as precipitating systems with cloud tops colder than -65° C over regions approximately 300 km or more in lateral dimension) provided a positive or negative feedback to the surrounding

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environment depending on the phase of the Kelvin Rossby wave within which the superconvective system was embedded. Modeling studies have also shown that cumulus-scale momentum transports can effect the large scale circulation (Helfand 1979; Mass 1979; Zang and McFarlane 1995) as well as modulate air-sea interaction processes (Trier et al. 1996.)

The cumulus component to the large-scale momentum tendency equation can be written as (Schneider and Lindzen 1976; Kershaw and Gregory 1997):

$$\frac{\partial \overline{V}}{\partial t} = \left(\frac{-1}{\rho} \frac{\partial \rho \overline{u'w'}}{\partial z}, \frac{-1}{\rho} \frac{\partial \rho \overline{v'w'}}{\partial z} \right), \tag{1}$$

where $\overline{V}$ is the large-scale average horizontal wind vector, u',v',w' denote the subgrid-scale (cumulus scale) zonal, meridional, and vertical wind, respectively, and the overbar represents a spatial average. The two terms on the right side of Eq. (1) represent the momentum flux divergence (i.e., the vertical gradient of the momentum flux) in the zonal and meridional directions, respectively.

Large scale numerical models (e.g., GCMs) cannot explicity resolve the effect of deep convection on the large-scale distribution of horizontal momentum. Parameterizations in these models traditionally approximate the convective contribution to the momentum tendency in terms of the cloud vertical mass flux (e.g., Schneider and Lindzen 1976; LeMone and Moncrieff 1994, Kershaw and Gregory 1997; Moncrieff and Klinker 1997). That is,

$$\frac{\partial \overline{V}}{\partial t} = \left(\frac{-1}{\overline{\rho}} \frac{\partial [\overline{\rho} w_c (v_c - \overline{V})]}{\partial z} \right), \tag{2}$$

where v_c is the horizontal wind vector in the cloud, $\overline{V}$ is the mean wind in the model domain, and w_c is the in-cloud vertical air motion. A major assumption in Eq. (2) is that the ascent of air parcels in cumulus clouds is rapid enough, rendering the in-cloud pressure gradient force inconsequential in accelerating the air parcel. As noted by LeMone and Moncrieff (1994), the formulation in Eq. (2) is analogous to mixing length theory and tends to result in a smoothing of the wind profile through the depth of the cloud. Schneider and Lindzen refer to the smoothing effect as “cumulus friction”.

Because of the large impact of mesoscale convective systems (MCSs) on the surrounding environment, many studies have attempted to analyze momentum transports in MCSs (LeMone 1983; Smull and Houze, 1987; LaFore et al. 1988; Gao et al. 1990; Gallus and Johnson 1992; Yang and Houze 1996; Lewis et al. 1998; Trier et al. 1998; LeMone et al. 1998, and others). Results of these studies have generally shown that, in contrast to Eq (2) above, the cloud horizontal wind can be significantly modified by pressure gradient forces and that momentum transports can actually increase the vertical wind shear, at least in the direction perpendicular to the orientation of the convective line in an MCS. LeMone (1983), LeMone et al. (1984), Gao et al. (1990), and LeMone and Moncrieff (1994) found that momentum transports parallel to the convective line orientation may be more consistent with the Schneider and Lindzen (1976) model.

Idealized analytic models (e.g., Moncrieff 1981; 1992) have successfully reproduced some observed characteristics of momentum transports in two-dimensional squall line type MCSs. Specifically, simulations of convection employing these parameterizations have shown a rearward-directed acceleration at mid to upper levels and a forward-directed acceleration at low levels. The combined effect of these flow branches acts to increase the line-normal shear, in accord with observations (LeMone and Moncrieff 1994). However, the idealized models described above are steady-state and two-dimensional. Parameterizations such as Zang and Cho (1991) have attempted to include the cloud pressure gradient effect in a simple cloud model; however, the parameterization required the cloud kinematic structure to be specified.

Other studies have shown that the momentum transports in different sub-regions of an MCS can be different from that of the MCS as a whole (Yang and Houze 1996; Trier et al. 1998) and that idealized two-dimensional models described above may only apply to a certain class of squall lines or portions of an MCS. In a study of the kinematic characteristics associated with precipitating convection during TOGA COARE, Kingsmill and Houze (1999) found that the air flow patterns sampled in west Pacific warm pool precipitating clouds were generally more complex than the idealized model kinematic structure in Moncrieff (1992). Clearly, more studies of the momentum transports and budgets associated with deep convection are needed to compare with numerical model parameterizations. This paper serves as a companion to a study by Petersen et al. 1999 (hereafter referred to P99). We use 2.5 hours of ship-borne dual-Doppler radar analyses to examine the momentum transports and resulting wind flow accelerations associated with a tropical MCS that passed through the TOGA COARE (Tropical Ocean Global Atmosphere Coupled Ocean Response Experiment; Webster and Lukas 1992) Intensive Flux Array (IFA) on 9 February 1993. The dual-Doppler data are examined in order to assess the importance of various terms in the momentum transport and budget equations over an extended time period as well as to interpret the impact of the system on the larger scale.

