9.7 MARINE ATMOSPHERIC BOUNDARY-LAYER STRUCTURE AND AIR-SEA FLUXES UNDER MODERATE TRADE WINDS REGIME

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## 1. INTRODUCTION

The main goal of the Rough Evaporation Duct (RED) experiment is to determine the effects of air-sea interaction on microwave and electro-optical signal propagation near to the sea surface . The characterization of the marine boundary layer structure and air-sea fluxes is therefore an essential component of RED. In addition to the the Marine Physical Laboratory's Research Platform Floating Instrument Platform (FLIP) which provided continuous point measurements in the lower 20 m of the air-sea interface, the Twin Otter aircraft of US Naval Postgraduate School's Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) was also deployed. In this paper we describe the aircraft measurements and focus on results relating to the characterization of the vertical structure of the marine atmospheric boundary layer (MABL) and the horizontal variability of the mean meteorological variables and turbulent fluxes of momentum, latent and sensible heats.

## 2. MEASUREMENTS

The CIRPAS Twin Otter aircraft was instrumented with wind, temperature, humidity, IR sea surface temperature and aircraft motion and navigation sensors. The response time of the relevant instruments was fast enough to resolve the smallest flux carrying eddies. A photograph of the aircraft showing the placement of the major instruments is presented in Fig. 1. More details on the instrumentation can be found in Khelif et al., (1999). For redundancy, two data systems were used. One recorded the data at 40 Hz and the other at 10 Hz, and data from each system were processed to yield meteorological data at 1 Hz and turbulence data at either 40 Hz or 10 Hz. The aircraft was based at MCBH Kaneohe, HI, and flew 14 flights from August 22 to September 15, 2001. The average duration of a research flight was 5 hours between approximately 1100 to 1600 local time. Practically all portions of a flight gathered research data, since the airfield was only a few miles from the RED area. As illustrated in Fig. 3, a typical flight pattern consisted of low level (30 m) tracks along the propagation path, profiles through the marine inversion to the trade-wind inversion, stacks above FLIP and upwind, and aerosol sampling legs. (Details on the RED geometry are given by Anderson et al. 2003.)

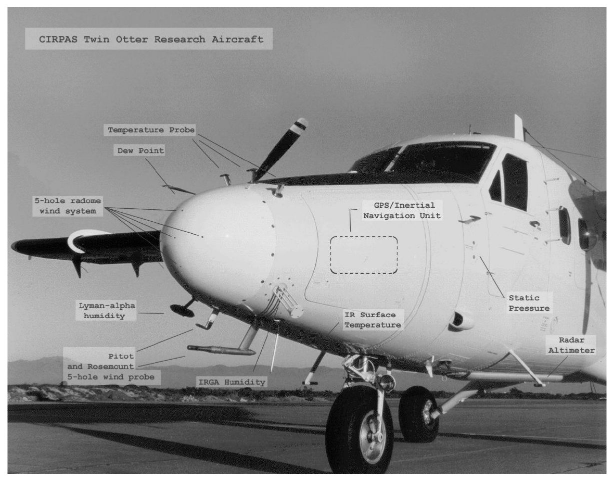


Figure 1: CIRPAS Twin Otter aircraft with meteorological and turbulence instrumentation for RED.

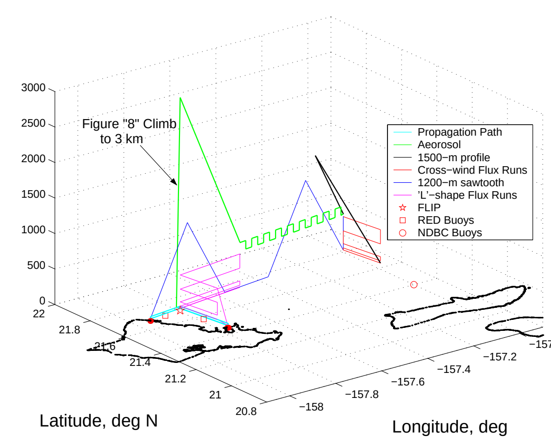


Figure 2: Typical Twin Otter flight track during RED.

