VAMOS Ocean-Cloud-Atmosphere-Land Study (VOCALS)

Science Plan

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Prepared by the VOCALS Scientific Working Group

1. Introduction to VOCALS

Interactions between the South American continent and the Southeast Pacific (SEP) Ocean are extremely important for both the regional and global climate system. The great height and length of the Andes Cordillera forms a sharp barrier to zonal flow, resulting in a coastal jet of strong southerly winds parallel to the west coast of South America. This, in turn, drives intense coastal oceanic upwelling, bringing cold, deep, nutrient/biota rich waters to the surface. As a result the sea-surface temperature (SST) is colder along the Chilean and Peruvian coasts than at any comparable latitude elsewhere.

The cold surface, in combination with subsiding warm, dry air aloft, is ideal for the formation of marine stratocumulus clouds. It supports the world's largest and most persistent, yet poorly observed, subtropical stratocumulus cloud deck, extending almost 2000 km off the west coast of South America from central Chile to the equator (Klein and Hartmann 1993). This region includes the east edge of the equatorial cold tongue and of the southeast trades that blow across most of the Pacific and as such is an important player in El Nino Southern Oscillation (ENSO), the Pacific Hadley-Walker circulation and atmospheric circulations over South America. Sunlight reflected off SEP stratocumulus clouds is a significant loss term in the global radiation budget. Figure 1 shows global maps of annual average SST, stratocumulus cloud cover, and top-of-atmosphere net cloud radiative forcing, showing how this region (and to a lesser extent the other cool oceans west of the subtropical continental landmasses) stands out compared to the low-latitude norm.

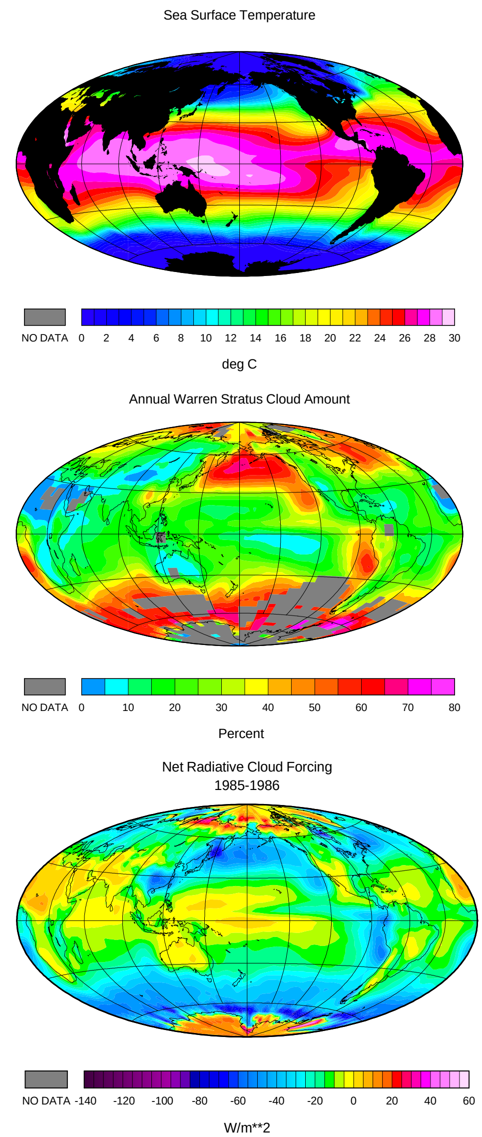

Figure 1 : Annual-mean climatological SST (top), stratus cloud amount from ship observations (middle), and ERBE-derived TOA net cloud radiative forcing (bottom).

The climate of the SEP involves important feedbacks between sea-surface temperature (SST), coastal topography and geometry, oceanic heat transport, clouds and aerosol. Some are common to other subtropical stratocumulus regions such as off the Californian or Namibian coast, but these feedbacks express themselves particularly clearly in the SEP. The Andes channel strong southerly winds along the coast, promoting vigorous coastal upwelling. Complex oceanic currents, eddies and waves distribute the cold water offshore. The cool water helps maintain the clouds, whose shade in turn helps keep the offshore waters cool. The clouds are formed atop the eddies of a turbulent boundary layer driven in large part by longwave radiative cooling near the cloud tops. Their albedo depends on concentrations of atmospheric aerosol (some of which is produced by human activity along the coast, and some naturally produced) on which the cloud droplets condense; in turn the clouds can scavenge this aerosol by drizzle and related processes.

Our imperfect understanding of these feedbacks and how to represent them in large-scale numerical models affects the skill of their predictions of the weather and climate system on all time scales. Three critical examples are (a) biases in tropical rainfall, SST, and winds on seasonal and longer timescales that repeatedly occur in coupled ocean-atmosphere models, which several studies have traced in part to errors in simulating ocean dynamics in the low-latitude coastal upwelling zones, and also in simulating of boundary layer clouds and their radiative properties (e.g. Mechoso et al. 1995, Ma et al. 1996); (b) our current lack of understanding and quantification of the indirect effect of aerosols upon cloud radiative properties, and (c) our inability to make consistently accurate regional weather predictions, especially in coastal areas dominated by low cloud. For example, Figure 2 shows the annual-mean SST bias in a control run of the recently released version 3 of NCAR's Community Climate System Model (CCSM3) (Collins et al. 2005), with roughly 140 km horizontal resolution in the atmosphere, and comparable zonal resolution in the ocean. Warm biases of 2-4 K occur along the west coasts of South America and Africa. There are lesser, but still significant, warm biases further offshore in the eastern subtropical oceans, along with an exaggerated equatorial cold tongue in the eastern Pacific.

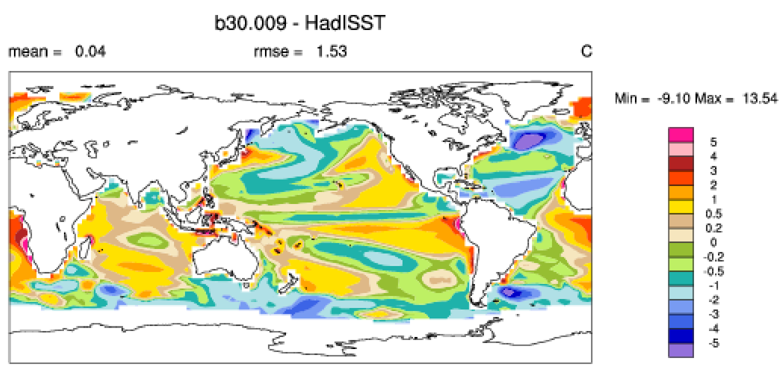

Figure 2: Annual-mean SST biases in CCSM3 1990 control run (Collins et al. 2005)

The scientific and modeling challenges created by this rich blend of feedbacks motivated the organization of the **V**AMOS **O**cean-**C**loud-**A**tmosphere-**L**and **S**tudy (VOCALS) described in this Science Plan. VOCALS is an international program that is part of the CLIVAR VAMOS (Variability of the American MOnsoonS) program. Participants in VOCALS currently include scientists from countries on the west coast of South America and the USA (Table 1). **The overall goal of VOCALS is to develop and promote scientific activities leading to improved understanding, model simulations, and predictions of the southeastern Pacific (SEP) coupled ocean-atmosphere-land system, on diurnal to interannual timescales.** Our two leading concerns are (1) the physical processes affecting the radiative and microphysical characteristics of the persistent stratocumulus clouds of this region, and (2) the ocean budgets of heat and other constituents, and how they determine the sea-surface temperature (SST) throughout this region.

In VOCALS, modeling, extended-time observations (including a wealth of new satellite sensors, buoy, island and coastal measurements), and intensive field observations (including annual buoy maintenance cruises) in the SEP are being coordinated to address these issues over the period 2003-2010. While extended-time observations are rapidly improving our understanding of this sparsely-traveled region, they have raised a set of interconnected scientific questions better addressed by an intensive field campaign, the VOCALS Radiator Fin experiment (VOCALS-RF) proposed for October 2007. These VOCALS activities, in addition to their scientific payoff, will nurture scientific collaborations between the U. S. and countries along the west coast of South America, and promote enhancements of the SEP regional ocean-atmosphere observing system and both regional and global climate predictions.

The scientific issues underlying VOCALS can be broken into four interconnected categories:

- Atmospheric, oceanic, and coupled model biases and model improvement in the SEP and other subtropical cool-ocean regimes.
- SEP aerosol-cloud interaction; implications for aerosol indirect effect and regional climate.
- SST distribution and the ocean heat budget in the SEP.
- Role of South America and remote forcing from tropics and midlatitudes, on diurnal to interannual (ENSO) timescales.

In Section 2 we discuss unique climatological features and observational assets of the SEP that make VOCALS attractive. We also summarize highlights from the small amount of prior observational research in this region.

In Section 3 we discuss each of these issues. For each issue, we:

- Summarize our current scientific understanding,
- Discuss why VOCALS is important to advancing our understanding of them and why the SEP is a particularly good place for such a study,
- Present summary science and modeling questions that VOCALS aims to address, and potential VOCALS 'deliverables' to the larger scientific and modeling community.

In Section 4, we summarize the companion VOCALS Implementation Plan. In Section 5, we describe ongoing external activities with which VOCALS is coordinating. Section 6 concludes with a brief discussion of what we need from U. S. and International CLIVAR to fully realize the VOCALS vision.

2. Geography, scientific history and unique features of the VOCALS region

2.1 Features common to other subtropical cool-ocean regimes

The SEP (here broadly defined to extend southward from the equatorial cold tongue to

35 S, and westward from the coast of South America out to 110 W) has many characteristics typical of subtropical cool-ocean regimes. In this section, we describe some of these typical oceanic and atmospheric characteristics, pointing out those that are still poorly understood and present modeling challenges.

Fig 3a shows microwave-derived mean SEP SST and scatterometer derived winds for October 2001. Equatorward along-shore winds produce cold-air advection and coastal upwelling, setting the stage for interesting ocean dynamics important to regulating SST.

The near-coastal SEP oceanic current and eddy structure well south of the equator is thought to broadly resemble the NEP. There is an equatorward surface geostrophic flow and a poleward undercurrent that is strongest in summer. This circulation pattern of the ocean is baroclinically unstable and develops mesoscale eddies that extend the current system several hundred km offshore in “squirts and jets” within cold filamentary ribbons and westward Rossby wave propagation. Fig. 4 shows the associated westward propagation of anomalies of sea-surface height and SST approaching 10 cm and 1 K in magnitude. The eddies provide shoreward heat and material transport that balance the upwelling supply of cold water and nutrients and the air-sea heat exchange. These structures are reinforced by standing eddies associated with alongshore coastline and bathymetric irregularities. While transient wind fluctuations generate coastal boundary waves that propagate poleward, much of the eddy variability is intrinsic to the ocean.