As an additional component to this study, we use a one-dimensional cloud model to examine differences in the thermodynamic environment that may have led to large differences in vertical structure observed between the squall line sampled by the ship radars and a separate squall line sampled by aircraft (located several hundred kilometers away from the ship dual-Doppler network) several hours later on the same day, despite similar wind shear profiles. Results show that, despite the simplicity of the model, the simulations reproduce the observed differences in cloud vertical structure between the MCSs reasonably well and indicate the role of low-level moisture in producing large changes in storm intensity, consistent with previous modeling (e.g., Lucas et al. 2000) and observational (e.g., Lucas and Zipser 2000) studies from the west Pacific warm pool region. These differences in thermodynamic properties would be expected to influence the resulting momentum transports in each MCS through changes in the cloud vertical mass flux profile (Eq. 1) as well as through feedback of the cloud microphysics (evaporation and melting) on storm evolution. Importantly, the observed differences in convective vertical structure are further shown to produce significant differences in the momentum transport of the two MCSs.

2. Methodology

An overview of ship-borne dual-Doppler operations and synthesis methodology for the 9 February squall line are provided in P99. Herein, we provide an overview of the momentum calculations and one-dimensional model simulations.

(*a*) *Retrieved momentum budgets*

Dual-Doppler syntheses were performed on the ship-sampled MCS (hereafter referred to as the ship-MCS) for approximately 2.5-h (0930-1210 UTC) at 10-min intervals. A storm motion vector (9.0 m s^{-1} from 210°) was also used since isochrone analyses (not shown) indicated that the convective line movement changed little over the 2.5-h analysis period. Each synthesis volume contained, in addition to the squall line of interest, various amounts of isolated convection. For the momentum analysis, only the squall line portion of the domain was used for each dual-Doppler synthesis volume. The discrimination between data within the line and outside the squall line was subjectively determined from inspection of radar reflectivity CAPPI's at an altitude of 2 km. Because dual-Doppler data were not collected from 0952-1002 UTC, data for these time periods were linearly interpolated in order to construct wind field time series.

Inspection of low-level CAPPIs showed that the orientation of the ship-MCS changed during the course of the dual-Doppler sampling period. Initially, the squall line had an orientation that was roughly northwest-southeast (Fig. 1a); however, the line developed an orientation that was approximately zonal after about 1030 UTC (Fig. 1b,c,d - see also P99). In order to facilitate comparisons in successive volumes, the momentum analysis was conducted in zonal U (east-west) and meridional V (north-south) coordinates. The total momentum flux in the U and V directions, ρUV and ρVW, were calculated in a storm relative framework for each radar volume. These terms were then decomposed into mean and perturbation components as follows:

$$\rho\overline{\tilde{U}W} = \rho\overline{\tilde{U}}\,\overline{W} + \rho\overline{\tilde{U}'W'}, \tag{3}$$

$$\rho\overline{\tilde{V}W} = \rho\overline{\tilde{V}}\,\overline{W} + \rho\overline{\tilde{V}'W'}, \tag{4}$$

to better assess the evolution of the momentum fields during the sampling period. The terms on the left of Eqs. 3 and 4 represent the total momentum flux in the zonal and meridional directions, respectively. The first (second) term on the right is the mean (perturbation) contribution and the ˜ represents storm relative wind. Equations 3 and 4 were applied to each of the 15 dual-Doppler synthesis volumes. The U and V momentum budgets were calculated according to:

$$\overline{\frac{\partial \tilde{U}}{\partial t}} = -\overline{\frac{\partial \tilde{U}^2}{\partial x}} - \overline{\frac{\partial \tilde{U}\tilde{V}}{\partial y}} - \frac{1}{\overline{\rho}}\overline{\frac{\partial \rho \tilde{U}W}{\partial z}} - \frac{1}{\overline{\rho}}\overline{\frac{\partial P}{\partial x}}, \tag{5}$$

$$\overline{\frac{\partial \tilde{V}}{\partial t}} = -\overline{\frac{\partial \tilde{V}^2}{\partial y}} - \overline{\frac{\partial \tilde{U}\tilde{V}}{\partial x}} - \frac{1}{\overline{\rho}}\overline{\frac{\partial \rho \tilde{V}W}{\partial z}} - \frac{1}{\overline{\rho}}\overline{\frac{\partial P}{\partial y}}, \tag{6}$$

where the left side of Eqs. (5) and (6) represents the storage (tendency) terms; first and second terms on the right hand side represent horizontal advection; third term on the right side is vertical advection; and fourth term on the right side is the work done by the pressure gradient. The overbars indicate an average over the squall line portion of the dual-Doppler domain.

Similar to LaFore et al. (1988), the technique to solve the budget terms was to:

- compute the horizontal and vertical advection components for each dual-Doppler synthesis volume;
- calculate the tendencies by finite differencing $\tilde{U}$ and $\tilde{V}$ over consecutive dual-Doppler synthesis volumes;
- calculate advection components corresponding to the storage terms by averaging the terms in successive synthesis volumes; and
- determine the work done by the pressure gradient as a residual.

