The Atlantic Stratocumulus Transition Experiment—ASTEX

Bruce A. Albrecht,*
Christopher S. Bretherton,+
Doug Johnson,#
Wayne H. Scubert,@
and A. Shelby Frisch&

Abstract

The Atlantic Stratocumulus Experiment (ASTEX) was conducted over the northeast Atlantic Ocean during June 1992 with substantial international collaboration. The main goal of ASTEX was to study the climatologically important transition between solid stratocumulus and subtropical trade cumulus cloud regimes using island, aircraft, ship, and satellite measurements. Typically, the boundary layer was found to support cumulus clouds detraining into a patchy and fairly thin upper-stratocumulus layer. The substantial microphysical variability between clean marine and polluted continental air masses observed during ASTEX affected both drizzle and cloud properties. Highlights of the ASTEX research strategy included use of the ECMWF operational forecast model for assimilation of ASTEX soundings to obtain improved regional meteorological analyses; "Lagrangian" measurements of boundary-layer evolution following an air mass using aircraft and balloons, extensive coordinated use of surface, airborne, and satellite platforms; and an extensive suite of island-based remote sensing systems including millimeter-wavelength radars. A summary of ASTEX is presented and some initial results are presented.

1. Introduction

Low-level marine stratus clouds are important modulators of the earth's radiation budget. They increase the albedo compared with the underlying ocean surface but have little effect on the longwave radiation emitted to space. Consequently, satellite analyses of the top-of-the-atmosphere radiation budget (e.g., Ramanathan et al. 1989; Harrison et al. 1990; Klein and Hartmann 1993) show that areas affected by these clouds can easily result in a net cloud forcing of -100 W m^{-2} and contribute substantially to a global net cloud forcing of about -17 W m^{-2} during the Northern Hemisphere summer. In addition, modeling assessments (e.g., Slingo 1990) show that modest changes in low cloud amount, cloud droplet size, or liquid water content could cause climatically significant changes to the global radiation budget. It is, however, difficult to include the effects of these clouds in models, since the clouds that are often less than 500 m thick are associated with weak large-scale forcing and are maintained by subtle balances among various physical processes. These processes include turbulence, radiation, entrainment, and drizzle.

Because of the importance of marine boundary-layer (MBL) clouds to our understanding of climate, marine stratocumulus clouds have been the focus of several recent field experiments from which collectively a great deal has been learned about shallow, solid, marine stratocumulus clouds. The most ambitious of these was the stratocumulus deployment during the First International Satellite Cloud Climatology Project Regional Experiment (FIRE) (Albrecht et al. 1988). However, these experiments did not sample the broken stratocumulus clouds and deeper boundary layers farther offshore that are typical of a large area of the subtropical stratocumulus regime and seem to form an important intermediate step in the breakup of stratocumulus to trade cumulus cloud fields. Consequently, the Atlantic Stratocumulus Transition Experiment (ASTEX) was designed to provide improved understanding of the processes responsible for the transition to broken cloud conditions and the processes that control cloud amount and type. The experiment was conducted 1–28 June 1992 over the eastern Atlantic. In this paper we describe the design of the experiment and present some preliminary results that highlight various studies currently in progress.

2. Experimental design

ASTEX was designed to address key issues related to the transition from stratocumulus to trade cumulus and the factors that control cloud properties.

*Department of Meteorology and Earth Systems Science Center, The Pennsylvania State University, University Park, Pennsylvania.
+Department of Applied Mathematics, University of Washington, Seattle, Washington.
#Meteorological Research Flight, Farnborough, England.
@Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado.
&NOAA/ETL, Boulder, Colorado.
Corresponding author address: Prof. Bruce Albrecht, Dept. of Meteorology, The Pennsylvania State University, University Park, PA 16802.
E-mail: B1A@PSUVM.PSU.EDU
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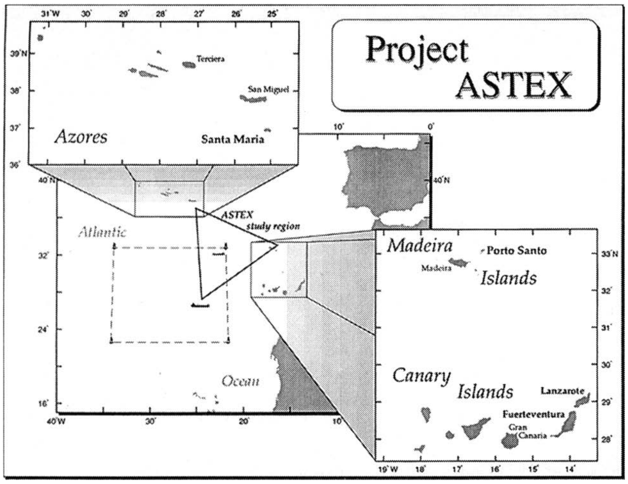


FIG. 1. The ASTEX study region.

It involved intensive measurements from several platforms to determine how the transition and cloud properties 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 lifting condensation level (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 so that parameterizations for general circulation models can be further developed. Another important goal of ASTEX was to provide observations for developing and testing algorithms for retrieving cloud properties from satellite observations.

The Office of Naval Research lead the ASTEX activities with strong support from the National Aeronautics and Space Administration. In addition, ASTEX was supported by the National Science Foundation, the Department of Energy, and the National Oceanic and Atmospheric Administration and had broad international support. More than 200 scientists, students, and support staff from the United States, United Kingdom, France, Germany, Portugal, Netherlands, Russia, and Spain participated in ASTEX and two related experiments—MAGE and SOFIA.

MAGE—the International Global Atmospheric Chemistry Program's Marine Aerosol and Gas Exchange: Atmospheric Chemistry and Climate program—was closely coordinated with ASTEX. The specific goals of the MAGE experiment included 1) developing and testing a Lagrangian strategy for studying chemical and meteorological evolution in a tagged boundary-layer air mass, using ships, balloons, and aircraft, 2) developing and testing new techniques for estimating trace-gas and aerosol fluxes across the air–sea interface by comparison with traditional approaches, 3) evaluating the impact of marine and continental aerosols on the formation and dissipation of stratocumulus clouds, 4) comparing the impacts of natural and anthropogenic sulfur, halogens, and hydrocarbons on marine aerosol chemistry, and 5) gaining experience with multinational and multiagency field experiments for addressing global tropospheric chemistry issues. Thirty-five atmospheric chemistry research groups from six countries were involved with MAGE. The chemical measurements supported the ASTEX efforts by providing a means to study the exchange of mass between the boundary layer and the free troposphere, to help in defining the source regions of the air being sampled, and to define and study chemical processes associated with aerosol production in the marine environment. As a part of MAGE, constant-level balloons were launched from a ship to support two Lagrangian experiments. These balloons drifted with the mean winds and measurements were made in the air masses tracked by these balloons.

SOFIA—Surface of the Ocean, Fluxes, and Interactions with the Atmosphere—involved scientists from several research groups from France and operated in conjunction with ASTEX. SOFIA was a study of heat, moisture, and momentum transfer between the surface and the atmospheric boundary layer on scales ranging from the local to the mesoscale. Details of this experiment are described in Dupuis et al. (1993). Particular regard was given to locating and making measurements around the Azores Current, which meanders through the region to the south of the Azores. SOFIA focused on developing satellite techniques for estimating the surface fluxes.

ASTEX involved coordinated measurements from aircraft, satellites, ships, and islands in the area of the Azores and Madeira Islands (Fig. 1). This area was chosen since satellite studies showed 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.

The experimental design for ASTEX was similar to that used during the FIRE 1987 experiment where a telescoping approach was used to explore scales of motion ranging from that of the cloud scale (microns to hundreds of meters) to the large scale (thousands of kilometers). Satellites and upper-level aircraft provided a description of large-scale cloud features, while 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 similar telescoping approach was used for SOFIA to develop and test techniques for estimating surface fluxes from satellite observations.

Satellite data were collected in support of ASTEX from METEOSAT, NOAA Polar Orbiter, Landsat, SPOT, and DMSP satellites. METEOSAT and NOAA polar orbiter images were used in the field for mission planning. Postexperiment analyses focus on using satellite data for retrieving fractional cloudiness, cloud reflectivities, liquid water, cloud-droplet size, aerosol optical depth, and sea surface temperature. The NASA ER-2 research aircraft, which flew missions at very high altitudes, provided a link between the satellite observations and detailed cloud observations obtained from islands, ships, and aircraft flying at lower levels. The instrumentation of the ER-2 included a lidar, high-resolution radiometer similar to those on the NOAA Polar Orbiters, and a Moderate-Resolution Imaging Spectrometer simulator (King et al. 1992).

