POST (Physics of Stratocumulus Top)

Proposal; April 12, 2007

SUMMARY

Stratocumulus clouds (Sc) off the west coast of California are studied using a combination of aircraft measurements and modeling. The objective is to improve the understanding of the physical processes that occur near Sc top, and that influence the entrainment process and boundary-layer evolution. The processes include wind shear, entrainment rate, CTEI (cloud-top entrainment instability), solar and infrared radiation, hydrometeor and CCN (cloud condensation nuclei) effects, and the formation and role played by the EIL (entrainment interface layer).

The study is a combination of field measurements and modeling. For the former, the CIRPAS Twin Otter research aircraft is deployed out of Monterey for ~20 flights in Sc. It carries a full complement of sensors to produce measurements related to those physical processes. Sensors include the UFT (ultra-fast temperature probe), PVM (fast particulate volume monitor), fast Lyman-Alpha hygrometer, PDI (phased Doppler interferometry probe), other droplet probes, gust probe, solar and infrared radiometers, and the standard set of Twin-Otter probes producing meteorology and aircraft operating properties. The aircraft is deployed primarily in fields of unbroken Sc with a stress on porpoising maneuvers vertically about Sc top to detect fine-scale behavior. Boundary layer profiles and near-surface horizontal legs are flown to deduce fluxes. NexSat and CloudSat products are compared to aircraft measurements and used to help vector the aircraft to fields of Sc. The analysis phase of the field study includes comparisons between the measured physical processes and the calculated cloud-top entrainment velocities with the purpose of clarifying the cause and effect for the latter.

The study models a wide range of scales associated with the physical processes. The LEM (linear-eddy model) looks at the finest scales associated with droplet size changes. New fine-scale LES (large-eddy simulation) is applied with grid resolution comparable to the several-meters scale found for the entrained parcel size. A mesoscale model (COAMPS) deals with the larger-scale behavior of the Sc and the boundary layer, and it provides predictions for deploying the aircraft. Parameterizations of the entrainment velocity are evaluated and improved. All the preceding relate closely to the aircraft measurements for initialization and comparison.

Intellectual Merit

Predicting the behavior and evolution of Sc found over large areas of the sub-tropical oceans has proved to be difficult, because of the imperfect understanding of the associated physical processes and the inability to measure them accuracy. High on the priority list for better understanding is the entrainment process. The literature shows a lack of measurement success and predictive capability for this important process that affects Sc lifetime. This study uses a unique combination of aircraft measurements and modeling to focus on this lack. For the first time co-located high-rate microphysical, thermodynamic, and turbulence probes are use in conjunction with a fixed-wing aircraft deployed for unraveling the physical interactions near Sc top. Advances in measurement technology and in modeling prompted the pursuit of this study.

Broader Impact

Improving the ability to predict the behavior of low-level stratocumulus found over large ocean areas is needed given their major contribution to the planetary albedo that affects the planetary radiation balance and thus global warming.

Proposal Description

1. Introduction

POST proposes to utilize the CIRPAS Twin Otter research aircraft in July of 2008 to study the stratocumulus (Sc) clouds found frequently at the top of the maritime stratocumulus-topped boundary layer (STBL) off the coast of California. A motivation to again perform a field study of these clouds is from their known influence on the planetary albedo and thus on the climate system, from the desire to predict their evolution, and from the results of the 2001 DYCOMS-II (Stevens et al, 2003a) study of Sc in the same region. A principal goal of DYCOMS II was to measure accurately from aircraft the entrainment rate (w_e) into the Sc and utilize this measure as well as the observed general characteristics of the Sc environment as "ground-truth" for testing w_e parameterizations (Stevens et al, 2003b) and LES behavior predicted by various modeling centers (Stevens et al, 2005a). The measurements of w_e as well as the modeling showed insufficient accuracy making their comparison less meaningful than desired. The w_e measurements (Gerber et al, 2005; Faloona et al, 2005) obtained during DYCOMS II with 4 independent methods on the NSF C-130 research aircraft ranged over a factor of about 2 - 3; and the modeling comparison is best summed up by Stevens et al, 2005a: "*Over all the results suggest that the use of the LESs to map out the behavior of the stratocumulus-topped boundary layer in this interesting region of parameter space requires a more compelling representation of processes at cloud top. In the absence of significant leaps in the understanding of subgrid-scale (SGS) physics, such a representation can only be achieved by a refinement in resolution - a refinement that, while conceivable given existing resources, is probably still beyond the reach of most centers.*"

The Stevens quote points POST in the desired direction of focusing on still poorly understood physical processes at Sc top that affect entrainment, and of using the improved knowledge to better parameterize the processes in models. Physical processes that need clarification and that will be addressed by POST include:

- The entrainment role played by the EIL (entrainment interface layer; also called inversion layer, interface layer, transition layer) which is a cool, moist, and cloud-free layer found between a fraction of cloud top and free atmosphere.

- The role of cloud-top shear in modifying the EIL, and thus affecting entrainment and mixed layer properties (e.g., Wang et al, 2006).

- The effect of cooling by the evaporation of cloud water due to entrainment on buoyancy production in Sc.

- The position with respect to cloud-top and the effectiveness of infrared radiative cooling (e.g., VanZanten and Duynkerke, 2003).

- The relationship between entrained cloud condensation nuclei (CCN) and incloud microphysics, including drizzle and dynamics (e.g., Kogan, 2006).

The timeliness to again study in POST these processes from a measurement and modeling perspective results from several factors: the less than satisfactory entrainment measurements in Sc off the California coast during DYCOMS II with the NSF C-130 aircraft were in part a learning experience from which POST can benefit, the need for better understanding CTBL processes associated with entrainment that affects Sc evolution and lifetime, and the advances made in the intervening years in modeling with higher-resolution LES and subgrid models that provide an improved capability for comparisons with observations.

We learned from DYCOMS II that the width of entrained parcels in Sc averaged only about 5 m near cloud top (Gerber et al. 2005). This dimension was substantially smaller than the ~20-m distance between the C-130 gust probe and the microphysics probes that produced this finding, making it difficult to calculate accurately entrainment fluxes. Also, ultra-high resolution microphysical and thermodynamic measurements needed to characterize scales entrainment and mixing were separated by ~60 times their resolution distance. The proposed use of the Twin Otter alleviates to a large degree these earlier shortcomings, because it is possible to co-locate the fast probes close to the gust probe on this aircraft's nose. During POST the Twin Otter will seek an environment with primarily unbroken Sc which we consider of sufficient complexity to address the above-mentioned physical processes. The additional complexity of rifts and POCs (Stevens et al, 2005b; Sharon et al, 2006) also found in some Sc fields is a topic of a Sc study (VOCALS) planned for later and will not be a focus of POST.

In the next section we summarize the scientific issues consistent with the POST effort, and list related hypotheses that POST will attempt to prove or disprove. The subsequent section will describe the research contributions proposed by the investigators to address these hypotheses.

2. Scientific Issues and Hypotheses

2.1 Entrainment Interface Layer (EIL)

Hypothesis H1: The turbulent kinetic energy originating from buoyant thermals in Sc is consumed by the entrainment process resulting in the cloud-free, moist, and cool EIL that separates Sc cloud top from the free atmosphere and that forms the environment from which air is ultimately entrained into cloud top.

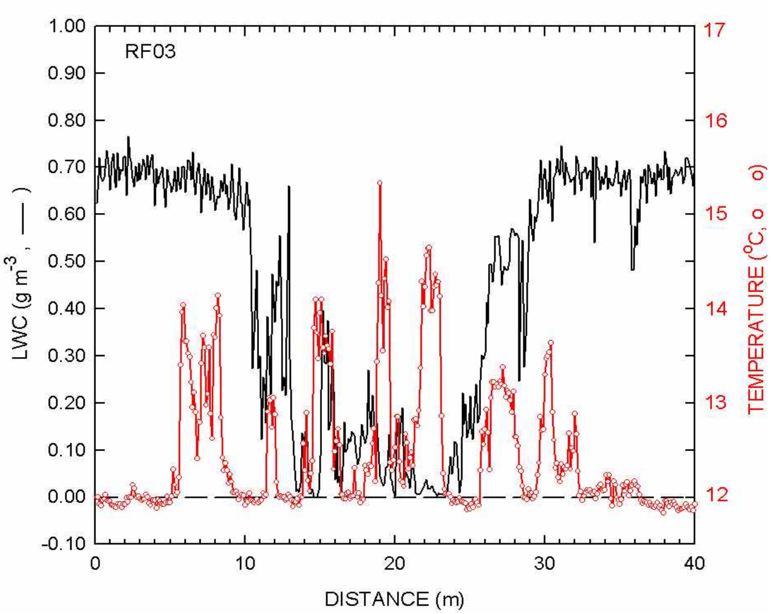

Figure 1 - 1000-Hz (10-cm horizontal resolution) measurements of LWC with the PVM (Particulate Volume Monitor) and the UFT (ultra-fast temperature probe for in-cloud and out of cloud measurements; Haman et al, 2001) made in a mixing episode near Sc cloud top from the C-130 aircraft during DYCOMS-II. A ~6-m separation on the aircraft wing of the probes prevents proper correlation of the data.

The existence of the EIL (entrainment interface layer) atop Sc was described by the British Met. Office in the 1970s and 1980s (Caughey et al., 1982; Nicholls and Turton,1986). They found a narrow cloud-free layer with properties intermediate between cloud and free atmosphere rather than a sharp 1-D interface between cloud top and free atmosphere favored by early modeling of the Sc interface (Lilly, 1968). It was suggested by Gerber (1996), Brenguier et al (2000), Lenschow et al (2000), VanZanten and Duynkerke (2002), and deRoode and Wang (2006) as well as others that the EIL is moistened and cooled by mixing with cloudy air. More recently mixing-line plots of conserved variables (see Stevens et al, 2003b; Burnet and Brenguier, 2006) showed the various thermodynamic states observed in the EIL in some DYCOMS II Sc.

