

# Drizzle and Entrainment in Coastal Marine Stratocumulus Clouds

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## LONG-TERM GOAL

The long term-goal of this project is to provide an improved description and understanding of the effects of drizzle and entrainment on coastal marine boundary layer clouds that will establish a basis for developing, improving, and evaluating cloud and boundary layer representations in LES, mesoscale and large-scale forecast models.

## OBJECTIVES

- Characterize vertical distribution of drizzle and how it relates to cloud circulations
- Investigate the relative role of cloud thickness and cloud turbulence levels on drizzle production
- Explore the mesoscale and convective-scale variability of drizzle
- Study the relationship of coherent eddies in the boundary layer to entrainment
- Document the structure and characteristics of entrainment circulations for a wide-range of stability and shear conditions
- Define the evolution of turbulence and coherent boundary layer structures during the formation and dissipation of coastal stratus

## APPROACH

Observations from a suite of surface-based remote sensing systems were used to resolve the fine-scale microphysical and turbulence structure in coastal stratocumulus clouds. The centerpiece for the surface-based remote sensing is a short wavelength (3 mm) Doppler radar. Spectral processing of Doppler signals from this radar is being used for cloud microphysical and turbulence retrievals. Liquid water path was observed continuously from the site using a microwave radiometer operated by Dr. Roger Marchand from Penn State University. Continuous observations of boundary layer height and winds were obtained from the Naval Postgraduate School (NPS) 915 MHz wind profiler. The Twin Otter research aircraft operated by the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) provided *in situ* observations for evaluating and improving the remote sensing retrievals and providing details of drizzle and entrainment processes.

# Report Documentation Page

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## WORK COMPLETED

Initial work on this project involved the development of hardware and analysis techniques for the June-July 1999 field deployment in Monterey. During this deployment the remote sensing systems were operated from a site on the shore of Monterey Bay near Marina, California. From 14 June to 9 July 1999 more than 100 hours of high-quality cloud observations were made with the UM 94 GHz radar. Doppler spectra were obtained at 3-second intervals and a vertical resolution of 30 m. Supporting observations were made continually with the microwave radiometer, two ceilometers, upward looking short-wave and long wave radiometers, standard surface meteorological instruments, and rawinsondes. The Naval Postgraduate School 915 MHz wind profiler provided continuous observations of low-level winds and boundary layer depth. A total of 20 flights were made with the CIRPAS Twin Otter to provide aerosol, cloud microphysics, and turbulence measurements in support of this and several other related projects. Descriptions of operations, instruments and synoptic conditions and results from initial analyses are available at the Drizzle and Entrainment Cloud Studies (DECS) Internet site <http://orca.rsmas.miami.edu/monterey/>