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## 3. RESULTS

To give an idea on the prevailing meteorological conditions during the RED experiment, means of radiometric sea surface temperature, $T_s$, ambient temperature, $T_a$, dewpoint temperature, $T_d$, air pressure, $P$, wind speed, $WS$ and wind direction, $WD$ obtained from a low level (30 m) run on each of the 9 flights shown are plotted versus the day in the year in Fig. 3. (The UTC time convention used is January 01, 2001 at 1200 corresponds to a day in year of 1.5 as agreed upon on the 3rd RED working group meeting.) Typical mid-pacific trade wind regime conditions are observed with $WS$ varying mostly between 6 and 10 m s$^{-1}$ and $WD$ mostly from the East. The sea surface temperature was high at roughly 26 °C and the $T_s - T_a$ difference was in general below 1 °C. The humidity was high as indicated by the high values (above 20 °C) of $T_d$.

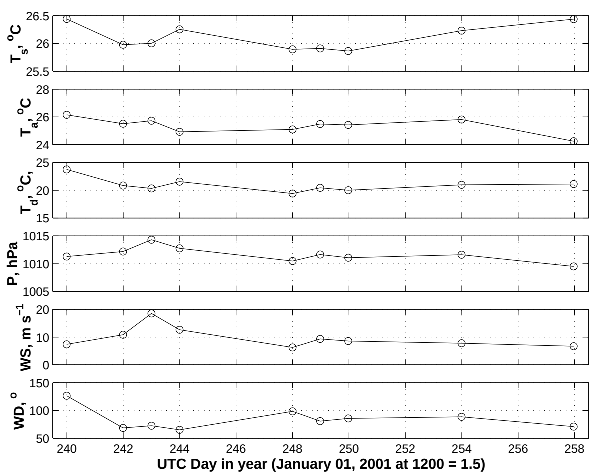


Figure 3: Means of (from top to bottom) radiometric sea surface temperature, $T_s$, ambient temperature, $T_a$, dewpoint temperature, $T_d$, air pressure, $P$, wind speed, $WS$ and wind direction $WD$ during RED. Data are from a single low level (30 m) run on each flight.

A compilation of profiles of $T_d$, $WS$ and potential temperature, $\theta$, obtained from the soundings flown during 9 RED flights are shown in Fig. 4 along with their tracks. The height $z$ used is the pressure altitude adjusted to radar altitude. The vertical span of the soundings varied from about 30 m at the surface to at least 1-km (above the MABL inversion). The deeper soundings were flown above the FLIP through the trades inversion in a spiral pattern required for the aerosol sampling. In the spiral tracks, the flow distortions around the aircraft exceeded the tolerated level by the wind measurements system and resulted in contaminated winds as evidenced by the oscillations in $WS$ profile. The scalars, however, were not affected by the flow distortions. The MABL height was determined from each individual $\theta$ profile as the jump in $\theta$ across the MABL inversion. The variations of MABL height throughout RED and also within each flight day are shown in Fig. 5. Following the color-coded scheme of the soundings times within a flight, it can be seen that, except for the the first 3 days when it increased, the MABL heigh decreased during the roughly 5-hour (1100-1600 local time) duration of the flight.

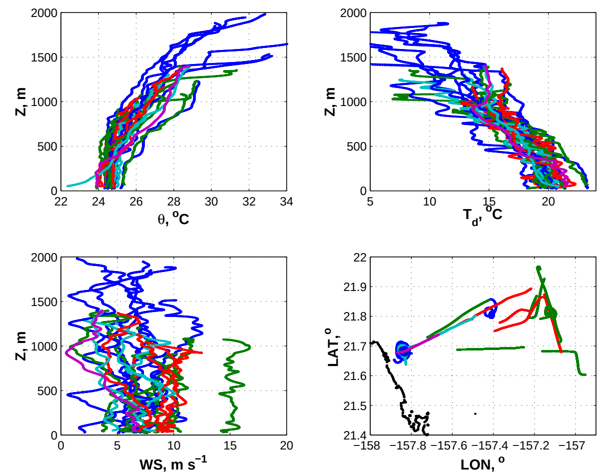


Figure 4: Profiles of potential temperature, $\theta$, dewpoint temperature, $T_d$, and wind speed, $WS$ during RED. The location of the profiles is shown on the bottom right frame.

