1.13 AIRCRAFT OBSERVATIONS OF MARINE BOUNDARY LAYER STRUCTURE IN THE AREA OF MONTEREY BAY

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1. INTRODUCTION

The marine boundary layer in the coastal zone is characterized by a complex structure. Air turbulence data collected in the area of Monterey Bay, California, using the CIRPAS/NPS Twin Otter aircraft during the Autonomous Ocean Sampling Network (AOSN-II, 2003) project were used to study the structure of the near shore boundary layer. Past work (Kalogiros and Wang 2004) has shown that measured surface turbulent fluxes were systematically lower than bulk estimates. The present analysis aims in understanding the discrepancies.

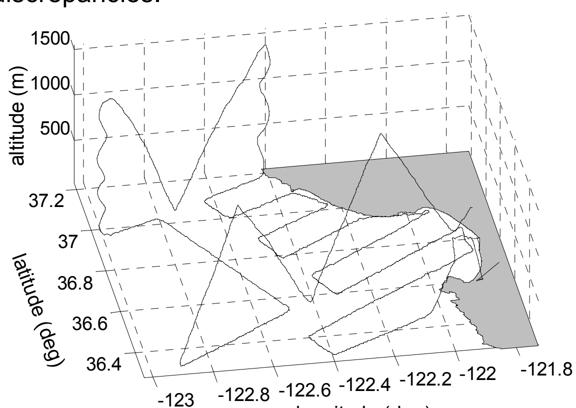

Figure 1. Typical flight pattern (3/17/2003).

The measurements include forty flights of near surface (30-40 m ASL) and sounding observations over Monterey Bay from morning to midday (Fig. 1) with limited stratocumulus cloud in the area. Turbulence measurements (10 Hz) were obtained with a radome probe and fast temperature and humidity sensors (Kalogiros and Wang 2002). Turbulence fluxes were calculated with the eddy correlation method and an inertial dissipation method.

2. VERTICAL CROSS SECTIONS

Aircraft vertical soundings were used to estimate boundary layer height in the experimental area. Low boundary layer height (Z_i, 300-600 m) was found at offshore locations with significantly lower values (below 100 m) inside Monterey Bay. Comparison of boundary layer structure from soundings made upwind and inside the Monterey Bay typically shows a collapse of the boundary layer within the Bay. Using the sawtooth soundings it was possible to make cross sections of the lower atmosphere layer structure at the "lines" of the soundings (see Fig. 1). Figure 2 shows a typical example.

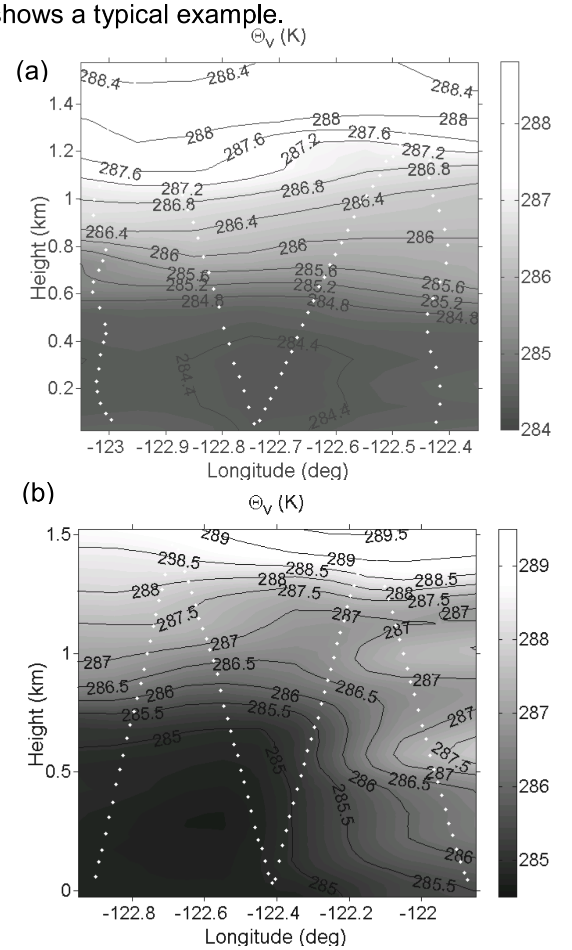

Figure 2. Virtual potential temperature (Θv) cross sections (a) upwind and (b) in the Bay on 3/17/2003 with northwest wind.