(*b*) *One dimensional model description*

To examine the sensitivity of cloud development in the ship-MCS and aircraft-sampled MCS (hereafter P3-MCS) to vertical distributions of temperature and humidity, which can in turn influence mass and momentum fluxes, simulations using a one dimensional cloud model were performed. Although a more complex two or three dimensional cloud model could have been utilized, the one dimensional model was chosen because of its relatively simple physics, which facilitated interpretation of the results. Moreover, the relatively short run-time of the one dimensional model allowed for numerous sensitivity tests to be performed.

The model dynamics and geometry closely follow that of Ferrier and Houze (1989) and is further described in detail in Petersen (1997). Briefly, the cloud model is formulated in cylindrical coordinates using a variable updraft radius. In general, the geometry and design of the model updraft are based on observations of updraft profiles in tropical convection during field programs such as GATE* (e.g., LeMone and Zipser 1980). The model microphysics includes a bulk representation of four separate classes of ice (cloud ice, snow, graupel, and frozen drops) in addition to water vapor, cloudwater and rainwater. The bulk microphysical scheme as implemented here, is a hybrid mixture of the Lin et al. (1983; LFO) and Rutledge and Hobbs (1983) parameterizations, and is a single-moment version and/or precursor to the "double-moment, 4ICE-scheme" described in Ferrier (1994). In order to simulate the cloud electrification, a model parameterization was also developed to represent the development of electrical charge and in-cloud electric fields (cf Petersen 1997). Electrification provided one additional validation component to the model since observations showed that the P3-MCS was highly electrified while the ship MCS had only slight electrical activity (P99).

(*c*) *Model initialization*

The one-dimensional model simulation required an appropriate specification of inflow sounding and forcing parameters. Here the goal was to compare the differences in thermodynamic characteristics between the ship-MCS and P3-MCS and the role these differences played in controlling the convective development of these two MCSs. The 9 February 06 UTC sounding from the RV Vickers (1.8° S, 155.3° E - co-located with the MIT radar see Fig. 2) was chosen as the basis for the inflow sounding for the ship-MCS simulation. This sounding was slightly modified in two ways to approximate conditions at the time of the squall line's passage over the ship radar domain (3-4 hours after the 06 UTC radiosonde launch); the surface mixed layer temperature was increased approximately 1° C to reflect surface warming prior to squall line passage at the ship site (as noted in both ocean buoy and Vickers ship meteorological data); and pressure levels above 360 mb were replaced with data from the 06 UTC Mona Wave sounding (0° S, 156° E see Fig. 2) to represent advection of a cirrus anvil (moistening) over the Vickers site at the time of the squall line passage. The net effect of these two modifications was to slightly increase the low-level stability and slightly decrease the upper-level stability from the original 9 February 06 Vickers sounding (see Fig. 3a).

For the P3-MCS, a composite sounding at 17 UTC (4° S, 156° E) was used based on a combination of in-situ sampling and dropsonde information below approximately 5 km and extrapolated radiosonde data above this level (LeMone et al., 1998). Analyses of the soundings were performed using the NCAR-SUDS (National Center for Atmospheric Research-System for User-editing and Display of Soundings) program. A comparison of selected environmental characteristics, based on the ship-MCS and P3-MCS soundings, are shown in Table 1.

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[*] GARP Atlantic Tropical Experiment

As discussed in P99, both the ship-MCS and P3-MCS soundings had similar environmental shear characteristics as evidenced by their hodographs (see Fig. 3b). Note that the modified ship-MCS sounding had somewhat higher Convective Available Potential Energy (CAPE) compared to the P3-MCS sounding (Table 1); however, the P3-MCS sounding had essentially no Convective Inhibition (CIN). As demonstrated below, the lack of CIN in the P3-MCS sounding had a significant impact on the resulting intensity of the simulated convection.

In addition to sounding selection, the one-dimensional model simulations required appropriate parameters for gust front forcing (GF) to be specified. Since these parameters (i.e., depth and intensity) could only be approximately observed (radar data suggested depth of gust front was 0.5-1.0 km and ship data recorded the maximum strength of gust front of about 15 kts at the surface), we chose a range of values and tested the model sensitivity using the ship-MCS sounding. Basically, no convection could develop in the simulation using a GF less than 5 m s^{-1} with the ship-MCS sounding.

For GF's greater than 4 m s^{-1}, a range of convective profiles occurred using the ship-MCS sounding; however all simulations using GF's of 5 m s^{-1} and depths between 0.6-1.0 km produced similar features: an approximately 15 km deep, martime-like cloud (radar reflectivities greater than 36 dBZ were confined to heights less than 7 km only snow, ice and small graupel occurred above this height). As discussed in Sec. 3, this structure is consistent with the dual-Doppler observations collected by the ship-borne radars (see also P99). It is likely that the GF in the ship-MCS and P3-MCS cases were somewhat different; however, we chose to utilize a uniform GF (GF of 5.0 m s^{-1} applied over a 0.8 km depth) for both cases in order to simplify comparisons of the 1-D model results for the ship-MCS and P3-MCS cases. Model simulations were run for a period of 3600-s.