It is presently unknown how the EIL relates to the entrainment process that affects Sc evolution; and little is known about the evolution and structure of the EIL. These uncertainties are reflected in the topics of two recent papers by Moeng et al (2005) and de Roode and Wang (2006). Gerber et al (2002, 2005) suggested that cloud detrains to condition the EIL until a near buoyancy match with the cloud permits air to be entrained into the Sc. The reliability of the latter needs to be taken in proper perspective with regards to the accuracy of the DYCOMS II measurements, because of the large separation between gust, fast-temperature (UFT) and fast-microphysical (PVM) probes on the DYCOMS II aircraft. Figure 1 shows the result of this separation between UFT and PVM where the data can not be clearly related to EIL Given these shortcomings, a better look at the EIL is desirable using the Twin Otter.

2.2 Entrainment

Hypothesis H2: Knowledge of the details of cloudtop interface behavior (local horizontal variability, EIL geometry and evolution, microphysics, drizzle, shear, entrainment-parcel thermodynamics and physical description, and vertical distribution of ir cooling) is necessary to yield acceptable estimates of $w_{e;}$ whereas, using basic STBL parameters including surface heat and moisture fluxes, cloudtop jumps, and buoyancy fluxes to estimate w_e is insufficient.

There are numerous papers dealing with Sc entrainment and with the measurement and parameterization of entrainment rate (w_e) into Sc. These include predictions related to CTEI (cloud-top entrainment instability; Randall, 1980; Deardorff, 1980; Yamaguchi and Randall, 2007), direct aircraft measurements of w_e using scalars and the "flux-jump method" (Faloona et al, 2005), and conditional sampling from aircraft of the entrained parcels (Nicholls, 1989; Wang and Albrecht, 1994; Gerber et al, 2005). Another method is to measure subsidence and vertical motion of cloud top (e.g., see Stevens et al, 2003b). An indirect method to estimate w_e is to analyze the STBL budgets for mass, moisture and liquid water static energy for a quasi-steady Sc environment (Stevens et al, 2003b; Caldwell et al, 2005). A novel approach (Wood and Bretherton, 2004) combines satellite observations with predicted free-atmospheric conditions and mixing line analysis. Many of the above references also review previous estimates of w_e in Sc, most of which reflect the continuing difficulty of estimating this important parameter.

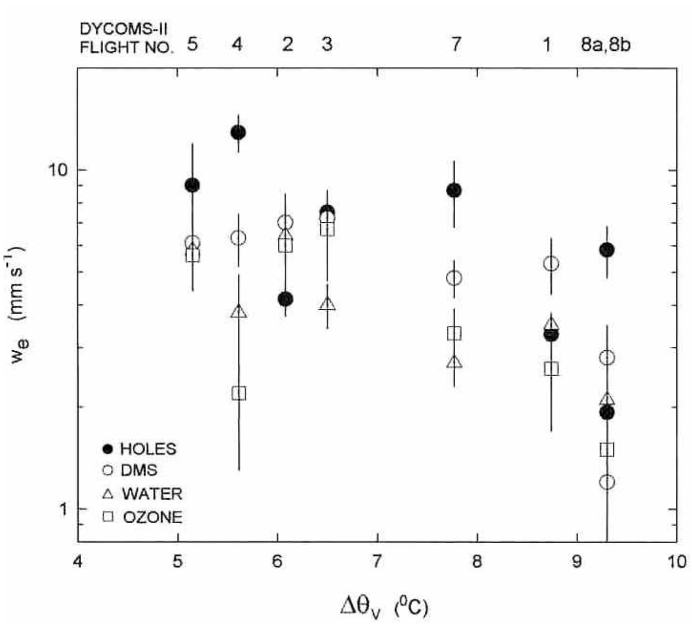

Figure 2 - Comparison of w_e for four independent measurements on the NSF C-130 during DYCOMS II as a function of the buoyancy jump ($_V$) at cloud top. Solid data are for conditional sampling of "cloud holes"(Gerber et al, 2005), and hollow data are for the "flux-jump"method using DMS, total water, and ozone (Faloona et al, 2005).

The latter two indirect approaches for measuring w_e do not rely on the details of the physical processes at Sc top. They produce w_e values averaged over time and area that are constrained by the longevity of the persistent Sc fields, and they are in general agreement with those values measured using the flux-jump method during DYCOMS II. It is not clear how well founded this agreement actually is (all finding w_e ~ 4 mm s^{-1}), because the indirect approaches are for daily w_e averages, while the DYCOMS-II w_e values are for nocturnal flights where w_e is thought to be maximum. Further, the DYCOMS-II directly-measured values of w_e published by Faloona et al (2005) and Gerber et al (2005) vary over a large range as illustrated in Fig. 2. Given the quasi-independent nature of the DYCOMS-II measurements makes it difficult to judge the validity of using w_e values averaged from the flux-jump scalars in Stevens et al (2003b) for comparisons to published parameterizations. In addition, the DMS (di-methyl sulphide) flux-jump w_e values suggested as the most reliable by Faloona et al (2005) are unlikely to be so, because a close look at the DMS measurements reveals excessive noise and inadequate response to the small scales leading to potential w_e underestimation. Thus the good agreement found by Caldwell et al (2005) between values of w_e from DYCOMS II and their mixed-layer budget analysis may be fortuitous. On the other hand, the conditional-sampling approach used by Gerber et al (2005) during DYCOMS II to estimate w_e also gives a mean value of ~ 4 mm s^{-1} when the mean nocturnal and the mean daytime w_e values are averaged. Also, COAMPS (U.S. Navy mesoscale forecast model) predicts a mean value close to the same value of w_e for DYCOMS-II flight RF01 (William Thompson, personal communication, 2006). These are encouraging results and they raise the question: is it necessary to know the details of the physical processes affecting w_e?

Hypothesis H3: Evaporation of LWC by entrained air in Sc contributes to buoyancy production that helps drive the larger cellular convection and that provides positive feedback for entrainment.

It is unclear why experimental evidence (e.g., Kuo and Schubert, 1988; Siems et al, 1990) does not support the positive-feedback mechanism for entrainment as described by the CTEI (cloud top entrainment instability) concept (Lilly, 1968; Randall, 1980; Deardorff, 1980; Yamaguchi and Randall, 2007), even though the criterion for Sc instability is observed. A possible explanation is the role played by the EIL (Gerber et al, 2005). However, the formation of the EIL must depend on the engulfment of free atmospheric air by some up-welling turrets in Sc that need to make intimate contact with the free atmosphere. Thus in this process some mixing fractions should create parcels with negative buoyancy that contribute to the larger-scale convection in the STBL. The unanswered question is how important is this possibility in comparison to mixed parcels with buoyancy that remains positive? Plots of the Sc-top and free- atmosphere mixing fractions (see Wang and Albrecht, 1994; VanZanten and Duynkerke, 2002; Burnet and Brenguier, 2006; Haman et al, 2007) do not sufficiently clarify this issue, because the measurements were either not sufficiently accurate or represented scales that were larger than scales associated with mixing and entrainment near cloud top. The high resolution data to be taken aboard the Twin Otter is needed to clarify the importance of CTEI associated with Sc.

2.3 Modelling

Hypothesis H4: Modeling results covering relevant spatial scales from microphysics to larger-scale dynamics compare favorably with POST observations of STBL behavior including shear, cloud-layer structure, EIL behavior, and entrainment rates.

It is important to include all relevant scales that affect STBL structure and evolution in trying to deal successfully with the behavior of the STBL from a modeling perspective. The smallest scales are on the order of mm which includes the responses of aerosol and hydrometeors, and somewhat larger scales are on the order of meters associated with entrained parcels at the top of the Sc as observed during DYCOMS II. Still larger scales include the average thickness of several tens of meters of the EIL, and even bigger are the dimensions of several hundred meters of the primary STBL convective circulation. Finally, mesoscale-sized influences such as coastal effects and sea-surface gradients must be included.

The finest resolution model is needed for predicting droplet size changes caused by entrainment, mixing, and activation of new CCN. Here the linear eddy model (LEM; Kerstein, 1988; Krueger, 1993) should be applied. LES modeling is needed to deal with scales associated with the entrained parcels and the dimensions of the EIL. For the former this requires LES grid resolutions on the order of 1m and not much larger for the latter given the DYCOMS-II measurements of parcel and EIL dimensions. Such LES modeling resolution is still beyond what is presently possible; however, the rapid increase in computer capability suggests that such resolution will be approached in the foreseeable future. LES with current resolutions can deal with larger-scale features in the CTBL; and mesoscale modeling is needed to model features with scales of tens of km that can influence the STBL.

While the full acceptance of ***H4*** would be highly significant, it is also unlikely given the past history of measurement and modeling comparisons for Sc which have rarely agreed and have usually shown large differences. It is more likely that the application in POST of advanced modeling and measurement approaches will cause some improvement in such comparisons. Thus the goal in POST is to establish to what degree ***H4*** can be accepted.

3. Research Contributions

The research contributions of the POST participants are described in this section. The contributions reflect the POST emphasis on observationally diagnosing in an improved manner the Sc entrainment process and the EIL using the Twin Otter aircraft. Key to this end is the deployment for the first time on a fixed-wing aircraftn fast-response temperature (UFT), microphysics (PVM), and moisture (Lyman-alpha) probes co-located in the immediate vicinity of the aircraft gust probe (see Siebert et al, 2006 and Lehmann, 2006 for related helicopter measurements in cumulus). The contributions further reflect other aircraft measurements and satellite sensing used to compile a comprehensive data set needed for initializing and comparing with the proposed modeling.