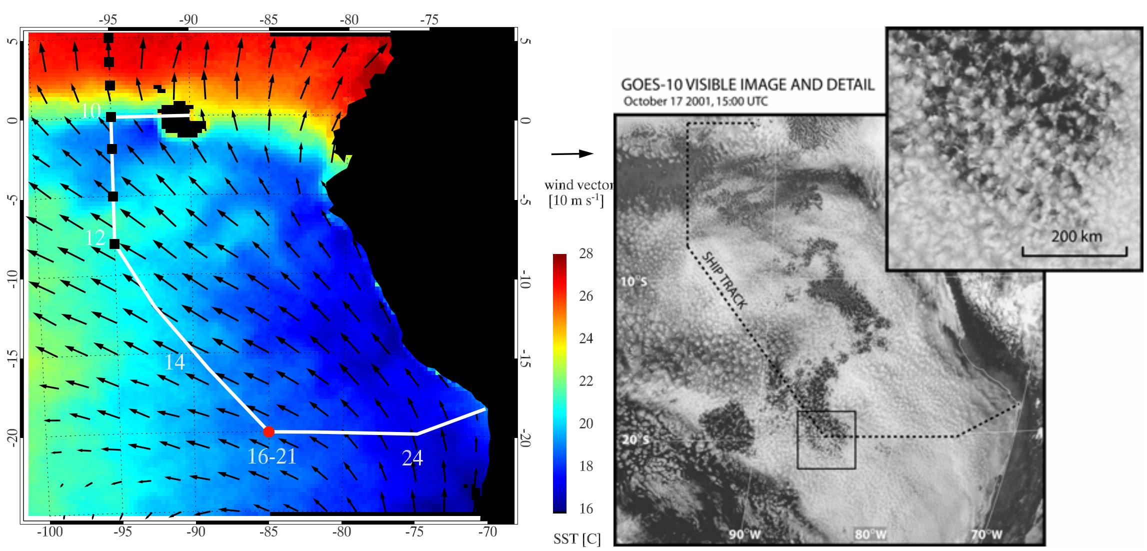

Figure 3: (a) TMI SST and Quikscat vector winds for October 2001. (b) GOES visible-wavelength satellite image showing extensive stratocumulus cloud cover over the SEP, with embedded regions of broken cloud cover called ‘pockets of open cells’ (POCs). The inset zooms in on the black square, which includes one such POC (Bretherton et al. 2004).

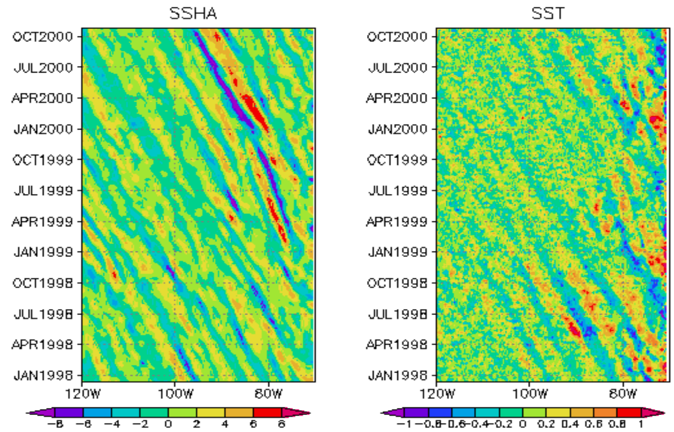

Figure 4: Bandpassed satellite-derived sea-surface height and temperature meridionally averaged from 18-22 S. Note anomalies propagating westward at 5-10 cm s^{-1} (S-P Xie).

The SEP cloud distribution and atmospheric structure also has many features seen in other subtropical cool-ocean regions. Fig 3b shows a typical visible-wavelength geostationary satellite image during October 2001, showing the extensive low stratocumulus cloud over this region, capped by a strong temperature inversion at 1-1.5 km above sea-level. Annual average ERBE-derived cloud radiative forcing (Klein and Hartmann 1993) and microwave-derived liquid water path (Weng et al. 1997) are somewhat larger than in NEP, mainly because the clouds persist through more of the annual cycle. Even near the coast, there is clear mesoscale patterning in the cloud albedo, a hint of the boundary layer dynamics that is integral to maintaining this cloud. Further offshore, there are intriguing regions of broken cloud (termed ‘pockets of open cells’ or POCs by Stevens et al. 2004) embedded within the solid stratocumulus regime, which may be a manifestation of aerosol-cloud interaction and which will be a focus for further study in VOCALS. Like other subtropical cool-ocean regions, the SEP is a region of very little significant rainfall (e. g. Short and Nakamura 2000), but occasional light drizzle is observed at the surface (Petty 1995) and drizzle may play an important climatological role in regulating mean cloud albedo (Albrecht 1989; Bretherton et al. 2004; Stevens et al. 2004). Much further offshore, there is a transition to trade cumulus convection with much lower cloud fraction. All of these features are also seen in the NEP, though with differences as intriguing as their similarities.

Klein and Hartmann (1993) showed that there is a close relation of monthly average fractional coverage of low cloud reported by ships in stratocumulus regimes (including the SEP) to the 'lower tropospheric stability', defined as the difference between 700 mb and 1000 mb potential temperature (which is very close to the SST). Because of the closeness of the SEP stratocumulus region to the equator, the 700 mb temperature varies less in this region over the annual cycle than the SST, and the cloud cover maximizes in austral spring, when SST is minimum. This is different than the Northern Hemisphere stratocumulus regimes, which are further from the equator. In those regimes, 700 mb temperature varies more than SST, and cloud cover, like 700 mb temperature, is maximum in the boreal summer. This is one manifestation of how the SEP and NEP stratocumulus cloud climatologies are both similar and different.

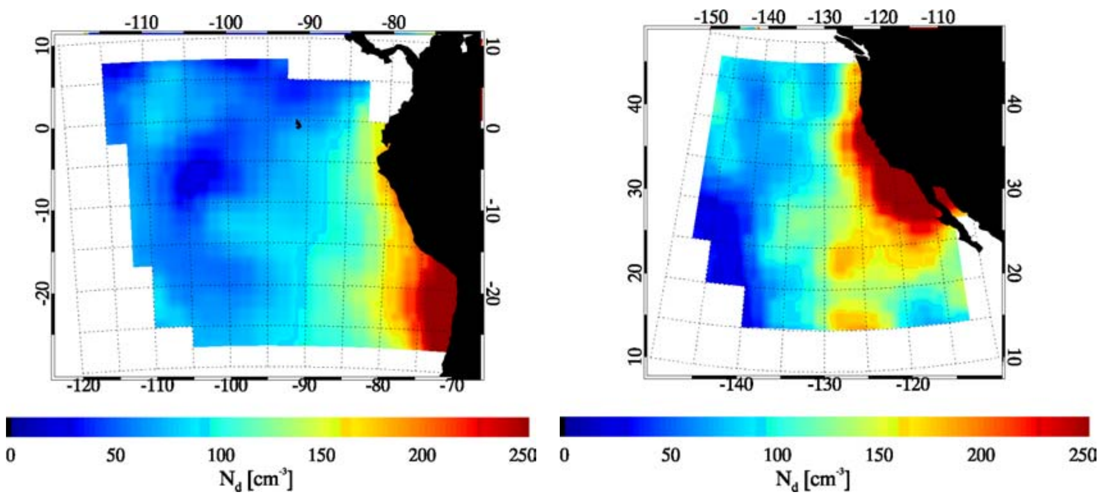

Fig. 5: MODIS retrievals of mean cloud droplet concentration for Sept.-Oct. 2000-2001 Regions of broken cloud cover or cloud above 2 km elevation are excluded (Rob Wood).

2.2 Unique features of the SEP

Despite its apparent similarities to the better studied NEP, there are several reasons for a SPE-focused study like VOCALS. These involve both SEP physical characteristics and observational considerations.

The first reason for studying the SEP is diversity. In the NEP, stratocumulus cloud and coastal upwelling are prevalent only poleward of 20 N. The SEP coastal orography, coastal orientation and surface wind distributions promote coastal upwelling, cool SST, and stratocumulus cloud in the SEP all the way to from mid-latitudes to the the equator, spanning a wide range of conditions and hence providing a rigorous test for coupled models. The diurnal cycle of mean vertical motion and stratocumulus cloud are also substantially stronger in the SEP than the NEP, providing another model test (Bretherton et al. 2004; Garreaud and Munoz 2004).

One important example of this geographical diversity is the distribution of atmospheric aerosol and its potential impacts on stratocumulus cloud and radiation. Aerosol contrasts across the region make the SEP into an attractive natural laboratory for looking at feedbacks between aerosols and boundary layer cloud evolution. Near the equator, humid lower-tropospheric easterly flow, overlies the cloud-topped boundary layer, likely affecting its radiation balance, turbulence and microphysics. South of 15 S, the air above the boundary layer tends to be very dry and clean, having mainly come from the southwest out of storm systems in mid-latitudes and the South Pacific Convergence Zone. The exception is near the South American coast, where along-shore winds allow both industrial and biogenic aerosol to accumulate both within and above the boundary layer.

Many studies have shown that the aerosol population is the principal determinant of stratocumulus cloud droplet concentration. Fig. 5 shows retrievals of Sept.-Oct. 2000-2001 mean cloud droplet number concentration in the NEP and SEP, made by combining visible and near-infrared radiances from the MODIS instrument on the Terra satellite. The retrieval (which is based on inferring the cloud optical depth and cloud droplet effective radius) becomes biased in the broken clouds common more than 1500 km offshore, so has been restricted to times and places where there is solid stratocumulus cloud cover over a region 10 km or more on a side.

Fig. 5 shows that SEP droplet concentrations are more than threefold higher near the coast than further offshore, especially poleward of 15 S. Similar behavior, but with different geographical structure due to frequent offshore flow from California, is seen in the NEP. Biogenic DMS production in upwelling regions, anthropogenic aerosol sources such as copper smelters and power plants along the coast, and smoke from biomass burning blown westward from Amazonia in the mid-troposphere near the equator, then entrained into the boundary layer, may all contribute to the SEP cloud microphysical gradients. Aerosol-starved stratocumulus may be more susceptible to drizzle-induced thinning, decoupling, and partial breakup, a VOCALS science theme we will return to in Section 3.2..

Fig. 6 shows the effect of geographical variations in cloud droplet concentration on TOA shortwave cloud forcing, compared to cloud with the same liquid water content but a spatially uniform effective radius of 15 microns (which would be typical of pristine marine conditions). Near the coast, the enhancement of shortwave cloud forcing due to the small cloud droplet radii created by high aerosol concentrations is approximately 15% of the mean. This suggests the importance of SEP aerosol variations to cloud radiative forcing.

