The EPIC 2001 Stratocumulus Study

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Some graduate students are lying on the deck of a research ship steaming across the tropical southeast Pacific ocean. The sun is at zenith, but they look up at the sky and yearn for Tahiti. They are strangely cold in their tee-shirts, the skies are leaden, and the water temperature is barely 20 C. They are unraveling the puzzles of the vast ‘climate refrigerators’ of the tropics -marine stratocumulus cloud layers.

Overlaying the cool southeast Pacific Ocean is the most persistent subtropical stratocumulus deck in the world. Stratocumulus cloud layers cool the tropics and subtropics by reflecting sunlight back to space that could otherwise warm the ocean surface. They favor the eastern subtropical oceans, where upwelling and cold currents keep the surface waters cool compared to the warm, dry, subsiding air aloft (Klein and Hartmann 1993). These low clouds play a key supporting role in the seasonal cycle of the East Pacific Ocean and global climate, and may feed back on El Nino-Southern Oscillation. However, they have proven particularly difficult for climate models to simulate because they are only a few hundred meters thick, typically lie under a sharp inversion, and are maintained by a complex blend of parameterized physical processes.

EPIC (the East Pacific Investigation of Climate) is a NSF and NOAA supported program to study physical processes central to coupled atmosphere-ocean interaction in the East Pacific. Its centerpiece was a field experiment in September and October of 2001 along the easternmost line of TAO buoys at 95 W. Three of its goals were to examine atmospheric deep convection in the ITCZ, ocean mixing and response to episodic deep convection, and cross-equatorial flow in the atmospheric boundary layer (ABL). These aspects of EPIC 2001 are described in a companion paper by Raymond et al. (2003).

In this article, we describe the final component of EPIC 2001, a stratocumulus study that took a pioneering look at cloud and atmospheric boundary layer (ABL) processes in the southeast Pacific region. Comprehensive ship-based remote sensing and surface measurements were taken during a two week cruise through this sparsely-traveled region during the month (October) when the stratocumulus in this region are most extensive. Scientific objectives included measuring the vertical structure of the ABL, understanding what physical processes are determining the stratocumulus cloud albedo (how much of the sunlight incident on the clouds is reflected back to space), and understanding the fluxes of heat and water that couple the atmosphere and the ocean in this region. Our measurements were particularly suitable for examining feedbacks between drizzle, cloud albedo, and ABL dynamics over the entire diurnal cycle. They also allow the stratocumulus in this region to be compared to the better studied stratocumulus of the northeast Pacific, and to those sampled in the CIMAR-5 cruise in austral autumn in the much more synoptically disturbed stratocumulus region off central Chile (Garreaud et al. 2001).

Stratocumulus albedo is strongly dependent on its thickness. Over thirty years ago, Lilly (1968) first elucidated the tight feedbacks between the clouds, radiation, turbulence and entrainment that regulate subtropical stratocumulus cloud thickness. Intense longwave radiative cooling in the cloud top drives turbulent eddies in the ABL. These eddies pick up moisture off the sea surface which maintains the clouds, but they also entrain filaments of warm, dry air from above the capping inversion. Entrainment affects both the cloud base and top. Entrainment constantly lifts the cloud top, maintaining it against large-scale subsidence. It also dries out the ABL, lifting the cloud base. More entrainment will usually lead to a thinner cloud. A thinner cloud drives less turbulence, establishing a negative feedback that helps establish an ever-changing balance between cloud thickness, entrainment, and turbulence modulated by external forcings such as changing sea-surface temperatures or subsidence rate, or the daily cycle of absorption of sunlight.

Subtropical stratocumulus clouds may drizzle appreciably, even when they are as little as 200 m thick. Even relatively light drizzle might deplete enough liquid water from a stratocumulus cloud to reduce its albedo. In some climate models, drizzle is the primary regulator of modelled subtropical marine stratocumulus cloud thickness and extent. In others, that role falls to entrainment. The two processes interact; modeling studies suggest that drizzle tends to reduce entrainment (e. g. Pincus and Baker 1994, Stevens et al. 1998). Very few observations are available to decide which models are correct.

Three months before EPIC 2001, the DYCOMS-II experiment also set out to improve our understanding of stratocumulus entrainment and drizzle processes (Stevens et al. 2003). DYCOMS-II used nocturnal flights into northeast Pacific stratocumulus clouds to obtain a beautiful dataset quantifying entrainment, turbulence and drizzle at the time of day when these processes are most vigorous. The EPIC 2001 stratocumulus cruise complemented the DYCOMS-II measurements by providing comprehensive documentation of the strong diurnal cycle of stratocumulus thickness, a more complete view of the time-space statistics of drizzle, and the perspective of a different region with a deeper boundary layer and generally lower aerosol concentrations. On the other hand, the aircraft data taken during DYCOMS-II and earlier experiments provides crucial context for interpreting our measurements. We are working with DYCOMS-II investigators to best exploit this synergy.

