Chapter 8

Observations of Cloudy Boundary Layers

B.A. Albrecht

Division of Meteorology and Physical Oceanography
Rosenstiel School of Marine and Atmospheric Science, University of Miami, USA.

Abstract

During the past 10 years there have been substantial, organized efforts to improve the observational basis for our understanding of cloudy boundary layers. The First ISCCP Regional Experiment (FIRE) and the Atlantic Stratocumulus Transition Experiment (ASTEX) were among these efforts. In this paper key issues addressed and raised by the recent observations are highlighted. Discussions of cloud-top entrainment, boundary layer decoupling mesoscale organization, drizzle, and the downstream evolution of cloud and boundary layer structure are included. On the basis of these discussions, unanswered questions concerning processes important for the maintenance of marine stratocumulus clouds are raised.

1 Introduction

Radiative and microphysical processes in cloudy boundary layers complicate the theoretical treatment of these layers relative to clear boundary layers. Unlike the clear boundary layer, radiative cooling due to longwave emission concentrated at cloud top can help generate the turbulence needed to maintain well-mixed conditions. Lilly (1968) first demonstrated the importance of the longwave cooling at cloud top, and later studies showed how solar absorption during the day can substantially modify the radiative budget of the cloud and give rise to diurnal variations in the cloud. Once clouds become more than about 100 m thick, they become quite black in the infrared making their tops good emitters of longwave radiation. The cooling is confined to a relatively shallow layer at cloud top with rates of 5–10 $^oC\,hr^{-1}$ not uncommon. The effects of solar radiation on the radiation budget of the cloud, however, become more complicated due to absorption through some depth of the cloud. This warming generally results in a day-time stabilization of the cloud that can counter the destabilization associated with the IR cooling at cloud top.

Phase change further complicates the treatment of boundary layer processes relative to clear conditions, although the use of appropriate conserved variables simplifies the treatment of the thermodynamics (Betts, 1973; Bohern and Albrecht, 1998). Potential temperature θ, which is often used to represent temperature structure in the clear boundary layer, can be replaced by liquid water potential temperature θ_ℓ (Betts, 1973). In a linearized form appropriate for the treatment of shallow layers it can be represented as $\theta_\ell = \theta - L\,r_\ell/c_p$ where r_ℓ is liquid water mixing ratio, L the enthalpy of vaporization, and c_p is the specific heat of the moist air. The conserved parameter that can be used to describe the moisture structure in the cloud layer is the total water mixing ratio $r_t = r + r_\ell$ where r is the water vapor mixing ratio. Below cloud base these quantities simply reduce to the clear boundary layer parameters $\theta_\ell = \theta$ and $r_t = r$. For a well mixed boundary layer, θ_ℓ and r_t constant with height, θ in the cloud layer increases with height since the temperature in the cloud layer decreases at the moist adiabatic lapse rate rather than the dry adiabatic lapse rate. The water vapor mixing ratio r in the cloud layer decreases with height and the liquid water mixing ratio ℓ increases with height. Equivalent potential temperature θ_e, which in linearized form can be written as $\theta_e \cong \theta + L\,r/c_p = \theta_\ell + L\,r_t/c_p$, is also conserved both in the cloud and the subcloud layer.

An important variable for describing the energetics of the cloudy boundary layer is the turbulence buoyancy flux. This flux is often represented using virtual potential temperature. In both clear and cloudy boundary layers the effects of water vapor on density are included by using virtual potential temperature $\theta_v = \theta(1+0.608q) \cong \theta(1+0.608r)$ where q is specific humidity. In the cloudy boundary layer the effects of liquid water on density can be included by noting that the density of the moist air (dry air and the vapor) with liquid water can be represented as $\rho = \rho_{air}(1 + q_\ell) \cong \rho_{air}(1 + r_\ell)$. The effects of the liquid water on parcel buoyancy for shallow boundary layers is often included by defining virtual potential temperature as $\theta_v = \theta + \theta_o(0.608r - r_\ell)$ where θ_o is a reference potential temperature.

Phase changes in the cloud layer coupled with the effects of liquid water on buoyancy effects punctuate the differences between clear and cloudy boundary layers. Liquid water paths in stratocumulus clouds are typically in the range of 10–100 g m^{-2} with optical depths of 1–10. Although the liquid water content of these clouds is generally less than that of deeper cumulus clouds, it is sufficient to complicate the treatment of buoyancy effects in the boundary layer and the radiative budget of the cloud layer and the underlying surface. Furthermore, the radiative processes, particularly in the shortwave fluxes, are sensitive not only to the cloud liquid water content but also the microphysical and macrophysical structure of the clouds.

Although the starting point for much of the recent work on cloud-topped boundary layers was the classic paper of Lilly (1968), when this paper was written there was relatively little observational work to support this theoretical treatment of marine stratocumulus. Even in the early 1980's the assessment was that there were insufficient observations available to test existing theories and models of marine stratocumulus (Randall et al., 1984). At the time of this assessment, studies of marine stratocumulus that used observations made off the coast of California in the summer of 1976 (Brost et al., 1982a; Brost et al., 1982b; Albrecht et al., 1985) and over the North Sea in 1982 (Nichols, 1984) were available and provided the basis for planning more comprehensive future studies. Further studies of stratocumulus observed over the North Sea are described by Nicholls and Turton (1986a) and Nicholls and Leighton (1986b). A tethered balloon and a surface-based acoustic sounder and microwave radiometer were used to study the turbulence, microphysical, and radiative properties of a nocturnal stratus deck that was observed over southeast England in 1976 (Roach et al., 1982; Caughey et al., 1992; Slingo et al., 1982). The radiative properties of summer-time Arctic stratus were studied in 1976 (Herman, 1977; Herman and Curry, 1984) using the NCAR Electra. In 1985 the Electra was used to study stratus off the coast of California (Lenschow et al., 1988; Kawa and Pearson, 1989; Weaver and Pearson, 1990) as part of the Dynamics and Chemistry Of Marine Stratocumulus (DYCOMS) Experiment. A key aspect of DYCOMS was that it attempted to provide a combined treatment of the chemistry and the physics of low-level stratus clouds.