This collapse of the boundary layer could be the effect of an expansion fan at the north part of the Bay under northwest wind due the turn of the coast towards east. However, after a careful analysis of various case studies including northerly and southerly wind from moderate to strong wind

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conditions, the low boundary layer heights were mainly caused by the low wind and its corresponding weak turbulence in the Bay, probably due to the lee-wave sheltering effect of the coastal mountains.

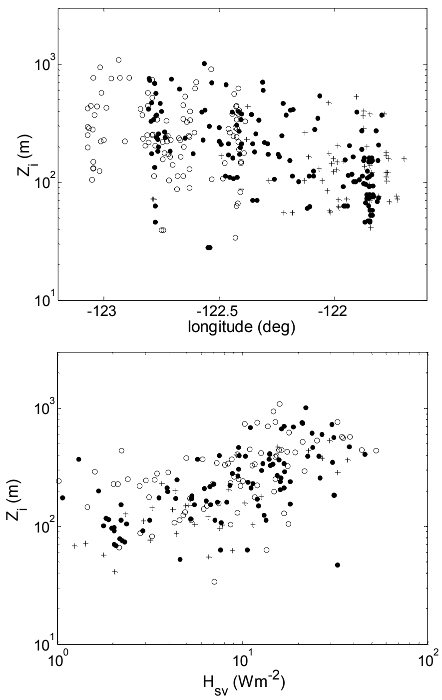

Figure 3. Z_i values against longitude and near sea surface buoyancy flux H_{sv}. Open and closed circles are from upwind and in the Bay soundings shown in Fig. 1

Figure 3 shows the correlation between the boundary layer height and the surface buoyancy flux, which may explain the low boundary layer height in the Bay. Due to influence of other dynamic factors such as large-scale subsidence and shear-induced entrainment, there is significant scatter of the data points in Fig. 3. When buoyancy flux is less than 0.1 Wm^{-2}, very small surface flux is observed and the two variables do not show any correlations. It is likely that turbulence in the very shallow boundary layers is dominated by mean wind shear.

3. FLUX PROFILES

We used the profiles of turbulence fluxes obtained from the vertical soundings to estimate the vertical flux divergence of the turbulence fluxes estimated from the near surface flight legs. A horizontal averaging length of 1.5 km was used for flux profiles, which corresponds to a vertical resolution of about 70 m required by the low boundary heights. This relatively small averaging length is justified because soundings were carried out in a sampling direction perpendicular to the wind direction and it was characterized by small turbulence scales (see the spectral analysis in next section).

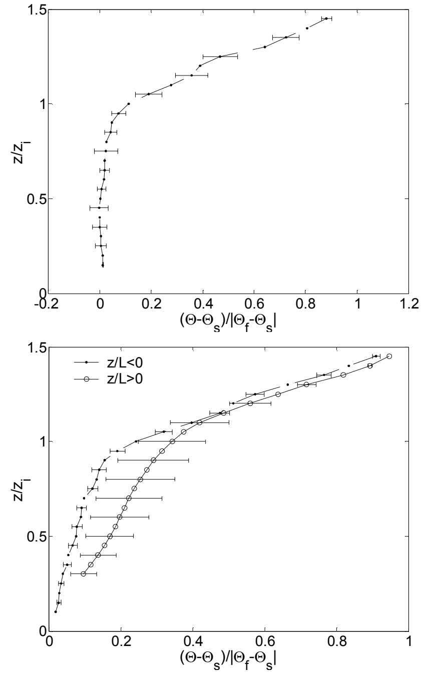

Figure 4. Average profiles of potential temperature Θ normalized with near surface Θ_s and "free atmosphere" ($1.5Z_i$) Θ_f values and standard deviation of the mean. Near surface stability z/L classes (L is the Monin-Obukhov length) are also shown.

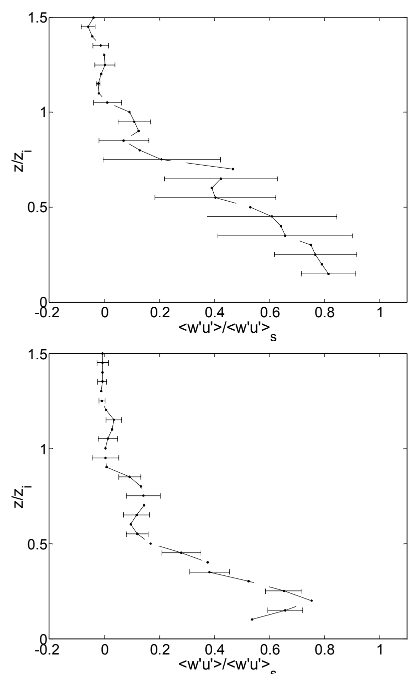

Figure 5. As in Fig. 4 but for along near surface wind momentum flux.