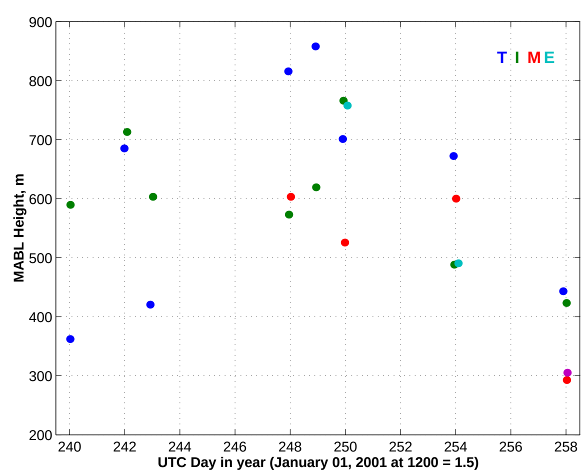


Figure 5: Variations of MABL height during RED as inferred from the inversion level on potential temperature profiles. Within a given flight, the time of each profile is color-coded as indicated by the color sequence of the letters of the tag "TIME" with blue being the earliest and cyan the latest.

The variability of the mean meteorological observations $T_a$, $T_s$, $WS$ and specific humidity, $q$, is shown in Fig. 6 for the last RED research flight 010914. The means were obtained from level and straight runs flown below 50 m. Very little variability was found in $T_s$ which varied between 26.3 and 26.7 °C. $T_a$ varied roughly between 24.2 and 25.4 °C. The specific humidity varied between 14.7 and 15.9 g kg$^{-1}$. The largest variations were observed on $WS$ which increased from 1.3 to 7 m s$^{-1}$. The plots of the latitude and longitude are given to help distinguish between the spatial variability like the decrease in $T_a$ and $T_a$ observed at UTC day = 258.035 and the temporal variability seen as the steady increases in $WS$ and $q$ which seem to occur independently of location.

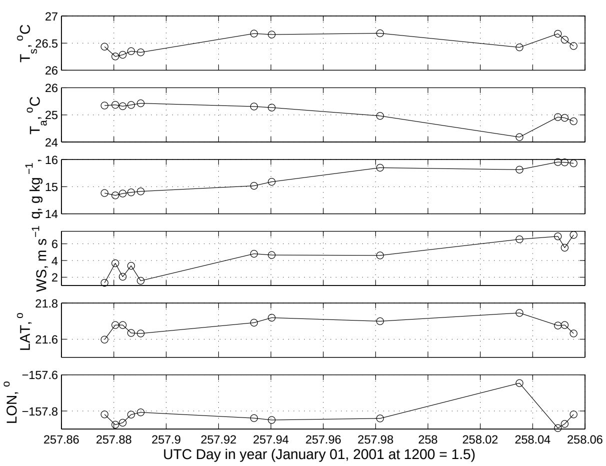


Figure 6: Variability of ambient temperature, $T_a$, sea surface temperature, $T_s$, specific humidity, $q$, and wind speed, $WS$ during flight 010914.

With the processed high-rate (40-Hz) data and from the definitions of the Reynolds averaged covariances between the vertical velocity fluctuations and fluctuations of the appropriate quantity, the along-wind stress, cross-wind stress, sensible heat and latent heat fluxes were calculated. The ogive technique (Friehe et al., 1991) was used. The fluxes were also estimated from the mean meteorological data using bulk aerodynamic formulas. The TOGA COARE algorithm (Fairall et al., 1996) which is suitable for the tropical conditions of RED was used. Comparisons between the directly-measured fluxes and the "bulk" fluxes of sensible heat, $Q_h$, latent heat, $Q_e$, and total stress, $\tau$, are shown in Fig. 7 for flight 010914. While there seem to be a reasonable agreement for $Q_e$ and $\tau$, the $Q_h$ eddy correlation values are significantly higher than their bulk counterparts. Spectral analysis did not reveal any anomaly with the temperature signal used. Further investigation is underway to find an explanation to this discrepancy. Maps of eddy correlation $Q_h$ and $Q_e$ for the RED research area are shown in Fig 8 for flight 010914.