3.1 University of California Irvine (Djamal Khelif, Carl Friehe)

Twin Otter Aircraft Gust Probe

The CIRPAS Twin Otter aircraft has been outfitted since 2000 with turbulence instrumentation consisting of a 5-hole radome "gust probe", redundant fast-response sensors to measure temperature (2 Rosemount flight test sensors and 2 thermistors) and humidity 2 Lyman-alphas and one LI-COR 7500), a GPS inertial unit to provide navigation and motion data and an IR downward-looking pyrometer to measure SST. Data from the gust probe and a selection of the remaining instruments and other meteorological sensor are recorded at 40 hz (or higher if desired) on a dedicated on-board rugged computer. The Twin Otter has a rather large nose compartment for mounting additional sensors. Figure 3 shows the atmospheric probes clustered around the nose ring slightly aft of the gust-probe system (some other sensors are also shown). Details on a similar radome wind system (gust probe) can be found in Khelif et al (1999).

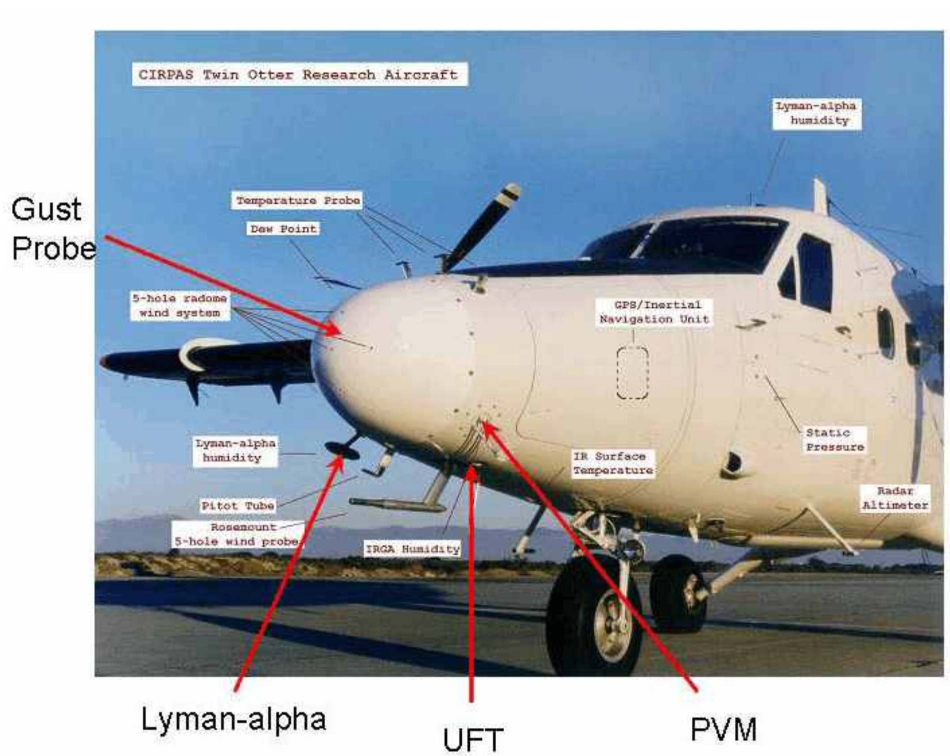

Figure 3 - CIRPAS Twin Otter with UCI turbulence and meteorological instrumentation. Approximate locations of the UFT, PVM, and Lyman-alpha probes are shown.

UCI has been responsible for the operation and maintenance of the turbulence instrumentation package as well as processing of the data from its dedicated data system. Results of reduced data from this package are displayed in real time on board at 1 hz. Immediately after a flight, the data are processed and made available to investigators along with plots of most variables. Final processing with post calibrations, etc., are done at UTC within approximately three months.

The Twin Otter was used in the Japan/East Sea experiment (Khelif et al, 2005) where good wind, thermodynamic, and turbulence data were obtained. Additionally, the Twin Otter was used in CARMA where absolute humidity data from the fast response Lyman-alpha and temperature data revealed the fine structure at Sc cloud top and helped identify areas of detraining air parcels that were found to be strongly correlated with high scattering efficiency (Hegg et al, 2004). This fine structure was also captured by the open path LI-COR fast-response humidiometer, although its measurements were susceptible to liquid water accumulation on the source and detector windows during prolonged Sc penetrations. To make this sensor more suitable for in-cloud measurements, we are working on the design of a special housing to prevent liquid water from reaching its windows.

For POST, in addition to the surface flux measurements, the gust probe system will be an integral part of the instrumentation to enable correlations amongst sensors within tens of cm from each other. Such desirable sensor co-location was not possible on the NSF C-130 research aircraft in previous field studies as pointed out by Gerber et al (2005). The proposed flight plan includes porpoising near cloud top for which the technique of Tjernstrom (1993) will be used to obtain turbulence statistics from these shallow slant profiles. A short portion of one flight will be dedicated to wind maneuvers to verify the accuracy of the gust-probe system. Our measurements will address the hypotheses ***H1*** (kinetic energy), ***H2*** (w_e estimates), ***H3*** (water vapor flux), and ***H4*** (comparison with modeling results).

Year 1: Our effort in year 1 will be dedicated to the preparation and active participation in the field experiment in close collaboration with the other participants and the flight facility. The preparation phase will include LI-COR housing fabrication, instrument calibrations, data-system software upgrade to integrate signals from new sensors and to accommodate a faster recording rate (50 hz), flight planning, and flight testing. As mentioned above, we will run the turbulence measurement package on the Twin Otter during the field phase of POST, and provide first-look processed data to other investigators within 1-2 hrs. after landing.

Year 2: We will work on final data processing and analysis. We will be collaborating with the POST group and in particular with H. Gerber (fast PVM data), S. Malinowski (UFT data), and Qing Wang (shear entrainment).

3.2 Warsaw University (Szymon Malinowski, Krzysztof Haman, and students)

UFT (ultra-fast-temperature) and Small-Scale Mixing

We focus our efforts on understanding details of small-scale mixing processes at the top of the marine Sc. In particular we want to verify whether hypotheses ***H1-H3*** are true.

This will be done as follows:

1) Conduct detailed studies of the geometrical properties of the cloud-clear air interface evolving in course of mixing. We will analyze temperature, LWC, and humidity structure in order to verify whether stratocumulus top can be described in terms of fractal geometry (see Malinowski and Zawadski, 1993; Malinowski et al, 1994).

2) Study correlations of small-scale fluctuations between temperature, humidity, LWC, and local properties of droplet spectra to understand whether observed mean droplet spectra in the topmost region of the Sc are resulting from the completed inhomogenous/homogenous mixing process, or are resulting from random sampling of evolving mixing events in quasi-stationary mixing processes at cloud top (Haman et al, 2007).

3) Compare (conditional statistics) data collected in the cloud regions capping the updrafts that penetrate the inversion with data collected at the edges of cloud holes and inside the cloud holes. In this way we want to investigate whether mixing events in both regions are different. We want to verify if above the updraft "primary mixing events" prevail; i.e., mixing of the air from above the inversion with near-adiabatic cloud parcels. This may be in contrast with cloud-hole regions where we expect "secondary mixing events"; i.e., mixing of cloudy air with air from the EIL (which may be formed in primary mixing events).

4) Following the measurement period of POST we would like to perform high-resolution numerical simulations in the spirit of Andrejczuk et al (2004, 2006).The goal is to compare high-resolution records obtained during the measurements with proxy records re-constructed from simulations.

In order to perform the above analyses, co-located high-resolution measurements of temperature, humidity, LWC, and droplet spectra are needed, along with reliable and fast measurements of turbulence. The Warsaw University group will modernize, prepare, and deploy the UFT thermometer capable of measuring temperature structure in and out of cloud at cm scale (Haman et al, 2001) onboard the CIRPAS Twin Otter aircraft. We will participate in POST during the duration of this study, including the post-study Workshop. Data collected by UFT will be processed by Warsaw University, and both raw and processed data will be available just after collection/processing for all POST participants. UFT data will be released to the scientific community in the same time frame as the rest of the POST data.

The Atmospheric Physics Division is already involved in preparing for POST. We are developing a new data acquisition system for the UFT, as well as preparing an advanced version of the UFT sensor to be used on the Twin Otter.

3.3 Desert Research Institute (Jim Hudson, and student)

Cloud Condensation Nuclei, Microphysics

The Desert Research Institute (DRI) CCN spectrometers (Hudson 1989) have operated successfully throughout nearly all ~1800 hours of ~300 flights during 27 aircraft field projects over two decades. These were done on ten different aircraft including a Twin Otter. So far 33 peer-reviewed journal publications have resulted. These instruments simultaneously obtain CCN concentrations at more than 50 supersaturations (S) over the range of interest for clouds—0.02-2% with time resolution as low as 1s. This time resolution is faster than other CCN instruments and thus the DRI CCN instruments are most suitable for deployment in POST, which is focused on high-resolution measurements.

