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6 June 1994

Bruce Wells
Office of Naval Research
University of New Mexico
Bandelier Hall West
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DTIC
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JUN 22 1994

Dear Mr. Wells:

Enclosed is the final report for contract N00014-84-K-0405. With the modification signed by you on 94May25, the final closing date was 94Apr30. This report outlines the accomplishments for the entire 10-year period of this contract.

Unfortunately, when I accepted a job with the private sector a year ago, the analysis of the data that was gathered during ASTEX had just begun. I began collaborations with other scientists who were interested in carrying on the my work, but Dr. Abbey was not open to supporting them. Thus, much of the work of the latter years of this contract remains unpublished.

Sincerely,

DTIC QUALITY INSPECTED

[Handwritten Signature]
Siri Jodha Singh Khalsa
Scientist,
Applied Research Corp.

cc: Robert Abbey



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13. ABSTRACT (Maximum 200 words) Work under this contract focused on turbulent processes in the marine atmospheric boundary layer (MABL) and how they effect mixing between ocean and the free atmosphere. In particular, we investigated specific mechanisms of this turbulence within the MABL and how these mechanisms responded to varying boundary and internal forcing. By developing, from both observational and theorretical perspectives, a coherent picture of MABL turbulence in terms of the mechanics of turbulence, we gained new insight into the behavior of the MABL which will lead to improved predictability.				
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**Turbulent Transfer in the Marine Planetary Boundary Layer
Contract No. N00014-84-K-0405**

Siri Jodha S. Khalsa
Howard P. Hanson

FINAL REPORT

The goal of this research is to gain a better understanding of turbulent transport and entrainment mechanisms in the marine planetary boundary layer (MPBL) through identification and analysis of the individual convective and entraining elements of the turbulent flow. This event-oriented analysis provides insights into fundamental aspects of MPBL dynamics, thermodynamics and microphysics control features such as inversion height, cloud amount, and cloud reflectivity.

The core of our observational methodology is conditional sampling of aircraft data. Time series of high-frequency fluctuations in wind components, temperature, humidity, liquid water and mixing ratios of chemical species and cloud droplet and aerosol particle data are subjected to a discrimination analysis. From this we obtain the characteristics of the significant mixing events in the time series which convey fundamental information on the MPBL. Analyses of aircraft data has been carried out in parallel with model development which incorporates explicit treatment of convective elements.

Our research program began with an aircraft study over the tropical central Pacific Ocean, the Christmas Island Experiment. A thorough statistical description of updrafts and downdrafts through the entire depth of the undisturbed MABL was obtained (Greenhut and Khalsa, 1987). Entrainment processes at the capping inversion were also investigated (Khalsa and Greenhut, 1987). Two types of coherent downdrafts were discovered near the inversion using conditional sampling of the aircraft data: downdrafts that were the result of overturning updrafts and downdrafts whose signatures suggested origins above the inversion.

The next project that we were involved with was the Frontal Air-Sea Interaction Experiment, FASINEX, whose goals were to describe the change in turbulence structure in the MPBL with a change in surface conditions across a sea surface temperature front.

The focus of later research was to learn more about the mechanisms that control the downstream evolution of marine stratocumulus (MSc) into fairweather cumulus. Aircraft measurements taken during the First ISCCP Regional Experiment, FIRE, marine stratocumulus field program off the southern California coast were being analyzed for evidence of cloud-top entrainment instability (CTEI) and cloud/subcloud layer decoupling, both mechanisms that can lead to cloud breakup.

Finally, we helped plan for and participated in the Atlantic Stratocumulus Transition Experiment (ASTEX), to further investigate the mechanisms that determine boundary layer cloud type and amount.

Another research direction that was begun towards the end of this contract was an attempt to improve the measurement and modeling of air-sea fluxes through a new statistical description of surface layer turbulence where the flow is decomposed of randomly distributed intermittent events having similar statistical properties obeying "local" stationary. Our reasoning was that if scaling laws, such as Monin-Obukhov Similarity Theory, could be shown to apply to these locally stationary events, then intermittency, which has been a limiting factor for in situ flux measurements, could be simply accounted for. As a result, statistically significant, short term estimates of air-sea fluxes could be obtained enabling improved parameterizations of these fluxes.

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FASINEX

In the unstable marine planetary boundary layer (MPBL) turbulence is responsible for distributing heat, moisture and other properties through the layer. Under quasi-stationary conditions the result is well-mixed vertical profiles of these quantities. When conditions at the upper or lower boundaries change this well-mixed structure is altered while the layer adjusts to these new conditions. FASINEX provided an opportunity to study the response of the MPBL to changes in surface forcing in the form of a 2°C discontinuity in sea surface temperature. Khalsa and Greenhut (1989) and Rogers (1989) examined a case in which the boundary layer flow was such that it brought air from over warm water to over cool water. Khalsa and Greenhut (1989) found that over the warm water evidence for enhanced entrainment at the capping inversion was evident deep into the boundary layer. Rogers (1989) documented the formation of an internal boundary layer, which is a shallow layer that is adjusted to the new surface conditions and which grows downstream until it has replaced the previous boundary layer. The formation of an internal boundary layer is typical for a transition from unstable to stable or near neutral.