3. Results

(*a*) *General description of evolution*

A detailed overview of the ship-MCS evolution during the dual-Doppler sampling period is presented in P99 and will only be briefly discussed here. For the purposes of the momentum analysis, an important characteristic of the ship-MCS was that the convective line orientation was originally northwest-southeast, perpendicular to the 1000-800 mb shear vector (Fig. 1a and Fig. 3b); similar to other COARE convective systems studied by aircraft (LeMone et al. 1998). Within an hour of entering the dual-Doppler domain, the orientation of the ship-MCS shifted to an orientation that was roughly parallel to the mid-level (800-400 mb) shear vector (Fig. 1b,c,d and Fig. 3b). This orientation was preserved for the remainder of the sampling period. Note that the P3-MCS maintained an orientation approximately parallel to the mid-level shear vector (LeMone et al. 1998; P99).

The ship-MCS remained primarily as a line of convection during the observation period although, at later times, a trailing precipitation region did develop (primarily on the western end; see Fig. 1). In order to assess changes in the momentum fluxes at different stages of its evolutionary history, the total sampling period was partitioned into three segments.

Stage 1 (0932-1032 UTC) represented the period prior to the shift in orientation of the line from northwest-southeast to a nearly zonal configuration (Fig. 1a). During this period the system went through relatively large increase in terms of vertical development.

Similar to Leary and Houze (1979), this stage represents the intensification period of the MCS. Stage 2 (1042-1122 UTC) represented the period during which the system remained relatively constant in terms of overall intensity. In Stage 2, the ship-MCS also broadened slightly (Fig. 1b). Stage 3 (1132-1212 UTC) represented the period during which the ship-MCS developed a significant trailing region of decaying echo on the western end of the line and decreased in overall intensity (i.e., dissipating stage as defined by Leary and Houze, 1979; Fig. 1c,d).

(*b*) *Ship-MCS momentum analysis*

(i) *Momentum fluxes*

Time-height cross sections of the average retrieved horizontal $\tilde{U}$ and $\tilde{V}$ winds and vertical air motion W for the squall line portion of the ship-MCS are shown in Fig. 4 (lifecycle stages overlaid). These plots show that the zonal wind was relatively invariant during the sampling period, especially at low levels. Westerly winds were found below 4 km at all times. At upper levels, easterly winds slightly decreased from stage 1 to stage 2 and slightly increased from stage 2 to stage 3. The overall depth of easterly flow generally deepened during the analysis period. In the meridional direction, northerly winds occurred at all heights. At low (upper) levels, the northerly winds decreased (increased) over time. The evolution of the vertical air motion field shows relatively large ascent during stage 1 followed by a significant decrease during stage 2, owing a combination of reduced updraft intensity and an increase in the contribution of downdrafts to the net vertical air motion. This trend continued in stage 3 so that, in the mean, downdrafts were prevalent at low and mid-levels in the late portion of the sampling period.

Figures 5 and 6 show profiles of the zonal and meridional momentum flux, respectively, composited for the different analysis stages as well as for the total sampling period. Comparison of Figs. 5 and 6 shows that the magnitude of the zonal and meridional momentum fluxes were both largest in stage 1 and decreased during the course of the sampling period. In the zonal direction (Fig. 5), the most significant change occurred between stage 1 and stage 2 at low levels (below 4 km) where positive momentum flux was replaced by weak negative flux. This change represented a transition from transport of westerly momentum in updrafts to a predominantly downward transport (Fig. 4). The transition from stage 1 to stage 2 marked the reorientation of the ship-MCS squall line to a more zonal configuration (Fig. 1a,b). However, note that the magnitude of the zonal momentum flux actually decreased in stage 2 at low-levels due to a combination of the increasing contribution from downdrafts to the total vertical air motion field (i.e., net reduction in vertical air motion) and a slight reduction in westerly wind. At upper levels, the reduction in zonal momentum flux was mostly due to the near cancellation of up and downdrafts across the system as opposed to a significant reduction in easterly flow (Fig. 4).

The total zonal momentum flux was dominated by the mean contribution for the majority of the sampling period. The mean represents the pervasive, system-scale transport. The zonal perturbation contribution was largest in stage 1, reflecting the cellular structure of the ship-MCS during this period. The perturbation component weakened in stages 2 and 3 because there was not much momentum flux accomplished by convective deviations from the mean mesoscale line dynamics (recall from Fig. 4 the decrease in updraft intensity after stage 1). The reorientation of the line, then, occurred when the line transitioned to a predominantly mesoscale feature.