Two groups of profile type were identified (Figs 4 and 5). One group of profiles (most cases) was characterized by clear mixing up to Z_i, which was determined as the base of the steep temperature inversion capping the boundary layer. The other group showed mixing only up to about half Z_i probably due to morning dissipation of stratocumulus cloud, which covered the area at night and on the early morning. Because most of the cases were in the first well-mixed group we used these average profiles for flux divergence correction of near surface fluxes in order to reduce them to values at the surface.

4. SPECTRAL ANALYSIS

Spectral analysis was applied to the near sea surface aircraft data in order to check the quality of data and limitations induced by the sampling procedure. A horizontal averaging length of 10 km was used in order to include all possible turbulence scales. We performed the analysis for along and cross wind sampling direction in order to identify possible non-isotropical structures.

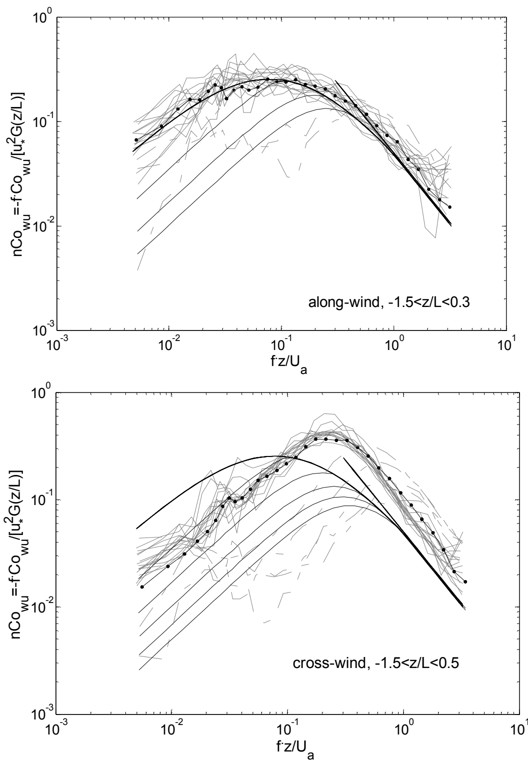

Figure 6. Composite (average normalized) co-spectra of along wind momentum flux <w'u'> for different categories of atmospheric stability parameter z/L. Frequency f is normalized with aircraft true airspeed U_a and altitude z.

Figure 6 shows the composite momentum flux co-spectra. Surface layer similarity functions (G(z/L) for momentum flux) from Kaimal and Finnigan (1994) were used in spectra normalization. Black lines are surface similarity predictions, gray lines are measurements for z/L<0, dots for near neutral conditions and dashed gray lines for z/L>0. Spectra follow surface layer similarity for along wind sampling, but they are quite different for cross wind sampling with energy shifted towards higher frequencies. Similar behavior was observed in heat and water vapor flux co-spectra.

Phase spectra analysis (Fig. 7) showed the presence of kilometer scale longitudinal rolls in the boundary layer that may affect the crosswind spectra. Longitudinal rolls are characterized by a phase difference between vertical wind velocity and the component across the average wind direction close to $\pm 90^o$ (Hein and Brown 1988). Interesting enough, they affect the atmospheric flow even near sea surface. This result may has significant effect on fluxes estimation using the eddy covariance method due to possible loss of 'energy' at low frequencies for along wind sampling if the averaging length is not large enough.

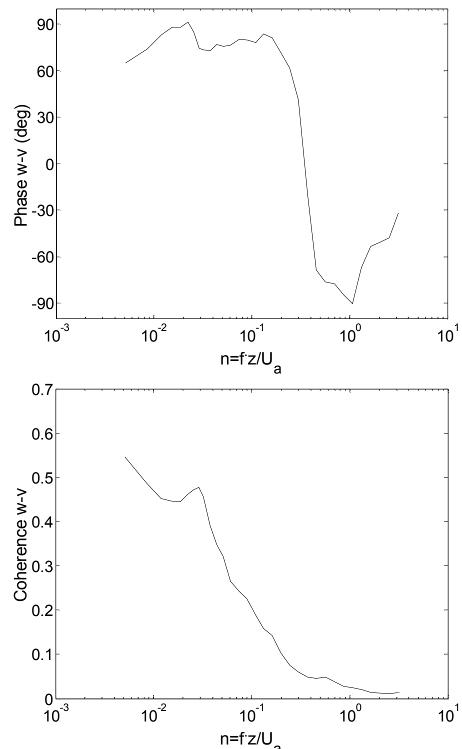

Figure 7. Average phase and coherence spectra between vertical and cross wind components w and v from near surface legs at a sampling direction 90^o off the wind direction.