Vertical structure and diurnal cycle of the southeast Pacific ABL

The NOAA research vessel *Ron Brown* played a key role in all phases of EPIC 2001. Its final mission, the stratocumulus cruise, is shown on Fig. 1. From the Galapagos Islands, the *Ron Brown* steamed west on 8 October to 95 W, then south along the remainder of the TAO buoy line into the southeast Pacific stratocumulus-capped boundary layer. It stopped for six days to maintain a buoy maintained by Robert Weller of WHOI at 20 S, 85 W (an important part of EPIC longer-term monitoring; see Cronin et al. 2002), then on 24 October reached the port of Arica in northern Chile. One can see in Figure 1 that the entire cruise track was characterized by cool SSTand southeasterly

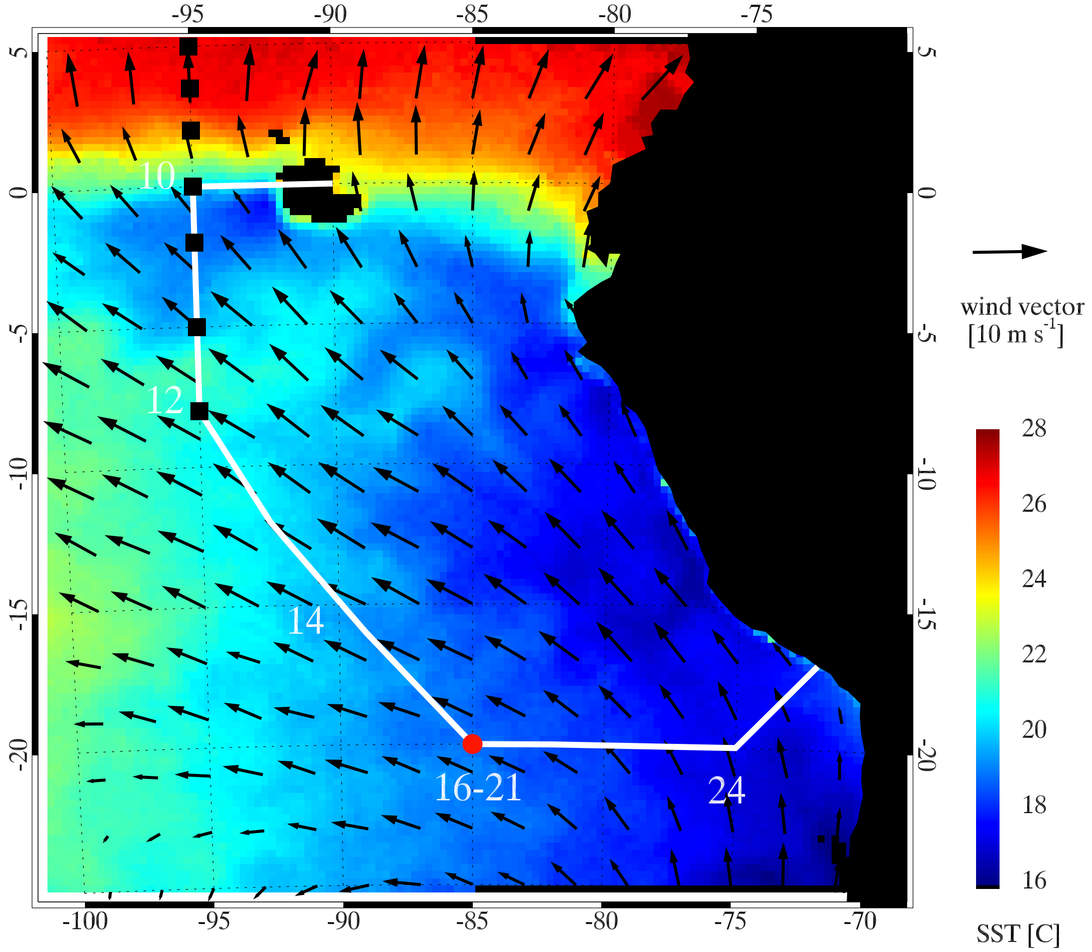

Fig. 1. The EPIC2001 stratocumulus cruise track. Numbers indicate the position of the *Ron Brown* at the beginning of selected days of October (UTC). The shading and arrors shows SST from the TRMM Microwave Imager, and 10 m wind vectors from Quikscat averaged over the cruise period. TAO buoys and the WHOI buoy are shown with black squares and a red dot, respectively..

trade winds. Fig. 2 (NEED) shows a GOES visible channel image for 1445 UTC on 19 October, which is typical for the period. Extensive stratocumulus, usually organized into cells 10-40 km across, blanketed the region throughout most of the cruise.