In the meridional direction, the magnitude of the low-level momentum fluxes were approximately a factor of two larger than the zonal fluxes in stage 1 but were of the same magnitude in stages 2 and 3. Negative values of meridional momentum flux imply northerly transport by updrafts (or southerly transport by downdrafts). At low levels (below 5 km), the reduction in meridional momentum flux was due to a combination of slightly decreasing northerly flow and a reduction in net vertical air motion during the later stages of the sampling period. Above 5 km, decreasing meridional momentum flux occurred despite increasing northerly flow above the melt level. The trend was due to the significantly weaker vertical air motions in the calculation of momentum flux, which counteracted the slightly larger meridional winds. The systematic decrease in the magnitude of the meridional fluxes through the stages is another indication of the line dissipating, leaving only weak mesoscale circulations by stage 3.

In summary, the momentum fluxes in both the meridional and zonal directions were most intense at early stages due to the relatively large contribution of updrafts. Despite the reorientation of the ship-MCS to a nearly zonal configuration, the momentum fluxes in both directions decreased, primarily due to an overall reduction in net vertical air motion as the contribution from updrafts and downdrafts nearly balanced each other. Thus, both updrafts and downdrafts contributed to the horizontal transport of momentum in the ship-MCS. These observations are in agreement with numerical results from Gao et al. (1990) for a mid-latitude squall line but are different than the numerical results of Kershaw and Gregory (1997) for a tropical MCS. This latter study found that the momentum transports were dominated by updrafts.

(ii) *Momentum budget*

The zonal and meridional momentum budget terms for the different lifecycle stages of the ship-MCS are shown in Figs. 7 and 8, respectively. As expected, the acceleration terms are largest in stage 1 when the system was most intense. The observed $\tilde{U}$ and $\tilde{V}$ tendencies appear to be dominated by the deduced pressure gradient term except at high elevations in the zonal direction and at the lowest elevations in the meridional direction (stages 1 and 2). The transport of low-level westerly flow (positive $\tilde{U}$) to the upper troposphere by the zonal vertical advection reinforced the zonal tendency above about 8 km. The large near-surface values of meridional vertical advection during stages 1 and 2 (Fig. 8) were a consequence of the relatively large meridional shear (Fig. 4). In both directions, the vertical advection term generally decreased after stage 1 due to the reduced vertical gradient in W (Fig. 4).

Similar to Trier et al. (1998) for a different TOGA COARE squall line and Yang and Houze (1996) for a mid-latitude MCS, horizontal advection made the largest contribution at upper levels. In the case of the ship-MCS, the relatively large contribution of horizontal advection to the zonal and meridional budgets was due to divergent outflow from cells on the western end of the ship-MCS (not shown). The tendency of the meridional wind showed an increase in low-level southerly flow that deepened over time above 1 km (Fig. 8). This feature is consistent with the development of mesoscale circulations across the system as described below.

Figure 9a shows the tendency of total $\tilde{U}$ and $\tilde{V}$ over the 2.5-h sampling period based on dual-Doppler wind data. In the zonal direction, the effect of the ship-MCS was to slightly reinforce the near-surface westerly flow that was associated with the passage of the tropical intraseasonal oscillation over the warm pool in February 1993 (Chen et al. 1996; Houze 2001). The low-level westerly accelerations are consistent with numerical simulations from a separate COARE squall line sampled during February 1993 (Trier et al. 1998). The resulting increase in low-level westerlies from the ship-MCS would be expected to enhance air-sea fluxes, in agreement with observations of other oceanic squall lines observed during COARE (Young et al. 1995; Weller and Anderson

1996; Saxen and Rutledge 1998). The largest accelerations across the MCS are in the meridional direction with enhancements of southerlies below 5 km and northerlies above this level. This acceleration pattern effectively wiped out the meridional shear that was present in the 0-6 km layer during stage 1 (Fig. 4) and implies mixing between the lower and upper meridional flow layers. Given that the orientation of the MCS was approximately zonal through the majority of the sampling period, the increase in low (upper)-level southerlies (northerlies) is consistent with the acceleration of rear-to-front (front-to-rear) flow across the squall line. As noted above, inspection of Fig. 8 suggests that the meridional tendencies were driven largely by the pressure gradient term. This feature was presumably associated with the development of hydrostatic low pressure rearward of the leading edge of the squall line (LeMone 1983).

Figure 9b shows the change in the horizontal wind components on 9 February 1993 from gridded sounding data. The gridded sounding winds are an interpolation of all the IFA sounding sites (including the Vickers) between 06 and 12 UTC to 2° S, 155° E. Because of the proximity of the Vickers to this location (see Fig. 2), the gridded sounding data in Fig. 9b is heavily weighted by the Vickers sounding. Despite the differences in technique and temporal sampling, comparison of Fig. 9a and 9b show that the gridded sounding and dual-Doppler wind components display similar trends in the change of the horizontal wind components below about 5 km, indicating that the ship-MCS had a measureable effect on the large-scale wind field. Both data sets show a small increase in westerlies in the lowest layers and an increase in easterlies above about 2.5 km, indicating a reduction of the zonal shear profile. The gridded sounding winds suggest a much larger increase in easterly flow above 2.5 km compared to the dual-Doppler wind data. The plots show an increase in meridional shear (i.e., increasing southerly flow) up to about 2.5 km in the dual-Doppler plot (Fig. 9a) and up to about 4.5 km in the gridded sounding data (Fig. 9b).