Several other aircraft were used during ASTEX to provide in situ cloud observations on scales ranging from the microphysical to the mesoscale. A C-130 operated by the U.K. Meteorological Research Flight and an Electra operated by the National Center for Atmospheric Research (NCAR) made turbulence, cloud microphysics, and radiation measurements. These two aircraft flew a variety of coordinated missions that were designed to study various physical processes and contribute to broader missions involving other platforms. In addition, the NCAR Electra was instrumented to make aerosol and chemistry measurements in support of MAGE. An instrumented C-131A aircraft operated by the University of Washington provided cloud physics and aerosol measurements in support of both ASTEX and MAGE. The ARAT Fokker F-27 aircraft supported SOFIA and ASTEX efforts with lidar, turbulence, cloud microphysics, and radiation measurements in the vicinity of the French R/V *Le Suroit,* which was generally located 50–100 km south of Santa Maria. A U.S. Navy P-3 operated by the Naval Research Lab was used to test an experimental infrared cloud imaging device.

Intensive suites of instruments were deployed on the island of Porto Santo near Madeira and the island of Santa Maria in the Azores to obtain surface and upper-air measurements and to probe cloud and boundary-layer structure with sophisticated remote sensing systems. Scientists from Colorado State University (CSU), NOAA's Wave Propagation Lab [WPL, now the Environmental Technology Laboratory (ETL)], and the University of Utah operated equipment from Porto Santo. The instruments located on Santa Maria were operated by The Pennsylvania State University (PSU), NASA Ames, University of Utrecht, and a division of Portugal's National Institute of Meteorology and Geophysics (INMG). In addition, scientists associated with MAGE measured chemistry and aerosol characteristics at Santa Maria.

Surface and upper-air measurements were also made from four ships that operated during the experiment. The German R/V *Valdivia* from the University of Hamburg and Max Planck Institute for Meteorology operated during the first two weeks of the experiment at a location near the southwest vertex of the triangle shown in Fig. 1. In addition, NOAA's R/V *Malcolm Baldrige,* which supported MAGE, was used by WPL to make remote and in situ atmospheric measurements. This ship operated throughout the array during the first two weeks of the experiment and spent the last week at the southwest vertex. Some upper-air and surface measurements were made from the R/V *Oceanus,* another ship that was used in support of MAGE. It was generally located to the northeast of Santa Maria. Both the *Oceanus* and the *Malcolm Baldrige* played important roles in the Lagrangian experiments that were carried out during ASTEX. All the constant-level balloons were released from the *Oceanus,* which then attempted to follow a track behind the balloons making surface measurements. Using model forecast trajectories, the *Malcolm Baldrige* attempted to position itself such that after two days it was directly underneath the balloons. The French ship R/V *Le Suroit* made surface and upper-air measurements just to the south of Santa Maria in support of SOFIA. A surface buoy operated by the Woods Hole Oceanographic Institute collected surface meteorological, radiation, and ocean current data from a point near the center of the triangle shown in Fig. 1. The data from this buoy were transmitted by satellite for subsequent analysis.

The observations from the islands and the ships provided surface meteorological conditions, surface radiative fluxes, and upper-air temperature, moisture, and winds to assist in a description of the large-scale fields of temperature, moisture, and winds. In addition, the remote sensing systems on these platforms provided high temporal resolution of cloud properties. These properties included cloud-base height, cloud-top height, and liquid water content. As illustrated during FIRE (e.g., Minnis et al. 1992; Albrecht et al. 1991), these observations provide detailed descriptions that can be used both to study cloud processes and to provide valuable ground-truth measurements for satellite retrievals. The remote sensing systems that were deployed during ASTEX are listed in Table 1.

TABLE 1. Surface-based remote sensing systems deployed during ASTEX.

Instrument	Measurement	Locations (affiliations)
Microwave radiometer	Liquid and water vapor path	Porto Santo (WPL) Santa Maria (PSU) R/V *Malcolm Baldrige* (WPL) R/V *Valdivia* R/V *Le Suroit*
Ceilometer	Cloud-base height	Porto Santo (CSU) Santa Maria (PSU) R/V *Malcolm Baldrige* (WPL) R/V *Valdivia*
Wind profilers and sodar	Wind profiles	Porto Santo (CSU; 404 MHz) R/V *Malcolm Baldrige* (WPL; 915 MHz) Santa Maria (INMG; sodar)
RASS	Virtual temperature profiles	Porto Santo (CSU)
Doppler cloud radar	Reflectivity, particle fall velocities, cloud-top height	Porto Santo (WPL; scanning, λ = 8.8 mm) Santa Maria (PSU; λ = 3 mm)
Doppler lidar	Backscatter, winds	Porto Santo (WPL; scanning, λ = 10.7 μm)

A major deficiency of the FIRE 1987 intensive observations was an inadequate definition of the large-scale fields of temperature, moisture, and winds. For ASTEX, a comprehensive regional analysis of the large-scale fields, including mean vertical motion, was performed by incorporating as many of the upper-air soundings as possible in real time into the Global Telecommunication System (GTS), in which form they could be assimilated into ECMWF and NMC operational analyses. The ASTEX region has very sparse routine upper-air coverage, with a station in the western Azores, one in the Canary Islands, and stations on the African and Portuguese coasts. The triangular shape of the ASTEX region was chosen to ensure that ASTEX soundings alone could provide crude estimates of the regional mass, temperature, and moisture budgets within the triangle. ECMWF collaborated by ensuring that the ASTEX special soundings were recognized by their data assimilation system, checking data quality, and providing a special high-resolution gridded regional dataset to ASTEX researchers. ECMWF, NMC, and the U.K. Meteorological Office forecasts were used in the field for mission planning and for trajectory prediction in support of the Lagrangian studies of airmass evolution.

Mission planning and field operations during ASTEX were directed from an operations center located on Santa Maria. Most of the aircraft were based at a large airfield that was built on Santa Maria during World War II. A summary of the operations during the experiment is provided in Bluth and Albrecht (1993a,b). Data collected during the experiment are being submitted by the individual investigators to NASA's Distributed Active Archive Center (DAAC) at Langley.

3. Highlights of the experiment

The ASTEX deployment was quite successful due in no small part to favorable weather conditions. The Azores high was well established by the second week of the experiment and provided the conditions necessary to support copious boundary-layer clouds in the study region (Fig. 2). During the first two weeks of the experiment the air in the region was extremely clean. However, an air mass from Europe moved into the ASTEX study region during the third week. During the fourth week of the experiment a rather deep storm accompanied by a strong frontal system moved through the area. By this time, however, most of the aircraft resources had been expended studying the extensive cloud systems observed during the first three weeks of the experiment.

A preliminary assessment indicates that the ASTEX dataset 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 polluted air masses extensively sampled,
- Lagrangian approach demonstrated,
- Diurnal cycle sampled,
- Upper-air data from islands and ships successfully assimilated by ECMWF, and
- Ceilometers, microwave radiometers, wind profilers, cloud radars, and other surface-based sensors successfully operated from islands and ships.

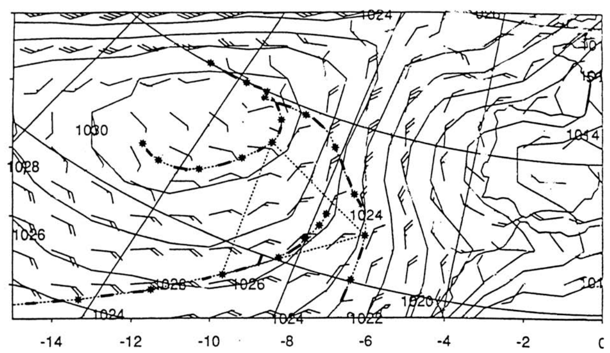


FIG. 2. Surface pressure and winds from ECMWF analysis for 1200 UTC 12 June 1992. Each full barb represents 5 m s^{-1}. Dashed lines with solid stars are 2-day forward and back trajectories through the three triangle vertices based on 1000-mb winds. Stars show the air parcel position every 12 h.