The February 16 case of FASINEX represented the opposite case, one in which the air flow was from cool to warm water. The adjustment of the boundary layer to such a transition is expected to be more rapid than in the warm-to-cool case since the downwind conditions are unstable and thus conducive to rapid mixing and adjustment of the MPBL to the new surface conditions. On Feb. 16 the NOAA WP-3D aircraft made measurements 35 km north and 64 south of the surface temperature discontinuity on a series of vertically aligned tracks. Composite profiles of winds, temperature and humidity were obtained from the ascents and descents that the aircraft made in executing these stacks.

The variation of temperature and humidity in the vertical are very similar on the two sides of the front, indicating that by the time that air had reached the location of the southern stack the boundary layer had been uniformly warmed and moistened. The inversion had risen from 1500 to 1700 m and cloud base, marked by the point where humidity begins to decrease with height, was slightly lower at the southern stack. Cloud amount had increased from 25% at the location of the northern stack to 50% at the southern stack.

The profiles of sensible heat flux, Q_s , are nearly identical, also suggesting that the boundary layer was in equilibrium with the surface forcing on both sides of the front. In both cases sensible heat flux is downward just below cloud base, a common occurrence.

On the cold side the vertical moisture flux, Q_E , decreases sharply with height in the subcloud layer, similar to the heat flux. The heat and moisture flux values near cloud base are such that the buoyancy flux is negative here, implying that there is little mixing taking place across cloud base. This suggests that the cloud layer was decoupled from the subcloud layer; only the strongest updrafts are able to penetrate this stable layer and initiate the few small cumulus clouds found there.

The moisture flux profile on the warm side tells a completely different story. The decrease with height is very slight; at cloud base the value of Q_E is only about 10% smaller than the surface value. Why, when all other indicators discussed so far indicate an equilibrium state, is the moisture flux profile on the warm side so different from that on the cold side?

As air flowed from cool to warm water the input of heat and moisture to the boundary layer increased. At the position of the southern stack this additional heat and moisture appeared to be uniformly distributed through the boundary layer. As the near-surface temperature and moisture increased, the air-sea contrasts were reduced and this, together with reduced wind speeds over the warmer water, produced new equilibrium surface values of Q_s and Q_E that were close to those over the cool water.

Despite the nearly identical surface latent and sensible heat flux values, there appeared to be greater entrainment across the inversion over the warmer water. Conditional sampling statistics show an increased frequency and greater vertical velocity magnitude for dry downdrafts over the warm water. These properties were seen well below cloud base. Conditional sampling also revealed that the humidity perturbations in updrafts and downdrafts were 3 - 4 times as large over warm water. This was the principal reason for the difference in moisture fluxes away from the surface.

Over warm water dry downdrafts produce most of the negative sensible heat flux at cloud base. Over the cool water it is cool updrafts, which have overshot their level of neutral buoyancy, that are mostly responsible for the negative Q_s and buoyancy flux. What is remarkable is how different processes on the two sides of the surface temperature discontinuity can produce such similar heat flux profiles.

We conclude that the boundary layer measured at the southern stack is not in equilibrium. We expect that entrainment will eventually dry out the cloud layer, reducing cloud cover and returning the Q_E profile to something resembling what it was over the cool water.

These results demonstrate that the MABL more readily adjusts to changes in temperature than it does to changes in moisture. This is due to the fact that entrainment across the inversion and input from the surface both tend to warm the boundary layer whereas the former tends to dry and the latter tends to moisten the boundary layer. Similar behavior over land has been reported by Mahrt (1990).

FIRE

Fast-response ozone measurements from flights of the NCAR Electra during FIRE MSC field operations have been used to conditionally sample entrainment events near the top of a marine stratocumulus cloud. A strong gradient in ozone across the top of the boundary layer off the coast of California allows this measurement to be used as a tracer of entrained air. However, the data from the instrument is quite noisy and special adaptive filtering techniques must be applied before the data can be used for this purpose.

Results from the analysis of the 7 July 1987 FIRE mission have shown the prevalence of evaporatively cooled, negatively buoyant air parcels within a persistent MSc cloud layer. This result is significant because it had been thought that production of such air parcels by the mixing of inversion and cloud layer air should lead to cloud breakup (Khalsa, 1989).

An analysis of the 16 July 1987 FIRE mission produced a startling result: that the water content of the atmosphere above the cloud-top inversion was sufficiently large in one region to provide a moisture source for the cloud (Hanson, 1989). This result is important in that it shows the importance of cloud-top entrainment in controlling cloud thickness, liquid water content, and radiative properties.