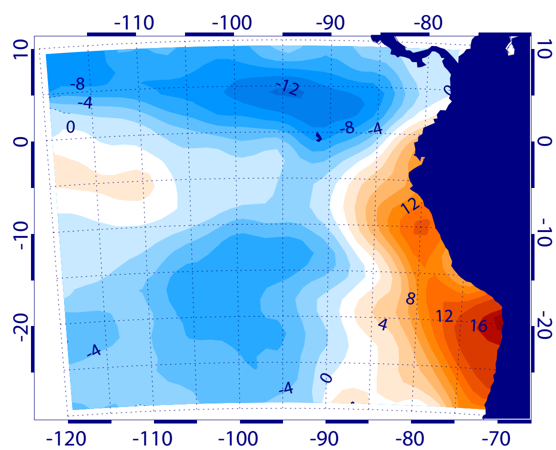

Fig 6: Component of Sept.-Oct. 2000 SEP shortwave cloud forcing [W m^{-2}] due to geographic variations in cloud droplet effective radius, inferred from MODIS (Rob Wood).

A second attraction of the SEP is the tight feedbacks between ENSO and its SST, ocean dynamics, and cloud characteristics, especially equatorward of 15 S (e. g. Bajuk and Leovy 1997). This makes it an important focal area for testing and improving climate models, which are the main tool for extended range climate predictions These models are challenged by the effects of complex current systems, equatorial upwelling, and the cloud-topped boundary layer structure on the SST distribution in the near-equatorial SEP. The Tropical Atmosphere Ocean (TAO) buoy array, deployed by NOAA to help monitor and forecast ENSO, provides high-quality long-term SEP atmospheric and oceanic measurements from moorings at 8S, 5S, 2S and 0S along 95 W and 110 W. Annual maintenance cruises to these moorings also take atmospheric soundings, some conductivity-temperature-depth (CTD) and acoustic Doppler current profiler (ADCP) sections, and other measurements. VOCALS will analyze and selectively enhance these measurements.

A third attraction of the SEP is the observational opportunities it presents well offshore. Figure 7 shows the geography of the region, including key offshore and coastal locations, overlaid on contours of mean annual SST. The WHOI IMET stratus buoy, sited at 20S 85W, has provided a research-quality dataset since October 2000, as do the aforementioned TAO buoys on the equatorial edge of the SEP. The isolated San Felix Island (27S 81W), about 1 km wide and nearly flat, is within the low-aerosol part of the cool-ocean stratocumulus region most of the year. The existence of a Chilean Navy base in this island provides unique sampling opportunities for ground instrumentation that VOCALS hopes to exploit. Further to the south, there is also a larger Chilean island, Juan Fernandez (31S 77W). The Galapagos Islands (2 S 89 W) are home to a NOAA profiler and radiosonde site that help document the free-tropospheric conditions at the equatorial edge of the SEP. These types of observations complement those available in the subtropical NEP. The NEP has been intensively studied within a few hundred km of the coast and has a high density of routine ship observations, but it does not have islands or high-quality long-term buoy observations within the core stratocumulus-blanketed cool-ocean regime several hundred km offshore.

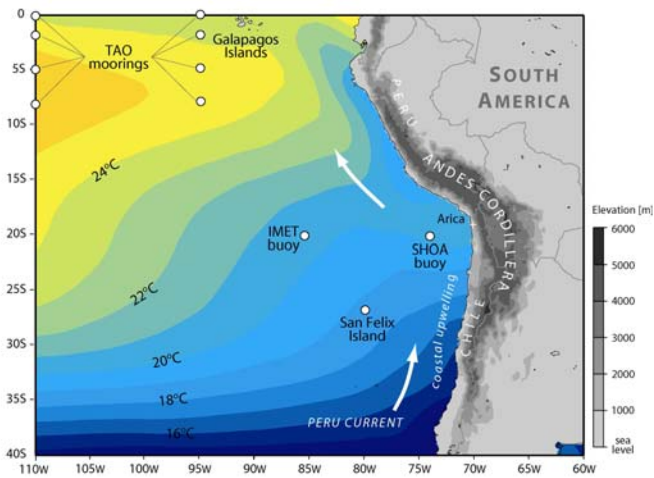

Fig. 7: Map of the SEP showing important VOCALS sites, overlaid on mean annual SST.

There are also buoys and other instrumentation nearer the South American coast, Two current meter arrays are already deployed along the Chilean coast. There is also a network of tide gauges along the entire S American coast.

2.3 Selected prior field studies focussed on the SEP

The SEP is much less well documented in the scientific literature than the NEP or subtropical Atlantic. However, there is now an adequate foundation for intelligent execution of the VOCALS extended process study and intensive field program in this region.

TAO buoys and measurements during maintainance cruises during Mar-May and Sep-Nov document features of the equatorial edge of the SEP, including its seasonal cycle and ENSO variability. Cronin et al. (2003) presented examples of the annual cycle in both atmosphere and ocean seen at selected buoys, and Bond et al. (REF) have shown the characteristic atmospheric boundary layer structure in maintenance cruise soundings.

The Chilean CIMAR-5 cruise (Garreaud et al. 2001) along 27 S from 70-110 W, during March, provided a unique cross-section through the south end of the stratocumulus regime, documenting the general rise of the inversion and reduction of cloud of the inversion offshore, episodes of drizzle, and the interaction of cloud and boundary layer properties with synoptic scale variability. The observed evolution of boundary layer structure with distance offshore was comparable to that observed at similar latitudes in the NEP and NE Atlantic

The EPIC 2001 stratocumulus cruise (Bretherton et al. 2004) was a two week exploratory cruise into the core SEP region during October 2001, starting southward along the 95 W TAO buoy line, then to the WHOI stratus buoy for a six day stay (track shown in Fig. 2.1), finally into Arica, Chile . On this cruise, the ship carried a large suite of surface-based remote sensing instruments, including lidar, 5 cm and mm-wavelength Doppler radar for sensing of clouds and precipitation. Radiosondes, ocean conductivity-temperature-depth (CTD) profiles, and surface-flux instrumentation, and primitive aerosol sampling rounded out an integrated measurement suite. The cruise documented a deep, generally well-mixed stratocumulus-capped mixed layer with an unexpectedly pronounced diurnal cycle in inversion height and cloud thickness. During low-aerosol periods, patchy nocturnal drizzle and more cellular cloud structure were prevalent, hinting at cloud-aerosol feedbacks, but the aerosol measurements were inadequate and of uncertain quality.

Observations from the WHOI stratus buoy now span three years. One interesting feature is the annual average surface heat flux at this site, which is consistently into the ocean with a typical magnitude of nearly 40 W m^{-2}, despite the persistent cloud cover. The ocean temperature and salinity profiles show this heat is flushed away by sporadic intrusions of cold, fresh water advecting into the buoy location due to mesoscale eddies or Rossby waves.

One of the first VOCALS activities has been the PACS-03 cruise (Kollias et al. 2004) to the WHOI stratus buoy in November 2003, on which NOAA/ETL deployed a similar suite of instrumentation as in EPIC 2001. Unlike in EPIC 2001, there was no scanning 5 cm radar to survey regional drizzle patterns, but there was a comprehensive aerosol sampling program that documented several large swings in ambient accumulation-mode (i. e. cloud-nucleating) aerosol concentration during a period of less than a week. Understanding what drives these large, 5-10 fold, changes in aerosol concentration at a site characterized by relatively steady trade winds and few obvious sources of aerosol that might arrive at this site from above the boundary layer is a mystery that VOCALS aims to solve.

3. VOCALS Scientific and Modeling Goals

3.1 Model biases and improvement in the SEP

Intercomparisons of general circulation models of the coupled atmosphere-ocean system (CGCMs), including seasonal-to-interannual forecast models used for ENSO prediction have documented large SST biases in most models similar to those shown in Fig.

2 for CCSM3, leading to errors in the distribution of the annual mean and seasonal cycle of tropical convection and winds (Mechoso et al. 1995; Davey et al. 2002). Most coupled models exhibit ENSO-like variability, but its period tends to be shorter (quasi-biennial) and often more regular than observed (e. g. Kiehl and Gent 2004). Most atmospheric general circulation models (AGCMs) have major difficulties in predicting the seasonal cycle and interannual variability of SEP boundary-layer cloud cover and its radiative effects, even when SST is appropriately prescribed.

These biases are not well understood. They presumably stem from errors in many physical parameterizations as well as inadequate vertical and horizontal model resolution. Deep cumulus convection, ocean upwelling and air-sea exchange along the equatorial cold tongue are challenging to parameterize, and undoubtedly play a role in these biases. Better observations of these physical processes were a focus of the East Pacific Investigation of Climate (EPIC) (Cronin et al. 2002; Raymond et al. 2004), and a major goal after EPIC is synthesis of those observations into parameterization improvements in global models.

The SST biases in the SEP, which are particularly large and important, are believed to stem both from errors in the surface heat budget and in ocean heat transport Hence a central goal of VOCALS is to improve parameterizations of atmospheric cloud-topped boundary layers and lateral ocean mixing by mesoscale eddies. Another main goal of VOCALS is to gather SEP observations and compare them with both regional and global coupled model simulations of the ocean heat budget, to better understand the regulation of SST and cloud cover across the SEP.

The WHOI stratus buoy and the TAO buoys provide ideal platforms for understanding the mean and variability of surface heat flux components over multi-year periods. These buoys all take ocean subsurface observations, have efficient real-time data delivery systems, and take measurements from which the turbulent latent and sensible heat flux components can be inferred. Currently, only the WHOI buoy measures radiative fluxes. During 1999-2002, M. Cronin and M. McPhaden of NOAA/PMEL deployed downwelling radiative flux sensors on most buoys on the TAO 95 W line and compared their observations with satellite retrievals and model/reanalysis simulations (Cronin et al. 2002, 2005). As a part of VOCALS, we propose installation of radiation sensors on the 12 buoys between the equator and 8 S along the 95W, 110W, and 125W TAO lines, providing valuable seasonal-to-interannual data on clouds and radiation in a part of the SEP that is particularly sensitive to ENSO. This is fairly inexpensive, would provide useful ground truth for continually evolving satellite remote sensing algorithms for inferring surface radiative fluxes, and would allow the full surface heat flux to be calculated at these locations. Dr. Cronin is prepared to lead a VOCALS analysis of such data and its comparison with relevant global models and satellite algorithms. The 125 W TAO line is of interest even though it is outside the core VOCALS region since it is in a stratocumulus breakup regions where cumulus clouds poorly resolved in satellite imagery may affect the radiation budget.

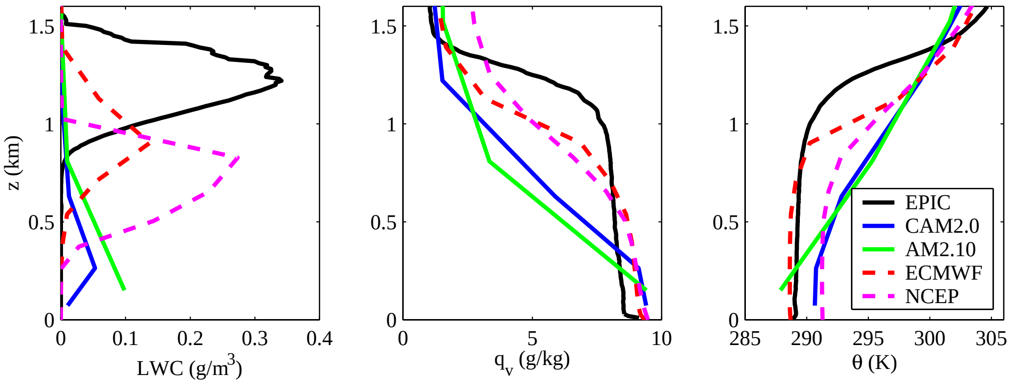

Figure 8: Mean liquid water content, humidity, and potential temperature from six days of EPIC microwave radiometer and rawinsonde observations compared with corresponding NCEP and ECMWF global forecast model analyses and October climatologies from NCAR CAM2.0 and GFDL AM2.10 GCMs (Bretherton et al. 2004).