These early studies provided some initial clues to the wide range of cloud and boundary layer structures that would be further explored and studied using more extensive observations from recent field programs. For example, the initial studies off the coast of California focused on the observations from three stratocumulus cases that varied substantially from case to case with cloud top heights from 500–1500 m and cloud thicknesses from 200–400 m (Albrecht et al., 1985). In addition, these early studies indicated the possible impact of drizzle and decoupling on the energetics of stratus clouds (Nicholls and Turton, 1986a) and showed that subtle changes in various parameters may result in substantial changes in cloud properties.

2 Recent Observations of Marine Stratocumulus

2.1 FIRE

The First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment (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). The principal observational tools used during FIRE included instrumented aircraft, satellites, and a suite of remote sensing systems and a tethered balloon operating from San Nicolas Island, which is located about 100 km off the coast of California. Studies made with FIRE data focused on a number of processes thought to be important for the generation, maintenance, and dissipation of marine stratocumulus. These studies included investigations of factors controlling cloud fraction and morphology, diurnal variations, entrainment processes, and the effects of aerosols on cloud microphysics. In addition, the data collected during FIRE have been used to evaluate and improve satellite retrievals and have provided detailed studies of radiative processes associated with marine stratocumulus.

2.2 ASTEX

The Atlantic Stratocumulus Transition EXperiment (ASTEX) was designed to address key issues related to stratocumulus to trade-cumulus transition and cloud-mode selection (Albrecht et al., 1995a). ASTEX involved intensive measurements from several platforms and was designed to study how the transition and cloud 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, and 4) mesoscale variability of cloud thickness and associated mesoscale circulations. 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 the Azores and Madeira Islands in the eastern Atlantic. 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 islands in this region provided suitable sites for surface observations and aircraft operations.

Although the experimental design for ASTEX was similar to that during FIRE 1987, 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 described large-scale cloud features; instrumented aircraft flying in the boundary layer and surface-based remote sensing systems measured the mean, turbulence, and microphysical properties of boundary layer clouds. A major deficiency of the FIRE observations was an inadequate definition of the large-scale fields of temperature, moisture, and winds. This deficiency was addressed during ASTEX by 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.

Based on the demonstrated utility of surface-based remote sensing during FIRE (Albrecht et al., 1990), the use of such systems was expanded for ASTEX to study the cloudy marine boundary layer. These sensors included millimeter-wavelength cloud radars, wind profilers, ceilometers, and several upward-looking microwave radiometers. This collection of sophisticated instruments provided data for characterizing clouds and the environment in which they form.

An extensive overview of the accomplishments made during FIRE and ASTEX is presented in Randall et al. (1996). In general, FIRE and ASTEX 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 validate models of marine stratocumulus. The presentation here focuses on some of the most significant findings of FIRE and ASTEX and raises key questions that may require further investigation.

2.3 Other Studies

Following FIRE and ASTEX there have been several smaller studies that have focused on stratus in other geographical areas. In 1993 aircraft measurements made near the northwestern tip of Tasmania (Boers et al., 1996) provided a unique set of observations in stratocumulus clouds associated with extremely low concentrations of CCN. Additional observations of marine stratus in the very clean southern hemisphere environment near Tasmania were made during ACE-1. An airborne cloud radar operated by the University of Wyoming the University of Massachusetts was used to define internal circulations in coastal marine stratus (Vali et al., 1998). The radiative and microphysical properties over the western North Pacific were studied using an instrumented aircraft (Fujiyoshi et al., 1995; Hayasaka et al., 1995).

Some recent studies have also been made in mid-latitude stratus clouds. A cloud radar was used to define stratus cloud structure in mid-latitude cyclones (Syrett et al., 1995) and drizzle in shallow continental stratocumulus clouds (Vali et al., 1995). Thomas (1996) explored the macroscopic structure of continental stratus using a suite of remote sensing systems. This continental stratus cloud study was based on observations made during a two-month period in the fall of 1994 over central Pennsylvania and included a description of cloud structures under a range of synoptic conditions. Work is in progress to define the turbulence and microphysical processes in these clouds. In addition, several researchers are studying the microscopic and macroscopic structure of boundary layer clouds using an extensive set of observations from surface-

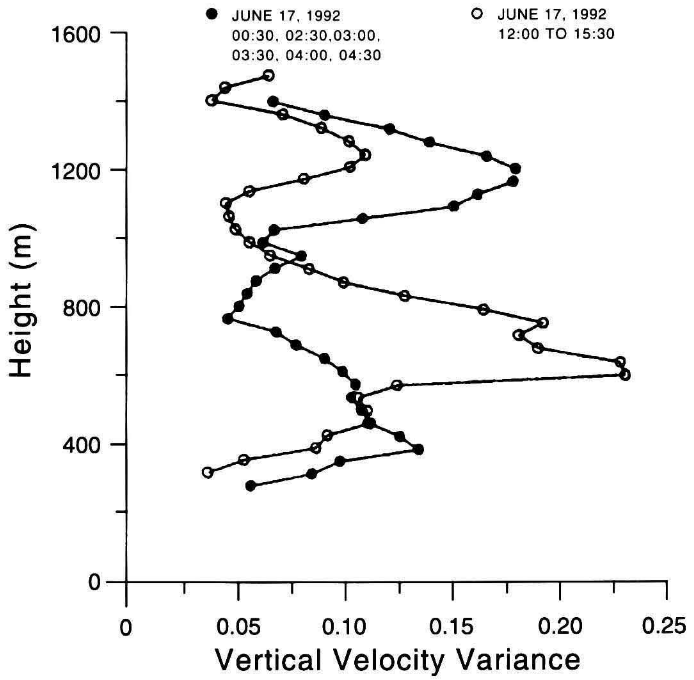

Fig. 1. Vertical velocity variance(m^2s^{-2}) in a stratus cloud as a function of height for a daytime and nighttime case from the island of Porto Santo. Cloud base is at about 375 m (Frisch et al., 1995b).

based systems operating from the Southern Great Plains (SGP) in support of ARM (Stokes and Schwartz, 1994). The instrumentation at the SGP ARM site includes ceilometers and microwave radiometers for characterizing clouds. An unattended cloud profiling radar (Moran et al., 1998) provides cloud boundaries, reflectivities, and Doppler velocities. Other instruments operating at the site are used to define boundary layer structure and the surface energy budget. The continuous operation of much of the instrumentation at the ARM site provides a detailed description of boundary layer clouds and the environment in which they exist.

