Maritime and Continental Stratocumulus

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1. Introduction

Low-level stratus clouds are important modulators of the Earth's radiation budget. ERBE analyses (e.g. Ramanathan et al. 1989; Harrison et al. 1990; Klein and Hartmann 1993) clearly show the contribution of these clouds to the cloud forcing (the difference between the net radiative flux observed at the top of the atmosphere and that for clear-sky conditions at the same location). Oceanic stratus clouds cover a large area of the Earth's surface and contribute substantially to a global net cloud forcing of about -17 Wm^{-2}. The regional distribution of the cloud forcing is not uniform as shown in Fig. 1. In addition, estimates like those of Slingo (1990) show that a decrease in the droplet size or increases in either the amount or water content of low-level clouds could balance the radiative perturbation associated with an increase in CO_2. Consequently, marine stratocumulus clouds have been the focus of recent major field programs (FIRE, First International Satellite Cloud Climatology Regional Experiment, 1987, and ASTEX, the Atlantic Stratocumulus Transition Experiment, 1992). These experiments have provided an unprecedented observational basis for understanding processes important for the formation, maintenance, and dissipation of marine stratocumulus clouds and their representation in climate models. Thus the FIRE 1987 stratocumulus experiment and ASTEX substantially reversed the situation in the early 1980's when (Randall et al. 1984) noted that there were insufficient observations to test existing theories and models of marine stratocumulus.

Stratocumulus clouds are also observed frequently over some land areas. A substantial area of negative cloud forcing over the northeast US is associated with low-level clouds observed in this area (Fig. 1). Although continental stratocumulus clouds may have less of an effect on the global cloud forcing than marine clouds, they substantially impact the local climate. Furthermore, if forecast and climate models are to realistically simulate continental temperatures and associated annual and diurnal cycles, they must properly represent the radiative effects of boundary layer clouds.

Representing continental stratocumulus processes in general circulation models is at least as challenging as it is for marine stratocumulus, since these clouds are also intimately connected to the dynamics of the boundary layer and have limited vertical extent. There are, however, few observations to guide the development of parameterizations of continental clouds or to evaluate whether our current understanding of marine clouds can be extended or generalized to continental clouds.

Part of the success of FIRE and ASTEX is due to the application of sophisticated remote sensing systems to define cloud and boundary layer properties. The technology and techniques developed have the potential for further increasing our understanding of boundary

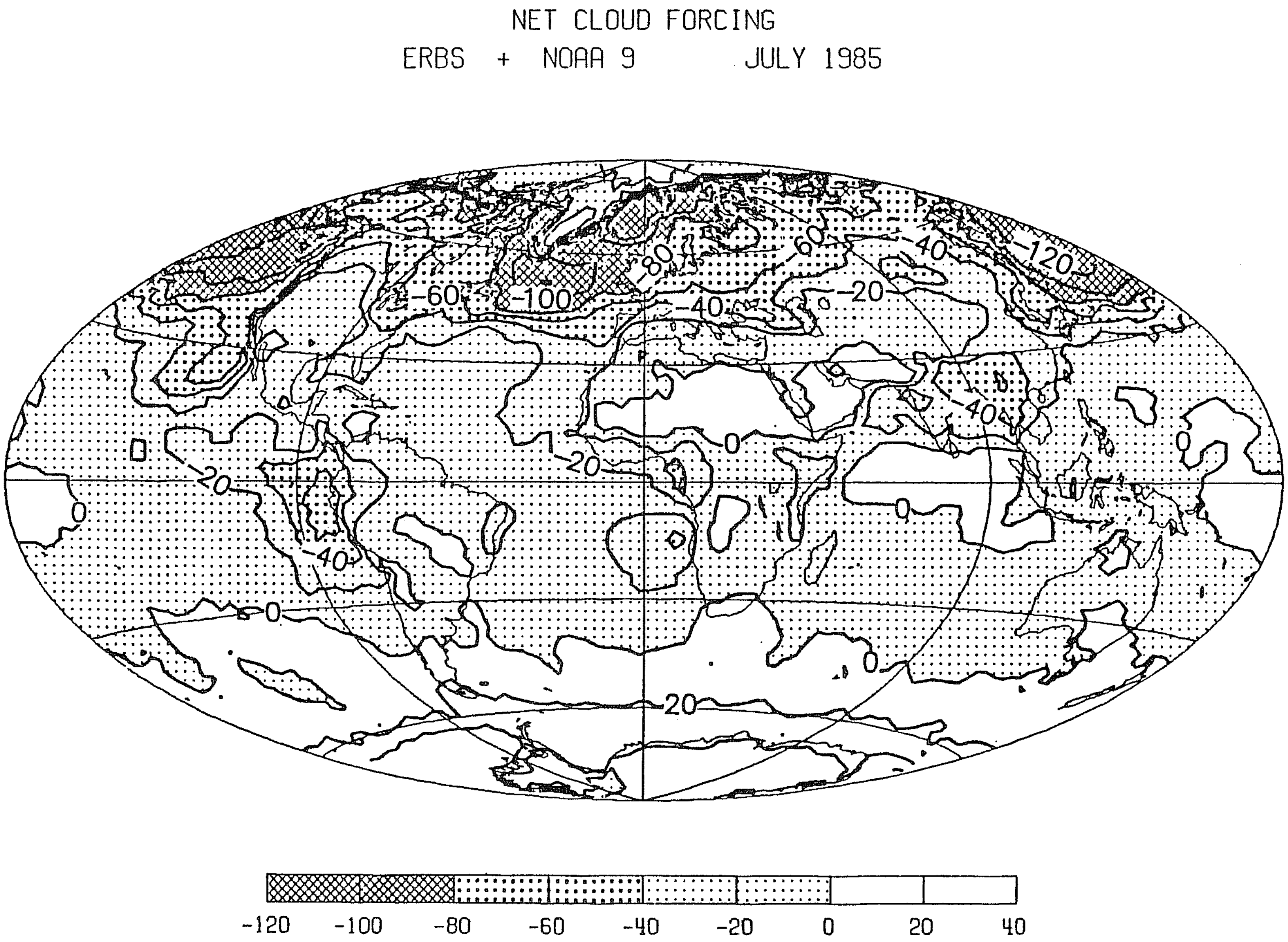


Fig 1 **Net cloud forcing from ERBE for July 1985 (adapted form *Harrison et al*, 1990).**

layer cloud processes. There is a need, however, to further develop these observational techniques with a clear strategy in mind for testing and developing models.

In this paper selected FIRE and ASTEX results relevant for the development and testing of boundary layer and cloud models are highlighted. In addition, some initial observations from continental stratus are discussed and potential needs for increasing our understanding of these clouds are identified.

2. Marine Stratocumulus observations during FIRE and ASTEX

The FIRE intensive observations of marine stratocumulus in 1987 off the coast of California marked a major step in increasing our observational basis for understanding marine stratocumulus (Albrecht et al. 1988). Studies made during this experiment focused on a number of processes thought to be important for the generation, maintenance, and dissipation of marine stratocumulus. These studies included investigations of diurnal variations, cloud-aerosol interactions, and precipitation and entrainment processes. Although mostly solid clouds were observed during this experiment, there was evidence that microphysical effects were important for cloud and boundary layer structure (Albrecht 1989). Furthermore, the fundamental role of decoupling in regulating cloud evolution has been addressed using the FIRE data (Paluch and Lenschow 1991).