3.1.1 Cloud and turbulence parameterization for stratocumulus-topped boundary layers

Historically, many GCMs have drastically underpredicted subtropical stratocumulus cloud cover because of its small vertical scale and difficulties in the simulation of turbulence processes that maintain the sharp inversion against subsidence of warm dry air. The large gap between parameterization performance and physical understanding has made it hard to use new observational findings to improve parameterizations. In many models, the boundary layer is too shallow. Figure 8, from Bretherton et al. (2004), shows an example from the EPIC 2001 stratocumulus cruise, which was the first systematic in-situ measurement campaign to document the cloud-topped boundary layer in this region. Six-day mean temperature and moisture profiles of 8-per-day rawinsonde soundings and microwave retrievals of cloud liquid water path at 20S 85W were compared with the NCEP and ECMWF operational model analyses at this location and time (which did not assimilate these soundings), and with October climatology for two leading U. S. AGCMs. Both AGCMs, and to a lesser extent both operational models, show too shallow an inversion. All models except NCEP also simulated too little and too thin cloud compared to these observations.

However, several modeling groups have recently reported encouraging progress in simulating the cloud climatology of this region. While the detailed approach taken by each group are somewhat different, their strategies have all been similar, carefully improving representations of moist turbulent processes, inversion structure, and entrainment of air into the boundary layer. Four such groups are participating in VOCALS. These groups, and papers they have recently published on this subject are: a UCLA effort led by C. Roberto Mechoso (Ma and Mechoso 1996; Yu and Mechoso 2001), a University of Washington effort led by Chris Bretherton feeding into the CCSM (Bretherton et al. 2004a; McCaa and Bretherton 2004), a University of Chile mesoscale modeling group led by Rene Garreaud (Garreaud and Munoz 2003), and an IPRC regional coupled modeling group led by Shangping Xie (Wang et al. 2004). Two other major modeling centers, UKMO and GFDL, have adopted the Lock et al. (2000) boundary layer parameterization scheme, which is philosophically similar to the approaches used above. These groups have also improved the extent and vertical structure of the SEP stratocumulus simulated in their models (Martin et al. 2000; GAMDT 2004).

Results from the UCLA coupled GCM (Yu and Mechoso 2001) in Fig. 9 show how improved simulation of SEP stratocumulus clouds can dramatically improve coupled climate simulations over the entire Pacific region. This model is unique in including an explicit, possibly cloud-topped, turbulent well-mixed PBL (with a depth prognosed by the model), below the remaining levels of the atmospheric model. Before 1998, this model, like most others, greatly underestimated subtropical stratocumulus cloudiness, resulting in a warm SEP and a spurious double ITCZ (Fig. 9, top). A sensitivity test with prescribed stratus cloud cover produced a much more realistic simulation of tropical eastern Pacific winds and rainfall (Fig. 9b). The poor model performance resulted from entrainment of excessively dry air into the PBL, suppressing cloud cover (Mechoso et al. 2000). A superficially small model improvement was made in the vertical interpolation of humidity, SE Pacific and equatorial E Pacific SSTs cooled several degrees. The simulated low level circulation and precipitation patterns were improved over the entire eastern Pacific (Fig. 9, bottom), lessening the spurious double ITCZ, enhancing cross-equatorial flow near the S American coast, and doubling the amplitude of the simulated El Nino to realistic levels.

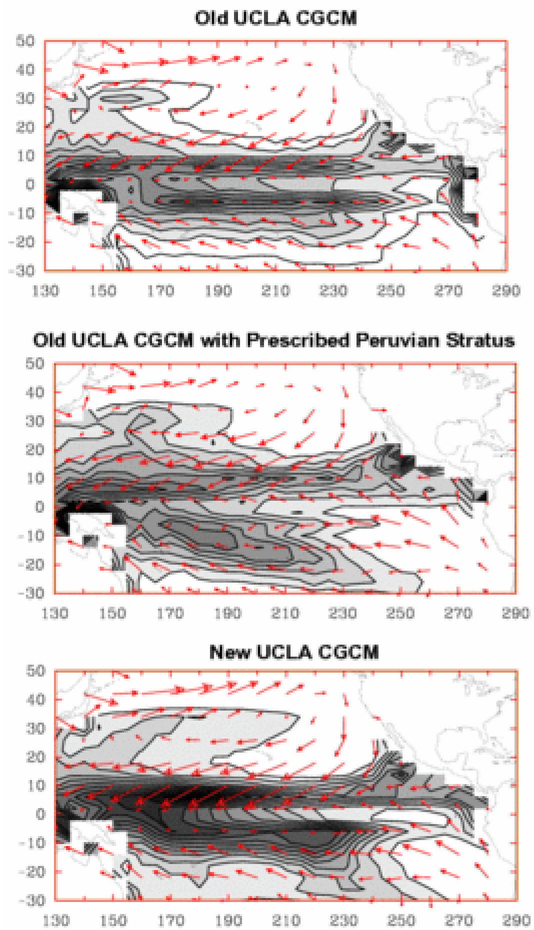

Fig. 9: Annual-mean precipitation and winds in the UCLA coupled GCM. Top: pre-1998. Middle: With prescribed stratocumulus. Bottom: After humidity interpolation fix.

Although these results are encouraging, the boundary layer cloud parameterization problem is not yet solved in this or other models. In the UCLA model, for instance, the stratocumulus cloud thickness and cloud base are still unrealistic in some regions, and precipitation from PBL clouds is arbitrarily disallowed. Others of the above models tend to underpredict cloud cover right along the coast, perhaps due to spurious lateral numerical mixing of air from the warmer, drier continental regions. However, parameterizations like these that can at least simulate stratocumulus clouds in the right geographic regions are well positioned to take advantage of new measurements of stratocumulus characteristics and processes and the insights that result.

Synoptic variability drives considerable day-to-day variability in cloud and boundary layer properties even in the relatively steady trade wind circulation of the SEP. This, together with the substantial observed diurnal cycle of cloud properties, will be discussed at lngth in Sec. 3.4. Here, we merely wish to note that ability to simulate the observed diurnal-to-synoptic timescale variability of the SEP cloud-topped boundary layer is a stringent test of an AGCM or regional model. As model-simulated time-mean cloud properties improve, we must ask whether the time-mean answer is right for the right reasons, or whether the right answer has been obtained by clever tuning which may have incorrect sensitivities to external forcings. If the model can simulate the high-frequency variability of the clouds when used in a forecast mode, this gives us more confidence that it can correctly simulate the sensitivities of the cloud to a range of external forcings.

In this spirit, VOCALS will spearhead applications of AGCMs, global forecast models, and regional models to short-range forecasting of SEP cloud and boundary layer properties, verified using both satellite and available in-situ observations (e. g. the TAO and WHOI stratus buoys and maintenance cruise data). Two VOCALS regional atmospheric modeling efforts, at IPRC and the University of Chile, have already begun to do this. To extend this effort to global models,

VOCALS hopes to develop connections to the recently-initiated NOAA Climate Testbed (http://www.cpc.ncep.noaa.gov/products/ctb that will allow us to better understand how skilful the new NCEP Coupled Forecast System (CFS) model is in predicting the synoptic variability of SEP cloud cover and radiative properties, as well as the evolution of SST anomalies within the SEP. A longer term VOCALS goal is to contribute through this framework to CFS model improvement; to be successful this will require active scientific collaborators within NCEP.

C. Bretherton of VOCALS also has nascent collaborations with CAPT (the CCSP-ARM Parameterization Testbed; http://www-pcmdi.llnl.gov/projects/CAPT/index.php; Phillips et al. 2004), a project at Lawrence Livermore National Labs to test AGCMs (especially the NCAR CAM) by using them as weather forecast models and comparing forecast dynamical, cloud and radiation fields with global and column observations. A particular focus of this and the NOAA Climate Testbed work will be comparison of forecast and observed cloud and surface flux variability at the WHOI stratus buoy.

3.1.2 Challenges in parameterizing cloud-radiation-aerosol interaction

One important process that has not been adequately addressed in any of these models is cloud-radiation-aerosol interaction in the stratocumulus regime, and the role of drizzle processes in these interactions. In part, this is because until recently, there have been inadequate observations of drizzle processes in stratocumulus clouds to test such improvements. For similar reasons, none of these models incorporate an interactive aerosol scheme. Hence, they do not include the uncertain but probably important aerosol indirect effect on climate due to anthropogenic aerosol affecting cloud radiative properties by changing typical cloud droplet sizes and cloud lifetimes. A series of studies (Lohmann and Feichter 1997; Lohmann et al. 1999; 2000; Ghan et al. 1997; 2001) have pioneered the addition of interactive aerosol to GCMs to estimate the aerosol indirect effect; however, much more comprehensive observations are needed to test such parameterizations.

3.1.3 Regional Ocean Modeling

SEP oceanic structure, budgets, and biases in global coupled models should be examined using the perspective of regional eddy-resolving ocean models with O(1-5 km) horizontal resolution embedded within the seasonally and interannually varying global climate. A VOCALS goal is to perform the first regional ocean model simulations for the SEP, and use them to diagnose heat, salinity, and tracer transports and budgets in the few hundred km closest to the coast. Idealized simulations will be used to examine the roles of specific physical mechanisms of interest. With this modeling infrastructure in place, we also intend to do regional ocean model simulations for the VOCALS-RF field experiment period to provide context for analysis of the observations.

The Peru Current is one of four major eastern-boundary, subtropical upwelling regimes, and its behaviors can usefully be studied by intercomparisons with the analogous regions off Africa and North America. The relatively mature NEP regional ocean modeling studies off the west coast of North America (e.g., Bielli et al. 2002; Marchesiello et al. 2003; Perlin et al. 2004) should in particular be exploited, and differences explored. Fig. 10 shows an example of the complex and realistic SST patterns associated with the complex dynamics simulated by such models.