2.4 Remote Sensing of Boundary Layer Clouds

The development of sophisticated remote sensing systems has provided a means of quantifying the macroscopic and microscopic structure of boundary layer clouds and the turbulence in the clouds. Surface-based systems include laser ceilometers for cloud base height, microwave radiometers for liquid water path, and mm-wavelength radars for cloud-top height and in-cloud reflectivities and vertical velocities. A key factor facilitating the use of remote sensing to study stratocumulus clouds has been the development of mm-wavelength cloud radars. An 8-mm wavelength Doppler radar currently operated by the National Oceanographic and Atmospheric Administration (NOAA) Environmental Technology Laboratory (ETL) was developed in the early 1980's (Pasqualucci et al., 1983) and upgraded several years later (Kropfli et al., 1990). The first 3-mm wavelength Doppler cloud radar was developed at the University of Miami (Lhermitte, 1987) and was followed by other 3-mm system developed at the University of Massachusetts (Mead et al., 1994; Pazmany et al., 1994) and Penn State University (Clothiaux et al., 1995).

The ASTEX deployment represented the first application of mm-wavelength radars to marine stratus clouds. The NOAA ETL radar was located on the island of Porto Santo in the Maderia Islands and the Penn State radar was operated from the island of Santa Maria in the Azores Islands. The cloud radars provided estimates of cloud-top heights, in-cloud turbulence, and cloud and drizzle characteristics (Frisch et al., 1995a; Frisch et al., 1995b; Miller and Albrecht, 1995; Wilczak et al., 1996). The NOAA ETL 8-mm wavelength system with its scanning capability was used to map the horizontal structure of the clouds and to track mesoscale cloud features (Kropfli and Orr, 1995; Wilczak et al., 1996). In addition, the utility of using a millimeter-wave radar on an aircraft for stratus studies has also been clearly demonstrated (Vali et al., 1995 and 1997). This approach allows for direct *in situ* measurements in support of the radar observations and an intrinsic mobility not available to surface-based systems.

Surface-based Doppler cloud radars operating in an upward pointing mode provide a powerful means of quantifying the turbulence structure in boundary layer clouds. An example of profiles of vertical velocity variance obtained from the NOAA/ETL 35 GHz Doppler radar in marine stratocumulus clouds observed during ASTEX is shown in Figure 1. Decoupling in this relatively deep boundary layer results in the double-peaked variance profile even during the night. During the day the variance peak near the top of the cloud is diminished relative to that observed at night–consistent with the decreased turbulence due to solar heating. Vertical velocity variances in a continental stratus cloud obtained from the Penn State 94 GHz operating over central Pennsylvania are shown in Figure 2. Here the variances from hourly statistics of 2-second data show a well-defined evolution of the variance profile as the boundary layer becomes decoupled later in the observing period.

Techniques for using cloud radars to define the microphysical structure of clouds have also been developed. The microphysical structure (mean radius and concentrations) of both cloud and drizzle was obtained from the NOAA ETL radar during ASTEX (Frisch et al., 1995a) using radar reflectivites and spectral width. A radar retrieval based on an adiabatic cloud model (Sassen and Liao, 1996) combined with radar reflectivity has been applied to observations made in a continental stratus cloud (Sassen et al., 1998). Cloud microphysical data collected from aircraft during ASTEX were used by Fox and Illingworth (1997) to assess the possibility of retrieving cloud properties from radar reflectivities. Some of the assumptions used in the retrieval schemes can

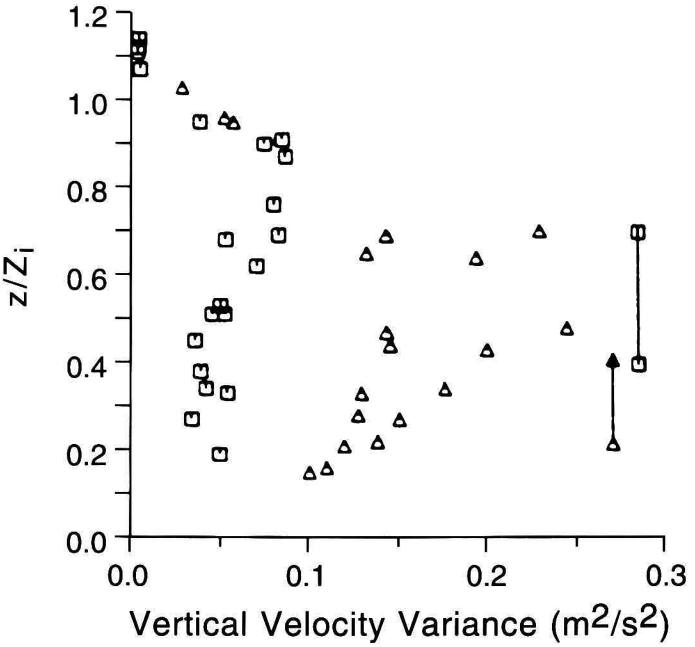

Fig. 2. Vertical velocity variance as a function of normalized height for several one-hour periods (LST) in a continental stratus cloud observed over central Pennsylvania on 18 November 1994. Cloud base is at about 300 m and cloud top ranges from about 750-900 m during the period. Values shown are the average variance calculated from 30-minute intervals within the time periods indicated at the top of the figure.

be relaxed by using microphysical retrievals based on Doppler spectra from mm-wavelength radars (Gossard, 1994; Babb et al., 1998). Furthermore the spectral techniques provide the possibility of separating drizzle from cloud returns.

