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HIGH RESOLUTION PROPERTIES OF THE EQUATORIAL PACIFIC MARINE ATMOSPHERIC BOUNDARY LAYER FROM LIDAR AND RADIOSONDE OBSERVATIONS

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1. INTRODUCTION

Water vapor and relative aerosol concentration were measured with two shipboard lidars from the ocean surface to tropospheric and lower stratospheric altitudes in support of the Central Equatorial Pacific Experiment (CEPEX) program, (Kuettner, 1993). The goal of CEPEX is to evaluate the "thermostat" hypothesis regarding feedback mechanisms between the tropical ocean and the atmosphere, (Ramanathan and Collins, 1991). This paper describes some of the features observed within the first two kilometers of the equatorial troposphere, known as the marine Atmospheric Boundary Layer (ABL), as well as the coupling between the ocean and the atmosphere.

From the Research Vessel (R.V.) Vickers, data were collected continuously over the equatorial Pacific from March 10th to March 21st, 1993. The route, at approximately 2° south latitude between Guadalcanal and Christmas Island, created a measurement transect between the warm pool of the eastern tropical ocean and cooler waters at more westerly longitudes. The opportunity to sample the atmosphere inside and outside the warm pool gives us the ability to evaluate the relationships between the ocean and the lower troposphere as functions of both sea surface temperature (SST) and longitude.

The Raman lidar collected vertical water-vapor concentration profiles up to 10 km during night and up to 4 km in the day, with an accuracy better than ± 0.25 g/kg. The elastic backscatter lidar collected relative vertical aerosol concentration profiles during both day and night to a height of 20 km. Its main function was to determine the height and thickness of clouds.

Sequential vertical lidar profiles (made as the ship progressed) were processed into 2-dimensional "images" of water vapor or aerosol concentration as a function of time. The high resolution lidar data illuminated the subtle relationship between mass and energy exchange and ocean-atmosphere coupling mechanisms, which were evaluated from shipboard measurements of SST and lidar estimates of the mixing layer inversion zone (MLIZ) height.

This paper will present the initial analysis of the structure of the atmospheric boundary layer. Finally, we will look at the implications of this structure for ocean-atmosphere coupling by comparing the height of the mixing layer with sea surface temperatures and other factors.

2. STRUCTURE OF THE MARINE ABL

The lower troposphere is divided into two primary regions; the free atmosphere (FA) and the ABL. The marine ABL is composed of several sub-layers including a surface layer (SL), a mixing layer (ML), an entrainment zone (EZ), and the interface between the surface-dominated atmosphere and the free atmosphere above it. This section will describe how these and other layers were identified, isolated, and used to understand the role of the lower troposphere in ocean-atmosphere interactions.

2.1 ABL Structure

Raman water-vapor lidar data and coincident radiosonde profiles were used to identify the structure of the marine ABL using changes in water vapor concentration with altitude. A typical vertical water-vapor concentration profile from lidar and coincident radiosonde data appears in Figure 1A. The figure shows a lidar profile (averaged vertically to 49.5 m) as asterisks and coincident radiosonde data as open circles. Also shown in the figure are the boundary layers locations interpreted from the profiles. Figure 1B shows the same lidar data, but with 3 m averages instead of 49.5 m (as asterisks), and the bulk Richardson (R_b) analysis profile as dots connected by a dashed line.

FIGURE 1A. Comparison of lidar (*) and radiosonde (o) water-vapor profiles from March 13, 2330 GMT, 1B. Lidar and Bulk Richardson (---) profiles from the same data as 'A'.

The ABL was divided into several sub-layers: the SL, ML, ML Inversion Zone (MLIZ), and the EZ. These layers were identified in the Lidar data by well defined changes in the slope of water-vapor concentration versus height (Figure

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1). The SL begins at the sea surface as a shallow layer less than 100 m thick with near saturated water vapor conditions of 18-20 g/kg that linearly decrease in concentration to 15 or 16 g/kg at 75 m. Directly above this layer, the humidity varies little with height when observed from time-averaged measurements, indicating the transition from the SL to the ML. Between 75 m and approximately 550 m, a convective boundary layer of well-mixed conditions is evident from the near-vertical slope in the ensemble lidar profiles (Figure 1).