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

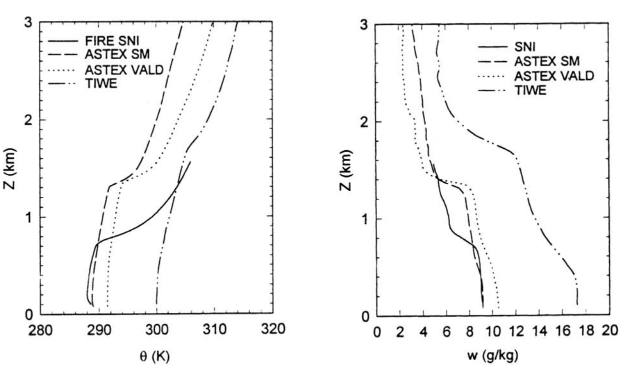
a. Region of transition sampled

Aircraft and surface-based measurements during ASTEX suggest 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. 3 where mean temperature and moisture profiles from radiosondes collected in nearly solid stratus during FIRE and more broken conditions during ASTEX are presented (Jensen 1993; Albrecht et al. 1995). In the FIRE mean sounding from San Nicolas Island (33°N, 120°W), moisture is almost uniform through the entire MBL that is "coupled" or turbulently well mixed. The moisture structure of the two ASTEX composite soundings from the island of Santa Maria (37°N, 25°W) and the German ship *Valdivia* (28°N, 28°W) clearly show a well-mixed subcloud layer, with a decrease of moisture or transition layer at 500–600 m that marks the base of a cumulus cloud layer. Stratocumulus clouds of 50–300-m thickness were common at the base of the trade inversion. Although the stratification in the cumulus layer is slightly stable, the lapse rate is still much greater than the moist-adiabatic lapse rate, leading to pronounced conditional instability. In addition to the FIRE and ASTEX composite soundings, a composite sounding obtained at the equator over the central Pacific (0°, 140°W) is included in Fig. 3. The soundings for this composite were collected in support of the Tropical Instability Wave Experiment (TIWE) (Chertock et al. 1993) during December 1991 where classic trade wind cumulus boundary-layer structures were observed for a 3-week period. The tropical composite sounding shows a deeper boundary layer, a somewhat more stable stratification in the cumulus layer, and even more pronounced transition layer separating the cloud and the subcloud layer.

The cloud cover corresponding to each of the composite soundings shown in Fig. 3 was estimated using a laser ceilometer operating at each location (Jensen 1993). The cloud cover was estimated by classifying each 30-s observation as either clear if no clouds were detected or cloudy if clouds with bases less than 3 km are observed. The cloudiness for each hour was then calculated using these 30-s classifications. The cloudiness during ASTEX is about 67% at Santa Maria and 40% at the *Valdivia* compared with 82% at San Nicholas and 25% during TIWE. Thus, ASTEX is clearly the intermediate between the solid clouds observed during FIRE and the broken fair-weather cumulus observed in the undisturbed trades.

A large number of measurements were made throughout the ASTEX region in cloud regimes that included the following:

(a) extensive sheets of stratocumulus,
(b) broken stratocumulus,
(c) cumulus under stratocumulus,
(d) trade wind cumulus, and
(e) clear skies.



	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. 3. Composite potential temperature and mixing ratio profiles for boundary-layer cloud conditions ranging from solid stratocumulus to broken trade cumulus. Inversion height was identified for sounding analyzed to define a nondimensional 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.)

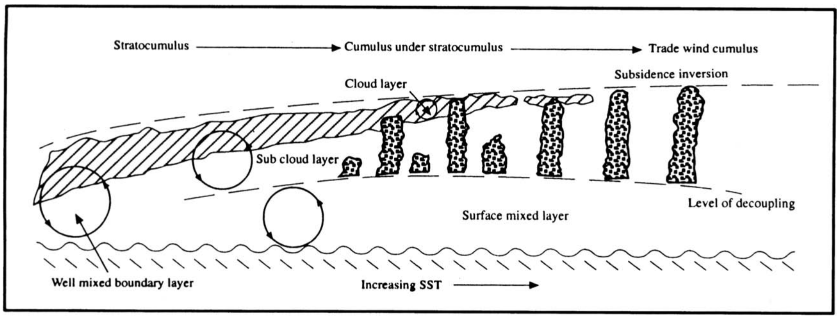


FIG. 4. A schematic of the transition from stratocumulus to trade wind cumulus.

somewhat paradoxical and poorly understood dual role of the cumulus clouds both as generators of the stratocumulus layers but also perhaps as the ultimate agents of their demise.

The structure of the MBLCCs was documented by the cloud radars located on Santa Maria and Porto Santo. Aircraft observations were also made in and around these systems. The WPL group on Porto Santo studied several of these systems using their 35-GHz-scanning cloud radar and found that they often persisted for more than three hours (Kropfli et al. 1992). A 94-GHz cloud radar operated from Santa Maria by PSU (Peters et al. 1993) probed several of these systems as they passed over the island. The radar returns from one of the systems is shown in Fig. 5a and clearly shows the anvil-like structure of the detrained stratus, the overshooting cloud top, and possible entrainment along the edges of the overshooting cloud tops. Figure 5b shows the air motion in one of these cells determined from ETL's scanning K_α-band radar on Porto Santo. This case shows a single updraft centered on the reflectivity core and penetrating up through the drizzle. No other significant updrafts or downdrafts are apparent. An idealized representation of the cell based on radar scans through several cells during ASTEX is shown in Fig. 5c.

It is possible to interpret these measurements in a manner that gives the most likely scenario of the transition from stratocumulus to trade wind cumulus. The schematic diagram shown in Fig. 4 illustrates one possible scenario. The extensive sheets of stratocumulus are found in the relatively shallow, well-mixed boundary layers that occur over the lowest sea surface temperatures (SST). In this region, diurnal variation is found to decouple the cloud layer from the surface during the day. However, as the air moves over warmer SSTs the boundary layer deepens and the cloud layer becomes permanently decoupled from a surface mixed layer (SML). The stratocumulus layer then thins as its moisture supply is reduced and slow entrainment with dry, free tropospheric air continues. As moisture builds up in the SML the convective available potential energy increases. Eventually, this moistening supports cumulus clouds that grow from the top of the SML. These clouds locally recouple the SML and the cloud layer and can either help maintain the stratocumulus by supplying it with moisture from the SML, or quicken its dissipation by enhancing the entrainment of free tropospheric air into the cloud layer. This cloud regime of cumulus under stratocumulus was the most commonly observed during the experiment, and on a large number of occasions the cumuli organized themselves into small mesoscale features [marine boundary-layer convective complexes (MBLCCs)] that would significantly thicken the stratocumulus. Substantial drizzle was often associated with these MBLCCs. Although we have depicted the cloudiness transition as being associated with increasing SST alone, in fact the downstream variation of other parameters such as mean horizontal divergence, free atmospheric temperature and humidity, surface winds, availability of cloud-condensation nuclei, and even downwelling longwave radiation can also affect the boundary-layer evolution. The challenge will be to use the ASTEX observations to determine how these parameters affect the transition. Furthermore, the observations should help clarify the

When a shallow stratocumulus layer transforms into a deeper layer with cumulus under stratocumulus, as shown schematically in Fig. 4, there arises the question of the importance of radiative cooling in driving turbulence in the stratocumulus. This question is being addressed using observations that were collected from the NOAA K_α-band Doppler radar located on Porto Santo. Figure 6 shows data from this radar taken from 1330 to 1353 UTC 17 June 1992. During this period the antenna was pointing upward to obtain vertical velocity statistics. These Doppler measurements can be interpreted as the vertical velocity of the air, if the cloud droplets are small enough to be air motion tracers. When cloud reflectivities are below -20 dBZ (as is the case in Fig. 6a), it is believed that droplet fall velocities are generally below 2 cm s^{-1}. Thus, the assumption that the droplets are air motion tracers appears valid in this case. The time average reflectivity profile of Fig. 6a shows a stratus cloud with echo bases near 900 m and tops near 1350 m above sea level. These statistics are for a time interval during which there was no obvious evidence in the radar scans of subcloud drizzle droplets. However, the high sensitivity of the radar makes it possible that some of the echo comes from below the mean cloud base. The cloud top appears quite sharp since the reflectivity drops from its peak value to undetectable levels over two range gates (37.5 m/range gate). Figure 6b shows the vertical velocity variance. Note that the upper half of the cloud is turbulent (0.11 $m^2 s^{-2}$) while the lower half is nonturbulent. Thus, if this turbulence is radiatively driven by cooling at cloud top, the downdrafts are unable to penetrate more than ~250 m. Figure 6c shows the skewness of the vertical velocity. Note that the skewness is negative in the turbulent upper half of the cloud. This, along with the cumulative distribution function for vertical velocity (see Gibson et al. 1993), indicates that the more intense downward fluctuations occur 40% of the time while the less intense upward fluctuations occur 60% of the time. Thus, the picture that emerges is one with upside-down convection originating in the region of intense radiative cooling near cloud top, but with the narrow downward plumes penetrating downward only a few hundred meters.