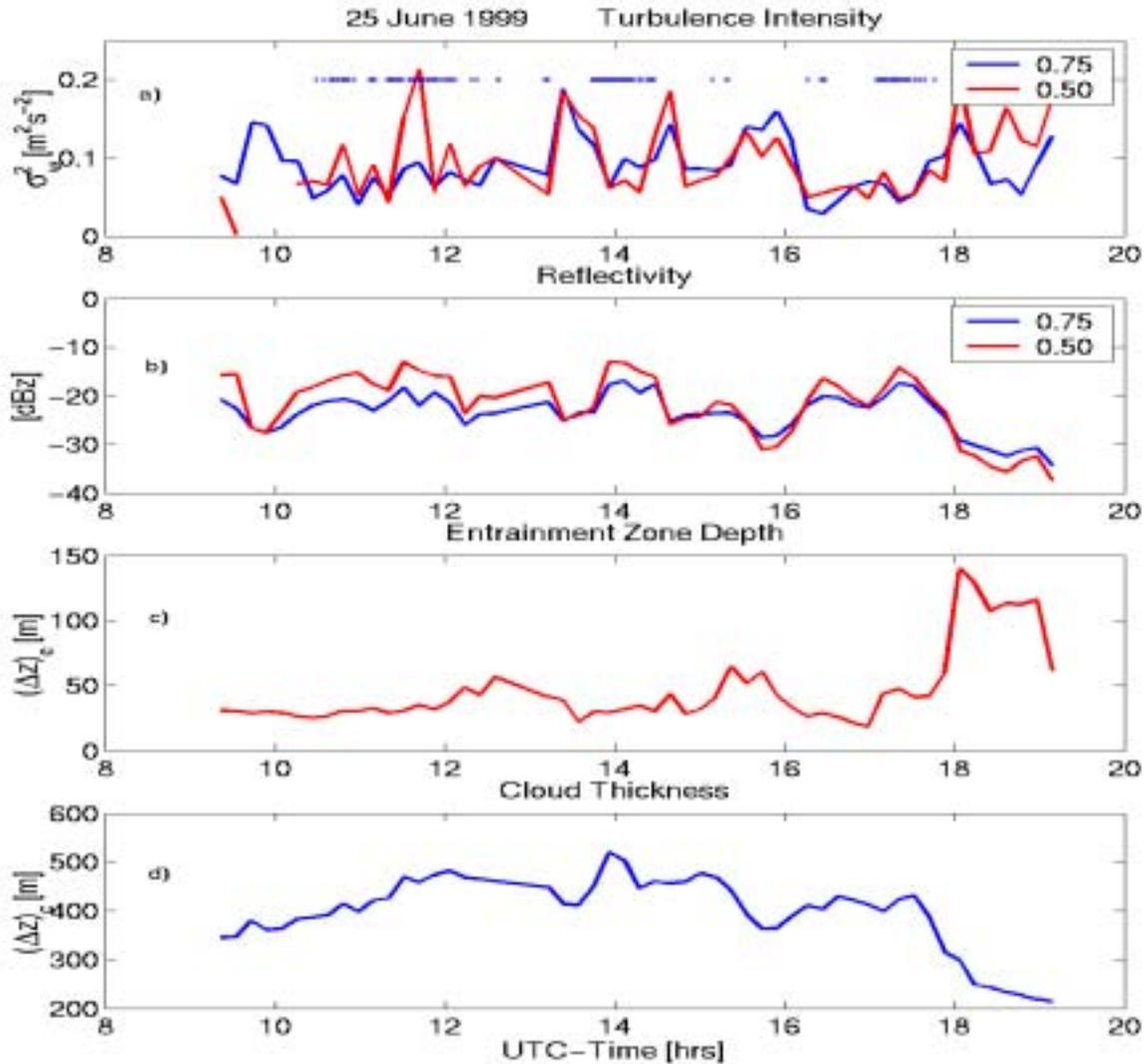
The spectral observations from the 94 Doppler GHz radar observations made during DECS have been processed to provide estimates of reflectivity (1<sup>st</sup> moment), mean Doppler vertical velocity (2<sup>nd</sup> moment), and spectral width (3<sup>rd</sup> moment) for all of the radar data collected. The radar observations have been combined with other remote sensing and in situ measurements to define the macroscopic structures of the clouds and their environment. A technique based on the Frisch et al. (1995a,b) method had been developed and tested and applied to all of the data collected during DECS to characterize drizzle. The moment data from the radar have been used to examine the relative role of cloud turbulence levels, the entrainment depth zone, and cloud thickness during drizzle and non-drizzle time periods. Mass flux profiles were obtained using techniques described by Kollias and Albrecht (2000).

Plans have been made to use a 95 GHz FM-CW radar, which has been developed under an ONR sponsored SBRI, on the CIRPAS Twin Otter to study entrainment circulations at the top of the cloudy boundary layer. This study is planned for summer 2002.

## RESULTS

Excellent cloud conditions were observed during DECS. Cloud top ranged from about 400-600 m with cloud base extending from near the surface to 200 m. Drizzle, mainly occurring during the night and in the early morning hours, was often observed in clouds that were more than 400 m thick. Drizzle and non-drizzle data periods were identified using the 1<sup>st</sup> and 2<sup>nd</sup> moment of the radar spectra. Drizzle was differentiated by a Reflectivity larger than  $-15$  dBz and a mean Doppler velocity of less than  $-0.5$  ms<sup>-1</sup>. Five days of observations have been analyzed in detail. These analyses include spectra of the vertical velocities observed in the cloud, vertical distributions of drizzle characteristics at 3-second intervals, calculation of the updraft and mass flux profiles using direct and statistical techniques, detailed time series of cloud macroscopic properties, cloud layer turbulence, and drizzle properties. On the days studied, observations typically extend from nighttime periods when clouds are relatively solid through the dissipation of these clouds during the day. An example of the analyses that have been completed for each case studied is shown in Figure 1. This figure shows the cloud turbulence, entrainment-depth, and cloud thickness during drizzle and non-drizzle time periods. These results are consistent with a suppression of resolvable scale turbulence during the drizzle periods. While this is not conclusive, it does agree with Feingold et al., (1999) findings of suppressed turbulence during drizzle episodes and contradicts the hypothesis that turbulence may enhance the formation of drizzle.