Studies have been made of the diurnal variations of marine stratocumulus over the island of San Nicolas Island during FIRE (Higgnet 1991; and Blaskovic et al. 1991; Betts 1990). The study by Higgnet (1991) provides an excellent contrast between the turbulence structure observed during the day and at night from tethered balloon observations. Although the Higgnet study was made during a period of good fetch from the open ocean, there are other days when coastal mesoscale circulations may perturb the diurnal cycle at San Nicolas relative to that over the open ocean. A simple demonstration of the daytime decoupling of the boundary layer observed during FIRE is illustrated by the potential temperature soundings shown in Fig. 2. The two soundings were obtained 500 km off the coast of California with the UK C-130 and the NCAR Electra separated by about 200 km. The initial sounding from the Electra shows some signs of decoupling with a stable layer at about 300 m. A comparison of the morning and the afternoon soundings indicates a substantial warming of the cloud layer observed by both aircraft with relatively little warming of the subcloud layer. This results in a strengthening of the cloud base inversion and further decoupling of the boundary layer.

Several aircraft flights with drizzle were observed during FIRE (Albrecht 1989). However, substantially less drizzle was observed from at San Nicolas Island. There were substantial variations in the cloud microphysics associated with the two areas sampled for the soundings shown in Fig. 2. Visible satellite images from this area indicate that the Electra was operating in a region of cellular convection associated with less reflective clouds than in the solid cloud sampled by the C-130. Cloud droplets sampled in the vicinity of the Electra

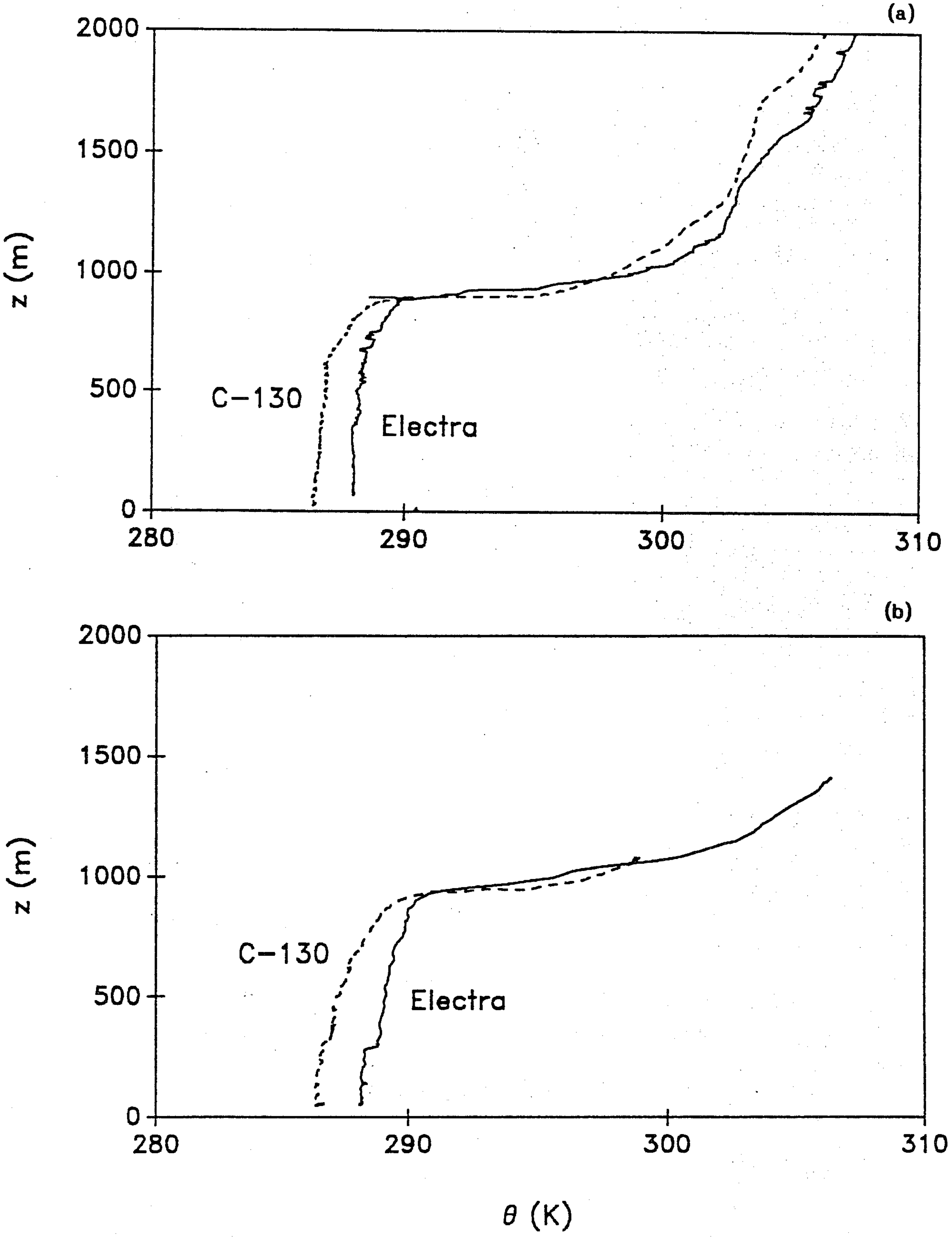


Fig 2 Potential temperature profiles in marine stratocumulus observed off the coast of California during FIRE from the UK C-130 and the NCAR Electra at a) approximately 1130 LST and b) 1500 LST.

are substantially fewer in number and larger than those sampled by the C-130 as shown in Fig. 3. In addition, drizzle rates (averaged over all turbulence legs made on 30 June, 1989) are estimated to be about 0.3 mm/day compared with near zero drizzle rates in the solid cloud sampled by the UK C-130. This drizzle may contribute to the greater decoupling observed in the area sampled by the Electra than that of the C-130.

Although the FIRE data sets added to our understanding of cloud-top entrainment, there is still considerable uncertainty about this process. Analyses of the thermodynamic jumps across the inversion observed at San Nicolas during FIRE (Kuo and Schubert 1988) increase the cases used to evaluate the criteria from cloud top entrainment instability. They do not, however, improve our understanding of the entrainment process. Siems et al. (1989) included some of the FIRE soundings in their study of cloud top entrainment. Conditional sampling techniques applied to aircraft data like those presented by Khalsa (1993) and Wang and Albrecht (1993) provide a better description of the structure of entrainment events, but still can not provide direct definition of the vertical structure of these events nor a clarification of the relative role of small-scale interfacial mixing and mixing enhanced by the large-scale eddies in the boundary layer. Thus major uncertainties about the entrainment mechanism remains.