These preliminary results suggest 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. These convective systems supply moisture to the upper-level stratus. Radiative cooling, however, supports turbulent mixing that helps maintain the upper stratus deck.

b. Variations in cloud structure in marine and continental air masses

Extreme variations in aerosol conditions were observed during ASTEX. As noted previously, the study was characterized by very clean (low aerosol concentration) air during the second week of the experiment. The chemists on the NCAR Electra noted that the air was as clean or cleaner than air they have sampled over the central Pacific Ocean (B. Huebert 1992, personal communication). 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. As a result, a very sharp boundary between the clean maritime and polluted continental air was observed. The contrast is illustrated in the visible satellite image shown in Fig. 7 where it can be seen that the stratocumulus in the continental air mass are more reflective than the cloud in the maritime air. In addition, the satellite image shows marked difference in cloud structure between these two areas.

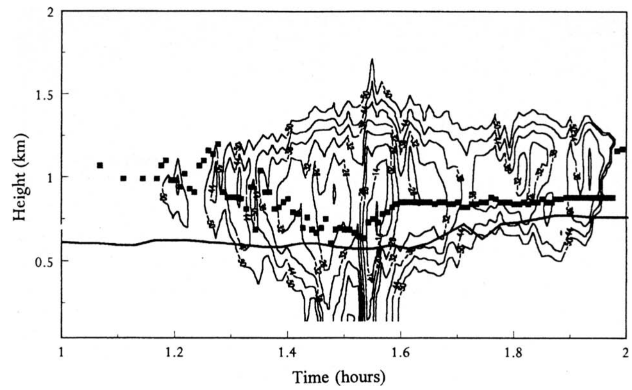


FIG. 5a. Time–height section of radar returns (dBZ) from the PSU cloud radar as a mesoscale cloud-band passes over the island of Santa Maria during ASTEX. Returns show overshooting cloud top, stratus anvil, and drizzle falling to the surface near the core of the cumulus. The contours are at 6-dB intervals with the weakest echoes at −50 dBZ outlining the cloud system. The filled squares are ceilometer-sensed cloud-base heights and the solid line is the LCL calculated from surface observations. (From Miller 1994.)

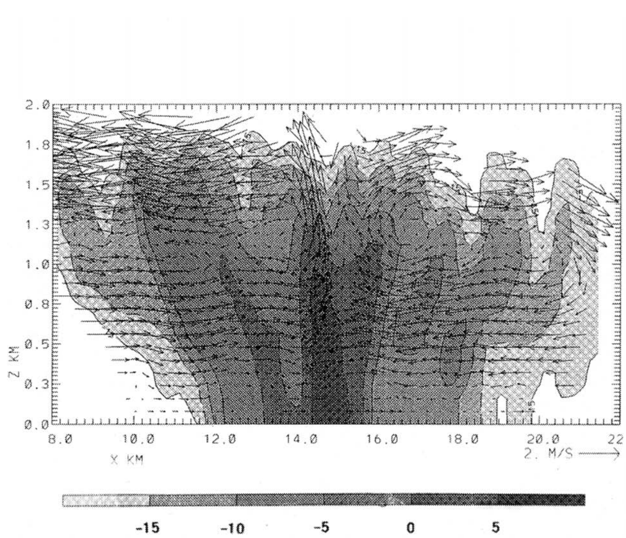


FIG. 5b. Radar-derived cell air motion projected onto a vertical plan oriented in the NW direction from the ETL cloud radar at Porto Santo. Reflectivity values in dBZ are shown as shaded areas. The highest reflectivity is about 10 dBZ. (Courtesy of R. A. Kropfi and B. W. Orr.)

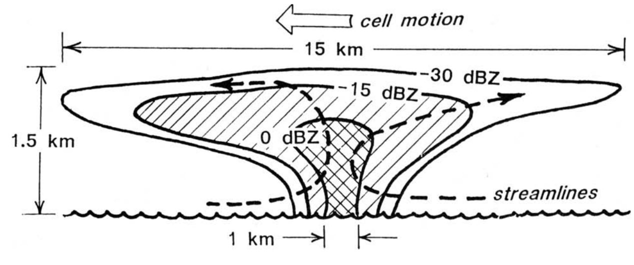
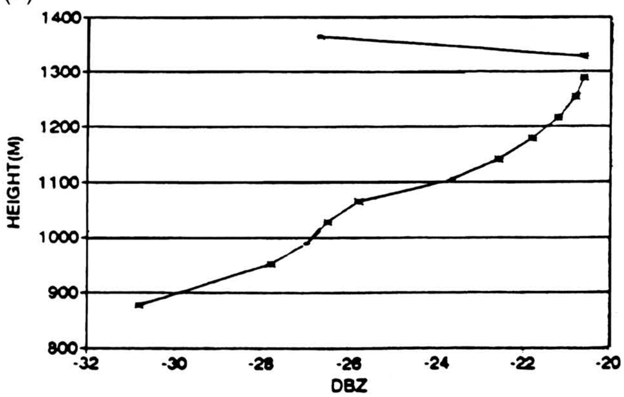
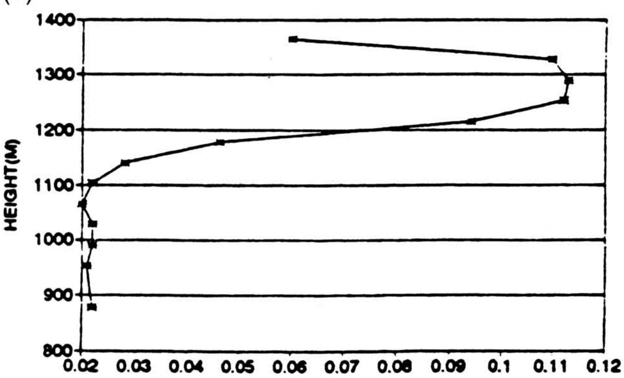


FIG. 5c. Idealized representation of a microcell based on RHI and PPI scans through several microcells with the ETL radar at Porto Santo during ASTEX. (Courtesy of R. A. Kropfli and B. W. Orr.)

(a)



(b)



(c)

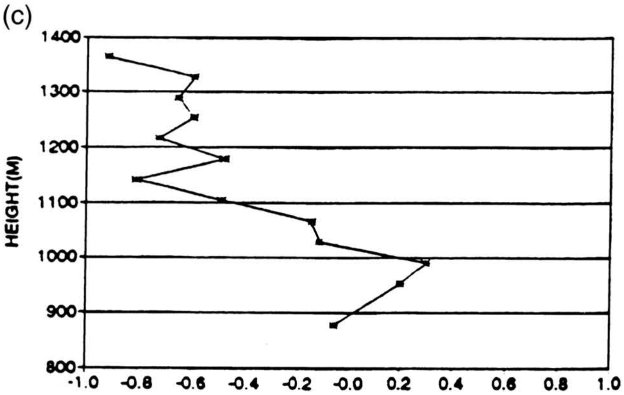


FIG. 6. Data taken from 1330 to 1353 UTC 17 June 1992, using the NOAA K_α-band Doppler radar on Porto Santo: (a) time average reflectivity, (b) variance of vertical velocity, and (c) skewness of vertical velocity.

The boundary between the maritime and continental air mass was investigated intensively with the aircraft. The contrast in cloud properties across the boundary was striking. This can be seen in observations, shown in Fig. 8, taken in profiles through the stratocumulus sheets in the two air masses. The continental air mass was characterized by substantially higher aerosol concentrations: 1700 cm^{-3} in the size range 0.1–3.0 μm compared with only 50 cm^{-3} in the maritime air mass. Even though only a small fraction of the continental aerosol particles were activated into cloud droplets compared with almost all of the maritime particles in this size range, the cloud droplet concentrations were significantly higher in the continental air mass. Cloud condensation nuclei (CCN) supersaturation spectra for the continental and maritime air masses are shown in Fig. 9.