Further, these observations have also allowed us to capture the evolution of cloud layer structure and the entrainment zone as the cloud thins and dissipates. The five days studied include 2 days when no drizzle is observed. Thus we can compare turbulence levels and cloud thickness and other macroscopic properties observed under these various conditions.



**Figure 1:** Evolution of turbulence and cloud macroscopic properties from ~10 hours of observations made from the UM 94 GHz radar and ceilometer for a stratocumulus cloud that exhibited episodic periods of drizzle as indicated by the +’s shown in panel (a). Ten-minute averages of 3-second data from the radar were used in this analysis and includes (a) vertical velocity variance  $\sigma_w^2$  at the 0.75 (blue line) and 0.5 (red line) normalized cloud depth levels, (b) radar reflectivity at these two levels, (c) entrainment zone depth (depth between the cloud top and 6 dBz increase in the reflectivity level below cloud top), (d) and cloud thickness. Data extend from 9 – 19 UTC (2-12PST) and capture dissipation of the layer at the end of the period.

## **IMPACT/APPLICATION**

The cloud and boundary layer observations made during the field phase of this project represent a unique data set for studying the dynamics and microphysics of coastal stratus clouds. Doppler spectra obtained from the cloud radar represent the most extensive and detailed observations of this type in marine coastal stratus. The analysis of these data has advanced our understanding of the drizzle processes. To date the most relevant accomplishment has been a demonstration of the utility of using Doppler velocity spectra from a 94 GHz radar for characterizing drizzle and entrainment in coastal stratus clouds. The extensive and unique set of radar observations made during DECS provide the basis for developing comprehensive statistics on drizzle characteristics, examining entrainment and drizzle processes, and developing observing strategies and analysis techniques for advancing the use of mm-wavelength radars for boundary layer cloud studies.

## **TRANSITIONS**

The techniques developed to retrieve cloud microphysics and turbulence from the radar observations provide a basis for further development and application of similar retrieval techniques for use with the 94 GHz radar that is being developed under an ONR initiative. The cloud and boundary layer observations made during the field phase of DECS will be available for comparison with the boundary layer and cloud structure from NRL COAMPS simulations made over the area of interest.

## **RELATED PROJECTS**

Several scientists were involved in related projects during the Monterey coastal cloud experiment. Qing Wang from the Naval Postgraduate School was heavily involved with the CIRPAS Twin Otter in support of a NSF study of the interaction between coastal flows and marine stratocumulus. Dean Hegg of University of Washington and Rick Flagan of CalTech were involved in aerosol studies using the CIRPAS aircraft during DECS. Graeme Stephens headed a NASA/DOE project in support of CloudSat, a NASA project to use a 94 GHz radar in space. In support of this project, an airborne cloud radar was operated by the University of Mass on a DOE Twin Otter during DECS. This aircraft flew coordinated patterns over the CIRPAS Twin

## **SUMMARY**

The use of a Doppler millimeter wavelength radar for remotely characterizing drizzle and entrainment in coastal stratus clouds has been demonstrated. These characterizations give a sampling of the vertical structures within clouds that is unattainable from conventional instruments and provides a new understanding of processes critical to the formation, maintenance, and dissipation of low-level clouds. This study will facilitate the deployment and application of an airborne millimeter wavelength radar being developed under ONR sponsorship. This air-borne capability will provide opportunities to study boundary layer clouds over marine areas that cannot be accessed easily by surface-based platforms. Our participation in this research has assisted the Rosenstiel School of Marine and Atmospheric Sciences at the University of Miami in establishing a well-recognized center for the application of mm-wavelength radars to meteorological scientific studies.

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