Five of the DRI-CCN aircraft projects were in California stratus (Hudson 1983a; Hudson and Frisbie 1991; Paluch et al. 1992; Hudson and Svensson 1995; Hudson and Xie 1999; Hudson et al. 2000; Yum and Hudson 2001a, 2002) and six others were also in marine stratus (Hudson and Li 1995; Hudson and Yum 1997; Yum et al 1998; Hudson et al. 1998; Yum and Hudson 2001a and b; Wylie and Hudson 2002; Yum and Hudson 2004). There were also surface CCN measurements associated with California coastal stratus (Hudson 1980; Hudson 1983b; Hudson and Rogers 1986; Hudson 1991; Hindman et al. 1993). A major stratus feature is the highly variable CCN concentrations just above cloud top, especially near California where there are usually layers of high concentrations more than 50% higher than below cloud (Hudson 2007a). But there are also sometimes (often?) low concentrations immediately adjacent to cloud top. These have been difficult to distinguish from the high concentration layers and the in-cloud measurements. But they should be distinguishable during the extensive porpoising and legs just above cloud top that are proposed here. CCN measurements within clouds are subject to splashing artifacts (false high concentrations) and false lower concentrations due to missing CCN within cloud droplets. Previously there has not been enough motivation to sufficiently discern the low and high concentrations just above stratus. These may in fact correspond to the EIL which is an important focus of POST.

Predecessors of the DRI CCN spectrometers compared well with the best CCN instruments tested in the last international CCN workshop (Kocmond et al. 1981; Hudson and Alofs 1981). The DRI instruments also agreed with size-resolved hygroscopicity predictions of CCN (Gasparini et al. 2006). Manuscripts will soon be submitted showing good agreement with DMT CCNs on aircraft during MASE and in surface measurements in Korea. In recent projects two DRI CCN spectrometers have made simultaneous measurements over different but overlapping S ranges. Since the lower part of the S range of an instrument is more challenging, the upper S part of the range of an instrument operating over a lower S range (e.g., 0.01-0.5%) can be used to check the performance of the lower S part of another instrument operating at a higher S range (e.g., 0.02-2%). Good agreement has usually been found approximately between 0.05 and 0.3% S (Hudson 2007a).

During the recent MASE project (July, 2005) off central California, which was at the same time and location proposed for POST, consistent solid stratus cloud layers were found. The major reason for the lack of cloud breaks was probably the high CCN and droplet concentrations that were consistently observed. Although this inhibited precipitation, droplet coalescence, nonetheless, apparently helped produce consistently lower CCN concentrations below these clouds. However, there was so much variability in the above cloud concentrations that the sign of the difference between below and above cloud concentrations was often supersaturation dependent. The relative differences in below and above cloud concentrations on different days was often related to relative differences in the back trajectories of the layers (Hudson 2007a). Coalescence and Brownian scavenging may be the reasons for the lower concentrations that were occasionally observed above cloud. The highly variable above cloud CCN concentrations (in contrast to more consistent sub-cloud concentrations) probably influenced droplet concentrations at many cloud levels. Therefore, it will be important to know the CCN concentrations at all levels in order to understand the effects of entrainment on the cloud droplet spectra in POST [i.e., ***H2*** (entrainment) and ***H4*** (modeling)]. Cloud droplet spectra in turn determine cloud albedo and precipitation efficiency, which are the largest climate uncertainty, the indirect aerosol effect (IAE; IPCC*,* 2001). The high-concentration layers above cloud top are mostly anthropogenic CCN, which is the general cause of IAE. An important outcome of POST will be to determine if and to what extent entrainment alters the microphysics of these clouds due to the highly variable anthropogenic CCN above cloud top.

A DRI CCN spectrometer will be mounted on the CIRPAS Twin Otter in June 2008 and this PI will operate it throughout the POST field study (July 2008). The spectrometer would also monitor occasionally the ambient aerosol volatility and size-supersaturation measurements to better characterize the CCN (Hudson and Da 1996; Hudson 2007b). A calibration rack for the CCN spectrometer will also be flown, weight permitting. In-situ calibrations would be done during ferry and within cloud legs of each flight. The calibrations are necessary in order to deduce CCN spectral measurements. Calibrations could also be done pre- and post-flights at the airport with the calibration rack outside of the aircraft. Preliminary CN and CCN concentration time plots and sounding plots will usually be made available to other investigators prior to subsequent flights.

Careful analysis of the spectrometer data will be necessary to distinguish the in-cloud from the out-of-cloud measurements by comparing with cloud droplet measurements such as with the PVM. This requires determining the lag time of the CCN spectrometer in relation to the cloud droplet measurements. Once the lag is established it should remain consistent for constant instrument flow rates. Comparisons will be made with the cloud droplet concentrations to determine the effective cloud supersaturations. Cloud base altitude and temperature measurements will be used to determine adiabatic liquid water contents at each level so that estimates can be made of adiabatic cloud droplet concentrations. This can be used to estimate the actual cloud supersaturations when compared with the CCN spectra (Hudson and Yum 2001, 2002) to produce the most meaningful "definition" of CCN. The effects of cloud top entrainment will be investigated by comparing the CCN spectral measurements with the cloud droplet spectral measurements at many levels. This will involve comparisons with other estimates of entrainment rates made by other POST investigators. The CCN spectrometer data will be reduced after the field study, and the data shared with all the POST investigators.

3.4 University of California Santa Cruz (Patrick Chuang, and student)

PDI Droplet Spectrometer, Microphysics

During POST, UC Santa Cruz (UCSC) will conduct measurements of the drop size distribution (DSD) using a phase-Doppler interferometer (PDI) (Bachalo and Houser, 1984; Bachalo and Sankar, 1998) in the size range of 4 to 200 um, with a sizing uncertainty conservatively estimated as ±1 um. The instrument has successfully flown on the CIRPAS Twin Otter during two past field missions the Marine Stratus Experiment (MASE), July 2005 and the Gulf of Mexico Atmospheric Composition and Climate Study (GoMACCS), September 2006.

Our typical data processing generates DSDs at 1 Hz with 128 logarithmically-spaced size bins in covering the entire size range. With a typical Twin Otter sampling speed of ~50 m/s, this corresponds to a length scale of ~50 m. However, higher time resolution measurements are highly desirable to achieve the objectives during POST. Based on our experience from MASE, the expected data rate when sampling in stratocumulus is ~1000 drops/s. This should be sufficient to generate 10 Hz (~5 m) DSDs with reasonable counting statistics, although it may be necessary to reduce the size resolution of the measured spectra in order to improve statistics.

Scientific questions relevant to POST objectives include the following: One of the primary goals of UCSC will be to work with the other POST PIs to address the over-arching questions and goals of the project. The DSD is strongly affected by a number of the critical processes believed to be involved in STBL dynamics, most notably entrainment (and subsequent evaporation, if any) and drizzle formation. The way in which these processes affect the DSD is generally highly distinct: cloud parcels where drizzle has formed generally exhibit a second mode (formed by collision-coalescence) at large size ~ 40 um, while entrainment typically shifts droplet number concentration to lower values (i.e. inhomogeneous mixing), but sometimes will also shift the DSD to smaller sizes (i.e. homogeneous mixing). These measurements, therefore, will support the faster PVM measurements which yields less information on why a region exhibits, for example, low LWC. Due to the central nature of these processes, the DSD measurements will be relevant to the testing of all hypotheses ***H1*** to ***H4***.

In addition, UCSC will also pursue specific science objectives related to cloud microphysical properties and evolution by examining the following questions:

How does entrainment mixing affect the cloud drop size distribution? The way that entrainment mixing affects the DSD is important for all processes that involve the microphysical scale, such as collision-coalescence, drizzle production, cloud albedo and IR cooling. In stratocumulus, measurements suggest that inhomogeneous mixing dominates at length scales larger than 10 m. However, this may be a function of the averaging length being incompatible with the mixing length scales, and therefore remains an open question.

How important is entrainment relative to drizzle in affecting the drop size distribution? Both entrainment and drizzle remove liquid water from cloud top, but are very different in their effects on the STBL (such as impacts on vertical energy and moisture budgets). In general, drizzle production requires collision-coalescence to broaden the DSD towards larger sizes. In contrast, entrainment mixing either reduces drop sizes (homogeneous) or drop number (inhomogeneous) or both. The microphysical signature of the two processes is therefore quite distinct, allowing us to determine the relative importance of these two critical processes, at least on a local (~10 to 100 m) scale. At larger scales, the picture is more complex, as addressed next.

How are drizzle and entrainment related to each other? On large-eddy scales, entrainment and drizzle feed back onto each other in complex ways. For example, entrainment can affect collision-coalescence rates not only through changes in the DSD, but also by possibly affecting production of turbulent kinetic energy, which in turn may alter turbulent collection and/or turbulent fluxes of moisture into the cloud layer. The myriad of feedbacks is likely to be best addressed through models. We propose to utilize a simple 1-D mixed-layer model (Lilly, 1968) to examine some of these interactions. Such a model, while simplified, can be a useful framework because the interactions are very transparent. More complex models (e.g. 3-D LES) may also be needed to study this question, and it is hoped that the LES simulations that will be conducted by the POST modeling PIs will play a role in addressing this question.

How do albedo-relevant microphysical parameters (cloud drop effective radius and dispersion) vary? What controls these parameters? Cloud albedo is one of the primary climate-related motivations for the study of the STBL. The effective radius and dispersion of the DSD are the controlling parameters of cloud albedo. We propose to examine how these properties vary spatially in stratocumulus. How are these horizontal variations affected by entrainment, drizzle, collision-coalescence, and the dynamical regime of the STBL.

Year 1: a. Participate in POST, including instrument integration on the CIRPAS Twin Otter.
b. Produce (within ~2 months) data files for other PIs to use in their analyses.

c. Collaborate with other POST PIs to address hypotheses ***H1*** to ***H4***.
d. Address the UCSC-specific scientific objectives outlined above.

Year 2: a. Complete Year 1(c) and 1(d) activities.
b. Publication of results.