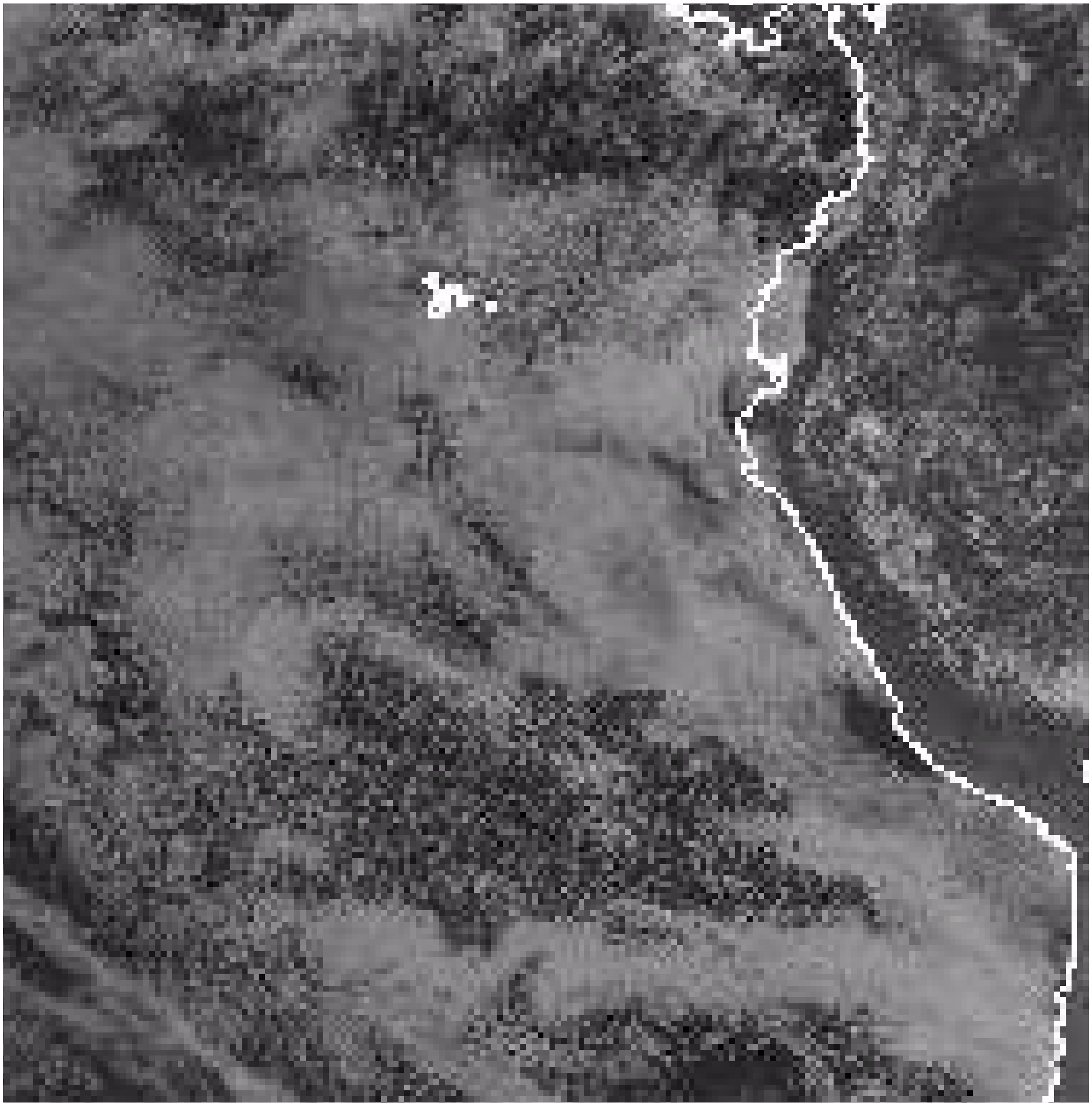

Fig. 2. GOES-East visible image for 19 October 2001 at 1445 UTC, showing the SE Pacific stratocumulus region. Considerable ‘mesoscale’ structure is evident in the cloud field on 10-40 km scales.

Some key measurements are given in Table 1. Three-hourly soundings complemented a suite of NOAA/ETL (Environmental Technology Laboratory) vertically-pointing remote sensing measurements, including a ceilometer for measuring cloud base, 8 mm wavelength Doppler radar for sensing of clouds and drizzle, and a microwave radiometer for measuring vertically integrated cloud liquid water. The 5 cm wavelength scanning radar mounted on the *Ron Brown* was used to survey the morphology and mean amplitude of drizzle within 30 km of the ship. Surface meteorology, turbulent and radiative flux measurements, occasional samples of drizzle drop size distribution, and limited measurements of aerosol concentration and composition provided a comprehensive near-surface view of the PBL.

Table 1: SE Pacific stratocumulus cruise measurements

PI	Institution	Key measurements
Yuter/Bretherton	U. Washington	Sondes, 5 cm scanning radar, meth blue
Raga/Baumgardner	UNAM (Mexico)	Aerosol concentration, sulfate fraction
Fairall/Uttal	NOAA/ETL	Cloud remote sensing, surface fluxes.
Weller	WHOI	IMET buoy, XBTs

Fig. 3 shows the temperature and moisture structure of the lower atmosphere from radiosondes launched eight times per day. A strong inversion invariably capped the ABL, with a 10-15 K potential temperature over as little as 100 m depth. The radiosonde temperature sensor has a response time of roughly 6 s during which time it rises 100 m, so it noticeably smears out the inversion in Fig. 3 compared to the humidity profiles, which rely on a faster-reacting relative humidity sensor and likely better show how sharp the inversion really is. The inversion deepened from 900 m to 1300 m as the ship headed southward away from the equator, then became somewhat shallower near the coast. Near the equator it was remarkably moist above the ABL, but in the core of the stratocumulus region it was very dry. Above the ABL, moist and dry layers can be seen descending with time following the ship track - we believe this is a manifestation of the persistent large-scale subsidence over this region. The stratocumulus clouds were 100-400 m thick.