Combinations of the measurements from the surface-based sensors systems have been key in providing many cloud properties. Albrecht et al. (1990) for example, combined the cloud-base heights from a ceilometer with cloud-top heights to calculate an adiabatic liquid water path that was compared with the liquid water path estimates from a microwave radiometer. Frisch et al. (1995a) combined the reflectivity and spectral width estimates from a 35 GHz radar with the liquid water path from a microwave radiometer to estimate cloud and drizzle properties. Dong et al. (1997) developed a scheme for retrieving the microphysical characteristics of stratus clouds using cloud top estimates from a 94 GHz radar, cloud base from a ceilometer, liquid water path from a microwave radiometer and surface shortwave irradiances from broadband radiometers.

An important contribution of FIRE and ASTEX was a demonstration of how sophisticated remote sensing systems could be used to define cloud and boundary layer properties. Even the simple characterizations of the properties of boundary layer clouds from ceilometers during ASTEX and FIRE represents a substantial contribution to the observational base needed to test parameterizations of clouds (e.g. Bretherton and Pincus, 1995c). Since then there has been further applications of these systems to study both marine and continental clouds. Although the technology and techniques developed have tremendous potential for further increasing our understanding of boundary layer cloud processes (White et al., 1995 and 1996), there is a need to further develop these observational techniques with a clear strategy in mind for testing and developing models and parameterizations.

3 Processes Explored

3.1 Cloud-Top Entrainment Instability

Another important difference between the clear and cloudy boundary layer is the entrainment process. Unsaturated air from above the inversion that is entrained and mixed with cloudy air in the boundary layer can under some circumstances become negatively buoyant. This possibility was first discussed by Lilly (1968) where he noted that the conditions for such would be satisfied if the wet bulb potential temperature (or equivalent potential temperature) decreased with height across the capping inversion. He suggested that this process might lead to the breakup of the clouds. The criteria for Cloud Top Entrainment Instability (CTEI) was later expanded by Randall (1980) and Deardorff (1980) to include the effects of water vapor and liquid water on buoyancy effects.

In generalized form the criteria for CTEI can be written as $\Delta\theta_e < -k\Delta r_t$ where Δ represents differences in a variable across the inversion. This form lends itself to comparison with observations. Kuo and Schubert (1988) made such comparisons using soundings that were made from San Nicolas Island during FIRE and from observations made from aircraft and radiosonde soundings made prior to FIRE. They found, however, that most of the soundings from San Nicolas were associated with solid clouds. Although about 25 % of the soundings satisfied the CTEI criteria defined by Randall (1980), less than half of these soundings were associated with broken cloud conditions. They summarized their results by plotting the differences across the inversion of $\Delta\theta_e$ as a function of Δr_t. There are some difficulties, however, in estimating these quantities from observations. If liquid water estimates are not available, which is often the case when using soundings from radiosondes, some approximation must be made to estimate r_t. There can also be difficulties in defining the inversion jumps from soundings since the structure at and above the capping inversion can be quite complicated (Siems et al., 1990; Albrecht, 1991). Despite some of the difficulties in using data to test CTEI, the $\Delta\theta_e - \Delta r_t$ diagram comparing observations with different theoretical formulations for k has been used in a number of studies (MacVean and Mason, 1990; Duynkerke, 1993).

One disadvantage of the use of the $\Delta\theta_e - \Delta r_t$ diagrams to evaluate the cloud-top entrainment instability is the strong dependence of θ_e on the water vapor mixing ratio. As a result the data from a diverse set of sources always fall along a line. These points, however, generally show a much less organized pattern if they are plotted on a $\Delta\theta_\ell - \Delta r_t$ diagram (Albrecht, 1991). The stability criteria in this coordinate system can be written as $\Delta\theta_\ell < -(1-k)\Delta r_t$. Albrecht et al. (1985) and Nicholls and Leighton (1986b) noted, that not all combinations of mixtures of cloud and clear air give saturated parcels. This theme was further discussed and quantified by Siems et al. (1990) and Duynkerke (1993b). The latter study showed that a more general approach to the CTEI could be made by considering the total buoyancy – defined as the mass of the parcel times the virtual potential temperature between the parcel and the environment.

Although soundings have been collected from a wide range of conditions to test CTEI, Betts and Boers (1990b) considered a case study with soundings across a clear and cloudy boundary that was observed during FIRE and argued that CTEI was a possible cause for the transition from a cloudy to a clear boundary layer. Kloesel (1991) however, noted that the clearing observed in this case was more likely due to the flow of warm air off of the coast of the western U.S. Although the FIRE data set did not provide a definitive resolution of the relationship between cloud transition and CTEI, conditional sampling techniques were applied to aircraft data (Khalsa, 1993; Wang and Albrecht, 1994) to investigate the physical processes associated with cloud-top entrainment. In these studies ozone from a fast-response sensor was used as a tracer for studying the structure of entrainment events. Wang and Albrecht (1994) studied a solid cloud case that satisfied conditions for cloud-top entrainment and found clear evidence of entrainment events (Fig. 3). Although the composite structure of these events was defined in this study, the conditionally sampled aircraft data provided neither 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. During ASTEX there were frequent observations of cumulus rising into stratus in the top part of the cloud layer (Wang and Lenschow, 1995; Martin et al., 1995). This relatively complicated situation did little, however, to illuminate the entrainment processes operating in solid stratocumulus clouds.

Thus, major questions that remain concerning cloud-top entrainment remain include:

1. What are the characteristics of the entraining interface and what factors control these characteristics?
2. What is the structure and evolution of entrained parcels?
3. What variables control the entrainment rate?
4. How does entrainment affect cloud microphysics?