Above 5 km, there are many discrepancies in the zonal and meridional wind tendencies between the dual-Doppler and gridded sounding plots. The dual-Doppler data indicates increasing northerlies and easterlies up to 9 km while the gridded sounding data suggests increasing westerlies and a mix of northerlies and southerlies in this height layer. There are a number of possible reasons to expect differences between the sounding and dual-Doppler fields: neglect of coriolis acceleration in Eqs (5) and (6) (LeMone 1983), though this effect should be small in the region of study; large-scale advection not captured in the dual-Doppler analysis; and errors in the dual-Doppler winds due to changes in storm advection as a function of time and height.

(iii) *Cloud model results*

In this section, we examine how differences in the thermodynamic environment may have lead to the large differences in vertical structure observed between the P3-MCS and ship-MCS. In Sec. 3.4, we show how the differences in vertical structure influenced the resulting momentum transports. Although the ship-MCS was sampled within 8 hours and within several hundred kilometers of the P3-MCS, the characteristics of these two convective systems was markedly different (P99). Given that the environmental shear characteristics of the ship and P3 MCSs were similar (Fig. 3b), it is of interest to identify thermodynamic characteristic(s) of the environment that may have played a role in producing the large differences in vertical structure.

A time-height cross section of the model microphysical and precipitation results for the ship-MCS is shown in Fig. 10. Salient features of the model run are summarized in Table 2. Important features of the ship-MCS simulation include: a double peak reflectivity maxima near 2 and 5 km, and a dual rainfall peak associated with warm rain collision coalesence (primary) and melting ice (secondary). Note that the height of radar reflectivity values exceeding about 35 dBZ is restricted to heights below 8 km (Fig. 10). Also, the height of the maximum vertical air motion is in the low to mid troposphere (i.e., near 5 km see Table 2). In terms of electrical characteristics, the one-dimensional model cloud using the ship-MCS sounding does not reach breakdown electric field strengths. These model results are consistent with both radar and electric field mill observations collected on-board the R.V. Vickers (P99; Petersen et al. 1996). Thus, both the model results and dual-Doppler/visual observations suggest that the ship-MCS displayed typical characteristics of oceanic convection: peak reflectivity in the lower troposphere, a sharp gradient of reflectivity above the 0° C level, peak vertical air motions less than about 10 m s^{-1}, and little electrical activity.

The model simulation results using the P3-MCS sounding are shown in Fig. 11 and summarized in Table 2. Although the echo top height is only slightly higher compared to the ship-MCS simulation, the model, in the P3-MCS case, produces a much more intense cloud with reflectivities of 36 dBZ extending to near 12 km, peak rain rates in excess of 75 mm hr^{-1}, and significant graupel-frozen drop concentrations above the 0° C level (Fig. 11). Figure 11 also indicates larger rain rates associated with mixed phase precipitation in the P3-MCS simulation compared to the ship-MCS. The results in Table 2 show that the peak vertical air motion of the P3-MCS is in the upper troposphere, above 11 km. These results are consistent with the dual-Doppler observations of the P3-MCS (Fig. 14 of P99). The model run using the P3-MCS sounding reached breakdown electric field strength at approximately 23 minutes into the simulation (about 17 minutes after the first echo appears) during the rapid intensification phase of the storm (Fig. 11). The simulated electrical activity is consistent with visual lightning observations from the NOAA-P3 aircraft (Smull et al. 1994). In this case, both the model simulation and observations suggest that the P3-MCS was much more intense than the ship-MCS, as evidenced by the reflectivity structures, microphysical distributions, and lightning activity.

Although other effects cannot be ruled out (e.g., gust front forcing), the model results suggest that differences in the environment thermodynamic characteristics may have played a significant role in the differences in vertical structure between the ship and P3 MCSs. In order to determine which thermodynamic layer(s) were important in producing the observed differences in vertical intensity, successive layers of the P3-MCS sounding were merged into the ship-MCS sounding. In particular, two layers in the lower troposphere were considered, where differences in the soundings could be expected to have the largest impact on cloud development:

- the surface to about 860 mb (VAR1) where the P3-MCS sounding was slightly cooler;
- the 900-740 mb layer (VAR2) where the P3-MCS was slightly more moist compared to the ship-MCS; and
- a combination of the surface to 740 mb layer (VAR3), where the largest differences occurred between the ship and P3 MCS soundings* (see Fig. 3a).

Selected results of the ship-MCS simulations with the inserted P3-MCS sounding layers are shown in Table 2. The results indicate that the VAR2 simulation (pasted P3-MCS 900-740 mb layer) had the most pronounced influence on the original ship-MCS sounding in terms of increasing the overall intensity of the simulated cloud. Although the VAR1 simulation (pasted P3-MCS surface-860 mb) did slightly increase the magnitude of peak

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* Insertion of the pasted layer(s) in the ship-MCS sounding required some smoothing (linear interpolation) of the temperature profile between the pasted layer and the original ship-MCS sounding in order to eliminate anomalous lapse rates in the sounding profile.

vertical air motion, radar reflectivity, and hydrometeor mixing ratios, this effect was much larger for VAR2. Moreover, VAR2 shifted the location of peak vertical air motion into the upper troposphere, in agreement with the observations.