Two features of Fig. 3 were somewhat unexpected. First, vertical gradients of potential temperature and humidity in the ABL were quite weak, approximating a ‘mixed layer’ structure. Such a structure suggests turbulent eddies efficiently mixing air through the entire boundary layer. At similar distances (1000-2000 km) offshore in the NE Pacific and Atlantic Oceans, the humidity decreases considerably with height within the ABL, associated with a process called ‘cumulus-coupling’ - a layer of cumulus clouds rising into the stratocumulus (Albrecht et al. 1995, Klein et al. 1995, Wyant et al. 1997). Because the area fraction covered by cumulus clouds is usually less than

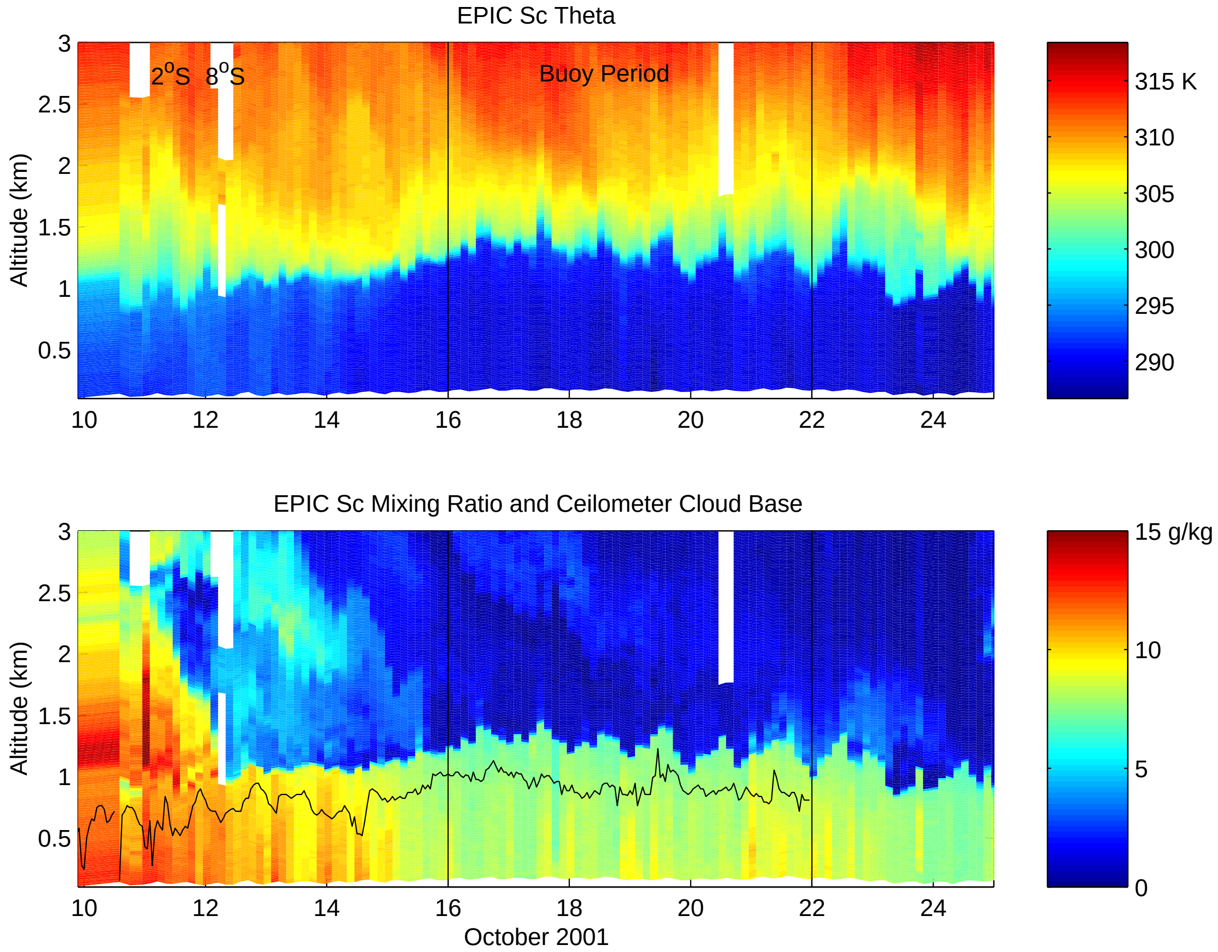

Fig. 3. Time-height cross-section of (a) potential temperature and (b) water vapor mixing ratio (bottom) from 8x-daily radiosonde launches during the EPIC 2001 stratocumulus cruise The black curve in (b) is the hourly-averaged ceilometer-derived cloud base; cloud top closely coincides with the ABL capping inversion base. Vertical lines bound the buoy period during which the *Ron Brown* was stationed near the WHOI buoy at 20°S, 85°W.

10%, much of the air in such an ABL is nonturbulent, allowing humidity gradients to build up. This structure is what we were also anticipating in the southeast Pacific, but we saw almost no cumulus clouds. One difference between the SE Pacific and these other regions is that the capping inversion remains very strong at distances over 1000 km offshore, which appears to inhibit the development of cumulus-coupling.