Conditional sampling of cloud microphysical properties and ozone mixing ratio measured by the NCAR Electra during the FIRE MSc field program has confirmed preliminary analyses which suggested that negatively buoyant air parcels existing within a persistent MSc cloud layer were produced by evaporative cooling. Nicholls (1989) concluded from his conditional sampling analysis that cool downdrafts near cloud top were produced through radiative cooling. Our finding is significant because it had been thought that production of negatively buoyant parcels by the mixing of inversion and cloud layer air should lead to cloud breakup. Conditional sampling results of this case also show that the drying effect produced by the sinking of such parcels through the cloud layer is compensated for by the supply of moisture from surface-based plumes, contrary to implications that the cloud layer was decoupled from the subcloud layer as indicated by weak mean buoyancy flux at cloud base (Khalsa, 1990).

When warm, dry air from above the inversion that caps the MPBL is entrained down into the top of a stratocumulus cloud layer, some of the droplets in the resulting mixture evaporate. Under certain conditions the resultant cooling can cause the parcel to become negatively buoyant and sink, thus enhancing entrainment. Knowledge of such events is critical to testing some of the proposed mechanisms for stratocumulus breakup. In measurements made near the inversion, it is difficult to distinguish such evaporative cooling events because radiative cooling can also produce negatively buoyant parcels. Furthermore, the fraction of inversion layer air typically found in such events is only 2 to 3 percent, making it difficult to identify these events by quantities such as total water mixing ratio. Ozone mixing ratio, however, provides a means of clearly identifying these events when suitably conditioned.

Conditionally sampled cloud droplet and aerosol data for entrainment events as identified through ozone mixing ratio have produced compelling evidence for evaporative cooling of these parcels. Particle spectra taken near cloud top in FIRE show an increase in smaller droplet sizes for high ozone air which is likely the result of evaporation, since for a given subsaturation the smallest droplets will decrease in size at a faster rate than large droplets. A peak in large aerosols for high ozone air is most likely the remnants of evaporated droplets.

The results cited above confirm the benefits of analyzing and modeling MPBL turbulence as being composed of discrete convecting elements. The most significant accomplishment of the past year has been the conditional sampling evidence of cloud-top entrainment instability within a persisting MSc cloud layer. Conditional sampling also shows that updrafts supplied the moisture needed to maintain the layer in the presence of CTEI.

The variance of vertical velocity was larger in the cloud layer and just below cloud base than at the 50m level above the surface, suggesting that CTEI was a major source of turbulence kinetic energy for the boundary layer. The fact that the cloud layer persisted despite this large input of turbulence kinetic energy by evaporatively cooled downdrafts suggests that the transport of moisture into the cloud layer by surface-based updrafts was compensating for the drying due to entrainment. A large upward moisture flux was in fact measured at cloud base.

In a model simulation of stratus-topped boundary layer, Siems et al. (1989) found that evaporative enhancement of entrainment (EEE) can lead to cloud breakup only when the cloud layer is cut off from the moisture supply from the surface. The cool/dry downdrafts we found just below cloud base were negatively buoyant, showing that the circulations produced by EEE extended well into the subcloud layer, preventing the decoupling of the cloud and subcloud layers.

The direct measurement of the properties of entraining downdrafts and penetrating updrafts has allowed us to test several aspects of theories dealing with the maintenance of marine stratocumulus layers. Further advances in the prediction MSc will follow from this combination of observation and theory.

MODELING

Results from integrations of a MPBL model that explicitly incorporates the mechanisms of turbulence transport and entrainment, namely, discrete updrafts and downdrafts, have been compared with statistics of updrafts and downdrafts obtained through conditional sampling analyses of aircraft data. The good agreement of the model with observations is encouraging to further development the model. Our analyses have also shown that diabatic processes (radiative transfer and phase change of water substance) have little effect on the plumes' dynamics. In addition, it appears possible to linearize these dynamics and thus to include the turbulence transport by the plumes in the MPBL model in a quasi-analytic fashion.

ASTEX

Analysis of fast- and slow-rate data collected by the NCAR Electra during the ASTEX field operations was performed in Santa Maria, Azores. This benefited flight planning and data quality evaluation. Also, evidence of contamination of surface sampling sites by an upwind island and signatures of surface ship wakes were discovered by this in-the-field analysis of the aircraft data.

On 16 June 1992, the NCAR Electra and UK C130 probed two different airmasses with distinct thermodynamic and microphysical properties. Low clouds in the vicinity of the R/V Malcolm Baldrige and R/V Oceanus were in the midst of a rapid breakup when the Electra arrived. Time series from subcloud flight legs show very warm and dry downdrafts with high concentrations of ozone, indicating entrained air. These observations are supported by conditional sampling analysis which shows that in the mean high ozone events are warm and dry downdrafts whose perturbations are larger in magnitude than the converse, low-ozone updrafts. Further analysis was planned to confirm the role of entrainment in the breakup process on this and other days.

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