3.5 Naval Post Graduate School (Qing Wang)

Shear-Induced Entrainment

The main focus of the NPS effort in POST is to understand the shear-induced entrainment process and to quantify this process in entrainment flux parameterizations. Specific questions to be pursued include a) Can we identify wave and wave breaking in the interfacial zone in the presence of mean wind shear? b) What are the characteristics of shear-induced mixing near the interface? How does mixing modify the cloud microphysics near the interface and below? c) How persistent are the shear-induced eddies? To what level can they penetrate into the boundary layer? d) Does shear in the interface enhance entrainment? e) How is entrainment due to shear parameterized. The following outlines specific efforts to be performed in each of the two years proposed by POST.

First year effort:

1) We will participate in the field measurement of POST. In particular, we plan to be actively involved in the planning of the Twin Otter measurements to generate the optimal flight plan for the overall objectives of POST.
2) Turbulence data reduction effort. We plan to work with CIRPAS (Johnsson) and UCI (Friehe and Khelif) on turbulence data reduction and calibration. Our past experience in this subject area with the CIRPAS Twin Otter measurements (Kalogiros and Wang, 2002 a, b) will be valuable in this task.
3) Examine the overall data quality for studying the fine-scale entrainment processes. In particular, we will examine the possible effects of liquid water on temperature, water vapor, and cloud droplet measurements which were known problems for in-cloud measurements (Wang and Lenschow 1995, Paluch and Lenschow 1991).
4) Case selection. Initial analyses on all POST flights will be performed to select cases of interests to our focus area: shear induced entrainment.

Second year effort:

The second year effort will focus on case analyses of shear-induced entrainment for POST cases. This analysis will address hypothesis ***H2*** to understand the small scale structure of the entrainment events and how they are connected to the structure of the EIL and particularly the wind shear across the EIL and above. In addition, we will combine the POST dataset with those from previous experiment to examine entrainment parameterizations, and thus address ***H4.*** We will:

1) Examine the characteristics of the entrainment events and relate the micro and macro properties of the events with the local shear conditions using the multiple porpoising legs and the horizontal legs from the Twin Otter measurements.
2) Calculate entrainment fluxes and entrainment velocity using multiple methods and examining the validity of existing entrainment parameterizations (e.g., Moeng 2000, Lilly 2002) using results from POST.
3) Develop improved entrainment flux parameterization to include the effects of wind shear across the inversion base. The POST data will add to our pool of data from previous field experiments for this purpose.

3.6 Gerber Scientific Inc. (Hermann Gerber)

Entrainment and EIL

Figure 4 shows a conceptual sketch illustrating physical processes affecting the STBL, processes that only have partial literature support, and that reflect the Scientific Issues and Hypotheses described in Section 2. The proposed effort will deal primarily with ***H2*** for which the conditional sampling of cloud holes generated by entrainment (Gerber et al, 2002, 2005) will be used to estimate the entrainment velocity w_e at Sc cloud top. The method relies on using the high-rate LWC data as the indicator variable for the presence of entrained parcels. This approach used on the C-130 during DYCOMS II resulted in reasonable range of w_e data on the C-130 during DYCOMS-II, values that can show improved accuracy over the previous aircraft data by optimizing the porpoising flight paths of the Twin Otter. An attempt will also be made to apply the "flux-jump" method (e.g., Faloona et al, 2005) to estimate w_e. The values of $w_e$wwill form one basis for comparisons with other measurements near Sc cloud top, and with modeling parameters that are thought to affect w_e.

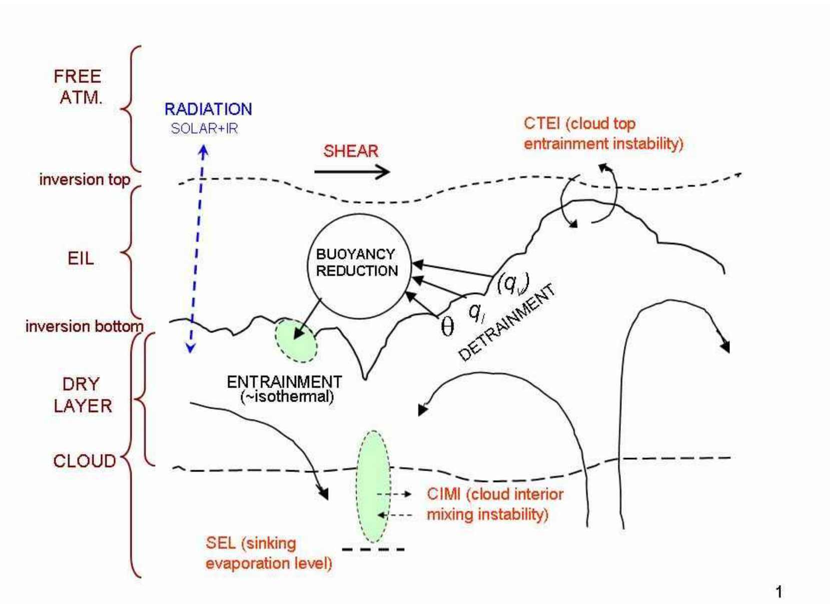

Figure 4 - Conceptual sketch of stratocumulus cloud top and the entrainment processes. EIL is the entrainment interface layer.

These measurements and modeling parameters include the role played by the EIL (moist, cool, cloud-free layer above cloud top) for which much still remains unknown (***H1***), including details of its geometry, thermodynamic and dynamic properties, and its relationship to CTEI and to w_e (***H3***). Measurements had suggested that the entrained parcels were basically isothermal (Gerber et al, 2005), thus negating the CTEI effect (e.g., Yamaguchi and Randall, 2007), and thereby causing inhomogenous mixing. However, this earlier suggestion was based on aircraft measurements that were less than ideal (e.g., Haman et al, 2007). The high resolution measurements of POST are designed to improve these earlier measurements to discover in part if CTEI plays a role and to what degree. Perhaps CTEI does play a role, as illustrated by Fig.1, because buoyant plumes contacting the free atmosphere are obviously needed to form the EIL.

The proposed effort will also participate in characterizing the EIL using the porpoising measurements from the Twin Otter. Of special interest is generating high-resolution "mixing diagrams" [such as mixing fractions ( ) vs buoyancy ($_v$), and $_l$ vs q_T] in the EIL using the fast UFT temperature and q_v measurements. These diagrams should provide new observational insight on the the dynamics within the EIL. Plotting vs $_v$ near Sc cloudtop has appeared in the literature several times (e.g., Wang and Albrecht, 1994; VanZanten and Duynkerke, 2002; Burnet and Brenguier, 2006; Haman et al, 2007), and in every case the assumption was made that the mixing occurs between free atmosphere and the cloud. That is not necessarily a good assumption. What may be happening is that numerous mixing events occur between the cloud and parcels in the EIL gradually reducing their buoyancy to the point where entrainment into cloud top is associated with a minimal buoyancy penalty. Figure 1 illustrates this possibility, in that the maximum temperature this mixing segment has for DYCOMS-II flight 3 is ~3 C, which is only 1/3 of the 9 C temperature jump between cloudtop and the free atmosphere for this flight. We also do not know what physical mechanism(s) ultimately entrains the air into cloudtop, nor do we know the hypothesized roles of CIMI and SEL as strongly LWC-depleted parcels caused by entrainment are forced to descend with the larger scale circulation; additional evaporative cooling may result. The high-rate co-located data on the Twin Otter will offer new insights on these processes.

Year 1: The P.I. will participate in the POST field study, and will deploy on the Twin Otter a fast PVM (Particulate Volume Monitor) for 1000-Hz measurement of LWC, PSA (total droplet surface area), and Re (droplet effective radius). Data reduction and analysis of the PVM measurement will we initiated, including the conditional sampling of entrained parcels near cloud top. He will participate in the post-POST science and data workshop.

Year 2: The effort for this year will continue to concentrate PVM data analyses, as well as collaborating with the POST participants that are measuring/calculating gust velocities, fluxes, ultra-fast temperature, and fast vapor mixing ratio; these all done in combination with the identification of entrained parcels using the conditional sampling approach. Also, collaboration will occur with the modeling efforts in providing parameters and profiles needed for those efforts. The P.I. will also serve as a collaborator with a proposed and related modeling effort ("Simulation and modeling of the entrainment interface layer in stratocumulus-topped boundary layers", Wunsch, Kerstein, Krueger) dealing with modeling scenarios similar to the Sc cloud-top scenario dealt with by POST. In both years the P.I. will perform the tasks associated with being the POST P.I. and manager.

3.7 University of Utah (Steven Krueger, and student)

Multiscale Modeling of Entrainment and Mixing

The goal of our project is to identify the mechanism by which air is ultimately entrained, and the scales that come into play in the mixing between the free atmosphere, the EIL, and the cloud, by using a combination of POST aircraft data and fine-scale numerical modeling; see hypothesis ***H4***.

Gerber et al. (2005;hereafter G05) concluded that the small temperature difference between the LWC-depleted downdrafts and the adjacent unaffected cloudy air at cloud top, and the existence of the entrainment interface layer (EIL) above cloud top, suggest that detrainment of cloudy air modifies the cloud-free EIL until a near buoyancy match is achieved between EIL and cloud top, at which point air is entrained into the cloud.

