P2.21 Small-scale variability of temperature and LWC at Stratocumulus top

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1. Introduction

Physics of Stratocumulus Top (POST), a research campaign focused on a detailed study of processes occurring in the uppermost part of Sc cloud and capping Entrainment Interfacial Layer (EIL), was held in the vicinity of Monterey Bay in July and August 2008 (Gerber et al., 2010). CIRPAS Twin Otter research aircraft, equipped to measure thermodynamics, microphysics, dynamics and radiation, collected unique data characterizing the cloud top region. Among them are 1000S/s (Samples per second, corresponding to ~5cm spatial resolution) records of fluctuations of temperature from the Ultra Fast Thermometer (UFT, Haman et al., 2001) and of liquid water content (LWC) from the Particulate Volume Monitor (PVM, Gerber et al., 1994).

Experience from the previous DYCOMS II campaign (Stevens et al., 2003), i.e. difficulties in analysis of fast response sensors mounted in various parts of the plane (see e.g. Haman et al. 2007), resulted in close collocation of key units for POST. In effect, PVM, UFT, two optical humidity sensors were located around a nose of the aircraft, inside which a turbulence 5-hole probe was located (Fig.1); 40S/s (~1.2m spatial resolution) records from sensors at common location can be directly compared. Additionally, 100S/s records from UFT and PVM (shifted by less than 50cm one from another) give information on temperature and LWC in air parcels as small as 0.5m. 1000S/s and faster records can be used for verification of the homogeneity of air volumes sampled with lower resolutions.

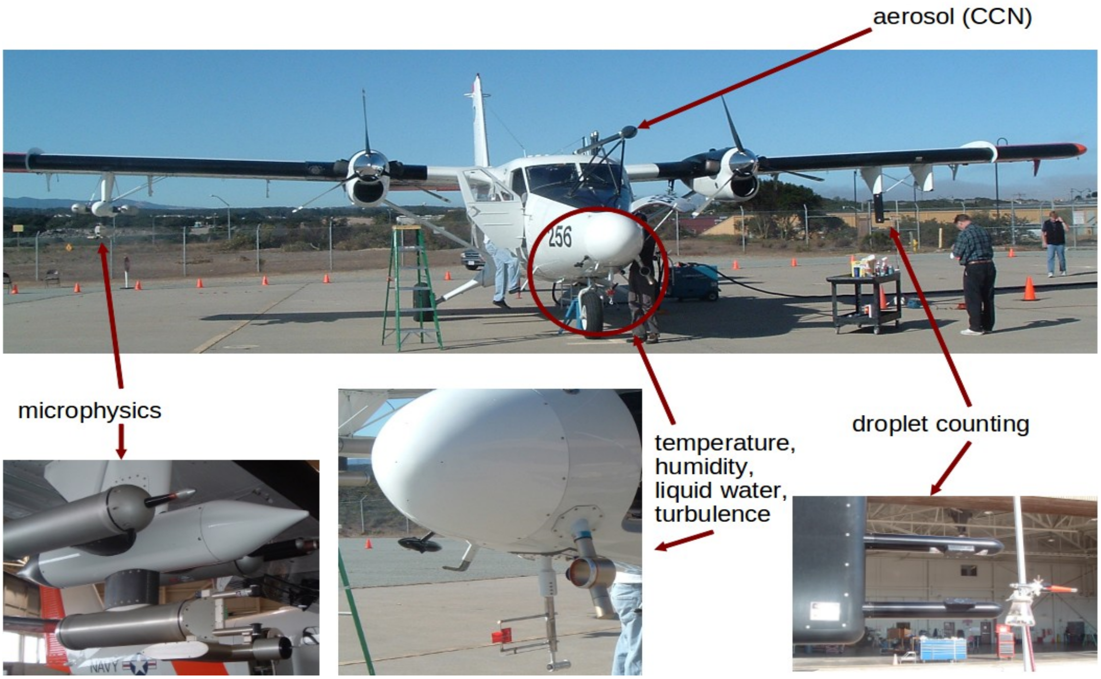

Fig.1 *CIRPAS Twin Otter and scientific instrumentation in Physics of Stratocumulus TOP (POST) research campaign. High frequency probes are located around the nose of the aircraft.*