The Atlantic Stratocumulus Transition Experiment (ASTEX) was designed to address key issues related to stratocumulus to trade-cumulus transition and cloud-mode selection. ASTEX involved intensive measurements from several platforms and was designed to study

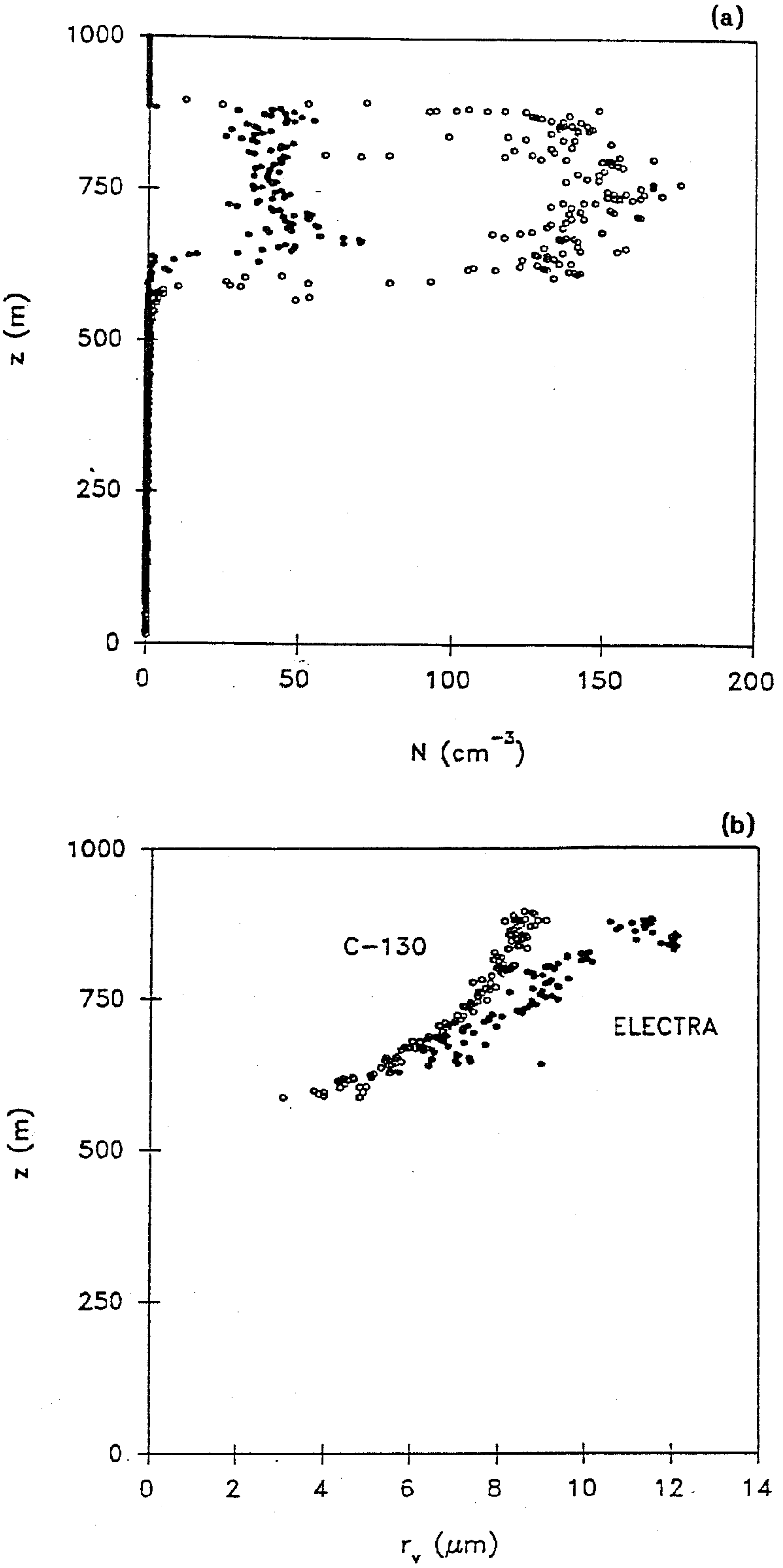


Fig 3 Cloud microphysical observations Forward Scattering Spectrometer Probes (FSSP's) on the C-130 and the Electra corresponding to soundings shown in Fig 2a. Includes a) droplet concentrations and b) mean volume radius.

how the transition and mode selection are affected by 1) cloud-top entrainment instability, 2) diurnal decoupling and clearing due to solar absorption, 3) patchy drizzle and a transition to horizontally inhomogeneous clouds through decoupling, 4) mesoscale variability in cloud thickness and associated mesoscale circulations, and 5) episodic strong subsidence lowering the inversion below the LCL. From a broader perspective ASTEX was designed to provide improved dynamical, radiative, and microphysical models and an improved understanding of the impact of aerosols, cloud microphysics, and chemistry on large-scale cloud properties.

ASTEX involved coordinated measurements from aircraft, satellites, ships, and islands in the area of Azores and Madeira Islands. This general area was chosen since satellite studies indicated that this region was characterized by cloud conditions ranging from solid stratocumulus decks to broken trade cumulus. Furthermore, this region was not directly influenced by continental effects, and two islands in this region provide suitable sites for surface observations and aircraft operations.

Although the experimental design for ASTEX was similar to that during the FIRE 1987 experiment, important enhancements were included. A telescoping approach was used in both ASTEX and FIRE to investigate connections between scales ranging from microns to 1000's of kilometers. Satellites and upper-level aircraft provided a description of large-scale cloud features, and instrumented aircraft flying in the boundary layer and surface-based remote sensing systems provided a description of the mean, turbulence, and microphysical properties of boundary layer clouds. A major deficiency of the FIRE observations, however, was an inadequate definition of the large-scale fields of temperature, moisture, and winds. This deficiency was removed for ASTEX by the making 4-8 soundings per day from the surface sites and ships and including many of these upper-air observations on the Global Telecommunications System (GTS) for assimilation into the ECMWF and NMC analyses. Furthermore, based on the demonstrated utility of surface-based remote sensing during FIRE (Albrecht et al. 1990), the use of such systems was expanded during FIRE.

The ASTEX deployment was quite successful due in no small part to excellent weather conditions. The initial results indicate that the ASTEX data set has the potential to make substantial contributions to our understanding of the processes noted previously as important for determining cloud type and amount. Highlights of the ASTEX field deployment include the following:

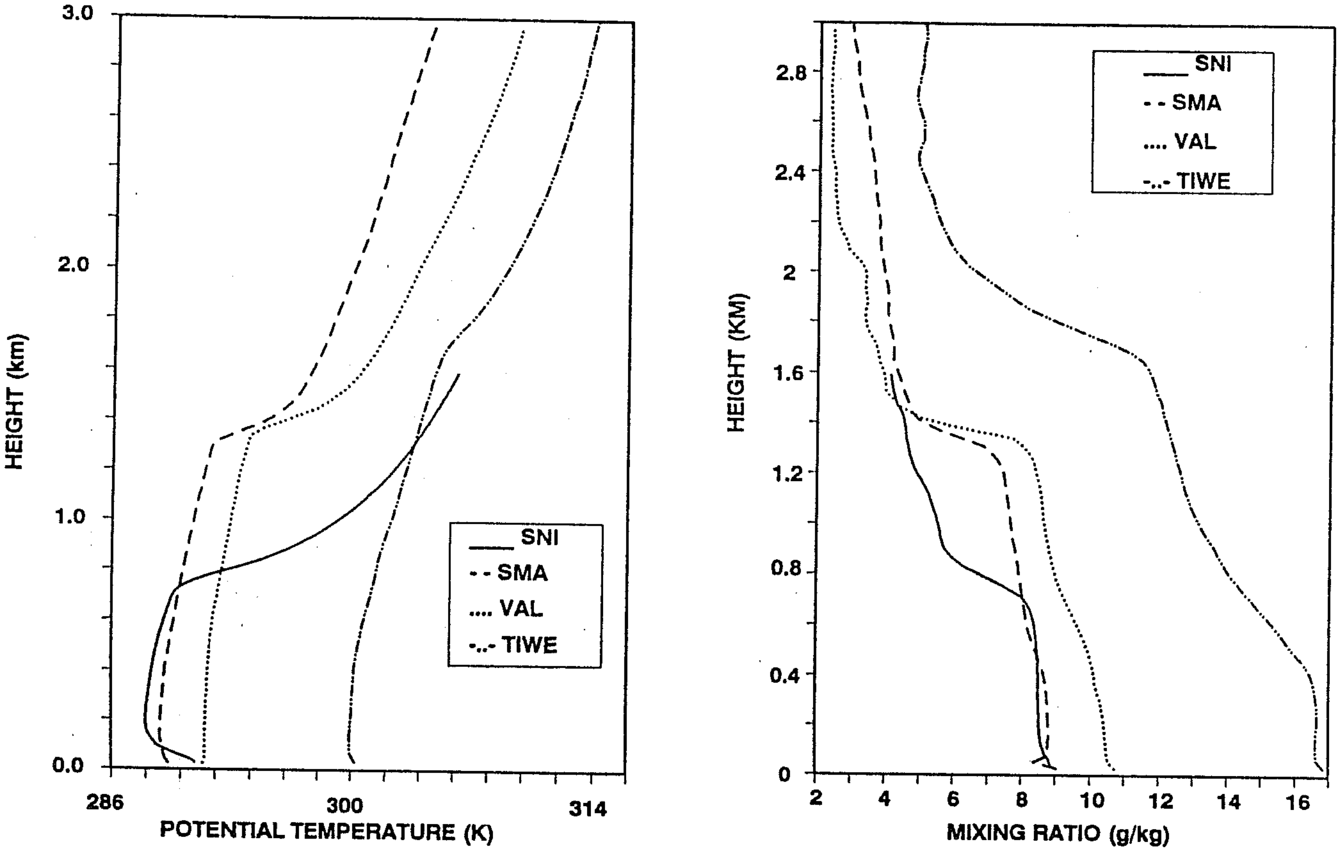
- Region of transition and transformation sampled,
- Substantial variations in clean and dirty air masses observed,
- Lagrangian approach demonstrated,
- Diurnal cycle sampled,
- Upper-air data from islands and ships successfully assimilated by ECMWF, and
- Ceilometers. microwave radiometers, wind profilers, and other sensors successfully deployed.

A short description of each of these highlights is presented below.

2.1 Region of transition sampled

Aircraft and surface-based measurements during ASTEX indicate that the stratus observed in this area differs from that just off the coast of California. Unlike the coastal California stratus, the stratus observed during ASTEX was generally associated with decoupled boundary layers. This is clearly illustrated in Fig. 4 where composite temperature and moisture profiles from radiosondes collected in nearly solid status during FIRE and more broken conditions during ASTEX are presented (Jensen 1993). The moisture structure of the two ASTEX composite soundings from the island of Santa Maria (37N, 25W) and the German ship Väldiviä (28N, 24W) clearly show a well defined subcloud layer structure with a decrease in moisture at the base of the cloud layer compared with the FIRE composite sounding from San Nicholas Island (33N, 120W). In addition to the FIRE and ASTEX composite soundings, a sounding obtained at the equator over the central Pacific (0S, 140W) is included in Fig. 4. The soundings for this composite were obtained during the Tropical Instability Wave Experiment (TIWE, Charlock and Fairall 1993) during December of 1991 where a classic trade-wind boundary layer structure was observed for a three-week period. The tropical composite sounding shows a deeper boundary layer an even more pronounced transition layer separating the clouds and the subcloud layer.

The cloud cover corresponding to each of the composite soundings shown in Fig. 4 was estimated using a laser ceilometer operating at each location. The cloud cover was



	SST	Cloud %	# of Soundings
FIRE SNI	15.7	0.82	65
ASTEX Santa Maria	18.2	0.67	119
ASTEX Väldiviä	20.9	0.40	58
Tropical Pacific (TIWE)	27.2	0.26	44

Fig 4 Composite potential temperature and mixing ratio soundings for boundary layer cloud conditions ranging from solid stratocumulus to broken trade cumulus. Inversion height was identified for each sounding analyzed to define a non-dimensional height scale z/z_i that was applied before the soundings were averaged. Average inversion height for each region was then used to dimensionalize the average profiles shown. (From Jensen 1993).

estimated by classifying each 30-second observation as either clear if no clouds were detected or cloudy if clouds with bases less that 3 km are observed. The cloudiness for each hour was then calculated using these 30-second classifications. The cloudiness during ASTEX is about 67% at Santa Maria and 40% at the Väldiviä compared with 82% at San Nicholas and 26% during TIWE. Thus ASTEX is clearly intermediate between the solid clouds observed during FIRE and the broken fair-weather cumulus observed in the undisturbed trades.

The decoupled conditions observed during ASTEX result in a moistening of the subcloud layer relative to the cloud layer. Although the stable layer often observed at cloud base limits the turbulent exchange between the cloud and the subcloud layer, the moistening of the subcloud layer increases convective available potential energy (CAPE). Thus in areas where an updraft in the subcloud layer reaches the lifting condensation level and penetrates the weak inversion at cloud base, there is the potential for the development of relatively vigorous cumulus clouds. These penetrating cumulus were often observed during ASTEX to help supply liquid water to the overlying stratus through detrainment at the base of the inversion that caps the cloud layer. These detrained cloud masses often have the appearance of the anvils associated with thunderstorms. Substantial drizzle is often associated with these marine boundary layer convective complexes (MBLCC's).

The structure of the MBLCC's was documented by the cloud radars located on Santa Maria and Porto Santo. Aircraft observations were also made in and around these systems. The NOAA Wave Propagation Laboratory tracked several of these systems using their 35

GHz cloud radar and found that they persisted for a number of hours (Kropfli et al. 1992). A cloud radar operated from Santa Maria by Penn State University (Peters et al. 1993) probed several of these systems as they passed over the island. The radar returns shown in Fig. 5 clearly show the anvil-like structure of the detrained stratus, the over-shooting cloud top, and possible entrainment along the edges of the over-shooting cloud top.

These preliminary results indicate that the transition is not a simple and rapid transition from solid stratus to broken fair weather cumulus. Instead, the transition is from solid stratus associated with well-mixed conditions to stratus that can be generated by long-lived, intermittent strong convective systems feeding on moist air near the surface in decoupled boundary layers.