This scenario is consistent with our analyses of a high-resolution 3D LES (large-eddy simulation) of a stratocumulus-topped boundary layer (STBL) based on DYCOMS-II flight RF02 (Krueger et al. 2007; hereafter KBZ). We used a grid size of about 5 m in x, y, and z near cloud top. With this grid size features less than about 20 m across are poorly resolved. As a result KBZ found that the mode width of simulated cloud holes (regions of reduced liquid water, analyzed exactly as G05 did) is about 20 m, whereas G05 measured the average aircraft penetration length of cloud holes near cloud top to be about 12 m, and mean width of about 5 m. The remaining properties of the cloud holes in the LES were remarkably similar to those detected by aircraft. In particular, the LES cloud hole average buoyancy relative to the adjacent cloud was essentially zero (-0.03 K; the only value reported by G05 was -0.02 K for RF03), and LES cloud hole average vertical velocity was -.15 m/s (G05 found -.26 m/s averaged over all flights).

The simulated EIL structure is quite similar to the observed structure. Its average thickness is about 30 m, which is somewhat larger than the observed value of 22 m for RF03, but its properties as a function of mixing fraction of free atmospheric air (Fig. 5) are close to those presented by Burnet and Brenguier (2007). (Negative mixing fractions can be diagnosed when mixing is accompanied by radiative cooling or droplet sedimentation). In particular, the average vertical velocity is downward only for mixing fractions less than about 0.2 as observed.

Does the good agreement between this LES and the observations mean that the SGS processes have been adequately parameterized? SGS mixing in the LES is likely to be too rapid because the SGS model assumes that there is no SGS variability, which implies that SGS mixing and evaporation are instantaneous. For example, this assumption can have an impact when cloudy air is detrained into a subsaturated part of the EIL. Longer existence of detrained cloud droplets might produce greater radiative cooling in the EIL, while delaying but not other wise affecting the evaporative cooling.

One of the obstacles to improving parameterizations of stratocumulus cloud-top processes is that no 3-D simulation yet performed can serve as a benchmark calculation. Further compounding the difficulty is that there is no true laboratory analog for the STBL. *The fine scale measurements of the EIL that we propose to make during POST should be able to resolve the structures that are SGS in current LES*. We will then be in a better position for judging what kind of improvements will be needed before LES models can produce benchmark simulations, and for evaluating attempts to make such improvements.

High-rate measurements of LWC using the PVM during DYCOMS-II (e.g., Fig. 16 in G05) indicate that cloud-top entrainment and mixing in Sc involves cm scales. We expect that POST measurements will confirm this, and more importantly will provide *joint PDFs* of temperature, water vapor, liquid water, and vertical velocity for various averaging scales in the EIL. However, such PDFs represent only the variability resolved by the measurements. We can also determine the degree of unresolved mixing (which is a measure of the unresolved variability) by comparing the *co-located* measured values of the preceding variables to values expected if each measurement were from a completely mixed parcel, or from a completely unmixed parcel with the same mixing fraction. The mixing fraction can be diagnosed from the total water mixing ratio, if there is no sedimentation, and the radiation cooling of the parcel can then be calculated from the liquid water potential temperature VanZanten and Duynkerke, 2002).

Is LES using a 1-m grid size an option? The computational requirements of an LES with a 6-m grid size are large already: KBZ used about 1 hr of CPU time for each simulated second.(Wall-clock time is considerably less because our LES executes efficiently using parallel processing). KBZ used a technique in which they successively spin up smaller and smaller scales of motion as the grid is refined. Two more grid-size halvings

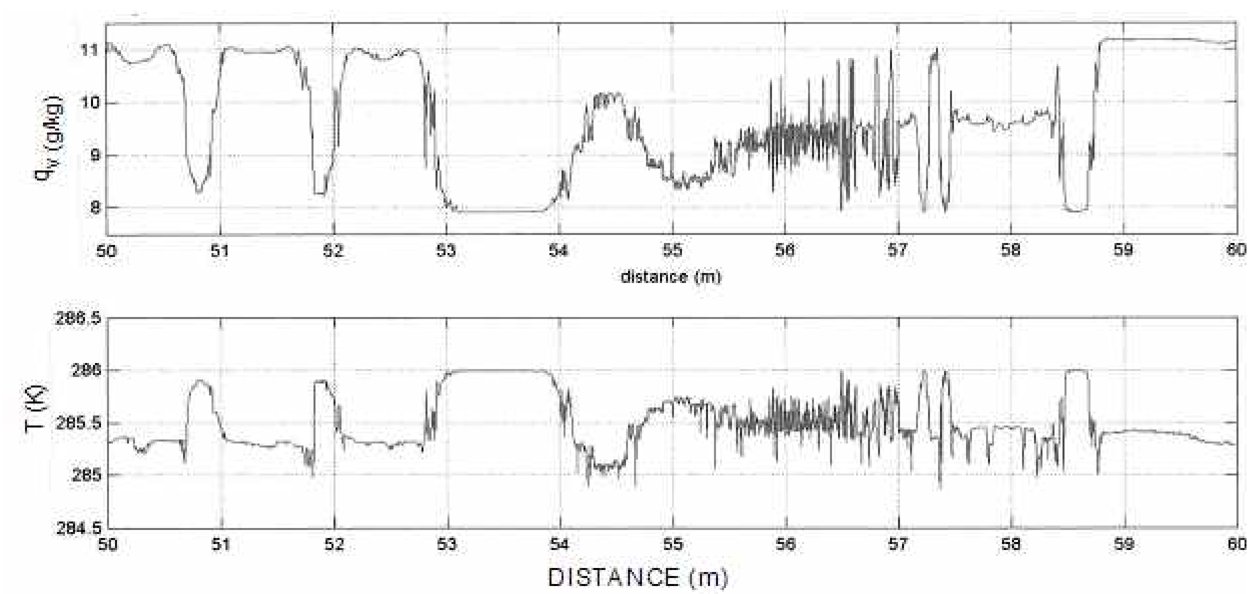

Figure 5 - 10-m record (1.67-mm resolution) of LEM (linear Eddy Model) output of water vapor mixing ratio (q) and temperature (T) for a 8-m wide parcel entrained into a trade-wing Cu with an updraft of 2 m/s. The temperature of the parcel is ~0.5 K warmer than the unaffected cloud. The data illustrates the various mixing states that are experienced on the way to final homogenization of the entrained parcel with the rest of the cloud.

would take us to about 1.5 m, with a CPU cost of about 250 hrs per second. A 5-min. simulation would take about 75,000 CPU hrs., which is feasible with current clustered multiprocessor systems, such as those at NCAR SCD.(My group has extensive experience executing our parallel LES on such systems).

An alternative approach to such a brute-force approach is to use a better SGS model to represent the fine-scale variability and mixing. A fairly simple improvement is to diagnose or predict the SCS scalar variances, then use these plus the grid-cell scalar means to specify a bivariate PDF with an assumed shape, such as a Gaussian (e.g., Sommeria and Deardorff, 1977).However in the EIL a single Gaussian PDF is not likely to be a good fit to the actual PDFs, which we expect to be highly bimodal, based on our LES results. The assumed PDF method can be used with more realistic PDFs such as those based on a combination of two Gaussians (e.g., Larson et al, 2002), but at the cost of additional prognostic equations.

We propose to use a novel, multiscale modeling approach to resolve cm-scale structure but circumvent the CPU constraints of 3D LES. In this approach, scales that are not resolved by the LES grid are resolved on a 1D domain in each LES grid cell by the Linear Eddy Model (LEM). The LEM was originally designed as a stand-alone model (Kerstein,1988; Krueger, 1993), but it has also been used as a subgrid mixing closure for LES of turbulent combustion (e.g., Chakravarthy and Menon, 2001). The LEM retains a distinction at all scales of the flow between the two processes involved in turbulent mixing: the reduction in length scale by turbulent advection and deformation, and molecular diffusion; see Fig.5.

In the LEM, liquid water content can be represented using a bulk approach, which predicts only its mixing ratio, or one can calculate the growth of individual droplets according to their local LEM environments. Both approaches have been successfully used in an entraining parcel model that incorporates the LEM (Krueger et al, 1997; Su et al, 1998). We propose to use both methods. The bulk approach will be used first because it is much less expensive, but can still be compared to high-rate measurements (e.g., Fig.4 in Krueger et al, 1997, shows model results using a grid size of 0.8 m).Later we will attempt to calculate individual droplet growth in the LEM domains (typically 100 droplets per meter).

3.8 Naval Research Laboratory (Shouping Wang, William Thompson, Tracy Haack, Anthony Bucholtz, Steven Miller)

Entrainment, Mesoscale/LES Modeling, Satellite Retrievals

Naval Research Laboratory (NRL) has many programs relevant to stratocumulus clouds and air-sea interaction in the marine boundary layer environment. Some of the current NRL research is intensively focused on the development and evolution of stratocumulus clouds over both open oceans and littoral areas. Therefore, the objectives of POST are consistent with these NRL research goals. The NRL strategy is to actively seek overlapping areas between the POST effort and those of NRL current and future programs and effectively collaborate with other POST scientists in these areas. The following issues have been identified as potential collaboration areas. The NRL effort in these areas with POST is of course contingent on the availability and priorities of Navy funds at the time of the POST mission.

1. *The cloud-top entrainment process.* This study has been actively pursued in the current NRL research project; it is also an important issue in some proposed future programs. The main focus is to, a) understand the wind-shear driven entrainment and its effect on the cloud properties, and b) investigate the impacts of microphysical processes such as the dynamic feedback of condensation/evaporation process (Wang et al., 2003) and the cloud droplet sedimentation (Bretherton et al., 2007). We will combine both modeling and observational approaches in this study. The NRL Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) is a versatile modeling and data assimilation system that includes comprehensive cloud, precipitation, aerosol and ocean components (Hodur, 1997). It was recently extended to perform as a LES model (Golaz et al. 2005). The NRL team intends to integrate the remote sensing and *in situ* measurements (particularly the high-frequency turbulence data near the cloud top) in POST into COAMPS-LES modeling system and carry out a number of specific case studies. We will attempt to address the scientific questions raised in previous sections in light of these simulations. Dr. Qing Wang of NPS plans to analyze the observations to investigate the wind-shear driven entrainment. We plan closely collaborate with her group. Based on the new understanding, we intend to address deficiencies in COAMPS mesoscale model entrainment prediction. The design of an entrainment parameterization appropriate for 3-10 km horizontal resolution mesoscale forecasts will be explored.