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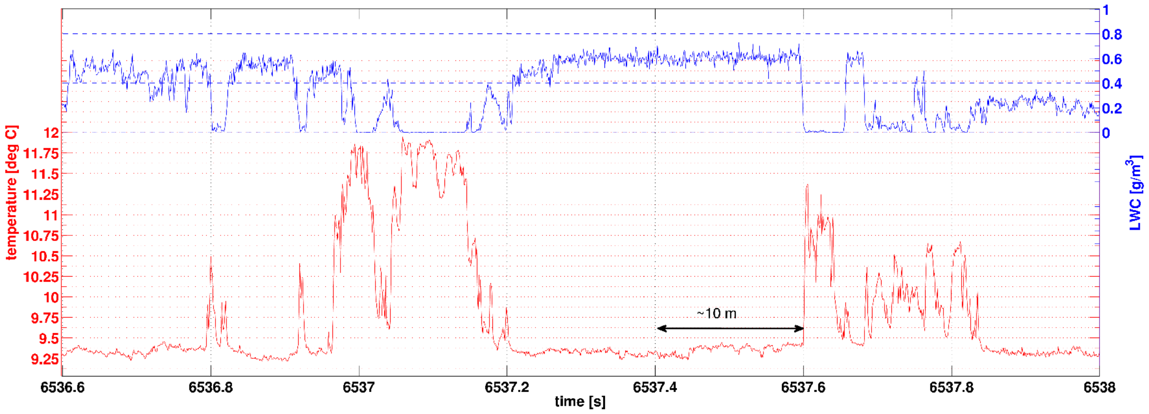

Fig.2 *Example records from UFT and PVM in the cloud-top region. 1000S/s signal as stored in the database. Intertwined cloudy and clear air filaments correlate with temperature fluctuations.*

The fastest (of the best resolution) sensor on-board was a new, improved version of the UFT thermometer, designed and fabricated specially for this campaign (Kumala et al., 2010). Two independent thermometric units were closely (5mm apart) collocated on the same sensor for redundancy. A new amplification system was designed in order to minimize possible electrical noise from avionics. Data were oversampled and recorded at 20kS/s, in order to get information on the temperature fluctuations and on the sensor performance.

Recorded signals were polluted with spikes due to the influence of avionic systems of the aircraft. A special algorithm to remove these spikes from the record was implemented. Data were synchronized with the reference time signal and averaged down to 1S/s to calibrate against the reference Rosemount thermometer. Calibration constants allowed for recalibration of the original high frequency records. Recalibrated time series were then verified and averaged down to 1kS/s, 100S/s and 10S/s. These data, as well as data from the other sensors are openly available from the database: http://www.eol.ucar.edu/projects/post/ .

An example of the temperature and LWC record at 1000S/s, demonstrating capabilities of the sensors is presented in Fig.2.

2. Temperature and LWC at the cloud top: a case study

In this section we analyse in detail records of temperature and liquid water content collected in one leg of TO13 research flight (August 9th, 2008). This leg contains vertical sounding through the whole boundary layer and lower troposphere (Fig.3), there are four horizontal segments taken to estimate turbulent fluxes of heat and humidity in the lower part of the ABL and inside the cloud deck, and 8 porpoises taken in the cloud top and lower parts of capping inversion (Fig. 4). Such pattern of a leg was typical for POST campaign, which was focused on measurements of structures at the cloud top and inside EIL above cloud.

Profiles of potential temperatures and mixing ratios of water in Fig.3 indicate Stratocumulus cloud present in the upper half of the atmospheric boundary layer. Cloud is capped with an inversion and a layer with a significant wind shear above (c.f. u and v in Fig.3). Remarkable fluctuations of temperature above cloud top and inversion (c.f. Fig.4) suggest the presence of turbulence above the cloud top up to 800m height. Turbulence results in intensive mixing manifested with a layer of constant potential temperature and water vapour mixing ratio between 700m and 800m heights in profiles in Fig. 3.

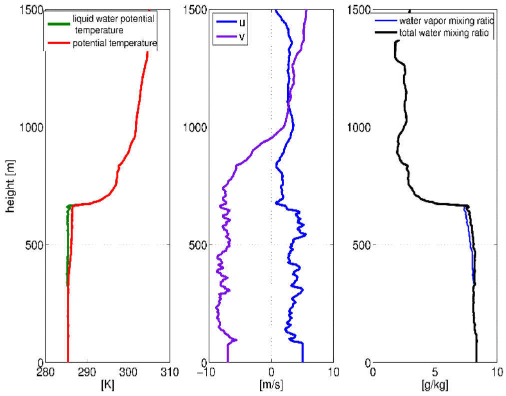

Fig.3 *Vertical profiles of temperature, water mixing ratio and wind taken at the end of TO13 research flight.*