2.2 Variations in cloud structure in clean and dirty air masses

Extreme variations in aerosol conditions were observed during ASTEX. During the second week of the experimental period very clean air was present in the study region. The chemists on the Electra noted that the air was as clean or cleaner than air they have sampled over the central Pacific. During this period drizzle was observed frequently from the aircraft and the islands -- often in association with the MBLCC's discussed previously. This clean air was replaced by a cloud mass moving westward from the European continent. This air mass provided a very sharp boundary between the clean and dirty air. This boundary was

Santa Maria, Azore Islands, June 21, 1992, 0100Z-0200Z

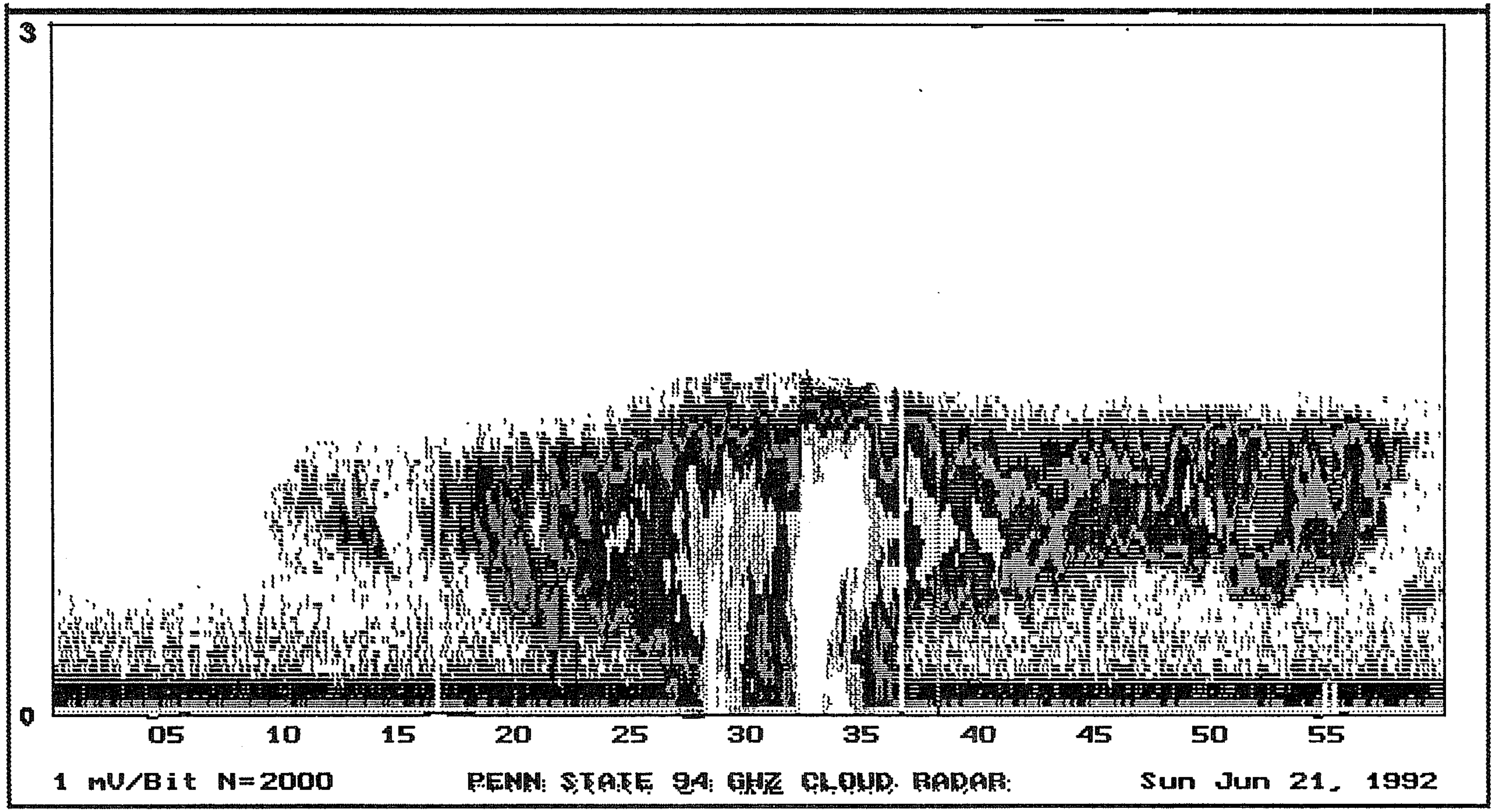


Fig 5 Time-height section of radar returns from the Penn State cloud radar as a boundary layer convective complex passes over the island of Santa Maria during ASTEX. The height scale is in kilmeters and the time scale is in minutes. Returns show overshooting cloud top, stratus anvil, and drizzle falling to the surface near the core of the cumulus.

thoroughly sampled with the aircraft. The contrast in cloud structure was striking as illustrated in Fig. 6. The continental air was characterized by substantially higher droplet concentrations and larger droplets than observed in the clean air mass. Drizzle was generally suppressed in the continental air mass. These conditions provided an exceptional data set for characterizing cloud characteristics associated with substantial differences in aerosol concentrations.

2.3 Lagrangian approach demonstrated

Two Lagrangian experiments were performed during the two-week period in the middle of the experiment. During these experiments an attempt was made to follow a tagged air mass for two complete days. The first Lagrangian was conducted in the clean air mass discussed previously and the second was in the dirty air mass. During the first Lagrangian the six constant-level balloons that we use to tag the air mass ended up in the ocean in a few hours due to loading by the drizzle. Measurements were made following a trajectory based on real time winds from the aircraft. This trajectory was in reasonable agreement with a trajectory from calculated using ECMWF analyses. During the second Lagrangian (when there was relatively less drizzle) two balloons were tracked for nearly 48 hours. These experiments allow budgets to be made without evaluating advective effects and provide a unique data set for testing one-dimensional models.