5. TURBULENCE TRANSFER COEFFICIENTS

An alternative inertial subrange similarity method was used to estimate surface fluxes, which was based on heat flux co-spectrum and the power spectrum of along wind component. The momentum co-spectrum was not used because of its deviation from similarity in the inertial subrange in cross wind sampling (Fig. 6). Figures 8 and 9 show the differences between the inertial subrange and the eddy correlation methods in the estimation of the neutral drag coefficient (C_{dn}). The bulk estimate by COARE (Fairall et al. 2003) is also shown. High values at low wind speed are possibly due to sea swell effect.

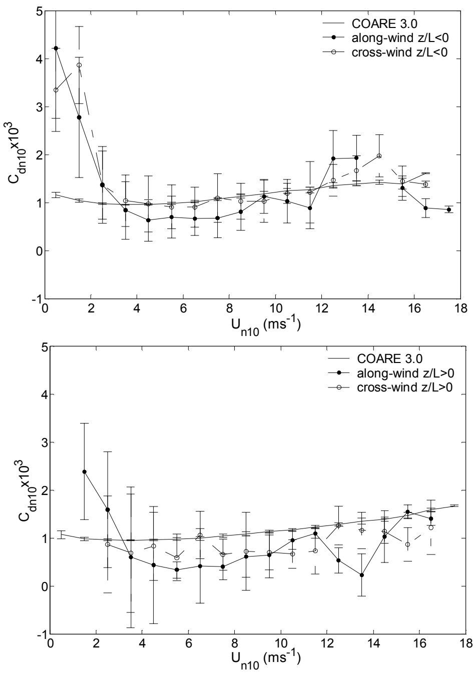

Figure 8. Neutral turbulence transfer coefficients of wind stress against neutral conditions wind speed at 10 m above sea surface (U_{n10}) estimated with eddy correlation.

Using the inertial dissipation method the transfer coefficients did not show the systematic underestimation in along wind sampling. The eddy correlation method in cross wind sampling shows agreement with bulk estimate for unstable conditions but underestimation for stable conditions. This is possibly the result of vertical flux divergence (especially under stable or not well mixed boundary layer according to Figs. 4 and 5), as a first attempt to correct fluxes for divergence has shown. The divergence effect was more significant in the heat flux case (not shown here). The boundary layer depth was usually below 400 m (Fig. 3) and, thus, the measurement altitude (30-40 m) could be frequently above the surface layer.

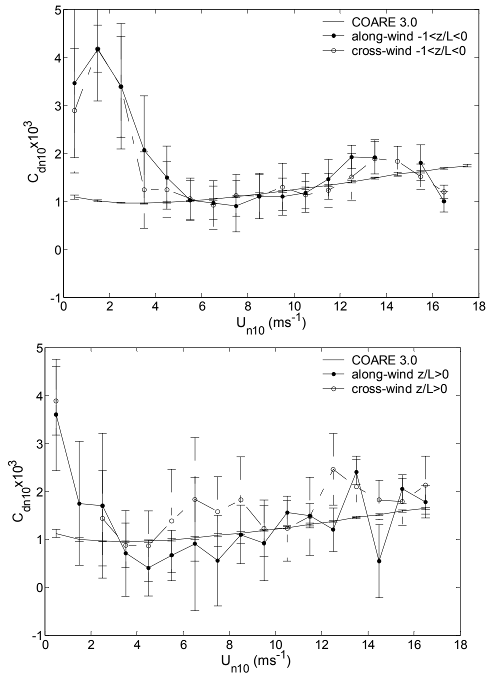

Figure 9. As in Fig. 8 but fluxes estimated with the inertial dissipation method.

6. CONCLUSIONS

Shallow boundary layer and longitudinal rolls in the coastal environment affect significantly the turbulence measurements near sea surface. Cross wind sampling is preferred because smaller turbulence scales are involved. Inertial dissipation methods for fluxes estimation avoid the effect of eddies' distortion by rolls. Flux divergence is not very significant for momentum flux, but this not the case for heat flux.

ACKNOWLEDGEMENTS

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