2. *The coastal mesoscale circulation and the entrainment*. Due to the complex coastline and topography along the central coast of Califoow-level jets frequently occurs, producing a significantly wind sheared inversion capping the well-mixed marine boundary layer (MBL) as discussed by Strom *et al*. (2000) and Burk and Thompson (1996). The entrainment regulated by the wind shear also controls the height of the MBL. We intend to use COAMPS and the POST data to explore the interaction between these two processes. NRL scientist have participated in several previous aircraft campaigns, including both providing real-time forecasts for mission planning and engaging in subsequent research utilizing flight and field data. These previous campaigns include Coastal Waves '96 (Dorman et al. 1999; Dorman et al. 2000; Haack et al. 2001), DYCOMS-II, and COSAT (Wetzel et al. 2001) and more recently AOSN off Monterey Bay. Process studies of individual case study days have been conducted to examine marine layer and stratus diurnal evolution and spatial variability. During POST, mesoscale model simulations of flight days will be essential in documenting limitations in the prediction of model-derived entrainment as well as potentially identifying specific processes contributing to cloud-top entrainment variability. COAMPS case studies and forecasts have also documented the rich variability in coastal mesoscale structure along the U.S. West Coast, including low level jets (Burk and Thompson 1996) and hydraulic effects (Haack et al. 2001; Dorman et al. 1999) associated with topographic forcing.

Since October of 1998 NRL scientists have been conducting 9-km resolution model forecasts over the U.S. West Coast and analyzing fields in support of a host of research objectives. These efforts entailed detailed examination of stratus and strato cumulus structure and evolution as well as surface forcing (Haack et al. 2005) in the context of air-sea coupling. Additionally, 3 km resolution forecasts for the Monterey Bay have been carried out in near real-time since summer 2003 in conjunction with AOSN objectives. This breadth of experience, our compatible research goals and availability of mesoscale model forecasts in this region, presents us with an ideal opportunity for collaboration and involvement with the POST field study.

3. *Satellite retrieval analysis.* Under the auspices of the NPOESS Integrated Program Office, NRL operates the NexSat web page (Miller et al., 2006; www.nrlmry.navy.mil/NEXSAT.html), which includes the study domain of interest to POST and could therefore produce near real-time satellite products to support such a field experiment (e.g., mission planning, flight coordination, and post-flight analysis). Included in the NexSat product suite are cloud mask/type (including low cloud detection at night), optical properties (optical depth, effective radius, water path), and cloud top heights. We produce these from GOES West for the East Pacific domain, with 1 km resolution in the day and 4 km at night. MODIS imagery down to 0.25 km pixel resolution is also available. We also process CloudSat radar data, providing cloud vertical profile information as well as light rain/drizzle regimes. Also of interest may be the QuiksCat scatterometer wind fields and MODIS/AVHRR aerosol optical depth products included on NexSat for this area.

While NexSat displays the data as imagery for ease of communication, we can make special arrangements to supply quantitative datasets for research purposes. NexSat offers a satellite pass prediction capability, facilitating the coordination of aircraft flights with key satellite overpasses. We would potentially benefit from any in situ data on cloud microphysics collected during the POST campaign, particularly in terms of the study of cloud top effective radius for marine stratocumulus and its potential correlation to drizzle modes (e.g., Miller and Stephens, 2001). We are currently using NexSat to support the Canadian CloudSat/CALIPSO Validation Project (C3VP), and previously (Summer 2005) it was used to support NASA's Tropical Cloud Systems and Processes IOP. Although we would not be a funded partner for this POST project, but we still envision participating and perhaps benefiting from the datasets. Conceivably we could open a dedicated "POST" box tailored with the specific applications and geographic coverage of interest, as we have done for the past experiments.

3.9 CIRPAS, Naval Post Graduate School (Haflidi Johnsson; see attached letter)

Twin Otter Instrumentation and Deployment

The instrumentation to be flown on the Twin Otter includes the following:

a. Standard Twin Otter Measurements

g. Lyman- Alpha (UCI)

b. PCASP, FSSP, CAPS, 2-D Probes
c. PDI (Phase Doppler Interferometer Probe)
d. UFT (ultra-fast temperature Probe)
e. PVM (particulate volume monitor)
f. Gust Probe
h. Lyman- Alpha (RAF/NCAR; Stuart Beaton)
i. CCN Counter
j. Satellite (NexSat, CloudSat, MODIS)
k. Digital Forward-Looking Video
l. Visible and IR Radiation (NRL/Anthony Buchholtz)

The flights of the Twin Otter will seek primarily unbroken Sc off the Monterey CA coast, with porpoising ~ 100 m above and below cloud top being stressed. The flights will also be conducted in a quasi-Lagrangian fashion following the mean flow in the mixed layer. Additional flight patterns will include horizontal paths near the sea surface for establishing surface fluxes, and will include profiles through the mixed layer to the free atmosphere to establish profiles of thermodynamics, microphysics, fluxes, and turbulence products needed for modeling. The deployment of the Twin Otter will depend on COAMPS modeling predictions, and on satellite remote sensing to establish a reasonable probability of intercepting Sc layers. The estimated 20 flights of the Twin Otter will be divided between night-time and day-time flights. The decision of where and when to fly the Twin Otter will also depend on input from the POST participants.

4.0 POST Science Team

Stuart Beaton; lyman-alpha, RAF/NCAR (*see letter of participation in Suppl. Docs. Section)*
Anthony Buchholtz; stabilized visible and ir radiation, NRL
Patrick Chuang; PDI and droplet spectra, UCSC
Carl Friehe; gust, lyman-alpha, temperature probes, UCI
Hermann Gerber; PVM, GSI (**P.I**., **manager**)
Wojciech Grabowski; modeling, MMM/NCAR *(see letter of interest in Suppl. Docs. Section)*
Tracy Haack; modeling, NRL
Krzysztof Haman; UFT, U. Of Warsaw
James Hudson; CCN, DRI
Haflidi Johnsson; Twin Otter, CIRPAS, NPGS (*see letter of participation in Suppl. Docs. Section)*
Djamal Khelif; gust, lyman alpha, temperature probes, UCI
Steven Krueger; modeling, U. of Utah (**Co-PI.**, **co-manager**)
Szymon Malinowski; UFT, U. Of Warsaw (**Co-PI***., see letter of participation in Suppl. Docs. Section)*
Steven Miller; NexSat/CloudDSat/Modis, NRL
William Thompson; modeling, NRL
Shouping Wang; modeling, NRL *(***Co-PI.***, see letter of participation of NRL team in Suppl. Docs. Section)*
Qing Wang; shear entrainment, NPGS
Rob Wood; satellite/entrainment, U. Of Washington *(see letter of participation in Suppl. Docs. Section)*
Takanobu Yamaguchi; modeling, CSU *(see letter of participation in Suppl. Docs. Section)*

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Warsaw, January 22nd, 2007

To Whom It May Concern

This is to express our interests in participation of the Atmospheric Physics Division (APD), Institute of Geophysics, Warsaw University, in POST (Physics of Stratocumulus Top) research project, planned for the next year.

Development and tests of the improved version of their Ultra-Fast-Thermometer (UFT), which is planned to be used in the measurement campaign on the board of CIRPASS Twin Otter research aircraft, is already included in the current (2007) research plan of APD and partially funded from our internal resources. A new electronic system together with the fast data logger, designed specially for the UFT thermometer, are under construction at the moment.

In case of successful application to NSF aimed at participation of APD in POST, subsequent research plans of APD will account for necessary data processing and analysis. We will also support dr Szymon Malinowski efforts to receive additional funds from Polish national and/or European resources.

Z-ca DYREKTORA
INSTYTUTU GEOFIZYKI
UNIWERSYTETU WARSZAWSKIEGO

dr Jacek Pniewski

DEPARTMENT OF THE NAVY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CA 93943-5100
CIRPAS
Center for Interdisciplinary Remotely-Piloted Aircraft Studies

Marina, 9 January 2007

Dr. Hermann Gerber
Gerber Scientific, Inc.
1643 Bentana Way
Reston, VA 22090

As per our earlier discussions, CIRPAS is prepared to support the POST experiment with its Twin Otter aircraft, instrumented with meteorological and particle instrumentation, as well as with office and laboratory space in its Marina hangar during the experiment. We will integrate other required instruments onto the aircraft, such as an ultrafast temperature probe (UFT), a fast particulate volume monitor (PVM), a Lyman Alpha hygrometer, and a CCN counter. Other instruments may be added as plans evolve and as aircraft power and capacity permit.

The flight activity will be conducted out of Marina, CA, in July 2008. We intend to fly a total of 100 hours in approximately 20 sorties, of which one or two may be primarily for shakedown and payload tests. Integration will take place earlier, at time coordinated so as to minimize interference with other possible flight activity.

The CIRPAS facility instruments will be calibrated and operated by CIRPAS personnel. Meteorological and particle size distribution data data will be reduced to ambient engineering units and will rest on thorough laboratory calibrations. All facility data will be freely shared with the other experiment participants, and will be available for quick look immediately after each flight. Data streams from some of the guest instruments may be integrated to the facility's data system as required, or as deemed desireable to minimize payload weight and power requirements.