The second unexpected feature was the strength and regularity of the diurnal cycle in the inversion height. This is seen particularly clearly in the humidity plot of Fig. 3 during the six day ‘buoy period’ at 20°S 85°W. The inversion (which also marks the stratocumulus cloud top) rises roughly 200 m each night from an early afternoon minimum value. In contrast, the cloud base shows little diurnal cycle, so the clouds are thinnest during the early afternoon. During most of the cruise (and

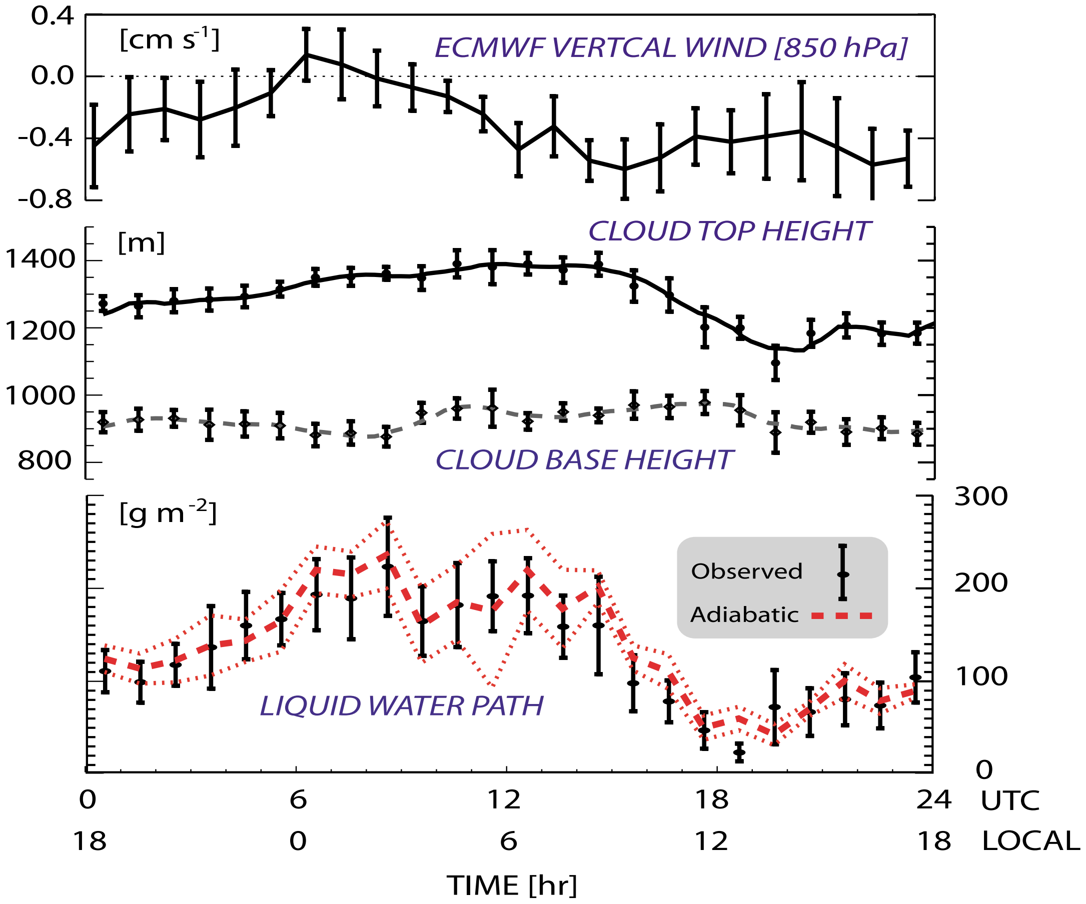

Fig. 4. The six-day mean diurnal cycle for the buoy period of ECMWF-predicted 850 hPa vertical velocity from hourly sampling of 12-36 hour operational forecasts, mm-radar-derived cloud top (inversion) height, ceilometer-derived cloud base height, liquid water path derived from the shipboard microwave radiometer, and adiabatic liquid water path derived from cloud thickness. Vertical bars show the standard deviation of hourly average values on individual days from the six-day hourly mean.

particularly in the buoy period) there was a solid overcast at night, and the clouds often became broken in the afternoon. Fig. 4 shows the average diurnal cycle over the buoy period. The cloud base is obtained from a ceilometer, the cloud top from the cloud radar. The cloud thickness can be compared with liquid water path derived from a microwave radiometer (Albrecht et al. 1990). If we assume that the clouds are vertically well-mixed or 'adiabatic', their liquid water content rises in a predictable way above cloud base, and we could predict the 'adiabatic liquid water path' for a cloud of a given thickness. The predicted and measured liquid water paths agree remarkably well, suggesting the clouds are in fact close to adiabatic.

Starting with the FIRE-I experiment in 1987 just off the California coast, many stratocumulus studies have seen a pronounced diurnal cycle in cloud thickness (Minnis et al. 1992), with an early afternoon minimum and early morning maximum in mean cloud thickness and in cloud fractional coverage. This has important consequences for stratocumulus feedback on climate, since the clouds are thinnest and least reflective when the insolation is largest. ABL processes can explain this diurnal cycle. During the day, solar radiation is absorbed in the clouds, largely cancelling the longwave radiative cooling from their tops and greatly inhibiting turbulence. This reduces the efficiency of moisture transport from the sea surface to the cloud layer, drying it out and lifting cloud base. Meanwhile, less turbulence causes less entrainment, allowing mean subsidence to advect the cloud top down. Both effects thin the cloud during the afternoon.