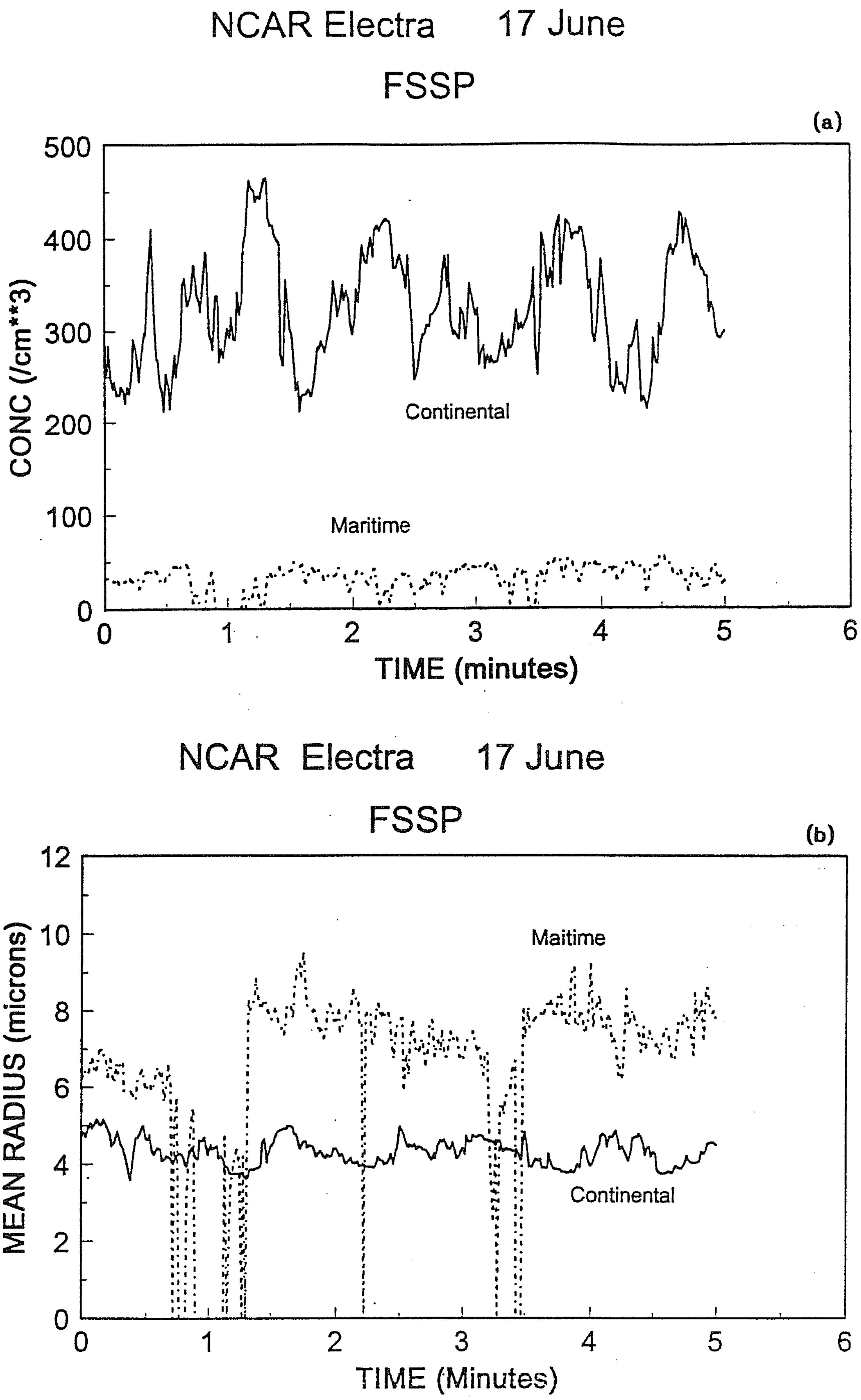


Fig 6 Comparison of a) droplet concentrations and b) droplet size from an FSSP on the NCAR Electra during ASTEX. The maritime and continental air masses sampled were separated by less than 100 km.

2.4 Diurnal cycle sampled

The ASTEX data were collected well away from the direct effects of the European continent. Island effects, however, can also disrupt the diurnal variations relative to open ocean conditions. Thus a careful comparison of the diurnal variations on the islands and those observed from the ships over the open ocean will be made. The ASTEX Lagarangian experiments provide an excellent opportunity to study diurnal effects, since aircraft measurements were made through the night during these experiments. Furthermore, the effects of advection can be removed from these measurements.

2.5 Assimilation of upper-air data from islands and ships in support of ASTEX.

Eight radiosondes per day were launched from Santa Maria, Porto Santo, the R/V Väldiviä from Germany during the first three weeks of the experiment and NOAA's R/V Malcolm Baldrige during the last week. Standard and significant level data for most of these soundings were transmitted to Santa Maria where they were transmitted to the Global Telecommunication System (GTS) by technicians from Lisbon's INMG (the Portuguese NWS). These data were then assimilated into ECMWF and other global analyses. Approximately 650 of the 820 soundings were placed on the GTS and about 90% of these were assimilated into the ECMWF analysis. This was clearly a difficult but major accomplishment. Assessments are in progress to determine how well the ECMWF analyses represent the boundary layer structure and other fields during ASTEX. The ECMWF analyses will be used to define large-scale divergence and other parameters needed to test regional and large-scale models.

2.6 Deployment of surface-based remote sensors

An extensive deployment of remote sensors was made for ASTEX to study the cloudy marine boundary layer. These sensors included two cloud radars, two wind profilers, a RASS, five microwave radiometers, four ceilometers, and a several upward-looking radiometers. This instrumentation provided data for characterizing clouds and the environment in which they form. This was the first deployment of cloud radars in a marine environment. They provide estimates of cloud-top height, reflectivity profiles, in-cloud turbulence, and drizzle characteristics. The scanning radar on Porto Santo was used to provide a horizontal mapping of the clouds to track cloud features of interest. The cloud base height from ceilometers are being combined with the radar cloud top to define cloud thickness. Simultaneous measurements of cloud liquid water path were obtained with microwave radiometers. At the same time, microwave radiometers provide integrated liquid water content. These measurements will be used to define the ratio of the observed liquid water path to the adiabatic liquid water path calculated from the cloud thickness following the technique described by (Albrecht et al. 1990). This instrumentation is being used to investigate the structure of the marine boundary layer convective complexes described previously.

3. Continental Stratocumulus

The most comprehensive analysis of continental stratus focuses on two days of stratus over the UK (Caughey et al. 1982; Slingo et al. 1982; and Roach et al. 1982, although strictly speaking these clouds were maritime in origin since the measurements were made over land). The measurements in these clouds were made with a tethered balloon, a surface-based microwave radiometer, a sodar, and surface *in situ* measurements. Although one would expect that many of the processes operating in continental clouds are similar to those in marine stratocumulus, the formation of these clouds may result from very different processes. Mixing due to wind shear and surface buoyancy fluxes may be more important for the generation of continental stratus than for oceanic stratus. For example, surface heating during the day over a relatively moist surface can result in the formation of boundary layer clouds. This case is illustrated in Fig. 7 where the cloud base height from a ceilometer is compared with the surface LCL. During the morning, solar heating results in the formation of boundary layer clouds at about 1500 UTC (1000 LST). These clouds are directly coupled to the boundary layer as indicated by the close agreement between the cloud base and the LCL. Later in the afternoon, a decoupling is indicated as the LCL and the cloud base diverge. The low-level lapse rates for this case were calculated using surface temperature measurements and estimates of temperature at 1 km and 1.5 km from RASS measurements. The lapse rates are shown in Fig. 8. The low levels are destabilized with the lapse rate reaching almost 9°C/km near the time when clouds form.