With my best regards,

Haflidi H Jonsson
CIRPAS Chief Scientist

Cost estimate for the CIRPAS Twin Otter in POST

Project Title:	POST				
Location:	Marina, CA				
Principal Investigator:	Dr. Hermann Gerber				
Integration and Preparation period:	Phy 08				
Operation Period:	Jul-08				
Days of integration/preparation in Marina	15				
Days of operation in the field	30	Research:	30	Ferry:	4
Total requested flighthours	100	Research:	100	Ferry:	0
CIRPAS staff:	2 Pilots, 1 Mechanic, 2 Scientists				

CIRPAS/Naval Postgraduate School Summary

	Time (workdays)	Time (hours)	Cost (dollars)			
FACULTY LABOR						
a) Chief Scientist	52.5	420	$ 28,067			
b) Scientist	59.5	476	$ 24,830			
c) Data Acq Specialist	0	0	$ -			
Total Salary =	112	896	$ 52,897			
Labor acceleration (leave and benefits) =	42.0%		$ 22,217			
Total Labor =				$ 75,114		
INDIRECT COST						
Authorized indirect costs incurred for the support of research projects at NPS are included in this proposal and included such items as indirect labor, bid and proposal costs, page publications charges, and symposium presentation travel subsequent to project completion. Formula: Total salaries x 0.21				$ 15,774		
Travel						
Per Diem	$144	3	$432			
Air Travel	$500		$500			
Rental car	0	48	$0			
Travel Total:				$932		
EQUIPMENT/SUPPLIES/MISCELLANEOUS						
a) Equipment/Supplies (<$2,500)		$ 500				
b) Equipment/Supplies (>$2,500)		$ -				
Total Equipment/Supplies/Miscellaneous =				$ 500		
Twin Otter Scheduled and Unscheduled Maintenance and Operating Cost						
Flight Hrs: 100	Rate: $636/hr			$63,600		
CONTRACTS/TRANSFERS						
a) Prime Contractor						
CALTECH		$128,741				
b) MPIR:Anthony		$60,000				
Total Contracts/Transfers =		$411,6		$ 188,741		
NPS Direct Cost =					$ 344,660	
CIRPAS Indirect Charge =	19.43%				$ 66,968	
TOTAL =						**$ 411,628**

DEPARTMENT OF THE NAVY
NAVAL RESEARCH LABORATORY
MONTEREY, CALIFORNIA 93943-5006

IN REPLY REFER TO
19 January 2007

Dr. Hermann Gerber
Gerber Scientific
1643 Bentana Way
Reston, VA 20190

Dear Dr. ~~Gerber~~ Hermann:

This letter is to express my support of your proposed field experiment POST aimed at understanding the physics of marine stratocumulus clouds. I particularly welcome the planned collaboration between you and the scientists of NRL at Monterey.

Marine stratocumulus clouds have profound impact on the near surface winds, temperature, moisture, visibility and radiative transfer. They are crucial elements for the local weather forecast, the global climate, and of particular interest, to Navy operations. NRL has several ongoing programs relevant to stratocumulus clouds in marine boundary layers. Some of the current and proposed future research is intensively focused on the development and evolution of stratocumulus clouds over both open oceans and littoral areas. Therefore, the objectives of the POST are consistent with these NRL research goals. I strongly believe that the collaboration between the NRL and POST will benefit both the NRL and the proposed POST mission.

The goals of the NRL participation in POST include (a) investigation of the cloud-top entrainment process; (b) new understanding of the interaction between the entrainment and the coastal mesoscale flow; and (c) improvement of the entrainment representation in COAMPS. The NRL scientists intend to participate in planning of the field program; carry out COAMPS simulations; conduct observational comparisons of modeled clouds, turbulence structure and mesoscale flow; and perform satellite retrieval analysis. Because the NRL participation does not explicitly require NSF funding for NRL, the effort described above will be contingent on the availability and priorities of Navy funds at the time of the POST mission.

My point of contact is Dr. Shouping Wang (831-656-4719, shouping.wang@nrlmry.navy.mil). Please feel free to contact Dr. Wang or me at (831) 656-4721.

Simon W. Chang

SIMON W. CHANG
Superintendent

NCAR NATIONAL CENTER FOR ATMOSPHERIC RESEARCH MMM
MESOSCALE AND MICROSCALE METEOROLOGY DIVISION
P.O. Box 3000 • Boulder, Colorado • 80307–3000

12 January 2007

Dr. Herman Gerber
Gerber Scientific
Reston, Virginia

Dear Herman:

This letter is to support your proposal for the POST (Physics of Stratocumulus Top) field project and subsequent modeling studies concerning physical processes near tops of stratocumulus clouds using data collected in TOPS. I am interested in validation model simulations of small-scale entrainment and mixing, and their effect on the cloud condensate and cloud turbulence.

Sincerely,

W. Grabowski

Wojciech W. Grabowski
Senior Scientist

Phone: 303 497-8974 • FAX: 303 497-8181 • Telex: 989764 • EMAIL: grabow@ncar.ucar.edu

NCAR

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2007-Feb-20

Dr. Hermann Gerber
Gerber Scientific
1643 Bentana Way
Reston VA 20190
hgerber6@comcast.net

Dear Dr. Gerber,

This is the official approval of the Earth Observing Laboratory for Stuart Beaton to participate in the Physics of Stratocumulus Top (POST) project scheduled for July 2008.

As Dr. Beaton informed you, his participation is dependent on the successful development of the fast UV hygrometer and the availability of an instrument. At this time he expects both requirements to be met.

Sincerely,

Karyn Sawyer
Assistant Director
Earth Observing Laboratory

Colorado State University
Knowledge to Go Places

Department of Atmospheric Science
200 W. Lake St.
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Fort Collins, Colorado 80523-1371

phone: 970 491-5237
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email: tak@atmos.colostate.edu

Thursday, March 15, 2007

Dr. Hermann Gerber
Gerber Scientific, Inc.
1643 Bentana Way
Reston, VA 22090

I would like to acknowledge that the POST (Physics of Stratocumulus Tops) field project will enhance our understanding of marine stratocumulus and the processes that are associated with this cloud type. I am pleased to be able to participate, and I look forward to the excellent scientific work that will be done under the auspices of POST.

Sincerely,

T Yamaguchi

Takanobu Yamaguchi

UNIVERSITY OF WASHINGTON

Robert Wood
Assistant Professor
Department of Atmospheric Sciences
Box 351640
University of Washington
Seattle, WA 98195

Phone: 206-543-1203
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April 10th 2007

Hermann Gerber
Gerber Scientific Inc.
1643 Bentana Way
Reston, VA 20190

Dear Dr. Gerber,

I am writing to express my support for, and interest in, the *Physics of Stratocumulus Top* (POST) project that you are currently planning. Many problems associated with the entrainment process in stratocumulus remain poorly understood, which ultimately hinder our ability to predict these rates in our numerical models. The small spatiotemporal scales involved are particularly challenging from both a modeling and a measurement perspective. What we do know, chiefly from modeling studies, is that entrainment has a profound impact upon the thermodynamic properties of boundary layer clouds. These responses have a first order effect upon the regional radiative impacts and feedbacks of these clouds in response to changes in our climate system.

Recent project such as DYCOMS-II have provided important new insight into the processes that can impact entrainment in the MBL and our methodologies for measuring it, and the POST project will seek to build upon these using a suite of measurements that are collocated on the aircraft in a way that was not possible during DYCOMS-II. This will allow better investigation into the microphysical, thermodynamic, and dynamic properties of the small parcels entrained into the MBL. Together with the proposed high resolution modeling work which will be specifically focused upon the entrainment process, and the constraints upon entrainment rates provided by satellite measurements (detailed below), I believe that POST offers the possibility of making some important strides in this challenging problem.

Sincerely

Robert Wood

Encl: CV, Statement of Interest

UNIVERSITY OF WASHINGTON

Statement of Interest in participating in POST

Robert Wood, University of Washington

"Satellite estimates of the entrainment rate of free tropospheric air into the cloud capped marine boundary layer"

Recent work (Wood and Bretherton 2004) has demonstrated the potential to estimate entrainment rates using a combination of satellite and reanalysis data. The methodology is based upon a determination of the terms in the mass budget of the marine boundary layer (MBL). Satellite cloud top temperature measurements are used, together with a realistic model of the MBL vertical structure, to determine the depth of the MBL. Reanalysis and Quikscat winds are used to determine the horizontal advection of MBL mass, and together with the reanalysis subsidence rates can be used to estimate the entrainment rate into the MBL. To date, the technique has only been used to provide seasonal timescale estimates of the diurnal mean entrainment rate.

For POST, the plan is to make seasonal and sub-seasonal estimates of the entrainment rate for the study region (off the Californian coast) which will complement the aircraft-derived estimates and the modeling estimates. We will also investigate the feasibility of using MODIS and other datasets such as CALIPSO to determine the diurnal cycle of MBL depth and entrainment rate, which will further help to put the aircraft data into context. In conjunction with a NOAA project I have funding to use geostationary satellite measurements in a Lagrangian context, we will attempt to examine the temporal evolution of boundary layer depth using thermal IR data over short periods of time (12 hours or less), which will provide important constraints for the rate at which the boundary layer grows. These are critical for assessing the performance of numerical models such as LES and single column versions of climate models.

Wood, R., and Bretherton, C. S., 2004: Boundary layer depth, entrainment and decoupling in the cloud-capped subtropical and tropical marine boundary layer. *J. Clim.*, **17**, 3576-3588.