Thus, the model results suggest that a slightly drier layer in the lower troposphere of the ship-MCS environment was primarily responsible for producing convection with reduced overall intensity relative to the P3-MCS. These results are in agreement with previous modeling and observational investigations of TOGA COARE MCSs showing that the low-level moisture field can have a significant impact on the resulting MCS characteristics (Lucas et al. 2000; Lucas and Zipser 2000). Figure 12 shows plots of virtual temperature excess for the ship-MCS and P3-MCS soundings normalized with respect to the peak values in each trace. The plots illustrate the combined effect of the near-surface warm layer and the dry layer between 900-740 mb in reducing the thermal buoyancy of air parcels in the ship-MCS sounding. The fact that the ship-MCS was not as intense as the P3-MCS may have been due to entrainment of drier air into the ship-MCS updrafts, which would be expected to reduce updraft buoyancy in the ship-MCS case compared to the P3-MCS (Lucas et al. 2000).

Note that when the combined P3-MCS surface-740 mb layer is inserted onto the ship-MCS sounding (simulation VAR3 in Table 2), the overall intensity of the simulated cloud is slightly more intense than the original P3-MCS simulation in terms of kinematic and microphysical characteristics. The reason is due to the fact that the ship-MCS sounding is slightly more unstable than the P3-MCS sounding above 360 mb (see Fig. 3a). However, the overall features of the P3-MCS simulation are well represented by the VAR3 model run, indicating that the two layers representing the surface-740 mb layer capture the bulk of the convective intensity differences between the ship and P3 MCSs. The results of the model simulations emphasize the potential impact of small changes in the environmental thermodynamic characteristics on cloud vertical structure. In turn, cloud vertical structure should also influence the vertical structure of momentum transport. In the next section, we demonstrate how the differences in thermodynamic structure are manifested through changes in the MCS momentum transports.

(*c*) *Comparison of ship-MCS and P3-MCS momentum transports*

The zonal and meridional momentum transports of the P3-MCS are shown in Fig. 13. The P3-MCS momentum fluxes were generated using 6 volumes of NOAA P-3 multiple-Doppler analyses collected over a roughly 50 minute time period. The P3-MCS plots can be compared to the corresponding ship-MCS plots in Figs. 5 and 6, although as noted in P99, caution is advised in quantitative comparisons due to the different radar sampling strategies, retrieval techniques, and life cycle characteristics of the individual MCSs. Inspection of these plots reveals that the ship-MCS and P3-MCS momentum fluxes display several similar features and some key differences.

For example, comparing the P3-MCS profiles in Fig. 13 with the total sampling period of the ship-MCS in Figs. 5d and 6d, it is apparent that the total momentum flux (zonal and meridional) is dominated by the mean contribution for both cases. Moreover, the zonal (meridional) perturbation momentum flux is in opposition to (same direction as) the mean contribution through the depth of the profile for both systems. Finally, both the P-3 and ship-MCS plots show that the total zonal momentum flux peak occurs in the upper troposphere.

Comparison of these same plots also show two important differences in the momentum transports of the ship and P3-MCSs. First, the total zonal and meridional momentum fluxes of the P3-MCS are at least a factor of two larger compared to the ship-MCS totals (Figs. 5d and 6d). In fact, this difference occurs when comparing the P3-MCS results to any of the ship-MCS sampling stage plots shown in Figs. 5 and 6. Also, note that the peak meridional total momentum flux in the ship MCS occurs near 1-2 kms compared to roughly 7.5 km in the P3-MCS. These results are consistent with differences in the updraft profiles as observed (P99) and modeled (Table 2) for the two MCSs. Thus, there is a large offset in the location of peak meridional momentum flux for the two MCSs as well as large differences in the magnitude of the meridional and zonal momentum fluxes which correspond to observed differences in MCS vertical structure. These differences in momentum transports between the ship and P3 MCSs would be expected to result in differences in the feedback of the convective to the surrounding environment through Eq. (1).

4. CONCLUSIONS

In this study, the momentum fluxes and budgets of a tropical oceanic squall line over a 2.5-hr period are analyzed using ship-based dual-Doppler radar data. The squall line, which occurred in the west Pacific warm pool region, was oriented perpendicular to the low-level shear at early stages but later shifted to an approximate zonal orientation, parallel to the mid-level shear. In terms of momentum fluxes, both the zonal and meridional components generally decreased in magnitude throughout the sampling period, mostly as a consequence of reduced updraft strength and increasing contribution of downdrafts to the net vertical air motion (as opposed to significant changes in the horizontal wind). Thus, both up- and downdrafts played an important role in the momentum fluxes of this MCS. Early in the sampling period, the low-level meridional fluxes were approximately a factor of two larger than the zonal fluxes. However for most of the sampling period, the profiles of zonal and meridional fluxes were of the same order of magnitude. Therefore, in terms of momentum fluxes, the squall line could not be viewed as two-dimensional or steady state.