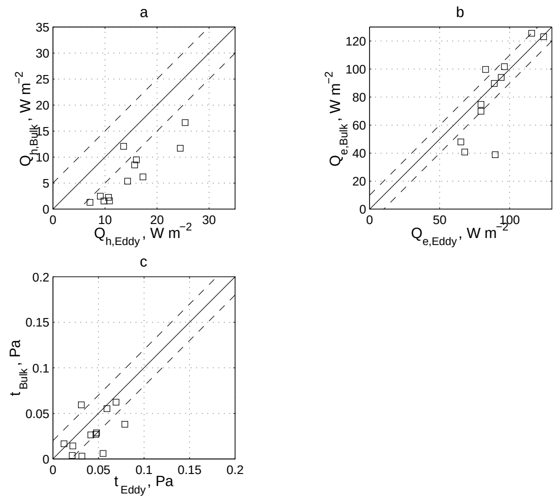


Figure 7: Comparison of air-sea surface sensible heat flux (a), latent heat flux (b) and and total stress (c) obtained from eddy correlation method and TOGA COARE bulk algorithm (Fairall et al., 1996) on flight 01914 (257.87-258.07 day in year 2001). Data are from runs below 50 m.

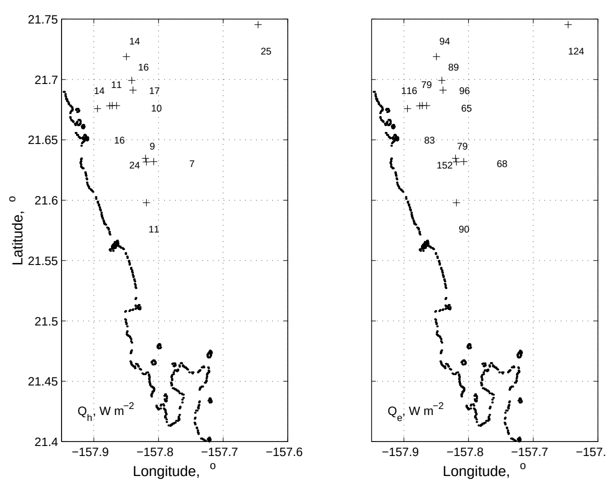


Figure 8: Spatial variability of surface sensible heat (left) and latent heat (right) fluxes on flight 010914 (257.87-258.07 day in year 2001). Data are from runs below 50 m.

To obtain an estimate of the flux divergence, the eddy correlations fluxes calculated for all straight and level runs for $z < 600$ m, are plotted vs z in Fig. 9. The decrease with z occurs roughly at a rate of -0.2 W m$^{-3}$ for $Q_e$ and at -0.02 W m$^{-3}$ for $Q_h$.

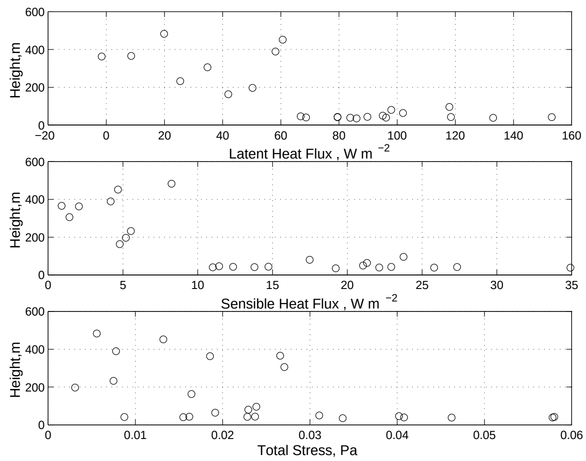


Figure 9: Flux divergence of latent heat (top), sensible heat (middle) and total stress (bottom) on flight 010914 (257.87-258.07 UTC day in year 2001).

## 4. CONCLUSIONS

Good quality meteorological and turbulence data were gathered by the CIRPAS Twin Otter during the RED experiment. On a typical flight, the eddy correlation surface fluxes were in the ranges 0.01 - 0.08 Pa, 7 - 25 W m$^{-2}$ and 65 - 152 W m$^{-2}$ for stress, sensible heat and latent heat respectively. Reasonable agreement was found for stress and latent heat flux between results from the TOGA COARE bulk formulas algorithm (Fairall et al. 1996) and the eddy correlation method. However, the eddy correlation sensible heat was found about 8 W m$^{-2}$ higher. Stacked runs pattern allowed to estimate the flux divergence.

The profiles obtained from the aircraft soundings showed that, for most days, MABL height decreased during the flight. The analysis is still in its early stage and it will be extended to the whole data set in the upcoming months.

## 5. ACKNOWLEDGEMENTS

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## 6. REFERENCES

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