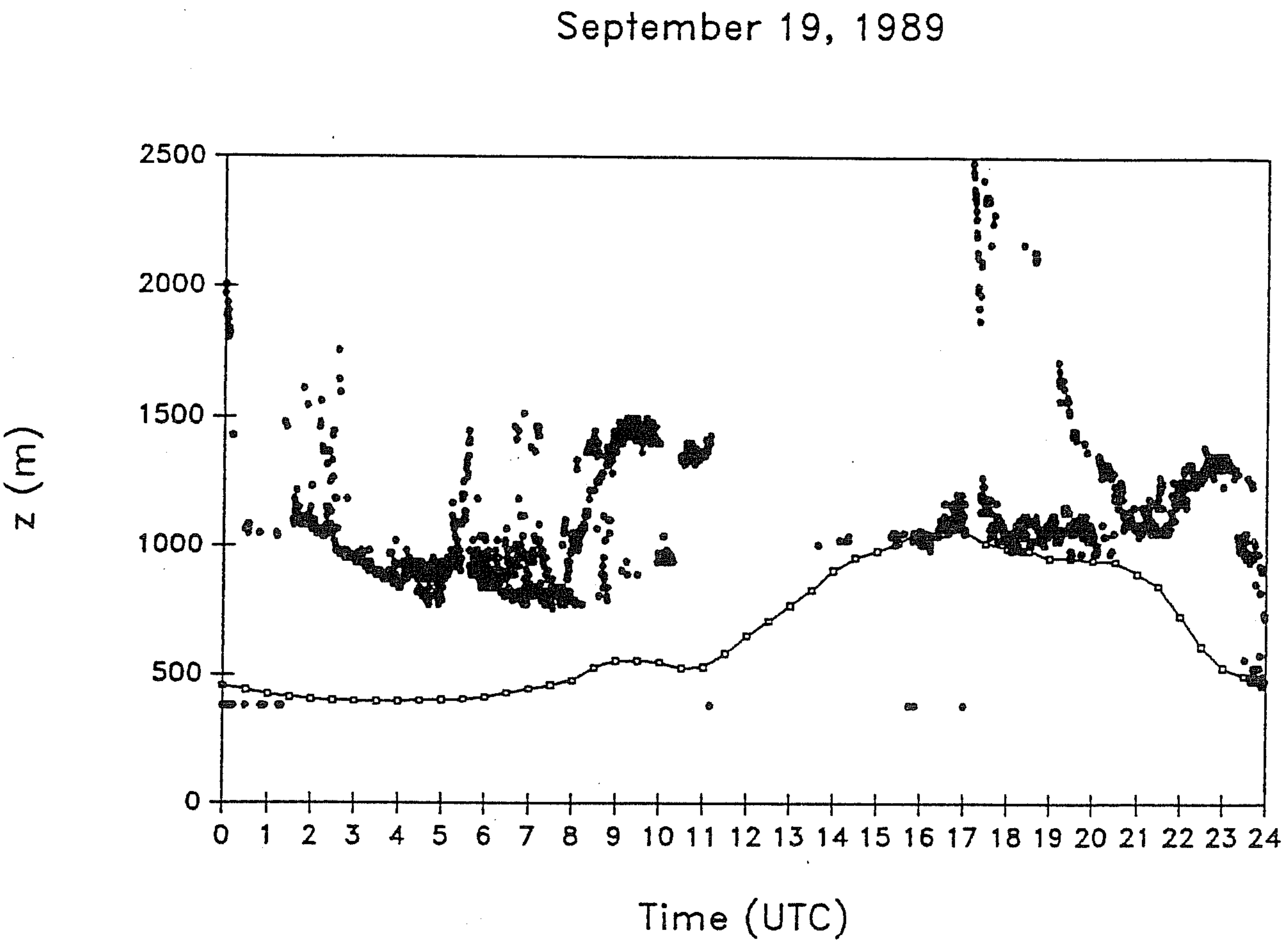


Fig 7 Comparison of calculated LCL's from surface observations to cloud base height from a laser ceilometer over central Pennsylvania. (Heights are MSL.)

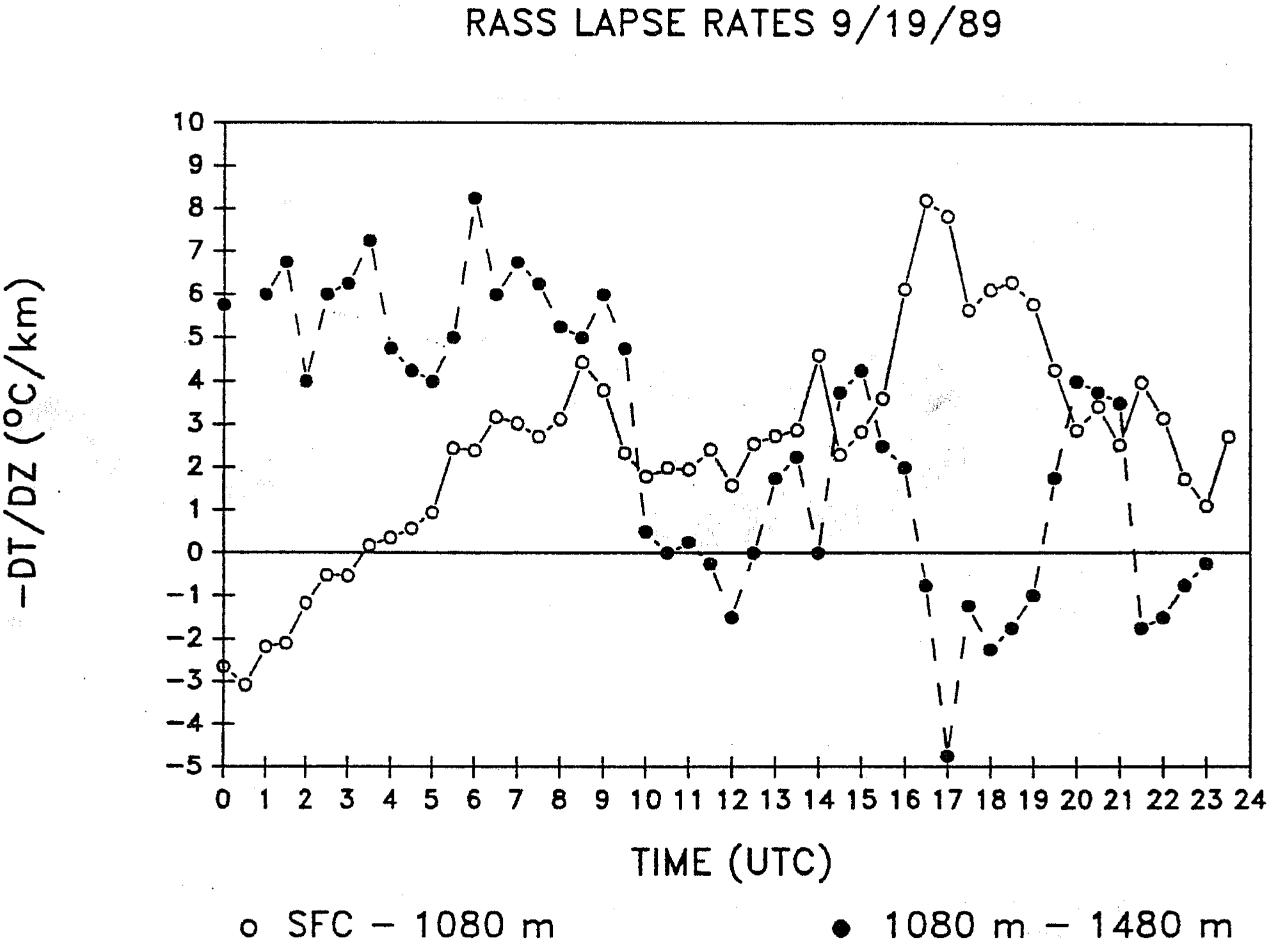


Fig 8 Low-level lapse rates corresponding to the cloud observations shown in Fig 7. The lapse rates in the 1-1.5 km layer were obtained form a Radio Acoustic Sounding System (RASS). The surface to 1 km lapse rates were obtained by combining surface *in situ* observations with RASS observations.