The liquid water content of clouds in the continental air is about twice that in the maritime air and the cloud droplets are smaller (by 5 μm) in the continental clouds than in the maritime clouds. Thus, these two effects result in continental clouds that were more reflective than the maritime clouds. These conditions provided an exceptional dataset for investigating cloud characteristics associated with substantial differences in aerosol concentrations. The strikingly different characteristics of the clouds on the maritime and continental side of the transition suggest that cloud microphysics and drizzle were having a significant impact on the boundary-layer dynamics. A detailed comparison of models and ASTEX observations should further clarify to what extent this is true.

c. Lagrangian approach demonstrated

Two Lagrangian experiments were executed during the 2-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 two experiments provided a study in contrasts

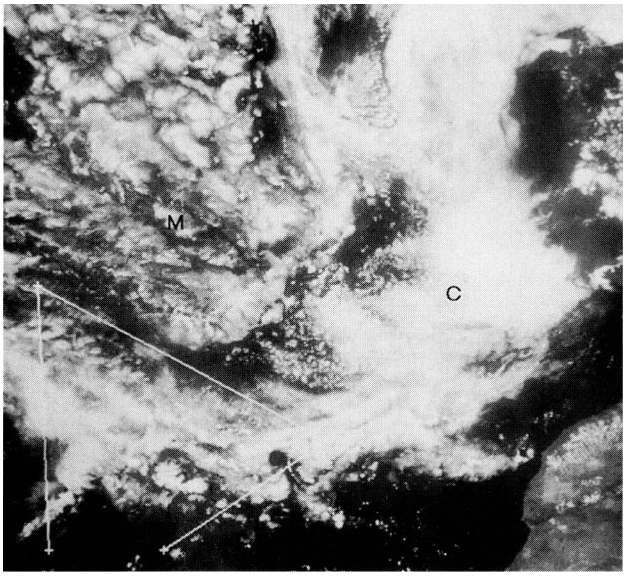


FIG. 7. AVHRR visible satellite image obtained on 16 June 1992 showing contrast between continental (C) and maritime (M) air masses in the vicinity of the ASTEX study region.

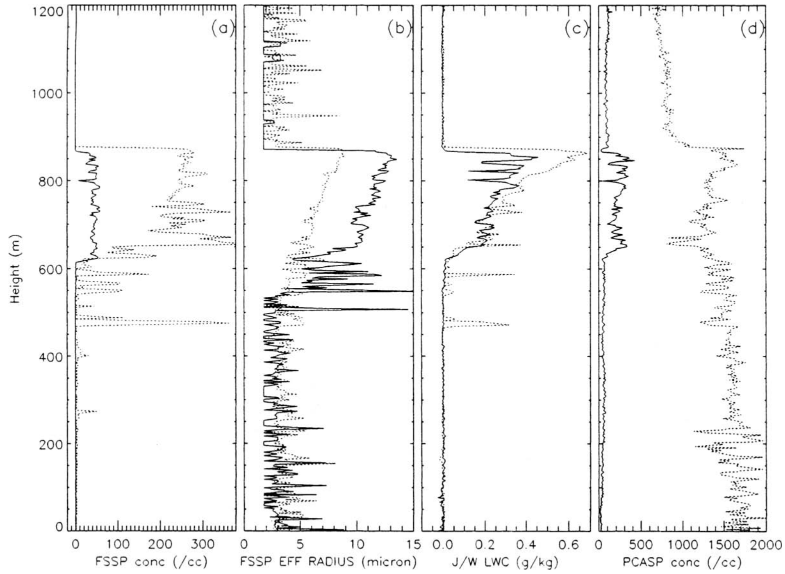


FIG. 8. Profiles made by the C-130 aircraft on 16 June 1992 in a maritime air mass (solid line) and a continental air mass (dashed) of (a) cloud droplet concentration measured by FSSP, (b) cloud droplet effective radius, (c) cloud liquid water content measured by a Johnson/Williams probe, and (d) concentration of aerosol in the size range 0.1–3.0 μm measured by a PCASP. (Note increases of aerosol concentration in cloud are an instrument artifact and are not real.)

(Bretherton and Pincus 1994; Austin and Bretherton 1994). The first Lagrangian experiment was conducted on 12–14 June in the clean air mass discussed previously. A 60-HPa-thick drizzling stratocumulus-topped MBL deepened rapidly to 170 HPa in 36 h as it moved under a weak upper-level subtropical low. As it deepened, the MBL evolved to a state in which cumulus clouds were rising into broken stratus, with evidence of deeper convection near the end of the experiment. The second Lagrangian, on 18–20 June, was in a polluted air mass. The MBL was 200 HPa deep, with vigorous 150 HPa or deeper cumulus clouds with updrafts of up to 5 m s^{-1} rising into patchy stratocumulus. The MBL depth and structure remained essentially constant through the 36-h duration of the experiment, except for a nocturnal increase in cloudiness. Only small amounts of precipitation in the form of cumulus showers were observed. During the first Lagrangian, the six constant-level balloons used 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 calculated using ECMWF analyses. During the second Lagrangian (when there was relatively less drizzle) one balloon was tracked for nearly 48 h. These experiments will allow budgets to be made without evaluating advective effects and provide a unique dataset for testing one-dimensional models.

Figure 10 shows the air mass trajectories during the two Lagrangian experiments and the location of the 18 aircraft soundings from the UK C-130 and NCAR Electra taken following each moving air mass. Figure 11 shows the evolution of the temperature and mixing ratio profiles in the second Lagrangian from the aircraft soundings. There is a 6–8 K trade inversion at 820 hpa and a pronounced 3 g kg^{-1} drop in the mixing ratio through the transition layer at 940–980 hPa just above the cumulus cloud base. Microphysical, chemical, radiation, and turbulence quantities from the Lagrangian missions are also being analyzed. For chemical budget studies, which were a key focus in MAGE, one must also deduce the entrainment rate of air from the free atmosphere into the MBL. Three approaches, all with large uncertainties, are being taken: 1) use of vertical velocities deduced from ECMWF analyses, 2) deduction of entrainment rate as the ratio of the turbulent flux of a conserved quantity (e.g., ozone) to the jump of this quantity across the inversion, 3) calculation of entrainment flux of water as a residual in the water vapor budget following the MBL air mass. All three approaches consistently indicate that the mean entrainment rate during both Lagrangian experiments was approximately 0.5 cm s^{-1}, similar to that observed in typical stratocumulus and trade cumulus boundary layers (Bretherton et al. 1994a).

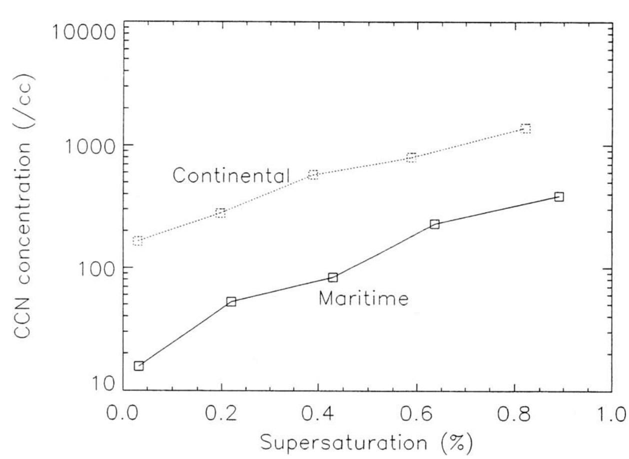


FIG. 9. CCN supersaturation spectra measured by a thermal gradient diffusion chamber on board the C-130 below cloud base in the maritime and continental air masses shown in Fig. 7.

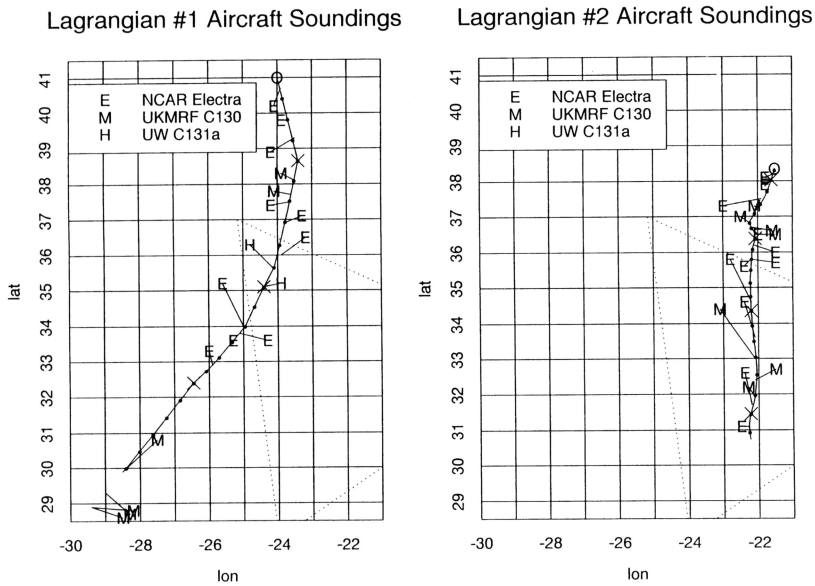


FIG. 10. Airmass trajectories during the two Lagrangian experiments. The solid line on each picture is the estimated MBL airmass trajectory. The ends of the line segments extending out from it indicate the positions of aircraft soundings. Each line segment is connected to the trajectory at the position corresponding to the sounding time; 'O' indicates the positions of the R/V *Oceanus* when balloons were launched.