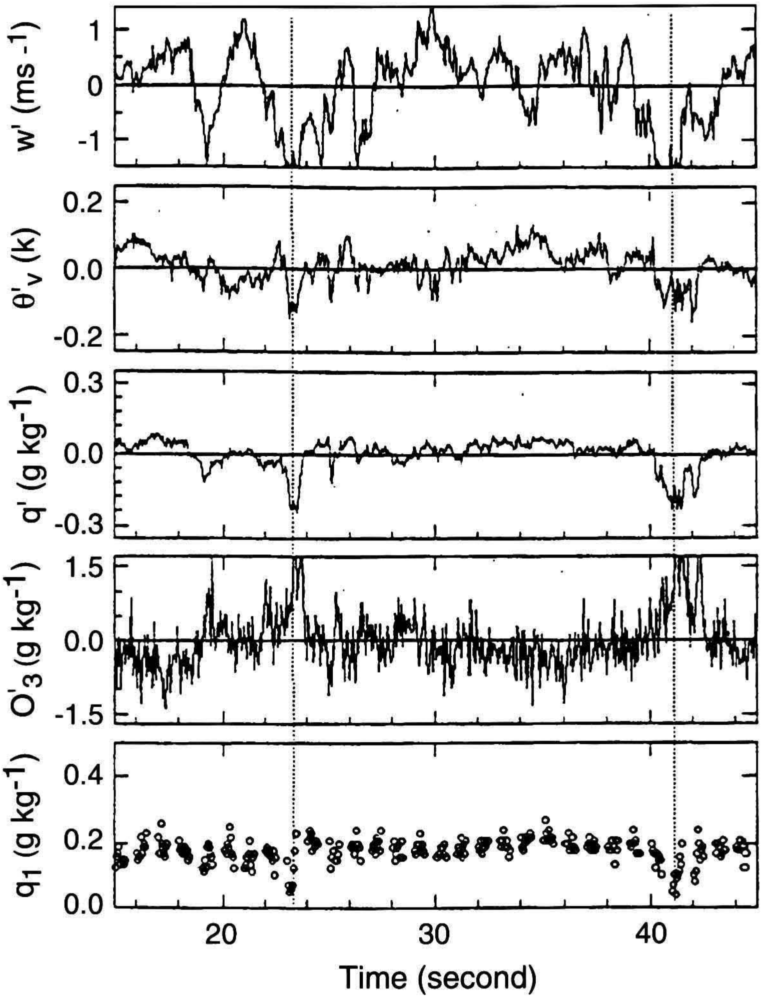

Fig. 3. A perturbation time series of vertical velocity w, virtual temperature θ_v, specific humidity q, ozone concentration O_3, and liquid water content q_l obtained from the NCAR Electra during a flight in a stratocumulus cloud observed off the coast of California during FIRE. Well-defined coherent events are indicated by the vertical dash lines (Wang and Lenschow, 1995).

Several studies from FIRE documented the diurnal variations of marine stratocumulus over the island of San Nicolas Island during FIRE (Hignett, 1991; Blaskovic et al., 1991; Betts, 1990a; Albrecht et al., 1990). The study by Hignett (1991) provides an excellent contrast between the turbulence structure observed during the day and at night from tethered balloon observations. Although the Hignett (1991) study was made during a period of good fetch from the open ocean, there are other days during the FIRE observational period when coastal mesoscale circulations may perturb the diurnal cycle at San Nicolas relative to that over the open ocean (Randall et al., 1996).

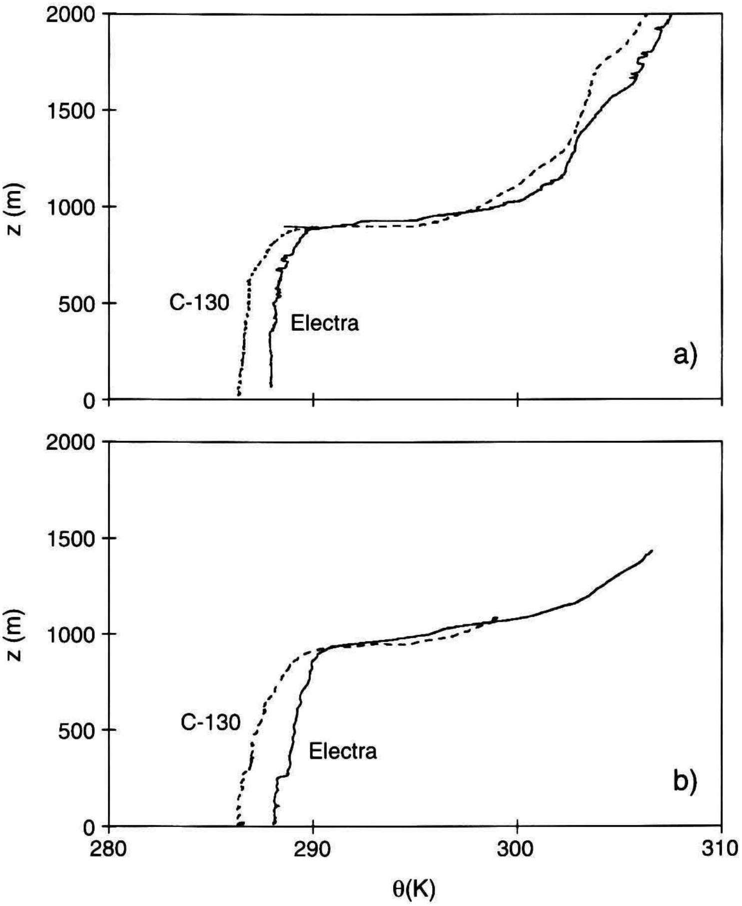

Fig. 4. Potential temperature profiles in marine stratocumulus observed off the coast of California during FIRE from the UK C-130 and the NCAR Electra at a) approximately 1130 LST and b) 1500 LST on 30 June 1987. Cumulus cloud base is near 300 m while the stratus deck extends from about 600 m to the capping inversion.