So what is the surprise? Based on prior observations and modeling studies (e g. Bougeault 1985), we had expected most of the cloud thickness variations to come from a varying cloud base. The inversion variations in the buoy period were much too large to explain plausibly through variations in entrainment rate alone. Instead, it became clear that there must also be a strong diurnal cycle in subsidence as well. Luckily, the long-term surface flux measurements at the WHOI buoy were being used at ECMWF for model validation. ECMWF was routinely storing hourly output from their operational forecast model at this location, which Martin Köhler of ECMWF generously provided to us for October 2001. Hua-Lu Pan of NCEP also provided us with a similar column dataset using their medium-range forecast (MRF) model. Fig. 4 shows the buoy-period mean diurnal cycle in subsidence from the ECMWF model at 850 hPa, roughly the height of the inversion. Subsidence was near zero near local midnight, then rapidly increased to maximum values in the late morning. Even after averaging over the entire month of October, the same diurnal cycle could be seen at slightly reduced amplitude. The NCEP analysis gave similar results. The diurnal cycle of subsidence amplifies the diurnal cloud thickness variations that we would get from internal ABL dynamics, probably leading to thinner, less reflective stratocumulus during the day. Through mechanisms such as this, the diurnal cycle may have an impact on the mean climate even over the remote oceans. But what makes the diurnal cycle of subsidence in the first place?

Non-tidal diurnal cycles of subsidence of diverse origin affect the ABL over many parts of the tropical oceans, even well away from continents (Ciesielski et al. 2001, Dai and Deser 1999). Using four-times daily ECWMF and NCEP reanalysis data, we have done a regional analysis of the diurnal cycle of subsidence over the SE Pacific. Between the Peruvian coast and the WHOI buoy, there is a six-hour phase delay (and a large reduction in amplitude) in the maximum subsidence, corresponding to a phase speed of 50 m s^{-1} . The subsidence wave has maximum amplitude in the mid-troposphere. Both of these are characteristics of an internal inertia-gravity wave, which could be forced by the diurnal cycle of heating over South America. The diurnal cycles of the vertical velocity fields in the two reanalyses are qualitatively consistent, but a better model-independent dataset is required to fully test the subsidence wave hypothesis.

Drizzle and Aerosol

So far as we can tell, the SE Pacific stratocumulus region is among the world's driest oceanic regions. No precipitation whatsoever was detected from October 2001-October 2002 by a rain-gauge mounted on the WHOI buoy. However, Petty's (1995) study of the COADS climatology of routine ship-observer present-weather reports suggests that the instantaneous frequency of precipitation in this region is roughly 1%, so we were optimistic that we might find some drizzling