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

Eight radiosondes per day were launched from Santa Maria and Porto Santo during the entire experiment, the R/V *Valdivia* during the first three weeks of the experiment, and the R/V *Malcolm Baldrige* during the last week of the experiment. Soundings were launched every 3 h during the Lagrangian experiments and less frequently throughout the experiment from the R/V *Oceanus.* Four soundings per day were launched from the R/V *Le Suroit.* This was the first regional experiment to successfully assimilate special soundings into operational analyses, a task requiring close coordination and communication among the sounding sites, Santa Maria headquarters, Portugal's INMG in Lisbon, and ECMWF. Standard and significant level data for most of these soundings were sent from the observing sites to Santa Maria where they were transmitted to the GTS technicians from INMG. Approximately 650 of the 820 soundings were placed on the GTS and about 90% of these were assimilated into the ECMWF operational analysis. ECMWF analyses agreed quite well with the actual soundings (Bretherton et al. 1994b) with systematic errors of less than 1 K and 1 g kg^{-1} at all heights and ASTEX upper-air stations. Figure 12 compares time–height sections of potential temperature at Santa Maria from sondes and from ECMWF analyses. The synoptic-scale variability evident in both the MBL and free atmosphere temperature and moisture was well captured by the analyses. At the south end of the ASTEX triangle, synoptic-scale variability was much smaller. The ECMWF analyses provide regional gridded datasets of such fields as surface pressure, winds, and SST (Fig. 13a), and 850-hPa vertical motion (Fig. 13b).

e. Diurnal cycle sampled

Four weeks of surface, upper-air, and remote sensing observations from the fixed stations at the comers of the ASTEX triangle provided an unprecedented description of the diurnal component of variability in a midocean MBL. The synoptic-scale variability in boundary-layer structure and cloud in the ASTEX region is greater than that off the California coast. Nevertheless, an analysis of METEOSAT movie loops indicates a diurnal cycle in cloudiness and cloud thickness in the deeper and more complex ASTEX boundary layer that was similar to that observed during FIRE 1987. The diurnal cycle was particularly noticeable during the first two weeks in June; during the latter part of the experiment high cloud often obscured the boundary layer clouds.

The island observing sites were on the north (upwind) sides of Santa Maria and Porto Santo. Although careful study is needed to determine how island effects may disrupt the diurnal variations compared with the open ocean, the same diurnal trends in cloudiness were observed at these sites as observed at 28°N, 24°W, an ocean site. Figure 14 shows the diurnal cycle of hourly averaged ceilometer-derived cloud fraction from the R/V *Valdivia* during 6–14 June, a period of steady trade winds during which the boundary-layer structure was very similar to the composite *Valdivia* sounding in Fig. 3. Figure 15 shows hourly histograms of the cloud base sampled every 30 s, a typical day during this period. Two 6-h periods of extensive stratocumulus cloud with bases at 1300–1500 m can be seen. Cumulus clouds with lower bases are much more frequent when the upper stratocumulus is also present. These probably correspond to the passage of several MBLCCs in each of these 6-h periods in which detrainment from the cumulus clouds is feeding stratocumulus. In contrast to FIRE 1987 (Hignett 1991), cumulus clouds are seen and the boundary layer remains decoupled at night as well as during the day.

The ASTEX Lagrangian experiments provide an excellent opportunity to study diurnal effects in a permanently decoupled boundary layer. Initial results

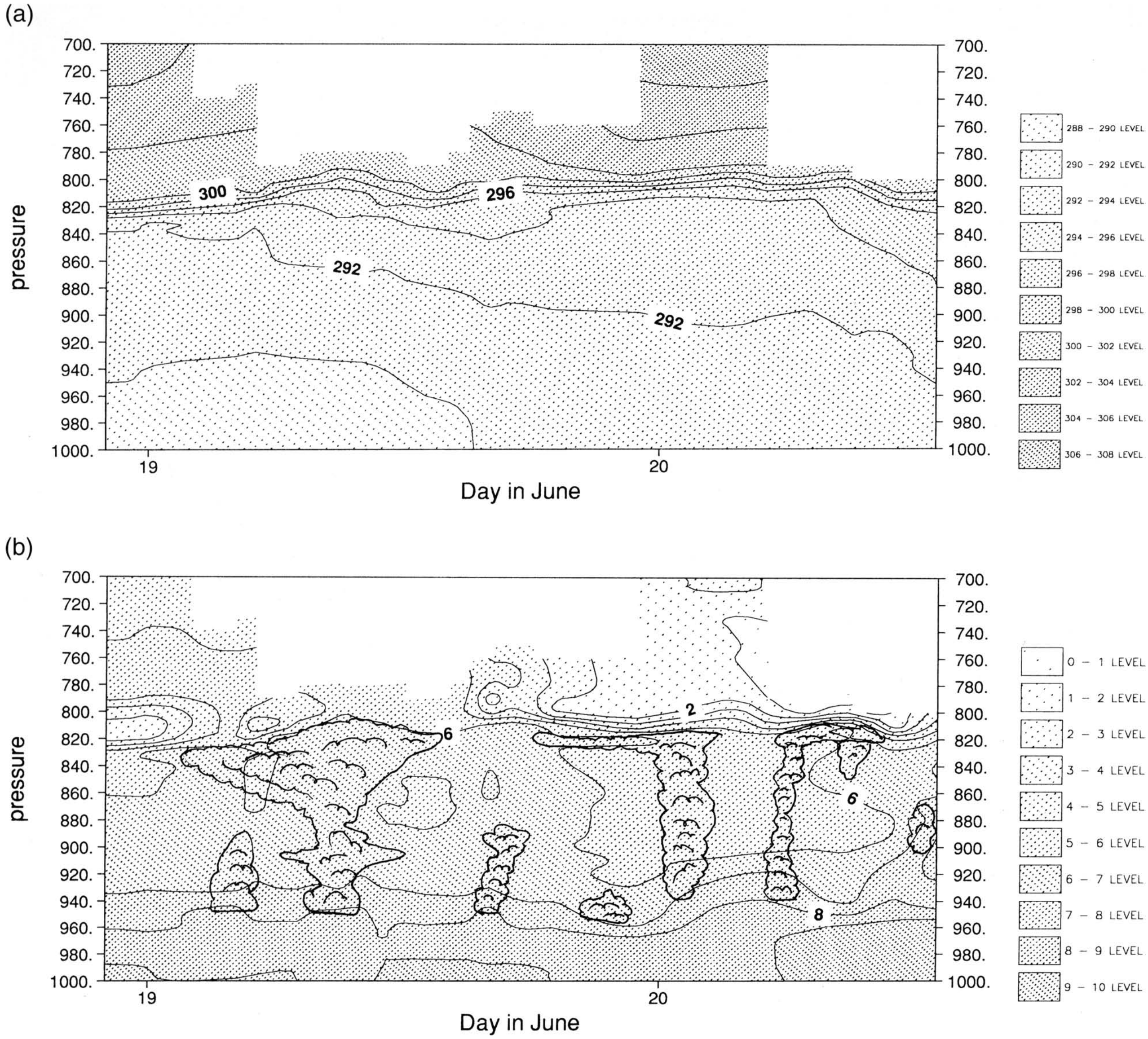


Fig. 11. Pressure time section of (a) potential temperature and (b) water vapor mixing ratio from aircraft soundings during the second Lagrangian. In (b) a schematic of the observed cloudiness has been overlaid. The soundings have been lightly smoothed by vertical averaging in 10-hPa intervals and time averaging using a filter with a triangular weighing function with a half-width of three hours.

indicate that the presence of cumulus clouds beneath the stratocumulus plays a fundamental role in supplying liquid water to and maintaining the stratocumulus layer and that the activity of the cumulus clouds undergo a diurnal variation. Furthermore, the Lagrangian experiments provided continuous aircraft measurements of the same air mass over periods of a day or longer and will be used to document turbulence and microphysical changes associated with the diurnal cycle.

f. 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 radio acoustic sounding system, a Doppler sodar, five microwave radiometers, four ceilometers, and several upward-looking radiometers as listed in Table 1. This instrumentation provided data for characterizing clouds and the environment in which they form. This was the first deployment of millimeter wavelength radars in a marine environment. They provided estimates of cloud-top height, reflectivity profiles, in-cloud turbulence, and drizzle characteristics. The scanning 35-GHz radar on Porto Santo was used to provide a horizontal mapping of the clouds and to track cloud features of interest. The cloud-top estimates from the radars are being combined with