Diurnal variations, however, were also observed over the open ocean during both FIRE and ASTEX. The daytime decoupling of the boundary layer observed during FIRE is illustrated by the potential temperature profiles shown in Fig 4. The two soundings were obtained 500 km off the coast of California with the UK C-130 and the NCAR Electra separated by less than 200 km. The morning sounding (Fig. 4a) from the Electra shows some signs of decoupling with a stable layer at about 300 m. The afternoon soundings shown in Fig. 4b indicates a substantial warming of 1–2 °C in the cloud layer with very little change in the subcloud layer temperature. The warming of the cloud layer results in a strengthening of the cloud base inversion and further decoupling of the boundary layer. During ASTEX the diurnal variations of boundary layer structure associated with a decoupled boundary layer were further documented (Miller and Albrecht, 1995; Rogers et al., 1995; Betts et al., 1995; Miller et al., 1998). Models have been successful in stimulating many of the features of the observed diurnal variability. For example, Duynkerke and Hignett (1993a) compared model simulations of the diurnal cycle with the observation described by Hignett (1991).

The effects of cloud microphysics and cloud macroscopic structure on solar heating in the cloud layer are key considerations when explaining and modeling the diurnal variability in the cloudy marine boundary layer. During FIRE King et al. (1990) used aircraft observations from an airborne multiwavelength scanning radiometer to study cloud absorption. Cahalan and Snider (1989) used surface-based radiometer, aircraft and LANDSAT observations to characterize structures within clouds. Using results from these studies Cahalan et al. (1994) estimated that the in-cloud structure resulted in 15% decrease in cloud albedo relative to the plane parallel case. Observations during ASTEX were used to further address the effects of cloud structure on the radiative properties (Cahalan et al., 1995; Hignett and Taylor, 1996). Some of the key questions remaining concerning diurnal variations in marine stratocumulus include:

1. Are the effects of small-scale variability in the cloud structure important in regulating the larger-scale radiative properties of these clouds?
2. How do air-land contrasts and boundary layer structure in coastal areas affect the diurnal variability of stratocumulus clouds?
3. What is the role of diurnal decoupling on the transition of stratocumulus to fair-weather cumulus clouds?

3.3 Decoupling

Decoupling was commonly observed during FIRE on flights made several hundreds of kilometers off the coast and was found to have an important impact on the cloud structure. The fundamental role of decoupling in regulating cloud

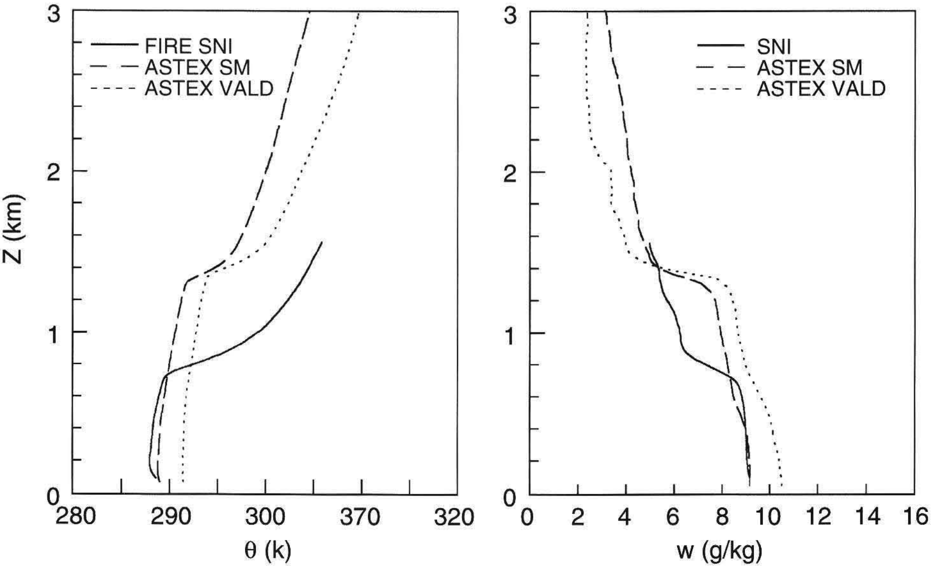

Fig. 5. Composite potential temperature and mixing ratio soundings for FIRE and ASTEX with average cloudiness ranging from cloud conditions ranging from solid stratocumulus to broken trade cumulus. Inversion height was identified for each sounding analyzed to define a non-dimensional height scale z/z_i that was applied before the soundings were averaged. Average inversion height for each region was then used to dimensionalize the average profiles shown. From Albrecht et al. (1995b).

evolution has been addressed using the FIRE data (Paluch and Lenschow, 1991). Aircraft and surface-based measurements during ASTEX indicate that the stratus observed in this area also 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. 5 where composite temperature and moisture profiles from radiosondes collected in nearly solid status during FIRE and more broken conditions during ASTEX are presented (Albrecht et al., 1995b). 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).

The cloud cover corresponding to each of the composite soundings shown in Fig. 5 was estimated using a laser ceilometer operating at each location. The cloud cover was 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 were 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 R/V Väldiviä compared with 82% at San Nicholas during FIRE. The nature of the clouds observed during decoupled boundary layer conditions have been extensively documented (Roode and Duynkerke, 1996; Duynkerke et al., 1995; Miller and Albrecht, 1995; Martin et al., 1995).

Although the ubiquitous nature of decoupled boundary layers over the subtropical oceans has been well documented, several key questions remain. These include:

(1) How are transition layers formed and maintained?
(2) What is the relative importance of drizzle and day-time solar heating for the dynamics of the transition layer?
(3) How are chemical and aerosol transports affected by decoupling?

3.4 Mesoscale Circulations

Mesoscale variability in stratus clouds was well documented in the FIRE observations made with instrumented aircraft. Turbulence spectra from aircraft observations clearly showed the importance of mesoscale variability for a wide range of cloud conditions (Nucciarone and Young, 1991). A more detailed description of the mesoscale circulations in clouds sampled during FIRE was developed using a compositing technique (Moyer and Young, 1994).