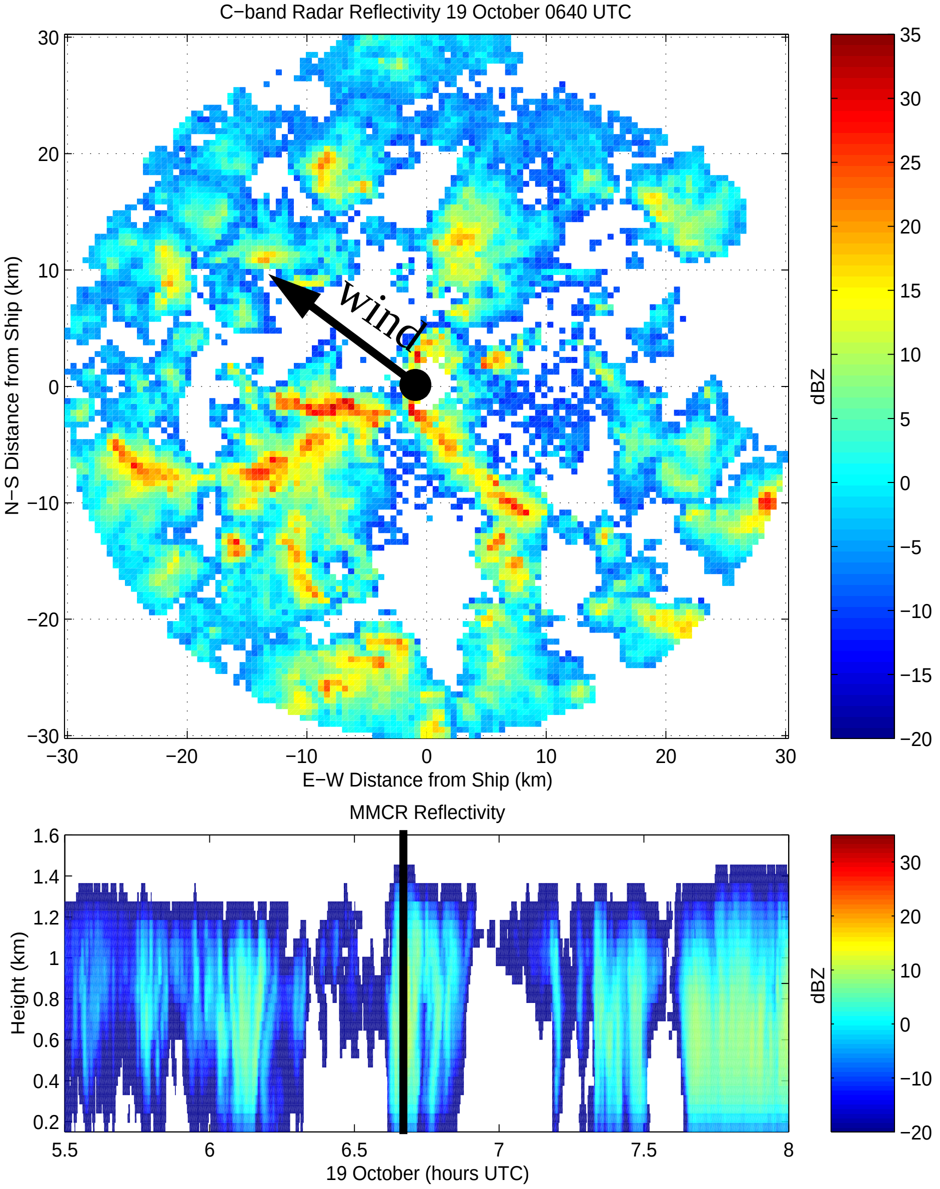

Fig. 5. Horizontal cross-section of 5-cm radar reflectivity at 1 km elevation during a heavy-drizzle period (upper panel; ship location at black dot, arrow shows ABL wind direction) and time-height plot of 8 mm radar reflectivity above the ship (lower panel,black line shows time of upper image). A drizzle cell is advecting . . over the ship.

stratocumulus at some point on the cruise. In fact, our radars observed copious drizzle, particularly at the WHOI buoy. Fig. 5 shows an example of a horizontal cross-section of radar reflectivity at 1 km above the ocean surface from the scanning 5 cm wavelength radar. It shows patches of reflectivities up to 30 dBZ (light rain showers), organized in cells 1-3 km across with a hint of polygonal organization that probably corresponds to the mesoscale cellular convection visible in the satellite image of Fig. 2. Also shown is a short time-height section of reflectivity from the NOAA 8 mm wavelength vertically pointing radar at the same time. The cells are advecting to the northwest. The high reflectivities extend down to the surface, indicating that some surface drizzle must be occurring. Patchy drizzle was common at night and in the early morning during most of the cruise.

However, quantifying the precipitation rate from radar data is challenging and involves large uncertainties. Since the stratocumulus clouds are so thin, the spectrum of raindrops cannot be assumed to be anything like that in mature cumulonimbus clouds. Small calibration errors in either radar can bias precipitation retrievals - the vertically pointing radar systematically reported somewhat lower reflectivities than the 5 cm radar (this can be seen even on Fig. 5). On selected occasion when ship observers felt drizzle, they exposed paper treated with methylene blue to capture images of the falling droplets, which were counted and sized to produce estimates of droplet size distribution, instantaneous local rainfall rate and radar reflectivity. We also used the vertical profile of reflectivity from the mm-wave radar to infer the evaporation rate of raindrops below cloud base and typical raindrop size. We combined these with the 5 cm radar reflectivity maps to produce estimates of area-averaged precipitation over a 30 km radius circle around the ship. We will report more fully on our precipitation retrievals in forthcoming papers, and regard our estimates of precipitation to have uncertainties of at least a factor of two.

With these caveats, Fig. 6 shows the inferred area-averaged precipitation rate at cloud base and the surface. About 4 mm day^{-1} of water evaporates from the sea surface in this region, so precipitation rates of 1 mm day^{-1} or more are highly significant to the water budget of the clouds. At cloud base, drizzle rates this high are common, but owing to the high cloud base in this region, 90% of the drizzle evaporates before reaching the surface and the surface precipitation rate seems be only a minor sink of water from the ABL. Hence, the impact of drizzle is indirect. Water is condensed in the clouds, releasing latent heat there, then falls as drizzle into the subcloud layer, which it cools by evaporation. This heating-above-cooling couplet is a stratifying influence on the ABL that tends to inhibit turbulence and entrainment, transports moisture less efficiently into the cloud layer and makes the cloud layer more horizontally inhomogeneous (Stevens et al. 1998). Models suggest that the net effect of these processes is to reduce liquid water path (Pincus and Baker 1994, Stevens et al. 1998). However, these models have only simulated shallow stratocumulus-capped boundary layers with low cloud bases. For such ABLs, drizzle is a more effective ABL water sink