The constant vertical distribution of water vapor shown in Figure 1 is the result of measurements made over periods longer than the convective overturning. An interfacial region caps the ML as an inversion zone (MLIZ), thus inhibiting the free exchange of mass and energy with the atmosphere above, Deardorff, (1980). Many investigators such as Lenschow and Stephens, (1980) and Greenhut and Khalsa, (1982) have observed that a thin entrainment region lies between the FA and the marine ML. However, from the measured changes in water vapor concentration with height we found that a deep entrainment zone 700 m thick, lies on top of the ML which appears more closely associated to the structure described by Carson, (1973).

The bulk Richardson number (R_b) was used to substantiate the vertical location of sub-boundary layers within the marine ABL from estimates of the local diabatic condition. Radiosonde data collected simultaneously with the lidar data was used to compute vertical profiles of R_b every 49.5 m using the formula due to Brutsaert, (1984). Boundary layers were identified when a change in slope of the R_b profile was associated with a coincident change in the average water-vapor concentration.

The R_b analysis confirms the location of the SL/ML boundary at 75 m, because the R_b values changed from convective (-5), to near-neutral, in accordance with a change in slope in water-vapor concentration (Figure 1B). The R_b profile remained near-neutral up to 400 m, and then it went to a more stable condition. In contrast, the lidar water vapor profile remained vertical from 75 m to 550 m (Figure 1B). Most likely, the radiosonde traversed a inter-plume region (downdraft) of low water-vapor concentration which produced a more stable boundary condition at a lower altitude (Figures 1A,B). The 250 m deep inversion zone is characterized by a steady decrease in water vapor concentration forming a stable atmosphere where convective growth is capped. Between 800 m and 1500 m the stability increased, further reducing the water-vapor concentration to about 50% (8 g/kg) of the surface value (Figure 1A,B). We interpreted the two profiles in this region to be the EZ where ABL moisture interacts with the FA, and is no longer dominated by surface processes. At 1500 m, the interface between the ABL and FA is reached.

2.2 Further Spatial Structure of Plumes

During the data acquisition period for Figure 1, the ship's speed was decreasing in preparation for a radiosonde launch. Between 800 and 1600 s the ship was moving under 0.4 m/s, creating an opportunity to evaluate some of the spatial properties of ABL structures. Using the recorded ship

speed to deconvolve the time-of-acquisition from distance-sailed, spatial information such as plume width was estimated from the observed coherent structures in the data.

The capping inversion at the top of the ML has been used by many investigators as a scaling parameter to describe ABL properties. Both Lenschow and Stephens, (1980) and Greenhut and Khalsa, (1982) scaled their plume width results to z_i , where z_i is the top of the Mixing Layer. In this study we used an average inversion-center height as z_i . In Greenhut and Khalsa, (1982) the typical plume widths were 120 m at a ML height of 950 m; from a distribution of several plumes, they developed an average event size relationship as $d_{av} = \pm 0.124 z_i$. Using this relationship and a z_i of 650 m, the modeled event size is 80.6 m, which is in good agreement with the 75 m width of the actual measured event.

2.3 Distribution of Water Vapor in the ABL

The statistical properties of the atmosphere above and below the ML were evaluated using a similar approach to that of Crum and Stull, (1987). Histograms were generated from the distribution of water-vapor within 0.2 z/z_i sections, approximately 130 m thick, at several locations within and above the ML. Histograms of the water-vapor within the ML at z/z_i between 0.1 to 0.7 show single-mode distributions at 15.5 g/kg, with relatively small variations of less than 1 g/kg, as shown in Figure 3C,D. In contrast, within the inversion region between 0.9 and 1.1 z/z_i the water-vapor variation is substantially wider (3.5 g/kg), possibly multi-modal, and show decreased absolute concentrations than the lower regions (Figure 3B). Above the ML, at 1.4 to 1.6 z/z_i , the water vapor concentration and variation dropped to approximately 12 g/kg and 3 g/kg, respectively, and is single-mode, as shown in Figure 3A. These histograms indicate that the time-averaged atmospheric concentrations in the ML are well mixed and uniform. Within the inversion, drier air from the EZ begins to mix with moist air within the ML, generating wide distributions of varied concentrations that comprise both ML and EZ properties. The higher altitude histograms show that the atmosphere above the inversion bears little resemblance to the properties of the ML.

FIGURE 2A,B,C,D Histograms of water vapor distribution from cross-sections within and above the ML.