The decoupled conditions observed during ASTEX were often associated with mesoscale circulations. The decoupling results in a moistening of the subcloud layer as transports between the subcloud layer and the cloud layer are restricted. 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 can in turn supply liquid water to the overlying stratus through detrainment at the base of the relatively strong inversion that caps the cloud layer (Martin et al., 1995; Wang and Lenschow, 1995; Roode and Duynkerke, 1996). These detrained cloud masses often have the appearance of the anvils associated with thunderstorms and 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 and Orr, 1995). A 94 GHz cloud radar operated from Santa Maria by Penn State University (Miller and Albrecht, 1995) probed several of these systems as they passed over the island. The radar returns shown in Fig. 6 clearly shows the structure of one of these

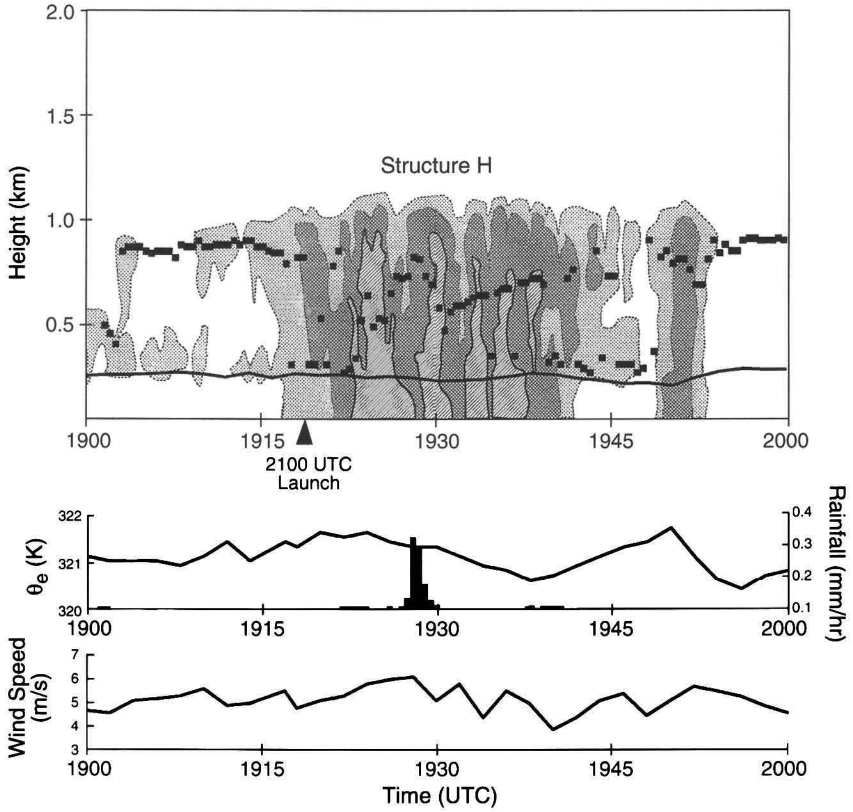

Fig. 6. Time-height section of radar returns from the Penn State cloud radar as a boundary layer convective complex passes over the island of Santa Maria during ASTEX. Cloud base height from the ceilometer is indicated by solid filled squares and the solid line indicates LCL of near surface layer air. Time series of θ_e, surface rainfall rate, and wind speed are shown beneath (Miller and Albrecht, 1995).

systems. The echoes below the cloud base obtained from the ceilometer indicate that drizzle was falling from this cloud system. Key questions concerning mesoscale features include:

(1) What factors give rise to mesoscale boundary layer cloud structures?
(2) Is the mesoscale organization important to the overall dynamics and microphysics of boundary layer cloud systems or is it simply an interesting feature of these systems ?
(3) What are the dynamics and energetics of mesoscale cloud structures?

Although mostly solid clouds were observed during FIRE, there was clear evidence that microphysical effects were important for cloud and boundary layer structure (Albrecht, 1989; Austin et al., 1995). Several aircraft flights with drizzle were observed during FIRE (Albrecht, 1989). However, substantially less drizzle was observed from San Nicolas Island. Cloud microphysics and drizzle properties of marine stratocumulus were observed to vary substantially in the mesoscale. For example, there were large variations in the cloud microphysics associated with the two areas sampled for the soundings shown in Fig. 4. 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 are substantially fewer in number and larger than those sampled by the C-130 as shown in Fig. 7. In addition, drizzle rates (averaged over all turbulence legs made on 30 June, 1989) are estimated to be on the order of 0.2 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 (see Fig. 4). Austin et al. (1995) have made a comprehensive study of the microphysical and drizzle characteristics observed on this particular day. In addition they compare optical depths from satellite with the aircraft observations.

Extreme variations in aerosol conditions were observed during ASTEX

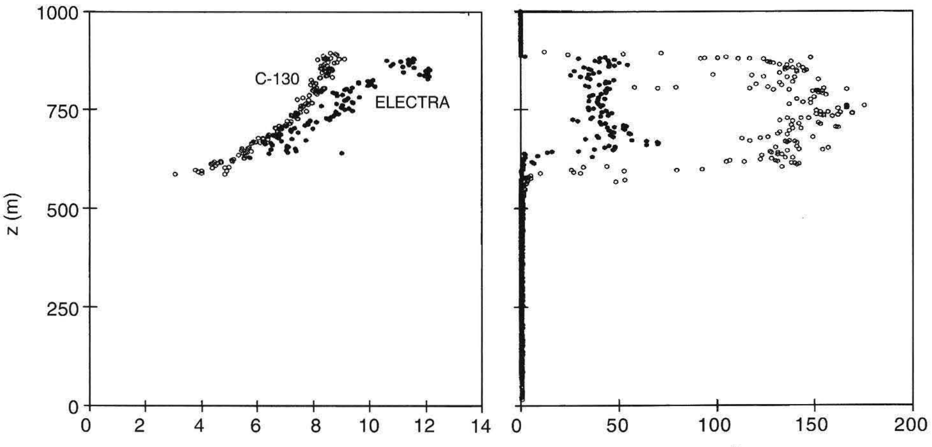

Fig. 7. Comparison droplet size (left) and droplet concentration (right) from Forward Scattering Spectrometer Probes (FSSP's) on the C-130 and the Electra. Aircraft were flying within about 200 km of each other during FIRE flight on 30 June 1987. From Miller and Albrecht (1995).