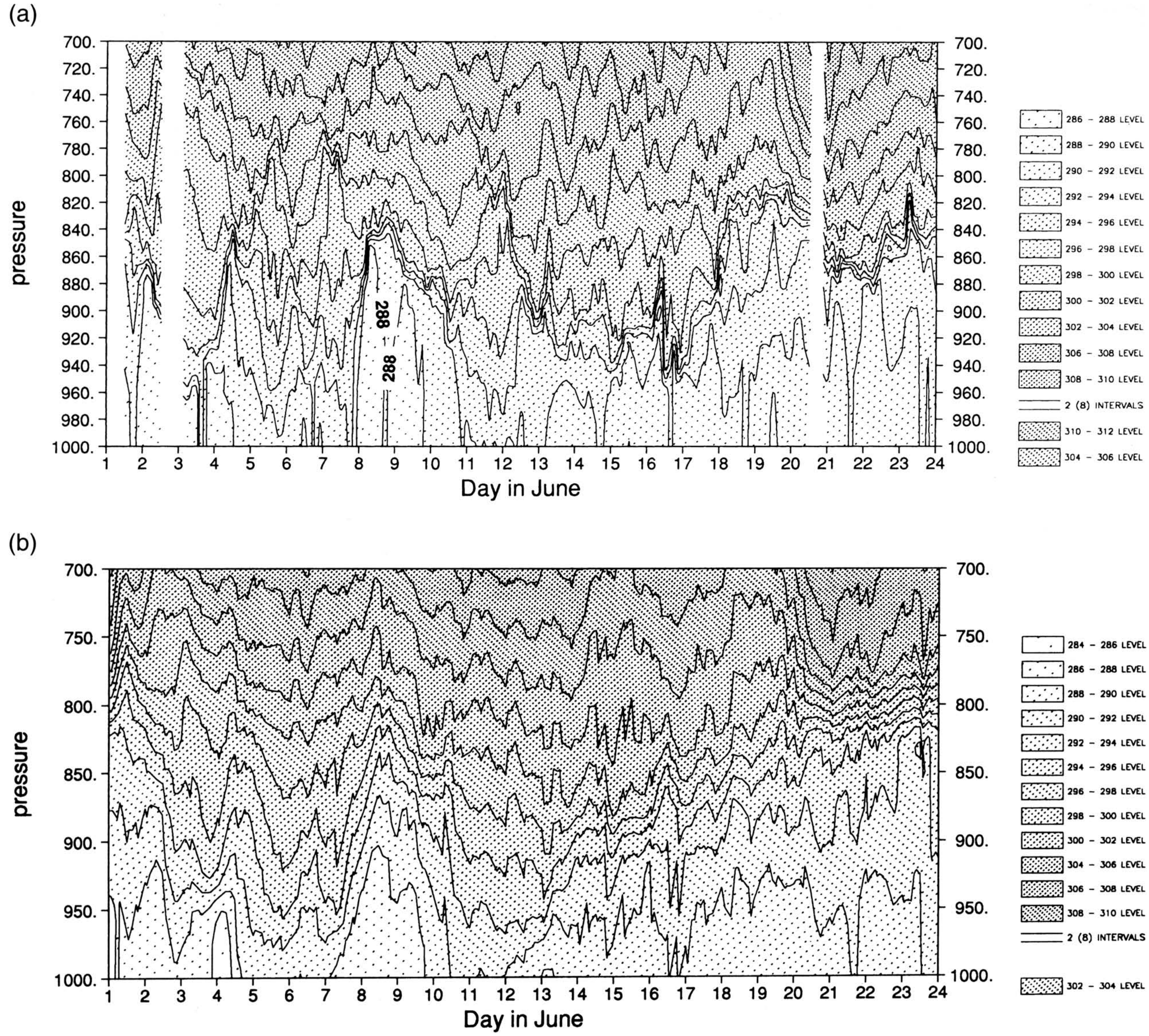


FIG. 12. Time–pressure sections of potential temperature for Santa Maria (a) from three-hourly radiosonde data averaged to 10-hPa vertical resolution and (b) from ECMWF analysis.

cloud-base heights from ceilometers to define cloud thickness. These measurements will be used to define the ratio of the observed liquid water path from the microwave radiometers to the adiabatic liquid water path calculated from the cloud thickness following the technique described by Albrecht et al. (1991). Since several of the remote sensing systems operated continuously during the experiment, they provided unique statistics on cloud properties that can be compared with satellite observations.

Examples of cloud properties that can be obtained from the ASTEX remote sensing systems are shown in Fig. 16. This figure shows data from the NOAA K_α-band radar and the CSU ceilometer on Porto Santo for a 20-min period just after 0000 UTC 17 June 1992. The stippled region shows the radar-determined cloud extent, while the ovals indicate the laser ceilometer cloud base. During this period there is an elevated stratus layer with underlying small cumulus. Under such conditions the radar and ceilometer cloud bases are in excellent agreement. Figure 16b covers a 1-h period from 0430 to 0530 UTC 17 June 1992. Also shown are radiosonde temperature and dewpoint temperature profiles, which are aligned on the time axis so that the data at a 1.0-km height are exactly timed. When the cloud is thin during the second half of the 1-h time interval, the radar and laser ceilometer closely agree on cloud base. During the first half of the period, shafts of drizzle fall from the lower part of the cloud (see also Fig. 5a). This drizzle is undetected by

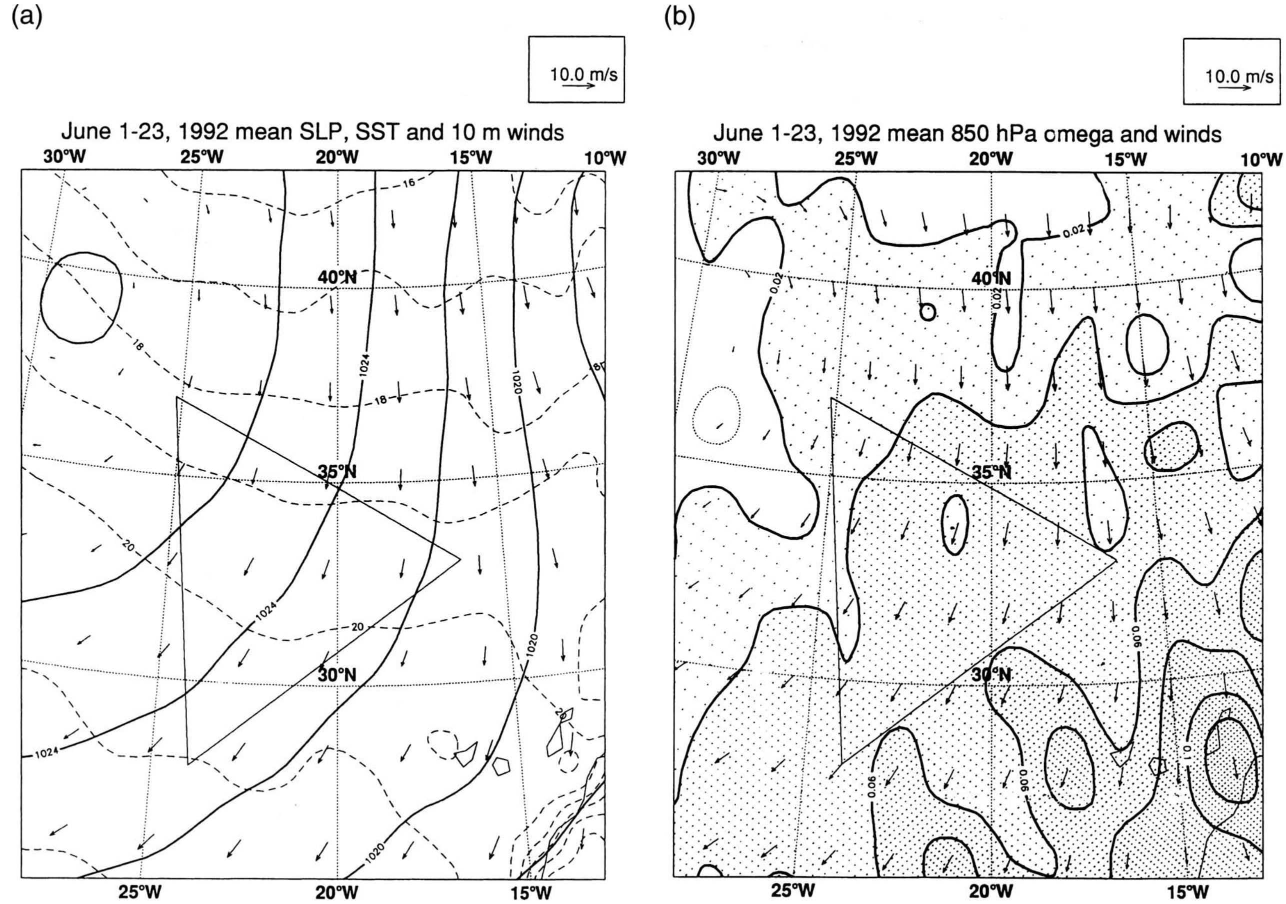


FIG. 13. 1–23 June mean ECMWF analyses of (a) surface pressure, 10-m winds, and SST; (b) 850-hPa winds and vertical pressure velocity in Pa s^{-1} (positive for downward motion).

the ceilometer, which places the cloud base near 900 m. In fact, such differences between radar base and ceilometer base can serve as a drizzle detector. In addition, several drizzle drop parameters can be determined from the zeroth, first, and second moments of the radar Doppler spectrum (Frisch et al. 1995).