3. ABL AND SST OCEAN-ATMOSPHERE COUPLING

A primary objective of this experiment is to determine how ocean and atmospheric transport processes are directly coupled through convection. Recent work on synoptic mechanisms for coupling water-vapor transport between the ocean and the atmosphere indicates that SST is a critical driver, Betts and Ridgway (1988), Stephens, (1990). Our study compares SST with the observable atmospheric parameter, Mixing Layer Inversion Zone (MLIZ) height. Our hypothesis is that changes in SST would affect surface driven convection, which in turn would be expressed in the height of the MLIZ. Fitzjarrald and Garstang, (1981) drew a similar conclusion from their analysis of GATE data. Our comparison of SST and the height of the MLIZ also showed an apparent correlation between the two.

3.1 The SST-MLIZ Relationship

SST and MLIZ height were estimated almost continuously aboard the R.V. Vickers as it sailed along its track. Every five minutes, a calibrated resistance temperature device with an accuracy of $\pm 0.1^\circ\text{C}$ recorded the SST from an intake manifold mounted near the bow of the ship. The MLIZ height was estimated from the available water-vapor Raman lidar data at the midpoint of the sigmoid curve that defines the MLIZ. The analysis used MLIZ height estimates from each day between March 10 and March 20. The MLIZ heights were plotted against SST, and a regression analysis was performed on the data as shown in Figure 3. Along with the MLIZ heights versus SST (open circles), suspect data points (asterisks), the best-fit line (dotted), 95% confidence intervals (dashed), and the mean (solid line) were also plotted in the figure. The least squares regression slope is -84 m per degree , the standard error is 49 m per degree , and the r^2 is 0.58 . This analysis shows that the regression relationship represents a weak, but statistically significant trend. Even though the r^2 is small, the fitted line and associated 95% confidence limits do not encompass the mean population line, and the standard error is smaller than the slope. If the population mean (a constant with no slope) were within the regression confidence limits, then the trend would be indistinguishable from the mean. Thus this plot shows that, as SST increased, MLIZ height decreased. Re-analysis of measurements made by Freije et al., (1991) over a 2 degree step-change in SST, showed a similar change in ML height of -56 m per degree . Betts and Ridgway, (1989) showed, in their coupled ocean-atmosphere model, that the cloud-base height (synonymous with the top of the convective mixing layer) decreases with SST by -21 m per degree . They felt that this behavior was not fully understood, and required more study. In addition, another modeling study performed by Albrecht, (1984) shows that, at low to moderate SST (23 to 28°C), the inversion height (as characterized by water vapor mixing ratio) remains constant as SST increases. These modeling studies support the contention that the MLIZ does not have to rise with the source term—SST, over the ocean.

FIGURE 3 MLIZ and SST regression relationship from lidar data acquired between March 10 to March 20, 1993. The open circles represent the MLIZ height at a given SST.

Both the lidar measurements presented here and the results from earlier studies are, at first glance, counter-intuitive. It is commonly thought that as the source temperature term increases, the subsequent convection increases, and the height of the MLIZ should rise, as described in Stull, (1988). The proportional relationship of MLIZ height with convection is certainly true over land however, over the ocean, with a nearly unlimited source of water, this does not necessarily have to follow. We propose two hypotheses to explain these observations; one that incorporates a feedback mechanism, and the other that invokes a simple, but indirect process. There is the possibility that convective transport of surface moisture aloft would create an atmosphere optically thicker to shortwave radiation within and above the ABL, allowing more radiation to be reflected or re-radiated upward, cooling the ABL, thus potentially reducing the MLIZ height, (Schubert 1976, Waliser and Graham, 1993). An alternative hypothesis is that the added water-vapor at higher SST allows condensation to occur at a lower Lifting Condensation Level (LCL), reducing the associated MLIZ height. A decreasing LCL with increasing SST should show a trend towards higher moisture (at constant altitude). Observations at 900 kPa show that a 1°C step change in SST resulted in a 1 g/kg change in water vapor concentration, giving credence to the LCL hypothesis. In either scenario, the CEPEX lidar and ship-borne observations indicate that the ocean-atmosphere system is intimately coupled within the ABL.