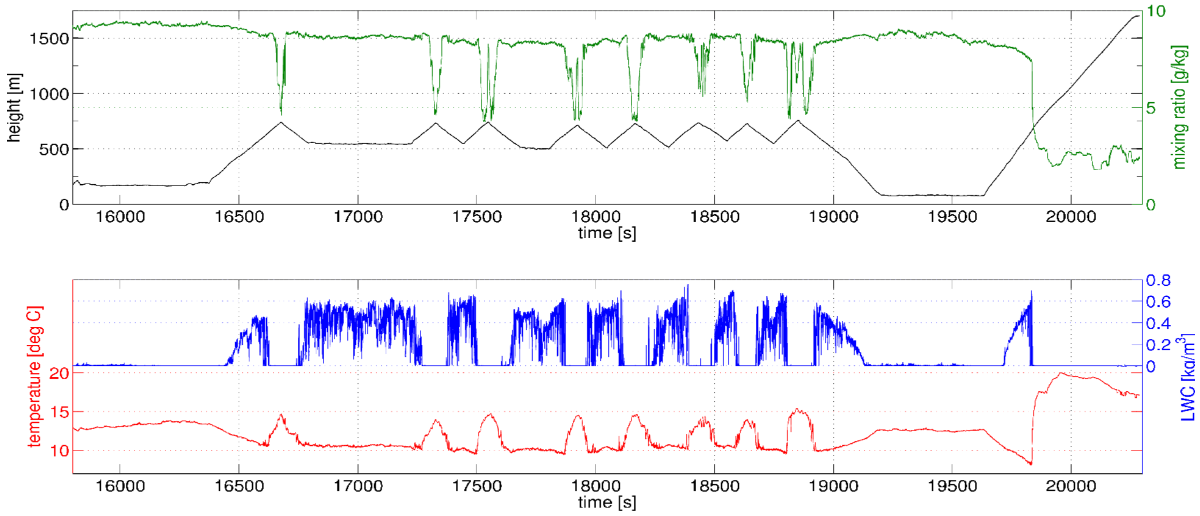

Fig.4. *Altitude (black), water vapour mixing ratio (green), LWC (blue) and temperature (red) in the investigated segment of TO13 research flight.*