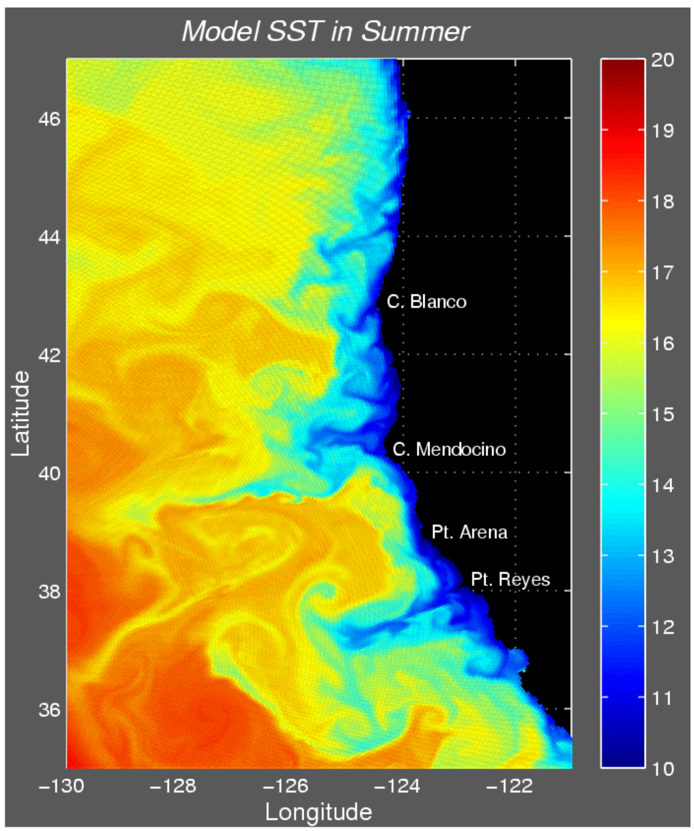

Fig. 10. Instantaneous SST from a regional ocean simulation of the summertime coastal NEP off California (J. McWilliams).

Ocean-atmosphere boundary layer coupling - for example, through SST and surface buoyancy flux influence on surface stress and low-level jet structure - has been found over much of the global ocean (e.g., Chelton et al. 2001) and may be relevant in the coastal zone as well (e.g., Samelson et al. 2002; Capet et al. 2004; Skyllingstad et al. 2005; Bane et al. 2005). This coupling is sensitive to the atmospheric vertical boundary layer structure and stratocumulus cloud cover, since cloud-top radiative cooling is a primary driver of boundary layer turbulent mixing, and it is similarly sensitive to the oceanic boundary layer structure including a strong diurnal heating cycle modulated by the cloud cover, orographically and thermally patterned wind forcing, and mesoscale eddy modulation of the boundary layer depth. This emphasizes the need for regional coupled high-resolution modeling in the coastal zone.

3.1.4 VOCALS goals for model and parameterization testing and improvement

- Diagnose terms in the ocean heat budget in coupled and atmospheric models and compare with observations, with the goal of understanding warm SST biases in this region.
- Use the seasonal cycle and ENSO variability in the SEP as a testbed for improving and intercomparing parameterizations of cloud-topped boundary layers and their interaction with aerosols in regional and global atmospheric models.
- Understand to the extent to which better coupled simulations of the SEP will improve the ENSO forecasting skill of those models.
- Test how skilfully regional and global models can predict synoptic variability in SEP albedo, cloud cover, cloud droplet number concentration and boundary layer aerosol, using satellite observations and VOCALS in-situ observations.
- Use regional ocean models to better understand the near-coastal currents and eddy fields and their transport properties.

3.2 Factors regulating the radiative and microphysical characteristics of SEP stratocumulus

3.2.1 Scientific issues suggested by EPIC-2001Sc, DYCOMS-II, and other prior research

One cannot effectively parameterize what one does not adequately understand. The past 35 year have seen steady progress in understanding of subtropical stratocumulus-topped boundary layers. Numerous field studies of stratocumulus in the North Atlantic and Northeast Pacific (NEP) have been made and are continuing (e.g. Albrecht et al., 1988; Albrecht et al. 1995; Stevens et al. 2003). However, key scientific issues concerning the formation, maintenance, and dissipation of marine stratocumulus clouds remain. Before EPIC 2001 and DYCOMS-II, a commonly stated guiding question was: Which is more important in limiting area and time-mean stratocumulus cloud thickness over the cool low-latitude oceans– evaporation of cloud by turbulent entrainment of dry warm air through the trade inversion, or rainout of particularly thick or clean patches of cloud? After these studies, we appreciate that in the low-aerosol regime typical of the WHOI stratus buoy location in the SEP (and less frequently also seen in the NEP), drizzle is important but influences the boundary layer in too organic a manner to render this question meaningful. Drizzle is common in late night and early morning, but mostly evaporates before reaching the surface, releasing latent heat of condensation into the cloud layer and evaporatively cooling the subcloud layer. This stabilizes the boundary layer, modifying the turbulence and likely also enhancing the mesoscale heterogeneity of the clouds, and thereby affecting mean cloud radiative properties. These studies also confirmed our expectations that drizzle is favored by low cloud-nucleating aerosol concentrations, and that even far from the coast, aerosol concentrations vary by up to a factor of ten from day to day for reasons that have not been fully explored. Thus, two outstanding fundamental scientific issues that we are addressing in VOCALS, both of which map onto the parameterization challenges discussed above, are aerosol-cloud-drizzle interactions and mechanisms affecting the mesoscale patchiness and fractional cloud cover.

3.2.2 Aerosol-Cloud Interaction

Observations in the SEP made during the EPIC 2001 field campaign (Bretherton et al. 2004) suggest that drizzle production is modulated by cloud droplet number concentration, which is directly related to aerosol concentration (e.g. Twomey and Warner 1967, Martin et al. 1994, Breon et al. 2002). Tantalizing evidence has been presented (Stevens et al. 2004) suggesting a direct link between drizzle and cloudiness in MBL clouds that is manifest through regions of broken cloud organized into roughly polygonal lattices, called "open cellular convection", embedded within otherwise overcast stratocumulus. These regions have been termed POCs, or "pockets of open cells" (Stevens et al. 2004); the GOES satellite image in Fig. 3b includes some nice examples.

Measurements suggest that POCs tend to be associated with low aerosol concentration (Petters et al. 2004), and intense drizzle production (Stevens et al. 2004). This link between drizzle production and cloudiness is central to the hypothesis of Albrecht (1989), namely that increases in anthropogenic aerosol may lead to a reduction in precipitation and a corresponding increase in global cloud cover and thickness. There have been attempts to test this hypothesis in GCMs (e.g. Lohmann and Feichter 1997, see also review paper by Haywood and Boucher 2000), with sensitivities to increases in anthropogenic aerosol varying widely between models. This is hardly surprising given (a) the huge quantitative differences in the sensitivity of the parameterizations of drizzle production to cloud microphysics (Wood 2005, Pawlowska and Brenguier 2003); (b) the inadequate representation of the turbulent structure and entrainment characteristics of cloud-topped boundary layers in GCMs (e.g. see Bretherton et al. 2004) which strongly interacts with their cloud (Bretherton and Wyant 1997) and precipitation (Nicholls 1987, Baker 1993) characteristics; (c) inadequate understanding of how to parameterize mechanisms modulating subgrid variability of cloud optical depth and precipitation. POCs are relevant to all three of these model uncertainties. There is a strong need for detailed observational studies of POCs, particularly studies with collocated aircraft in-situ measurements and ground/shipborne remote sensing, to determine whether POCs do indeed evince a fundamental mechanism whereby aerosols can influence MBL cloudiness.

Fig. 11 shows a two-month "climatology" of the frequency of occurrence of open cellular convection during September/October 2000 constructed using a neural network method applied to MODIS data (Wood and Hartmann 2005). This clearly shows that open cells occur almost twice as frequently in the accessible regions (<1000 km from the coast) of the SEP than in the NEP. In addition to demonstrating the climatological significance of open cellular convection in regions dominated by marine stratocumulus, it also highlights the suitability of the SEP as a location for a field program to examine POCs. During September/October 2000, open cells were present almost 40% of the time at the IMET Buoy (85W, 20S) and around 20% of the time at San Felix Island (80W, 27S). However, there are almost no direct observations of the variability of aerosol or cloud droplet size distributions that we think may be associated with POCs. These observations are crucial to interpreting satellite observations that we do have, so that the link between aerosol variability, drizzle, and cloud organization can be convincingly made, and the role of anthropogenic vs. natural aerosol can be understood. In particular, open cell organization is also associated with largely non-precipitating shallow clouds, e.g. the climatological transition from stratocumulus to trade cumulus cloud regimes. These open cell convective clouds are usually seen further offshore, between 1500-2000 km from the coast in both the NEP and SEP, or in midlatitude cold air outbreaks. How much aerosol variability affects the cloud fraction in either region is an important question which we do not know how to answer with satellite observations alone.

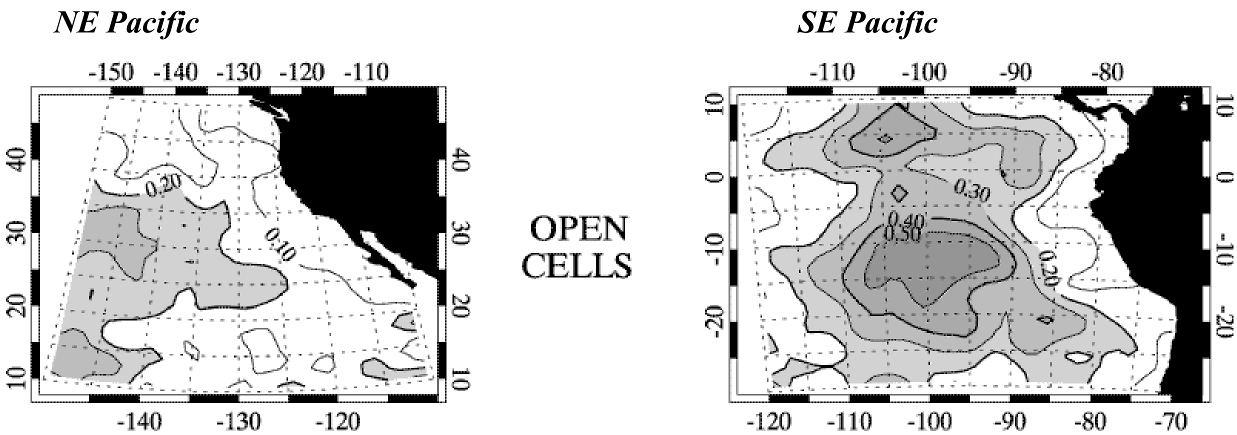

Figure 11: Average frequency of occurrence of open cellular convection in the NE Pacific (left) and SE Pacific (right) subtropical regions during September/October 2000 (Wood and Hartmann 2004).

3.2.3 Aerosol production and variability

We believe POCs are associated with spatiotemporal patchiness in boundary layer aerosol, but our understanding of the latter is quite scant, especially in the SEP. Chemical transport models suggest that there are significant sources of both anthropogenic and natural aerosol that can influence the near-coastal SEP (Chin et al. 1996), with an extremely strong fall-off in anthropogenic influence westwards. Satellite retrievals of the cloud droplet effective radius over the SEP mirror these strong zonal gradients (Han et al. 1994, see also Fig. 5), with an increase in effective radius away from the coast. The optical thickness of a cloud is inversely proportional to its effective radius and increases linearly with liquid water path (vertically integrated liquid water content). Therefore, the causes of variability in effective radius and liquid water path need to be understood in order to accurately determine the radiative properties of clouds.