3.2 Effect of Local Storm Systems

In Figure 3 several suspect points (denoted by asterisks) were not included in the regression analysis, and are located far outside the least-square-fit line. These points are possibly associated with deep convection events giving rise to high altitude clouds which were observed by the elastic lidar. In Figure 4, the points "B" and "D" are above and below the trend line respectively, and Figure 4 shows that these points were-acquired when high altitude clouds were present. The

four plots in Figure 4 show the data from the miniature elastic lidar as relative-backscatter-intensity return-signals (solid lines) as a function of height from two days at four periods. Clouds are identified by enhanced returns, such as in plot B, between 11.5 km and 16 km. Point A in Figure 4 was acquired under clear-sky conditions 90 minutes before point B (Figure 4). The typical sub-visible cirrus clouds observed by the elastic lidar are relatively sparse, less than a few hundred meters in thickness, in contrast to the massive cloud systems shown in Figure 4. Thus, the ship sailed in 90 minutes from clear sky conditions (A) to a high cloud region (B), which was probably formed by meso-scale weather and possibly by deep convection. Synoptic and regional weather analysis indicate that at this time, scattered localized deep convective systems were observed by satellite (Williams, 1993). The SST-MLIZ height relationship that was found associated with the suspect localized deep convection occurred between 27.5 and 28°C, which is in agreement with the empirical findings of Graham and Barnett, (1987). As with points A and C in Figures 3 and 4, deep convection was found to induce both depressed and elevated ML heights by Gaynor and Ropelewski, (1979) and Johnson, (1981). Zhang, (1993) found that the relationship between deep convection and SST was highly variable, and proposed that ABL convective circulation patterns might be responsible for the variability. Most of the points in Figure 3 that lie within the regression limits are from clear sky periods, but those points that reside within the regression limits being produced under partially cloudy conditions are associated with major synoptic weather patterns as identified in Williams, (1994).

FIGURE 4A,B,C,D Elastic backscatter normalized return signals from selected periods showing clear-sky conditions (A,C) and high cloud conditions (B,D).

3.3 Other Effects

The effects of measurement location, winds, and time-of-day were also evaluated to determine if there were additional factors obscuring or amplifying the MLIZ-SST relationship. Greenhut and Bean, (1981) noted that tropical convergence or subsidence zones were related to longitudinal variations in the MLIZ height, independent of SST. Tropical synoptic downwelling from major circulation patterns could

compress the boundary layer. Variations in MLIZ height with SST and winds were evaluated as functions of longitude to test whether equatorial downwelling is a major component of the observed SST-MLIZ relationship. The period between days 79 and 81 (144°W and 152°W) of CEPEX in Figure 5A shows that there was a long period of longitudinal change without significant SST change. The MLIZ height data that corresponds to this period shows a similar lack of change suggesting little or no longitudinal effect (Figure 5B). Figure 5A also shows two instances when the SST as a function of longitude shows "ramp" patterns, as SST rise to about 29°C and then fall off to 27.5°C or 28°C. The first ramp is from 176E to 168W and the second ramp is from 168W to 159W. These fortuitous circumstances were used to evaluate the MLIZ-SST relationship by separating the data into two spatially distributed populations that have similar ranges of SST; from 27.5 to 29 °C. The slopes of the regressions between MLIZ and SST from the ramp groups should have similar slopes as the SST-MLIZ relationship of the entire data set shown in Figure 3. In other words, if the relationship were valid, then regardless of where or when the data were taken, the MLIZ height should depend solely on SST and not on longitude. The change in MLIZ heights that correspond to the SST ramps in Figure 5A are shown in Figure 5B. The MLIZ-SST slope from the entire data set is -84 m per degree, and the slopes from the first and second ramps are -79 m per degree and -65 m per degree, respectively.

FIGURE 5A,B SST (A) and MLIZ (B) data as a function of longitude during CEPEX showing the SST ramps and their affect on MLIZ height.

Coupled ocean-atmosphere models suggest that wind might play an important role in ML properties (Betts and Ridgeway, 1983). Winds clearly play a significant role in the development and transport of turbulent fluxes, although, it is not clear that there is any direct correlation to scalars or boundary layer height, (Bradley et al., 1993). A regression analysis of MLIZ height as a function of wind speed indicated no trend because the mean and best-fit were within the 95% confidence limits, suggesting that wind has little effect on MLIZ height during CEPEX.

The affect of the diurnal cycle in MLIZ height was investigated as it relates SST. The variations in the MLIZ

height and SST were compiled over the course of a 24 hour period on day 73 and plotted in Figure 6A (MLIZ versus time), and 6B (SST versus time), respectively. The least-squares regression analysis shows that, while the MLIZ height or SST does vary with time-of-day to produce a non-zero slope, the regression line is statistically inconclusive, and one can conclude that diurnal processes are not responsible for the SST-MLIZ relationship (Figure 6).

FIGURE 6A,B. Diurnal trends in MLIZ (A), and SST (B) as a function of time-of-day between days 72 and 73.