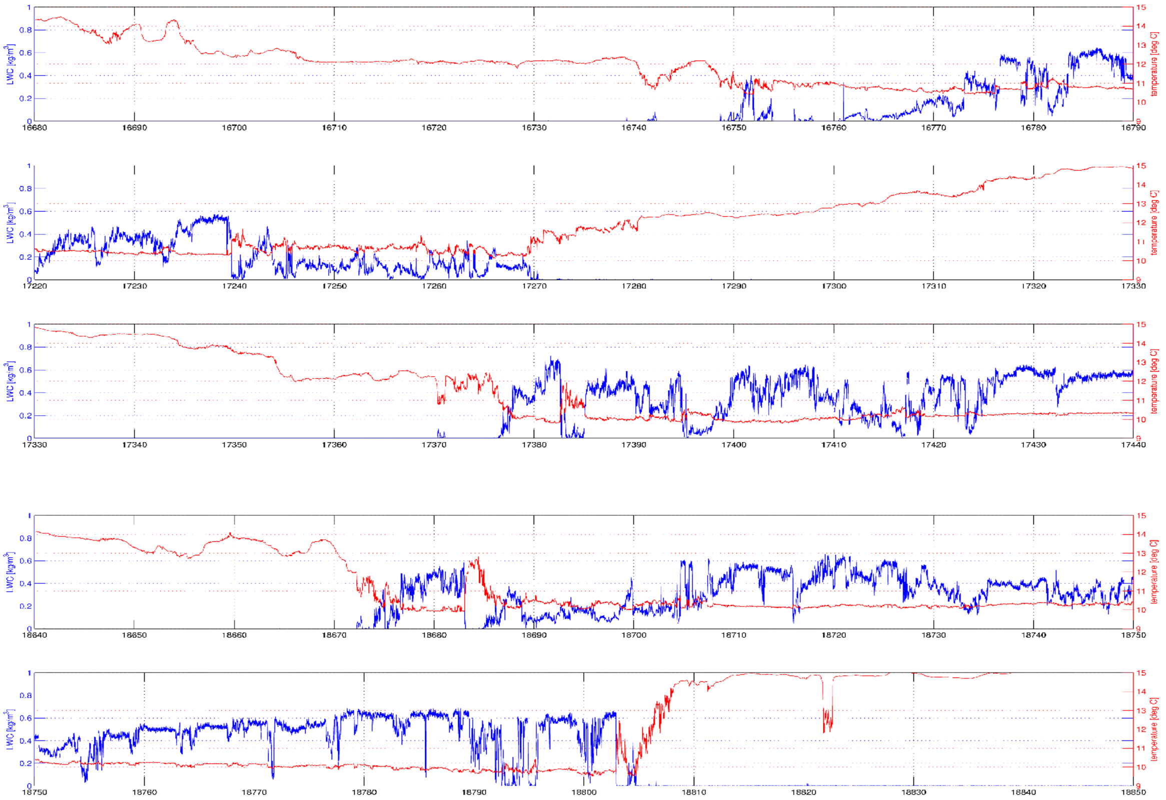

Fig.5 *100S/s (~50cm spatial resolution) records of temperature and LWC on few porpoises from the investigated leg of TO13 research flight. Notice remarkable temperature fluctuations above cloud (four uppermost sections), regions of depleted LWC close to the cloud top (sections 1,2,4), sharp temperature jump above sharp cloud top (lowest section).*

Fig.5 documents characteristic patterns of LWC and temperature fluctuations in cloud and above with ~50cm resolution (100S/s data). They were collected on porpoises and records can be interpreted as slightly inclined cross-sections through the cloud top region and EIL. Notice the presence regions of depleted LWC at the cloud top, suggesting volumes diluted by previous mixing. Three uppermost panels in Fig.5 show substantial temperature variations above cloud, defined as the region with presence of liquid water on PVM record. These variations are sometimes smooth and monotonic and sometimes characterized by presence of sharp jumps and ramps, signatures of active turbulent eddies. Two lower panels in contrast show sharper temperature inversion just above the cloud top and weak or almost no temperature fluctuations above.

Such a variability of temperature and LWC demonstrates that EIL has complicated spatial structure. It may evolve in time: large eddies appear due to dynamical instability and disappear leaving flat, pancake-like mixed spots.

Presence of mixed spots in a layer above the cloud (characterized by constant potential temperature and mixing ratio as in Fig.3) suggests that dynamics of EIL and cloud top may differ from that when Sc is capped with a sharp inversion and stable layer. Results illustrating possible dynamical effects of differences are shown below.

3. Cloud holes

In this section we analyse horizontal segments of TOF13, inside the Stratocumulus deck, close to the cloud top. Upper panel of Fig. 6 presents 100S/s records of temperature and LWC collected between 16790-17220s at the altitude of 550m. Lower panel shows corresponding correlations of fluctuations of temperature T' and liquid water LWC'. Fluctuations are defined as differences between the actual (100S/s) values of LWC and T and their 500m running means centred on a given point. Positive values of <LWC' T'> suggest that both fluctuations are of the same sign in the "cloud holes", i.e. regions with depleted liquid water content.

Typically in cloud holes observed in DYCOMS II by Gerber et al., (2005), numerically modelled by Kurowski et al., (2009) and theoretically discussed by Haman, (2009), one should expect positive correlations <LWC' T'>. In such holes decreased LWC and temperature drop are effects of evaporative cooling in descending, negatively buoyant parcels. holes. Such a picture is not the case here, plot clearly shows that depleted water correlates with increased temperature. One may expect, that cloud holes as in Fig.6 are not effect of negative buoyancy due to evaporative cooling.

In Fig.7 histograms (empirical probability distribution functions, PDFs) of <LWC' T'> on horizontal segments of TO13 flight are collected. It can be seen, that two PDFs differ from the others due to the existence of long negative tails. One comes from the segment presented in Fig.6, the second from the segment recorded at 17680-17820s at a height of 504m. Both are in a physical vicinity of the profile shown in Fig.3, documenting turbulent mixing at the cloud top and above.

Typical PDFs characterizing other horizontal legs of TO13 (left panel in Fig.7.) and TO10 (August 4th, 2008, right panel in Fig.7) show in contrast positive