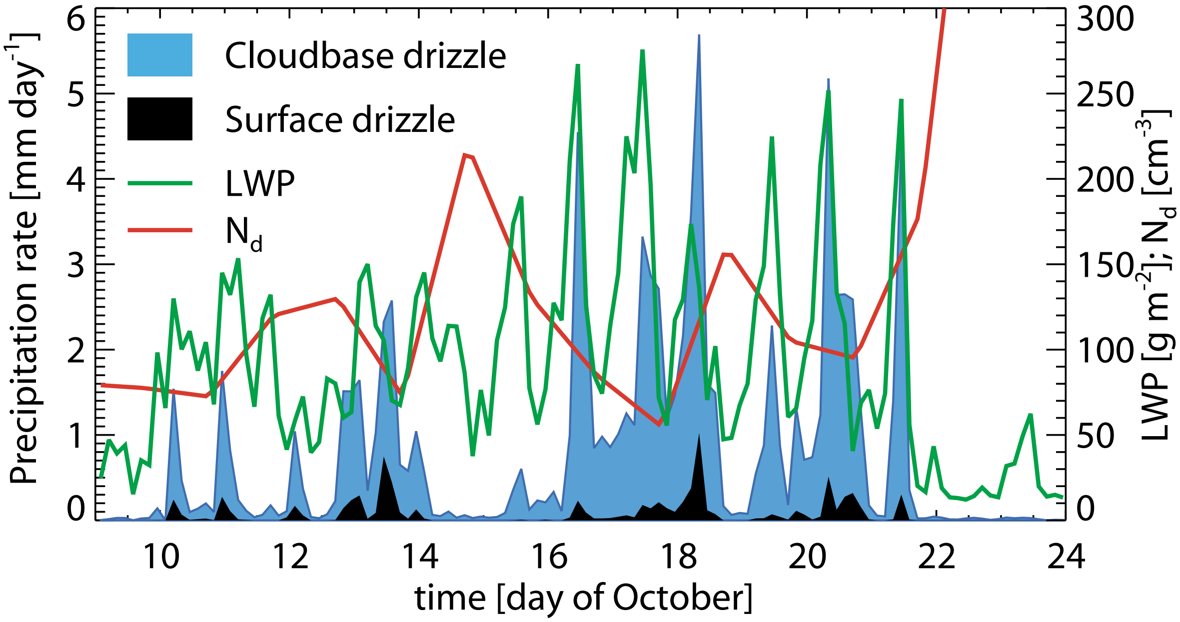

Fig. 6. Cloud base drizzle rate showed a marked diurnal cycle, increasing at night in phase with the liquid water path (LWP). Drizzle was greatly enhanced in 'cleaner' clouds with smaller inferred cloud droplet concentration N_d. Most drizzle evaporated before reaching the ocean surface.

than in EPIC 2001, since a much smaller fraction of precipitation evaporates before reaching the surface. Hence, we cannot be too confident of the applicability of these model results to the EPIC 2001 ABL, where the subcloud layer is deep. In any case, the observed drizzle flux through cloud base seems large enough that the impact of drizzle production on ABL turbulence and entrainment should at times be quite marked .

In addition, Fig. 6 shows the liquid water path, and an estimate of the cloud droplet concentration derived from simultaneous daytime surface observations of the cloud optical depth, the liquid water path, and the cloud geometrical depth. The diurnal cycle of cloud thickness and liquid water path strongly modulate the drizzle falling from cloud base. Variations in cloud droplet concentration seem to be playing a similarly important role. The 'cleanest' clouds with lowest droplet concentrations of 60-80 cm^{-3} occurred on 17-18 October. During these days, cloud base drizzle was substantial even during the daytime. On 14-16 October, when droplet concentrations rose to as much as 200 cm^{-3}, much less drizzle was observed despite liquid water paths that were almost as large. Near the coast, very high cloud droplet concentrations ('dirty' clouds) were observed; satellite retrievals of cloud optical properties in this region also tend to show markedly lower effective radii near the coast. Since the ABL winds usually blow northward up the coast, this is probably due to dispersal of anthropogenic aerosol produced by industrial activity along the Chilean coast.

Conclusions

The EPIC 2001 stratocumulus cruise was a resounding success. An unexpectedly well mixed stratocumulus-capped boundary layer capped by a strong inversion was encountered throughout. A strong diurnal cycle was observed, with thicker clouds and substantial drizzle during the late night and early morning. This was driven in part by local diabatic processes but was reinforced by a surprisingly pronounced diurnal cycle of vertical motion. The vertical motion appears to be an inertia-gravity wave driven by daytime heating over South America that propagates over 1000 km offshore. Although drizzle was often copious, it mainly evaporated before reaching the ocean surface. ased on our observations, we surmise that entrainment of dry, warm air is the primary regulator of cloud thickness in this region, but that drizzle may be having an impact by considerably reducing entrainment, especially when the cloud is cleaner. In this way, drizzle may actually *thicken* the clouds by keeping the boundary layer moister. This has important consequences for the indirect effects of aerosols on climate through their effect on cloud radiative properties. The first indirect effect or Twomey effect is that increased aerosol concentrations lead to more cloud droplets, and if the same mass of cloud liquid water is partitioned into more, smaller droplets with more combined surface area, the cloud is more reflective (Twomey 1977). The second indirect effect is that the increased cloud droplet concentration can affect the thickness or lifetime of clouds, principally through precipitation processes (Albrecht 1989). Modeling studies have suggested that drizzle suppression by increased aerosol increases marine stratocumulus thickness. This would enhance the cloud albedo and further amplify the Twomey effect on climate. However, it is not at all clear whether this result carries over to an EPIC-like stratocumulus layer in which almost all drizzle evaporates before reaching the surface. Sophisticated dynamical-microphysical models simulating the full spectrum of observed cloud-topped marine boundary layers will be necessary to understand whether the second indirect effect is in fact of comparable magnitude to the Twomey effect, or whether it is in fact much smaller.

To this end, we are using various types of ABL models, ranging from mixed-layer models to single-column models that mimic what GCMs might simulate to large-eddy simulation models, to get a better understanding of the drizzle-turbulence-cloud thickness feedbacks hinted at by the EPIC observations. The more comprehensive nighttime snapshots of turbulence-drizzle-aerosol interactions from DYCOMS-II should also be invaluable comparisons. The GCSS (GEWEX Cloud System Study) Boundary Layer Cloud Working Group hopes to conduct a series of LES and single-column model intercomparison studies based on both of these field experiments to improve our understanding of what we think are large model-to-model differences in the simulation of drizzle microphysics in stratocumulus and its feedbacks on stratocumulus cloud thickness and albedo. Under the auspices of the international CLIVAR program's VAMOS (Variability of the American Monsoons) initiative, the VEPIC (VAMOS-EPIC) study (http://www.atmos.washington.edu/

~breth/VEPIC/VEPIC_Science_Plan.pdf) is being developed to coordinate continued enhanced measurements, diagnostic and modeling studies of this region.

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