The micro-scale behavior of some ABL structures was found to be counter-intuitive; as the sea surface increased in temperature, the height of the mixing layer inversion zone decreased. The hypothesis put forward to describe this observation invokes a more complex relationship than a simple surface-atmosphere system reacting to radiative forcings. Alternative explanations, such as synoptic subsidence from tropical circulations, winds, or diurnal cycle, were not found to be satisfactory. Furthermore, traditional measurement techniques alone from instruments such as radiosondes, are insensitive to the subtle behavior of these surface-atmosphere interactions.

4. SUMMARY AND CONCLUSIONS

Two lidars, a Raman water-vapor, and elastic backscatter, were used during CEPEX to measure and characterize the marine ABL and lower troposphere. The backscatter lidar measured aerosols, primarily the height and thickness of cloud layers, showing the presence of thin sub-visible cirrus layers. The Raman lidar made nearly continuous measurements of water vapor from the surface to 4 km during the day and 10 km at night. Agreement between simultaneous radiosonde and lidar water-vapor data (both taken from the ship) is good to an altitude of several kilometers, typically within ± 0.25 g/kg. Maximum water vapor values observed were 18-20 g/kg.

Plots of sequential, vertical lidar scans as the ship progressed show alternating dry and moist regions. Because convection is the dominant mechanism for water-vapor transport, we interpret these regions to be those of

well-defined moist convective upwelling plumes and dry downwellings with heights between 600 m to 700 m and widths between 50 m and 100 m. The measured characteristics of these coherent plumes agree well with previous investigations of Tropical Pacific ABL convection.

Small disagreement between the lidar and radiosonde data is observed in three regions. First, disagreement at sharp boundaries is probably due to the relatively low resolution of the radiosonde humidity sensors (time-constants being typically between 30 s and 120 s) compared with the Lidar's 3-10 s response. Thus, radiosonde measurements tend to be spatially and temporally smoothed, rather than representative of the local environment sampled by the lidar. Second, in the far field, disagreement comes from the fact that radiosondes can take up to several hours to reach altitude (of order 10 km), during which time they may have experienced horizontal drift, and changing atmospheric conditions from those measured by the lidar. Third, disagreement at the top of the mixing layer is partially due to the horizontal location of the radiosonde rising through it. The lidar data has shown that the top of the mixing layer is made up of spatially coherent, horizontally-alternating moist and dry regions. The radiosonde, passing through the top of this layer must find itself in either a dryer (balloon rose between plumes) or wetter (balloon rose within a plume) region than the lidar multi-scan averaged value.

This analysis showed that boundary layer discontinuities caused by low-frequency intermittent events, such as plumes, have an impact upon the interpretation of ocean-atmosphere interactions that are not observed by more traditional instruments such as radiosondes.

The nature of the coupling between the ocean and the atmosphere was investigated through a comparison of observed SST and mixing layer inversion zone (MLIZ) height. One might expect, as the SST increased, so would the height of the MLIZ. Instead, a counter-intuitive relationship was found—as SST increased, the MLIZ decreased over a SST range of 27-30°C independent of longitude. While true for calm conditions, this relationship is undercut by nearby, deep convective storm events that seem to replace statistically varying local convective elements (cells) with large meso- or synoptic-scale organized systems. Thus, to see the relationship, care must be taken to exclude observations of the MLIZ height when such large scale disturbances are nearby. Also, observations in other regions of the ocean at different temperatures apparently do not show this result. Evidently, this effect, if true, is confined to a narrow range SSTs under tropical ocean conditions. More observations are needed, as well as careful study with boundary layer models. In any event, delineating the energy conditions necessary for such an effect could have some bearing on the CEPEX goal of understanding the relation of the boundary layer to the thermostat hypothesis.

Mass and energy exchange between ocean and atmosphere was found to be primarily from low-frequency, intermittent, convective plumes. The micro-scale effects of moist plumes, dry downwellings, etc., in the mixing layer should be accounted for in estimation of fluxes. It may turn out that fluxes increase with SST even when the MLIZ is

dropping. One possible reason for this is that, when conditions cause the height of the MLIZ to drop, the resultant smaller working volume requires less buoyancy to transport water vapor to the top of the convective layer, the remainder being available for increasing the flux across it. A detailed, dynamic boundary layer model will be required to elucidate the driving mechanisms in this complex region.

Lidar offers the researcher an improved tool in the study of the micro-scale structure and processes of the atmosphere. Data collected from lidar will be of great value in determining the ocean-atmosphere phenomenology which affects the climatology of the Central Pacific.

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