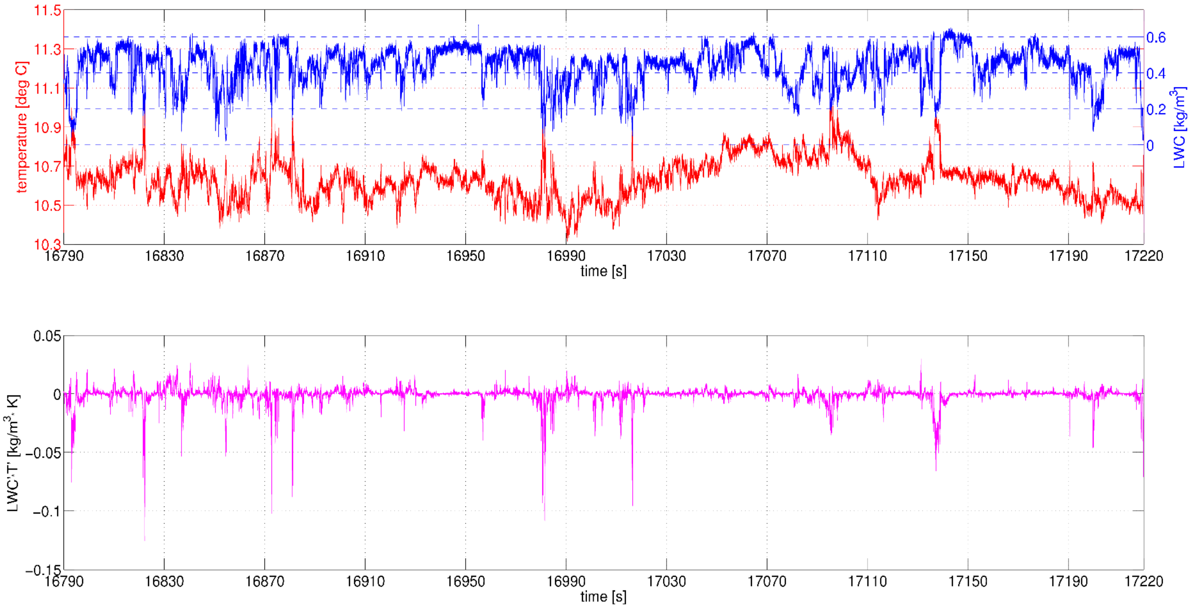

Fig.6. *Upper panel: 100S/s LWC and temperature record in horizontal section of TO13 research flight at the height of 550m, few tens of meters below the cloud top. Notice that regions of depleted LWC often correlate with the positive temperature fluctuations, as indicated in the lower panel, where correlations <LWC' T'> are displayed.*

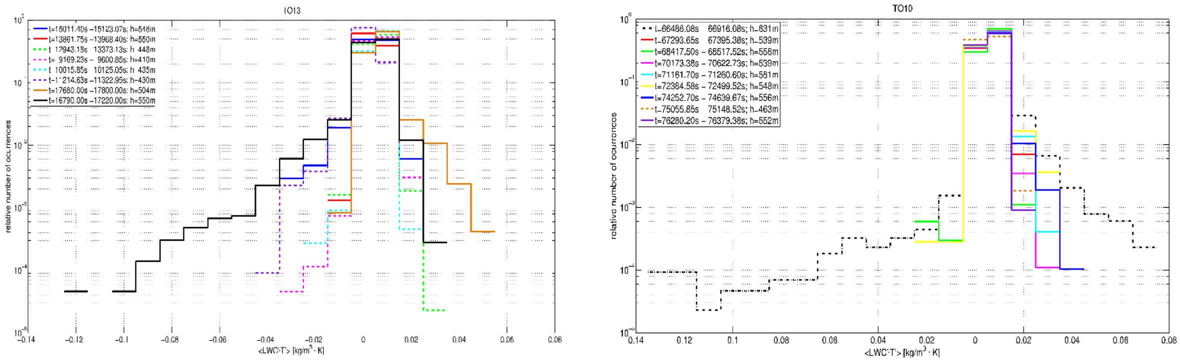

Fig.7 *Histograms of correlations <LWC' T'> on horizontal legs inside cloud deck in flights TO13 (left panel) and TO10 (right panel). It can be seen that weak positive correlations prevail. Strong negative correlations occur frequently in some legs of TO13 only.*

skewness and absence of long tails on the negative side, as expected in cloud holes with depleted (or absent) LWC and temperatures below the environmental, where parcels slowly sink through the cloud deck due to the negative buoyancy.

We may hypothesize that prevailing negative correlations <LWC' T'> in two high legs of TO13 indicate regions of active eddies at the cloud top. These eddies are effects of Kelvin-Helmholz like instability in a strong wind shear and may dynamically force down parcels of positive buoyancy.

Above example indicates that various mixing patterns and scenarios at Stratocumulus topped boundary layer are possible. They depend on the details of atmospheric stability, wind shear, thermodynamic and radiative conditions. Such mechanisms, as hypothesized above on a basis of analysis of vertical profiles and high resolution records of thermodynamic parameters, require mode studies. Additional investigations in spirit of these performed by Gerber (2010), Wang Q. et al. (2010), Hill et al., (2010) are important in this context. Crucial, however are high-resolution numerical simulations, following e.g. the idealized case of TOF13 flight, as modelled by Wang S. et al., 2010. Only combination of analysis of in-situ data and modelling may give enough insight into complicated temporal and spatial variability of mixing process needed to construct reliable parametrization of entrainment into Stratocumulus capped boundary layer for weather forecast and climate models.

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