and resulted in large variations in cloud properties. During a one-week period of ASTEX. drizzle was observed frequently from the aircraft and the islands – often in association with the MBLCC's discussed previously. The continental air sampled in other periods 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. Martin et al. (1995) found that cumulus penetrating into status resulted in substantial variability in cloud microphysical properties. These conditions provided an exceptional data set for characterizing cloud characteristics associated with differences in aerosol concentrations. Gerber (1996) analyzed aircraft observations of drizzle characteristics in marine stratocumulus sampled during ASTEX and found a well defined threshold between light and heavy drizzle that depends on cloud thickness and droplet concentrations. Stratocumulus clouds sampled in the clean air masses near Tasmania (Boers et al., 1996) were found to be substantially depleted of liquid water by drizzle. Observed liquid water contents in these clouds were about 50% of the adiabatic values. Major unanswered questions about drizzle in marine stratocumulus include:

(1) What is the spatial and temporal evolution of drizzle and how does it affect entrainment and cloud dynamics?
(2) What is the role of giant nuclei and CCN in general on drizzle production?
(3) Does turbulence within the cloud enhance drizzle production?
(4) How does drizzle modify boundary layer aerosol concentration and composition?

3.6 Cloud Transitions

A major goal of ASTEX was to study the transition from solid stratocumulus to fair weather cumulus. The 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. Thus, even while the appearance from satellite is that of solid cloud decks, the seeds of transitions are well established even during this time. Aspects of the transition were documented using observations that were obtained on two Lagrangian experiments carried out during ASTEX (Bretherton and Pincus, 1995a; Bretherton et al., 1995b; Roode and Duynkerke, 1997a). Although this unique set of observations following an air mass for two days has proven to be useful for the evaluation and testing of models, the range of conditions that were sampled during these observations is limited compared with the full range of conditions extending from the subtropics to the ITCZ. The ASTEX observations were key in describing aspects of the stratocumulus to trade-cumulus transition. These measurements, however, were most in a region which mostly represents the early phase of the transition with cumulus rising into stratus.

Despite the utility of these new observations for the testing of models and theory, observations further downstream in the equatorward trade flow are largely missing and leave major unanswered question regarding cloud transition. These include:

(1) What is the role of the various physical processes that account for the transition from cumulus rising into stratus to a regime of fair-weather cumulus with no overlying stratus?
(2) How does the thermodynamic structure of the boundary layer evolve along trajectories that includes the full range of cloud conditions from stratus to cumulus rising into stratus to fair-cumulus?
(3) How do conditions in the ASTEX region compare with transition regions off the coast of California and other stratocumulus areas?

3.7 Continental Cloud Processes

Even though continental stratus clouds directly affect a relatively small area of the earth's surface compared with their marine counterparts, they affect local climate and weather and are linked closely to surface temperature and water budgets as well as diurnal cycles. Changes in cloudiness or other properties of continental stratus clouds may help explain a substantial portion of the observed increase in global temperatures during the last century due to a decrease in the diurnal range of surface temperatures over the continents (Karl et al., 1993). Furthermore, continental stratus clouds impact aircraft operations and the presence of drizzle in winter-time continental stratus can lead to dangerous icing conditions (Marwitz et al., 1997). Despite their importance, even a basic description of continental stratocumulus is mostly lacking. Some initial studies of continental stratus clouds have focused on a description of cloud structure rather than processes (Syrett et al., 1995; Vali et al., 1995; Thomas, 1996; Sassen et al., 1998).

Although many of the processes that operate in marine stratocumulus clouds may also operate in continental clouds, the relative importance of various processes may differ. In addition, surface and synoptic conditions may be much more complex over land than over water. The surface heat and moisture fluxes over land will be sensitive to the surface wetness, vegetation, and incident solar energy. Thus there are additional feedbacks between boundary layer clouds and the surface fluxes that are not operating in marine stratocumulus and are poorly represented in forecast and climate models.

4 Summary Remarks

A wide range of questions concerning the processes operating in marine stratocumulus remain unanswered despite substantial progress in developing an extensive set of observations. One of the difficulties in unraveling the complexities of marine stratocumulus has been that processes like decoupling and drizzle do not have similar counterparts in the clear boundary layer or close analogs in oceanic boundary layers or laboratory simulations. At the same time, however, the development of sophisticated remote sensing systems and retrieval techniques has provided new methods for studying the internal circulations in stratocumulus clouds and the effects of those circulations on entrainment and cloud microphysical processes. These advances will provide new observations for evaluating large-eddy simulations and other detailed cloud microphysical models.

The eastern Pacific off the coast of the southwestern US was once considered a prime area for observational studies of marine stratocumulus clouds since this area is frequently covered by persistent stratus during the summer, the large-scale weather patterns over this area are relatively steady, and the simplicity of the underlying ocean surface should simplify the analysis relative to conditions over land where terrain effects and complicated interactions with the underlying surface may complicate the treatment of the lower boundary. But despite these simplifications, the internal processes operating in marine stratocumulus clouds have been found to be much more complicated than those first envisioned by the pioneering work of Lilly (1968). Research during this past ten years, however, has helped define the questions and issues that still need to be addressed for a wide range of cloud and boundary layer conditions over extensive areas of the world's oceans. Advances in technology will provide a means for addressing these questions during the next ten years.

Acknowledgments

Mr. Pavlos Kollias kindly provided the vertical velocity variances uses in Fig. 2. I am grateful to Lila Ptak, Terry Faber and Jean Carpenter for their assistance with the preparation of this manuscript. Portions of the works discussed and reviewed in this paper have been supported by the National Science Foundation (ATM9596207), the Office of Naval Research (N00014-91-J-1992), and the Department of Energy (DEF00297ER62337).