In other cases, the large-scale forcing may have a more direct effect on the formation of continental stratus than in the subtropics. Mid-latitude cyclones often have stratus associated with them as shown in Figs. 9 and 10. These figures show a sample of observations made with the Penn State 94 GHz radar as a mid-latitude cyclone moved over a site in central Pennsylvania. As the storm approaches, low-level stratus clouds form under an upper-level cloud. These clouds form even though the jumps across the capping inversion indicate conditions favorable for cloud-top entrainment instability. Furthermore, the returns from the 94 GHz radar are observed well below the visible cloud base defined by a laser ceilometer. This indicates the generation of larger droplets falling from the clouds. The intensity of these low-level returns increases until about 7 hours later when precipitation is observed at the ground. As the storm and the upper level clouds moves out of the area two days later, a low-level stratus deck forms (or is advected into the area) as a weak cold front moves through the area. The clouds also form under a capping inversion in this case. Unlike the stratus observed earlier the cloud base from the ceilometer agrees well with the cloud radar returns indicating little production of a large droplets.

4. Conclusions

Overall, the FIRE and ASTEX results should continue to contribute both to our understanding of the physical processes operating in marine stratocumulus and the direct verification of parameterizations and models of varying complexity. It is still a major

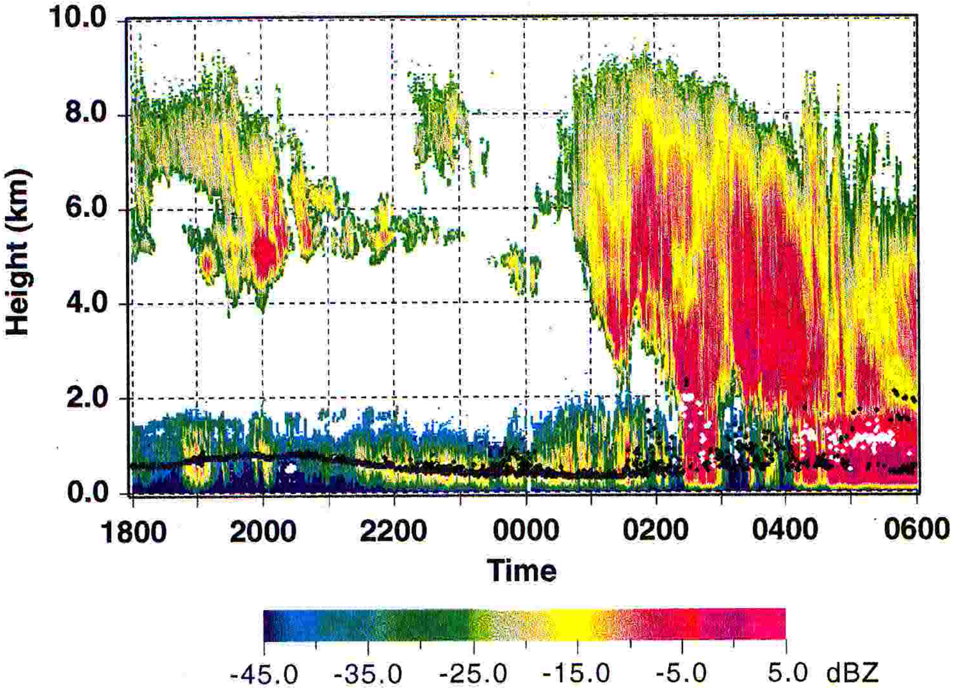


Fig 9 Time-height section of radar reflectivity from the Penn State cloud radar as a midlatitude cyclone approaches central Pennsylvania on 9-10 April 1993. The solid dots are cloud base heights from a laser ceilometer.

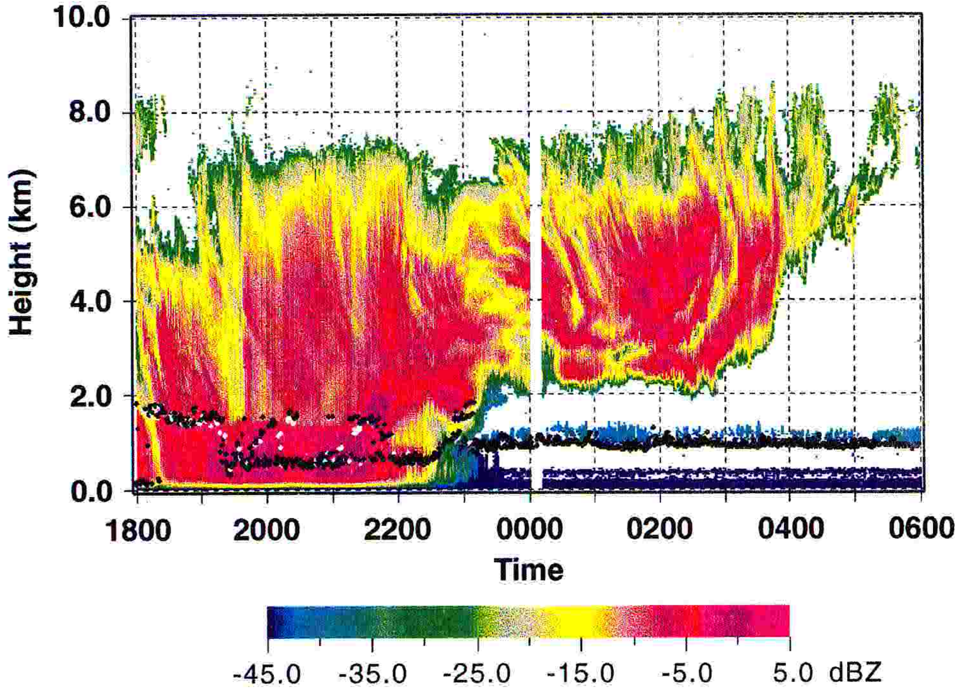


Fig 10 Same as Fig 9 but as the cyclone moves to the northeast of the site on 11 April 1993.

challenge to fully use these observations for this purpose, since several processes operating in stratocumulus are not fully understood. An important first for ASTEX was the extensive assimilation of over 600 ASTEX soundings into the ECMWF analyses. This accomplishment will greatly extend the usefulness of the ASTEX data set for model testing and development. The extreme variations in aerosol concentrations observed during ASTEX provide a unique opportunity to study cloud aerosol interactions

The FIRE and ASTEX show that decoupling is critical to our understanding of cloud transitions and that the decoupled boundary layer is probably the norm over much of the world's oceans. Thus solar absorption in the clouds and drizzle process are fundamental to the transition. These transition process are often operating in stratocumulus that may appear to be relatively solid from satellite images.

Our understanding of continental stratus lags that of the marine counterparts. Any observations in continental stratus should be carefully compared with those of marine stratocumulus to facilitate the transfer of understanding between these cloud types.

The observations made during ASTEX and FIRE clearly demonstrated the utility of using remote sensors for defining cloud properties. Although observations made in marine stratus can be used to improve parameterizations and model formulations, it is important that the needs for current future modeling efforts be carefully considered in the development of new techniques for describing cloud structure.

ACKNOWLEDGMENT

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