3. Conclusions

Overall, ASTEX has produced an excellent dataset that will increase our understanding of the physical processes responsible for producing cloud transitions in marine stratocumulus. These data will be used for verification of parameterizations and models of varying complexity. It is still a major challenge to fully use these observations for this purpose, since several processes operating in stratocumulus are not fully understood.

The initial ASTEX results show that decoupling in the atmospheric boundary layer is critical to our understanding of cloud transitions. Consequently, solar absorption in the clouds, drizzle, and a general deepening of the boundary layer, which are processes important for decoupling, are fundamental to the transition. These transitional processes are often operating in stratocumulus that appear to be solid from satellite images. Mesoscale, cellular structures in these stratus clouds may be maintained by long-lived, mesoscale convective systems that feed off of moisture that accumulates in the boundary layer when it becomes decoupled. Substantial work is needed to understand and model these mesoscale systems and to evaluate their role in regulating cloud characteristics.

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 dataset for model testing and development. Furthermore, the extreme variations in aerosol concentrations observed during ASTEX provide a unique opportunity to study cloud aerosol interactions. ASTEX and MAGE collaborated to successfully execute two Lagrangian experiments in which for the first time the evolution of cloud, chemical, and boundary-layer properties in a given air mass

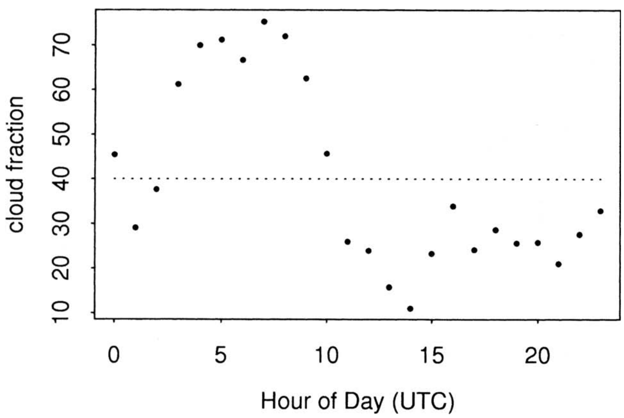


FIG. 14. Three-hour average fractional cloudiness measured by ceilometer aboard the R/V *Valdivia* (28°N, 24°W) during a steady trade wind period 8–15 June 1992. Note the prominent diurnal cycle. (30-s R/V *Valdivia* celiometer data courtesy of G. Kruspe, Max-Planck Institute, Hamburg, Germany.)

was followed for 36 h. The observations made during ASTEX and FIRE clearly showed the usefulness of using remote sensors for defining cloud properties.

We are now in a unique position to develop and refine parameterizations and models for the cloud-topped boundary layer. The ASTEX results suggest that any physically based parameterization must allow for boundary-layer decoupling and include a parameterization for shallow cumulus clouds in decoupled boundary layers. Unlike in shallower boundary layers, decoupling appears to occur independent of solar absorption or drizzle. The observed fractional cloudiness is also intimately tied in with the mesoscale cellular structure of these boundary layers. Recent parameterizations of Wang (1993) and Tiedtke (1993) may provide a framework for incorporating these insights. ASTEX should also advance our understanding of the importance of aerosol concentration for boundary-layer cloudiness, but this will require further analysis and detailed model comparison.

ASTEX has generated an unprecedented database for understanding processes important for the formation, maintenance, and dissipation of marine stratocumulus clouds and their representation in climate models. The FIRE 1987 stratocumulus experiment and ASTEX may substantially reverse the situation in the early 1980s when Randall et al. (1984) noted a scarcity of observations to test existing theories and models of marine stratocumulus that existed at that time.

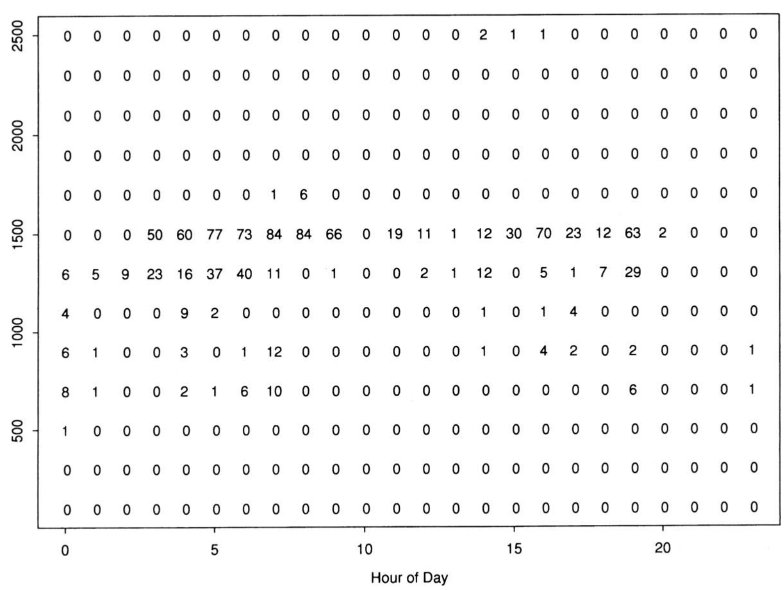


FIG. 15. Diurnal average of a histogram of cloud-base heights in 200-m bins, 8–15 June, 28°N, 24°W. Each observation of cloud-base height is the lowest cloud base retrieved from a 30-s ceilometer measurement.

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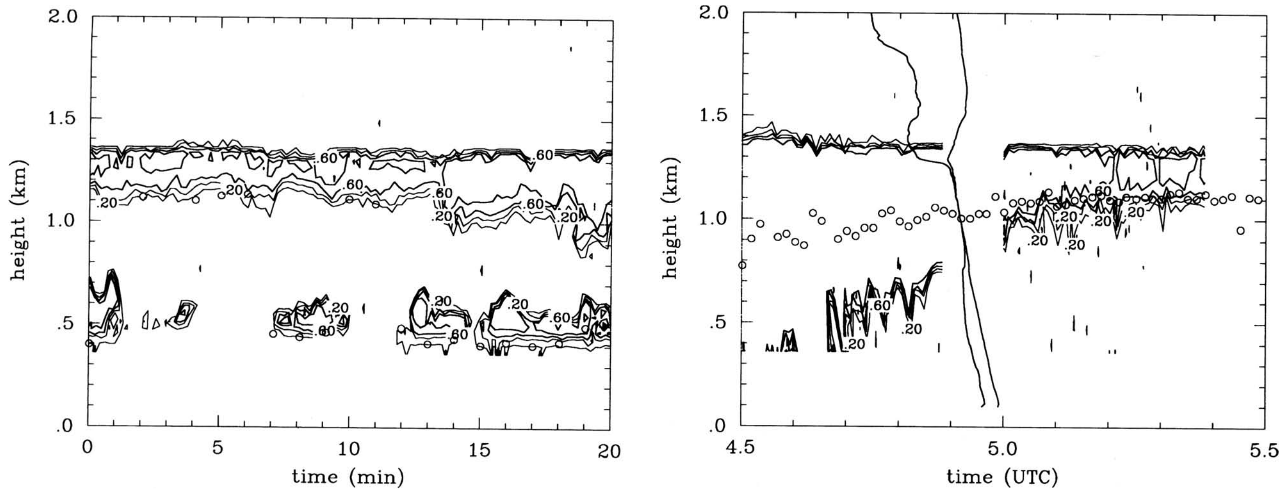

FIG. 16. Data taken on 17 June 1992 using the NOAA K_α-band Doppler radar and the CSU laser ceilometer on Porto Santo. The stippled regions show the radar-determined cloud extent, while the ovals indicate the laser ceilometer cloud base. (a) During this period of elevated stratus with underlying small cumulus, the radar and ceilometer cloud bases are in excellent agreement. (b) During the first half of the 1-h period from 0430 to 0530 UTC, shafts of drizzle fall from the lower part of the cloud. This drizzle is undetected by the ceilometer.

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