An analysis of the zonal and meridional momentum budgets showed that the vertical advection term was generally weak throughout the sampling period, consistent with the weak vertical air motions. Horizontal advection was significant at upper levels, primarily as a consequence of divergent outflow from more intense convection on the western end of the squall line. The deduced pressure gradient term in the momentum budgets was mostly positive in the zonal direction; however, a negative pressure gradient perturbation, which deepened over time, was deduced in the meridional direction. This feature may have been associated with hydrostatically-induced low pressure rearward of the leading edge of the squall line. Moreover, a near-surface positive gradient perturbation in the meridional direction was consistent with surface pressure observations during the squall line passage.

Results from a one-dimensional model using the environmental soundings from the ship-MCS and another aircraft sampled MCS (P3-MCS) were consistent with the radar and lightning observed differences in vertical structure of these convective systems. As described in a previous study (P99), radar and lightning observations indicated that the P3-MCS was much more intense compared to the ship-MCS, despite the fact they were sampled on the same day within several hundred kilometers of each other. Furthermore, both systems occurred in environments with similar wind shear profiles. The model simulations indicated that a slightly drier layer between 900-740 mb in the ship-MCS environment and subsequent entrainment of drier air in the ship-MCS updraft cores was likely responsible for producing the large differences in observed vertical structure.

A comparison of radar data from each MCS further indicated that these differences in vertical structure impacted the resulting momentum transports, emphasizing that small changes in the environment can have a large impact on the resulting MCS characteristics, in agreement with previous observations and modeling studies of precipitating convection in the west Pacific warm pool. These results suggest that the P3 and ship MCSs would have different effects on the large-scale environment through their respective momentum transports.

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TABLE 1. Comparison of thermodynamic and shear characteristics of the ship-MCS and P3-MCS soundings.

Sounding	CAPE (Jkg^{-1})	CIN (Jkg^{-1})	LCL (mb)	LFC (mb)	NSMR* ($gmkg^{-1}$)	1000-800 mb shear (°) (ms^{-1})	800-400 mb shear (°) (ms^{-1})	0-6 km shear (°)
Ship-MCS	2308	9	938	898	18.6	240 9.0	101 16.5	3.9
P3-MCS	1789	0	945	939	18.5	220 6.7	81 16.5	3.8

*Near Surface Mixing Ratio

TABLE 2. One dimensional model cloud characteristics for the simulations using the ship-MCS and P3-MCS soundings.

Model run	zt (km)	wmx (ms^{-1})	wmxht (km)	wmn (ms^{-1})	wmnht (km)	dmx (dBZ)	dmxht (km)	rmx $(mmhr^{-1})$	qtmx $(gmkg^{-1})$	qwmx $(gmkg^{-1})$	qrmx $(gmkg^{-1})$	susp (kg)	rain (kg)
Ship-MCS	14.5	10.4	5.4	-3.1	0.6	49.3	5.1	36.7	4.1	2.5	3.0	0.66x10^{6}	0.12x10^{8}
VAR1	14.1	12.0	6.8	-3.3	3.8	51.8	5.1	59.3	5.1	2.6	3.8	0.91x10^{6}	0.24x10^{8}
VAR2	16.5	17.5	11.2	-4.2	3.2	52.8	5.1	57.5	5.6	2.7	4.4	0.24x10^{7}	0.21x10^{8}
VAR3	16.6	18.1	12.8	-4.2	3.2	53.1	5.1	77.1	5.9	2.6	4.8	0.27x10^{7}	0.53x10^{8}
P3-MCS	15.8	15.3	11.6	-3.6	3.4	52.0	1.5	74.9	5.2	2.6	4.6	0.24x10^{7}	0.31x10^{8}

All simulations were performed using a gust front forcing of 5 m s^{-1} applied over a depth of 0.8 km.
VAR1: ship-MCS simulation with P3-MCS surface-860 mb layer inserted
VAR2: ship-MCS simulation with P3-MCS 900-740 mb layer inserted
VAR3: ship-MCS simulation with P3-MCS surface-740 mb layer inserted
zt: maximum echo-top height (km) based on a mixing ratio of 1 gm kg^{-1}
wmx: maximum updraft velocity (m s^{-1})
wmxht: height of maximum updraft (km) wmn: minimum downdraft velocity (m s^{-1}) below the 0° C level
wmnht: height of maximum downdraft (km)
dmx: maximum radar reflectivity (dBZ)
dmxht: height of maximum reflectivity (km)
rmx: maximum surface rain rate (mm hr^{-1})
qtmx: maximum total hydrometeor mixing ratio condensate (gm kg^{-1})
qwmx: maximum cloud water mixing ratio (gm kg^{-1})
qrmx: maximum rain water mixing ratio (gm kg^{-1})
susp: total mass of hydrometeor condensate left in suspension at the endo of model run (kg)
rain: total mass of accumulated surface precipitation (kg)