Variability in the cloud effective radius is largely controlled by variability in the aerosol concentration, size distribution, and chemical composition, which are generally thought to play a more important role in marine boundary layer clouds than variations in updraft speed and thermodynamics. Aerosols that can act as nucleation sites for cloud droplets are termed cloud condensation nuclei (CCN). In the marine boundary layer, the concentration of CCN is strongly correlated with the concentration of aerosols with diameters larger than approximately 50 nm (often called the accumulation mode). Smaller aerosols are too small to efficiently act as CCN, and do not typically form cloud droplets. The effective radius tends to be large in a cloud growing in a low CCN boundary layer, because the available liquid water is shared among fewer droplets. It is therefore crucial to understand the sources and sinks of these particles if we are to understand the variability in cloud droplet sizes. Fig. 12 is a ten day time series of the size-stratified aerosol concentration measured during the PACS03 cruise in the SEP to the WHOI stratus buoy. It shows how variable the aerosol characteristics are on synoptic timescales. The upper maximum, called the accumulation mode aerosol, and which CCN are generally drawn from, is occasionally absent (e.g. on 16 Nov.), indicating highly pristine conditions in which production of small new nucleation-mode aerosol particles becomes important. The dramatic aerosol variability in the seemingly steady flow regime of the southeasterly trades is rather striking and not currently explained.

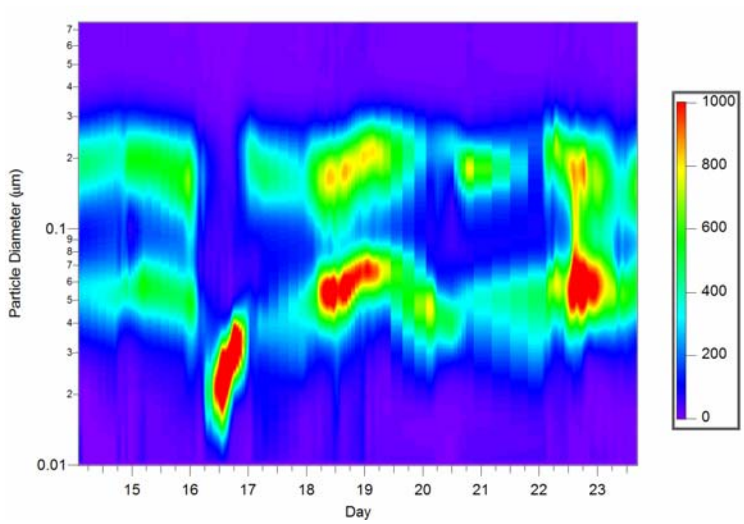

Fig. 12: Time series of aerosol concentration from PACS03, size-stratified along the vertical axis. CCN are usually drawn from the upper maximum in the size spectrum, corresponding to accumulation mode aerosol of diameter exceeding 0.1 micron. Note high degree of day-to-day variability (Kollias et al. 2004).

While CCN concentrations range from <10 to >200 cm^{-3} in remote oceanic MBLs, the total aerosol concentration (including the Aitken, accumulation, and coarse modes) is surprisingly stable at a few hundred particles per cm^{-3}. This implies that there must be a source of gas-to-particle conversion (GPC) that continually restores the population (Clarke et al. 1998). There is considerable debate about whether the major source is actually within in the MBL. This stems from the idea that the MBL typically has a large aerosol surface area that condensable vapors will favor over the energetic barrier of new nucleation (Covert et al. 1996). However, a number of observational studies do show compelling evidence indicating that nucleation of new particles can occur in the MBL (Clarke et al. 1998, Kollias et al. 2004, Petters et al. 2004). Coastal regions are particularly prone to nucleation events (O'Dowd et al. 2002).

New nucleation results in very small particles that require several days to grow and coagulate to a size sufficient to be effective CCN (Hoell et al. 2000). Processes by which these particles are produced and lost through precipitation scavenging require investigation, though this is also being studied in other ongoing projects in the NEP.

Models of new nucleation generally do not favor new particle formation in the MBL (Raes et al. 1995, Clarke et al. 1998), but these have attempted to simulate only the GPC of sulphuric acid produced via the oxidation of dimethylsulfide (DMS) which is considered to be the main oceanic aerosol precursor species (Charlson et al. 1987). Mass spectrometry of recently nucleated particles in the MBL show large fractions of iodine-containing species (O'Dowd et al. 2002) that have been shown in smog-chambers to successfully nucleate even at high relative humidities that are unfavorable for sulphuric acid GPC. Iodine production over the coastal zone is related to algae, but this source alone is insufficient to account for the observed concentrations of certain iodine species over the open ocean.

Recent inventories of sulfur production from ships (Capaldo et al. 1999) suggest that even over the remote ocean, a significant fraction of the sulfate aerosol production can be anthropogenically produced. In the NE Atlantic and Pacific where several field programs to investigate aerosol-cloud interactions have been conducted (e.g. ASTEX, Albrecht et al. 1995; ACE-2, Johnson et al. 2000; DYCOMS-II, Stevens et al. 2003), estimates suggest that 50-80% of the atmospheric sulfur dioxide is ship-produced (Capaldo et al. 1999). Although subsequent research (Davis et al. 2001) has cast some doubt on the quantitative aspects of the Capaldo et al. findings, it seems likely that only in the remote regions of the Southern Hemisphere, such as the SEP, that a truly unpolluted aerosol environment can be found which provides an analogue to pre-industrial conditions over the oceans of the Northern Hemisphere.

3.2.4 Refining satellite retrievals of boundary-layer cloud and aerosols

In the SEP, in-situ observations are sparse, and for VOCALS we are relying heavily on satellite-derived estimates of SST, surface winds, water vapor, and cloud and aerosol properties, as well as gridded reanalyses. One reason that now is a good time to conduct VOCALS is the ‘data firehose’ of exciting new information over remote ocean regions provided by new satellite instruments such as MODIS on Terra and Aqua, the TRMM Microwave Imager (TMI), and the soon-to-be-launched Calypso/CloudSat combination of a downward pointing lidar and 3 millimeter-wavelength ‘cloud’ radar and lidar. In additional, new data assimilation techniques based on better weather forecast models are greatly improving the reliability of reanalyses over remote ocean regions..

But VOCALS aims not only to be a user of such data, but a testbed for improving satellite-derived algorithms, especially for cloud microphysics and aerosols. As in the NEP, the stratocumulus cloud has an attractively simple structure for remote sensing, because it contains no ice, has a relatively uniform cloud top height, and usually is the only cloud layer in the atmosphere boundary layer. This has led to the development of sophisticated multiwavelength techniques for estimating mean (or ‘effective’) cloud droplet radius r_e, cloud liquid water path, and even the presence of drizzle. In VOCALS, we are looking at early results from such retrievals and comparing them with our limited in-situ data. We have found problems with current MODIS retrievals drastically overestimating r_e in regions of highly inhomogeneous or broken stratocumulus such as POCS (which is not unexpected, since those retrievals assume plane-parallel radiative transfer). Unfortunately, POCS are of central interest to VOCALS, so we are collaborating with several experts on alternative algorithms (for instance using multiple infrared wavelengths) that are less biased in cloud fields with substantial mesoscale heterogeneity.

Similarly, in the likely event that CloudSat and Calypso are still operational at the time of VOCALS-RF, the in-situ observations of drizzling stratocumulus of the SEP from aircraft, the ship radars and the ARM Mobile Facility on San Felix Island will form a wonderful comparison with the satellite combination and the rest of the 'A-Train'. VOCALS goals include testing the utility of CloudSat for stratocumulus drizzle retrieval, and using the space-based lider to gauge the importance of entrained free-tropospheric aerosol to SEP boundary layer cloud microphysics. The VOCALS-RF implementation will try to collocate in-situ measurements under satellite overpasses when possible.

3.2.5 Summary VOCALS aerosol-cloud-drizzle science questions

- What is the interplay between entrainment, drizzle and SST in limiting the thickness, mesoscale heterogeneity, and extent of marine stratocumulus clouds over the SE Pacific? How much does this vary by season and location?
- What physical processes are responsible for generating pockets of open cells (POCs) and within an otherwise overcast stratocumulus cloud regimes?
- What are the aerosol characteristics in both the coastal and remote SEP region? How do the contrasts affect cloud microphysics, and how are they related to POCs? Does a POC cause aerosol depletion through scavenging, or is depleted aerosol a POC precursor? What are the major sources and sinks of aerosol over the coastal and remote SEP, both natural and anthropogenic?
- What can we learn from the SEP about the aerosol indirect effect on climate?
- How can current and planned satellite retrievals of stratocumulus cloud microphysical properties (e. g. effective radius or cloud droplet number concentration from MODIS) and precipitation (from CloudSat or MODIS) be improved, including under broken cloud conditions?

3.3 The SST distribution and the ocean heat budget in the SEP

3.3.1 Role of horizontal fluxes in ocean eddies and Rossby waves

Wind-driven coastal upwelling and the northward Peru Current strongly depress coastal SSTs. However, cool SSTs extend 1500 km or more offshore. The maintenance of the SST distribution of this broader region is an important problem in the SEP and other subtropical cool-ocean regions. As mentioned in Section 3.1, coupled models tend to exhibit warm SST biases throughout such regions. This has often been attributed to insufficient reflection of sunlight from parameterized boundary layer cloud, but warm SST biases remain even in coupled models which have simulated clouds of adequate albedo. The WHOI stratus buoy provides a unique opportunity to gain insight into the heat budget of a subtropical cool ocean regime well offshore of the coastal upwelling zone. In both the upwelling zone and further offshore, the flow is complex and time-varying. Satellite altimetry and SST maps reveals mesoscale eddies 50-200 km across, Rossby waves, and coastally-trapped Kelvin waves playing an important role as in the NEP (e.g. Kelly et al. 1998). A scientific issue VOCALS aims to address is the role of this eddy and wave field in affecting SST well offshore by fluxing cold water out from the coastal upwelling regions. A preliminary study of the three-year mean heat budget at the WHOI stratus buoy suggests that heat flux divergence by mesoscale eddies is the most plausible process to balance the roughly 40 W m^{-2} net heat flux into the ocean measured at the buoy during this period.

One might imagine that Ekman transport would also create a large offshore flux of cold water. As shown in Fig. 13, this is indeed the case, but only out to 400 km from the coast. Further offshore, the SST contours are nearly parallel to the Ekman transport, so Ekman-induced ocean heat transport is almost insignificant. We are not aware of careful estimates of advection of heat and salinity by other mean currents in this region; the role of offshore vertical advection (upwelling) and uncertainties in vertical mixing processes may also not be negligible. Careful diagnosis of heat-budget terms in both regional eddy-resolving and global-scale ocean models will be used in VOCALS to compare with and interpret the limited observations that we have, and compare the SST and eddy and mean-flow heat, salt, and tracer convergence between eddy-resolving and global ocean models. In the analogous California Current upwelling regime, the lateral eddy and Rossby wave flux is a dominant component of the offshore heat and biogenic tracer budgets (Marchesiello et al. 2003; Gruber et al. 2005), and a similar approach can be applied to the Peru Current. Such model comparison studies would also help us understand how broadly representative the heat and salinity budgets at the WHOI stratus buoy are, and if there are offshore regions in the low-latitude SEP with fundamentally different balances in the model-simulated ocean heat budget, where they might be and why they are different.

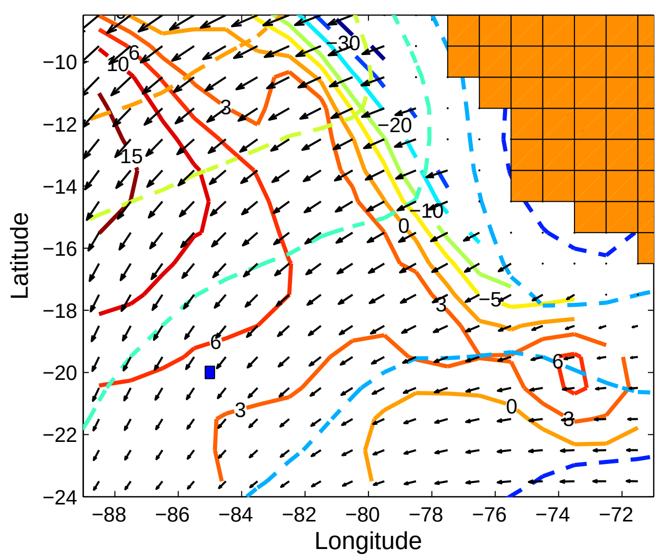

Fig. 13: The annually averaged Ekman advective heat flux (solid contours and labels in W m^{-2}) for the VOCALS region, based on observed time-varying SST and surface wind stress. The direct transport of upwelled water by the wind is only important for the heat budget within a few degrees of the coast. Further offshore the Ekman transport (annual average shown in arrows) is largely directed along mean SST contours (dashed contours).

A single measurement location provides an important anchor point, but is inadequate for understanding what eddy or wave scales and structures dominate the eddy heat flux convergence, if this heat flux convergence is in fact as large as 20-40 W m^{-2}, how far offshore the eddy heat flux convergence is significant, and how this affects the regional SST distribution. We plan to learn what we can about the typical vertical and horizontal structure of eddies in this region by collecting the existing scientific cruise data for this region, including SST, sea-surface salinity, 1-4 km deep CTD and 250 m deep ADCP sections. In upcoming buoy maintenance cruises, we propose to also carry out high-resolution expendable bathythermograph (XBT) sections for detailed sectioning of mesoscale eddy features. Satellite altimetry and microwave-derived SST are also very useful for this purpose. Analysis of these data sets will help determine an optimal sampling strategy for quantifying lateral heat flux as part of the VOCALS-RF intensive field experiment. The current VOCALS-RF plan for estimating this flux is a spatial survey of the vertical structure of the oceanic wave and eddy field in this region using measurements taken from two ships. Scales of 200 km and greater will be sampled by towed SeaSoars (Pollard 1986) or other underwater gliders. Mapping of nutrient concentrations as well as heat and salinity will provide additional insight into relevant mixing processes. Since nutrient-induced phytoplankton blooms can affect the depth over which sunlight is absorbed in the ocean column, nutrients may even be somewhat active tracers. Drifters, some with thermistor chains extending below the mixed layer base, will be deployed to better resolve smaller scale features and Lagrangian transports in the eddy field. Microstructure observations might provide useful constraints on the relevance of vertical mixing processes at selected locations within the eddy and current field. Altimetry will be used to put the SeaSoar sections into better spatial context. This would provide a rich context for understanding the long-term buoy time series and altimetry data, as a well as a comprehensive observational comparison with coupled and regional ocean model simulations, and thereby helping us better understand the role of lateral ocean mixing in setting the regional SST distribution of the SEP.

3.3.2 SST-cloud interaction

Theoretical and numerical modeling studies have clearly indicated that the thermal structure and general circulation of the entire eastern Pacific is strongly affected by the presence of boundary-layer clouds (e.g., Ma et al. 1996, Philander et al. 1996, Gordon et al. 2000). Stratocumulus decrease the surface insolation. They also intensify lower-tropospheric longwave radiative cooling, which strengthen the northeasterly trade winds (Nigam 1997) in the SE Pacific. Both of these effects presumably contribute to cooling of SSTs. Coastal upwelling by the enhanced winds further cools the upper ocean near the coast. In turn, cooling of SST is generally thought to help maintain the stratocumulus by strengthening the overlying trade inversion and inhibiting entrainment of dry, warm air (Klein and Hartmann 1993; Norris and Leovy 1994), though this is not universally the case (e..g. cloud cover variations associated with tropical instability waves on the eastern Pacific equatorial SST front, as documented by Hashizume et al. 2002). This suggests a positive feedback between cool SST and more boundary-layer cloud cover which may make these cool-ocean regions sensitive to external forcings and a more dynamic component of ENSO.

However, the feedbacks between clouds and regional SST distribution have not been quantitatively studied in this region, and may be more subtle than the above argument suggests. In particular, the ocean heat budget also responds to the vertical structure of the atmospheric boundary layer (ABL). A more turbulent ABL will tend to entrain more warm dry air from aloft and maintain a lower surface relative humidity. This promotes stronger latent heat fluxes that cool the ocean.

As an example of how this can play out in a coupled model, a comparison was made between the climatological annual-mean surface heat budget in the two versions of NCAR's coupled model, the CSM and CCSM2, at the WHOI stratus buoy location (C. Bretherton, pers. comm. 2004). The CSM had a 2 K warm bias over much of the offshore SEP. This had been blamed on inadequate simulated cloud cover, and indeed the CSM simulated 30 W m^{-2} too much radiative flux going into the ocean. The CCSM had little radiative flux bias at this location. The puzzle was that the CCSM2 nevertheless had almost the same warm SST bias as the CSM. The reason was diagnosed to be a large, compensating 30 W m^{-2} decrease in the CCSM2-simulated latent heat flux compared to CSM, which left the net heat flux into the ocean almost unchanged. This latent heat flux change was due to the CCSM2 boundary layer being far too shallow and moist, with the clouds largely in the form of fog. Thus, a poor ABL vertical structure entirely compensated the better clouds. Interestingly, leading current global climatologies of latent heat flux still differ regionally by more than 30 W m^{-2} over parts of the SEP, making it hard to use these climatologies to test the veracity of the ABL vertical structure. This emphasizes the value of flux-reference sites like the WHOI stratus buoy and other high-quality in-situ observations such as the PACS cruises and proposed VOCALS-RF field experiment. Another significant modeling goal of VOCALS is also to more carefully understand whether cloud-SST feedbacks in the SEP affect ENSO, and whether this is represented by any current coupled models in a manner consistent with our empirical understanding. Such feedbacks might be direct (by cloud-radiative or surface flux feedbacks on ENSO SST and wind anomalies) or indirect (by changing the seasonally varying mean state of the cold tongue and ITCZ, affecting the model-preferred ENSO periodicity and amplitude). For instance, the ENSO cycle in many CGCMs is too fast, and the cold tongue tends to be too cold compared to the waters to the south and north. An important open question is whether there is a strong relation between these two biases or an important dependence on SEP cloud feedbacks.

An interesting issue is whether mesoscale SST anomalies (or even mesoscale anomalies in ocean DMS production) noticeably imprint themselves on the regional cloud distribution. These SST anomalies are up to 0.5-1 K, but air blows across them in a few hours, leaving boundary layer turbulence and clouds little time to adjust to them. Microwave observations from space of SST, surface wind and cloud liquid water might help expose any correlations that may exist. If they do, a regional model comparison would be fruitful.

3.3.3 Summary VOCALS SST, ocean heat budget, and ocean mixing science questions:

- What are the dominant controls on the SST, salinity and nutrient concentrations in the offshore regions?
- Do mesoscale eddies or oceanic Rossby waves play a dominant role in fluxing heat from coastally upwelled water to regions further offshore? If so, what is their structure? Are the eddies also affecting biogenic aerosol production well offshore?
- Is a positive feedback between SEP SST and boundary layer cloud radiative forcing anomalies evident on seasonal and interannual timescales? If so, how important is it

for ENSO, anthropogenic climate change, and the seasonal cycle of rainfall in the East Pacific ITCZ and South American monsoon?

3.4 The role of S America and remote forcing

Stratocumulus clouds and SSTs in the SEP are affected by free tropospheric temperatures, low-level winds, mean subsidence, aerosols, and synoptic variability. Many of these factors are intimately tied to the South American continent. The Andes are a formidable barrier to low-level zonal flow, helping isolate the E Pacific from Amazonia. Diabatic heating over the Andes and Amazonia has a strong diurnal cycle and induces a low-frequency Rossby wave response to the west. Both factors modulate subsidence over parts of the SEP (Silva Dias 1987; Rodwell and Hoskins 1996; Gandu and Silva Dias 1998; Neelin et al. 2004; Bretherton et al. 2004; Garreaud and Munoz 2004). Philander et al. (1996) suggested that the northwest-southeast orientation of the S American coast is favorable for coastal upwelling by the low-level winds, helping maintain cold SSTs and sustain stratocumulus clouds up to the equator. Seasonal and ENSO-related changes in tropical ITCZ rainfall and SST also interact with the SEP as tightly linked parts of the global tropical Hadley-Walker circulation (e. g. Ma et al. 1996). The cloud-induced cooling of SST may be a positive feedback on all these processes. A goal of VOCALS is to clarify these interactions on all timescales, recognizing that the SEP not only feels remote effects, but also produces them. Numerical modeling studies are a key element in our strategy, in close coordination with diagnostic analysis based on existing and new observations. The scientific issues can broadly be divided into seasonal, synoptic and diurnal timescales.

3.4.1 The SEP seasonal cycle, the Andes and the South American monsoon

The strength of the trade inversion and mean subsidence help determine the PBL depth and cloud properties, which in turn affect SST. Richter and Mechoso (2004) have performed AGCM sensitivity experiments in order to examine the response of low-latitude stratocumulus to removal of orography over Africa and South America. They found that in both cases, removing the orography lowers the mean lower free-tropospheric air temperature over the ocean to the east, significantly decreasing the inversion strength and cloud cover. A sensitivity study to removal of Andean orography in a higher resolution regional model also found simulated stratus cloud cover was reduced (Xu et al. 2004). A similar response was found to smoothing the true topography to a T42 spectral truncation comparable to that used in an AGCM. This study concluded that reduced subsidence (as depicted in Fig. 13) was the main factor reducing the cloud cover.

Modeling and theoretical studies also indicate that the subsidence over the SEP is coupled to convective heating over the Amazon and Altiplano (Rodwell and Hoskins 1996; Gandu and Silva Dias 1998). Well offshore, reanalyses suggest that the subsidence is fairly uniform and driven primarily by radiative cooling. Near the coast, in contrast, the subsidence is stronger and the PBL is shallower. Fig. 14 shows a simulation of the vertical motion field at 500 mb in a dry atmospheric primitive-equation model (including topography) in response to an idealized steady Amazonian heat source . The region of ascent (dashed contours) is collocated with the heat source. The compensating subsidence is broadly distributed throughout the tropics, but maximizes southwest of the heat source, directly over the region of maximum stratus cloud cover. We note that the simulated subsidence is only about 10% of the climatological subsidence seen over the subtropical SE

Pacific (Pacific ITCZ heat sources are also of great importance). However, the experiment does not include potentially important feedbacks involving radiative cooling and mean zonal winds interacting with the orography.

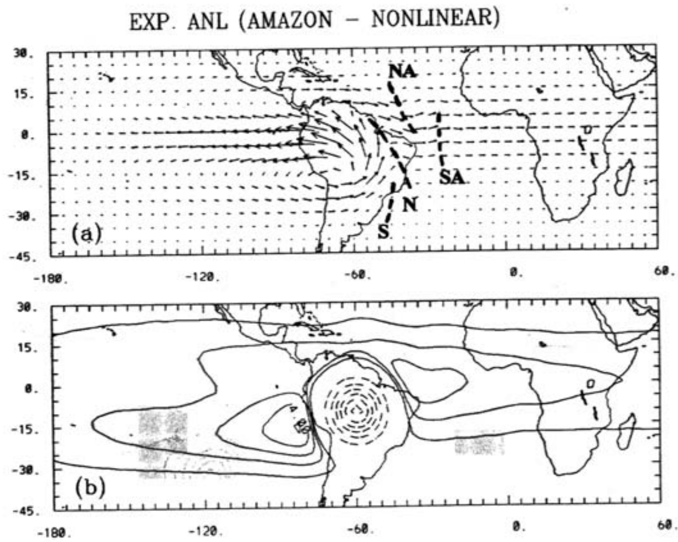

Fig. 14: 500 mb ω in a dry primitive-equation model including topography, in response to a specified, realistically strong, deep convective heat source over Amazonia. Solid contours (interval 1 hPa d^{-1}) indicate subsidence. Dashed contours (interval 20 hPa d^{-1}) indicate forced ascent over the heating region (Gandu and Silva Dias 1987).

Such atmosphere-only studies suggest that orography and continental heating contribute somewhat to the seasonal cycle of SEP clouds and SST. A more complete study requires consideration of oceanic feedbacks resulting in SST changes. As part of VOCALS, we plan to do sensitivity experiments to continental orography and Amazonian land-use change experiments with coupled SST. In coupled experiments without orography, we anticipate even larger simulated cloud cover decreases along with warmed SEP SST, which might feed back on South American and ITCZ rainfall patterns. Amazonian land use change will affect South American rainfall; the main question is whether this induces noticeable changes in the SEP, and whether the coupled response (in rainfall, for instance) to a land-use change feels any effects from SEP SST perturbations. Such experiments provide insight into differences between and nonlocal impacts of the subtropical cool-ocean regions, and can help us understand whether, for example, high-resolution orography or more faithful simulation of continental and oceanic deep convection is important to improving simulations of the SEP coupled system.

In addition, VOCALS participants will carefully re-examine the veracity of the modeled response to ENSO of the latest versions of both AGCMs (i.e. with specified time-varying SST) and coupled GCMs.The emphasis will be on the eastern Pacific, using satellite and buoy-derived SST, cloud cover, and TOA and surface radiative fluxes as metrics.

3.4.2 The diurnal cycle

Clouds over the SEP exhibit a much stronger diurnal cycle of cloud cover (Rozendaal et al. 1995) and cloud liquid water path (Wood et al. 2002) than the MBL clouds at comparable latitudes in the northern hemisphere. Regional model simulations (Garreaud and Muñoz 2004) suggest that a large-scale subsidence wave formed by the interaction of the coastal jet along the Chilean coast with dry convective heating over the western Andean slopes can travel at least 1000 km over the SEP and lead to a strong diurnal cycle of subsidence, as seen in Fig. 15. The phase of the wave appears to strengthen the existing diurnal cycle of MBL depth and cloud liquid water path. Recent satellite measurements of surface divergence from the Quikscat microwave scatterometer (R. Wood, personal communication 2004) suggest that the peak-to-peak amplitude of the divergence over much of the SEP can be 40-60% of the mean, with reduced subsidence during the night over the region of climatological maximum low cloud cover (Bretherton et al. 2004). This has a rectified effect on the clouds and their radiative properties because it allows the MBL depth to deepen more rapidly at night resulting in thicker, more water-laden clouds (Garreaud and Muñoz 2004) compared with MBLs without the diurnal cycle of subsidence. These clouds are more prone to early-morning drizzle, and are then followed by rapid thinning aided by the increased daytime subsidence that reduces the efficiency with which the clouds can reflect sunlight back to space.

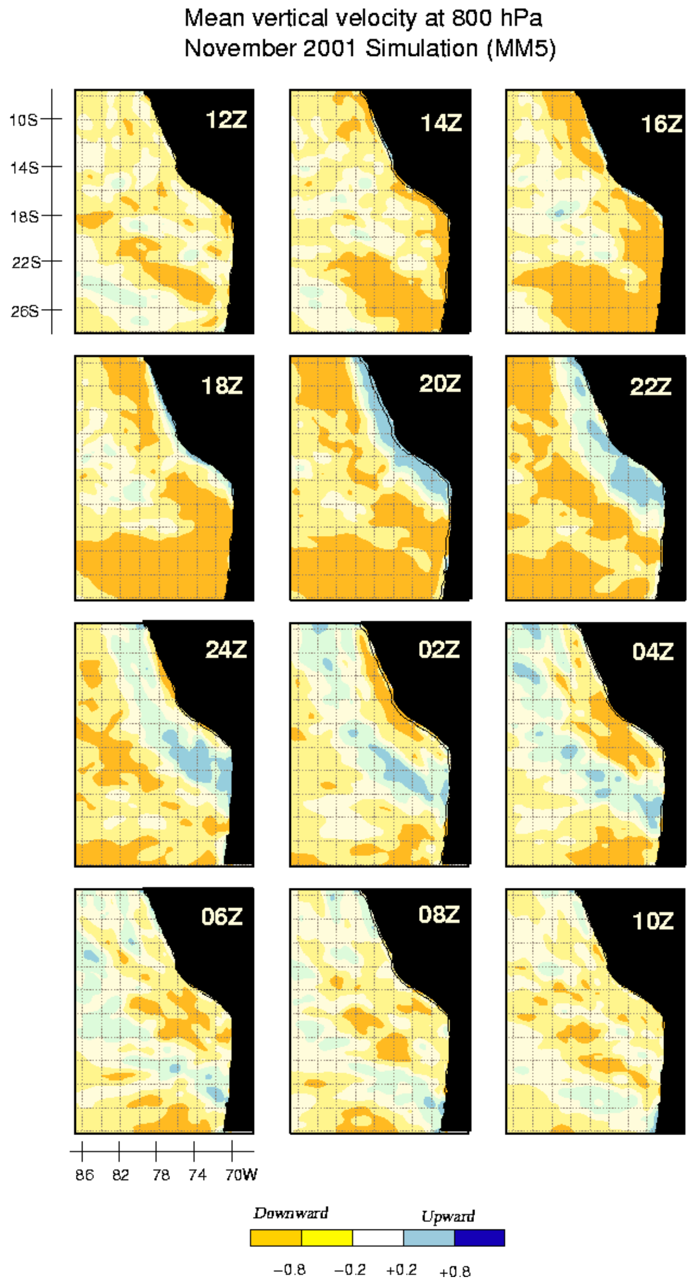

Fig 15: MM5-simulated mean diurnal cycle of 850 hPa vertical velocity [cm s^{-1}] for 20 days of Nov. 2001 (Garreaud and Munoz 2004).

Under VOCALS, further modeling work will be carried out to examine the vertical structure, phase speed, seasonal cycle and climatological significance of this large-scale subsidence wave. It is also important to test these model predictions against further observations. In particular, we propose to take eight-per-day radiosonde measurements and make transects with an unmanned autonomous aircraft during the VOCALS-RF field experiment to document the diurnal cycle of the lower free troposphere at various distances from the coast.

3.4.3. Synoptic timescale variability in the SEP

Although the SEP is a trade wind regime with less day-to-day change in weather than many parts of the world, synoptic-scale (2-10 day timescale and 200-2000 km space scale) variability in the SEP is significant and is important to inhabitants of the west coast of South America. The fishing industry uses forecasts of winds and coastal upwelling to position boats in nutrient and fish-rich waters. Urban pollution in the inland valleys is synoptically modulated. Even a temporary cessation of upwelling in austral fall off the coast of Peru can permit SSTs to rise high enough to support deep convection and coastal flooding. Further south, in central and southern Chile, the SEP blends into the storm track; here there are strong teleconnections between ENSO and winter-season precipitation. Thus, The statistical character of synoptic variability is a key aspect of SEP climate, affecting both clouds and SST. It also provides an important test of regional and global models on timescales which we can sample well. Observations from the VOCALS-RF field study will need to be interpreted in their synoptic context.

The SEP is under the influence of the subtropical anticyclone year-round, leading to dry, stable weather conditions. Nevertheless, extratropical disturbances over the south Pacific may reach the southern edge of the SEP, affecting ABL clouds and winds as far north as 20S. Synoptic disturbances commonly found at these subtropical latitudes are (a) low-level coastal lows, (b) mid-latitude air incursions, and (c) upper-level cutoff lows.

Coastal lows are shallow, mesoscale low-pressure centers under a mid-tropospheric ridge, most commonly observed in central Chile (Garreaud et al. 2002) but also as far north as 20 S (Rutllant et al. 2000). Just to the south of the coastal pressure minimum, a tongue of low-level, dry, cloud-free easterly flow extends westward from the Andean slope as much as 1000 km offshore (Fig. 16). The injection of continental aerosols into the SEP during coastal-low events has not been quantified, although Huneeus et al. (2005) has done some numerical simulations of sulfur transport during coastal lows.

Active, sharp cold fronts are hardly observed to the north of 30 S, although under special circumstances they can reach northern Chile and southern Peru (e.g. Garreaud and Rutllant 1996). However, the cold, post-frontal mid-latitude air can spread further north, causing thickening of the MBL and stratocumulus, and occasionally producing drizzle (Fuenzalida and Orgaz, 1981).

Upper-level cutoff lows develop to the west of the subtropical Andes several times per year (Montecinos and Pizarro 2000). Ahead of or under a cutoff low, there is anomalous mean ascent, often leading to cloud thickening and drizzle. To the south of a cutoff low, there is deep easterly flow sometimes accompanied by ABL cloud clearing.

Extratropical activity over the SEP is reduced during the austral summer as the mid-latitude storm track shifts poleward. During this season, however, deep convection develops over the Altiplano (central Andes). Rainy and dry periods 1-2 week long tend to alternate, These are associated with strength and position of the middle to upper tropospheric Bolivian high (e.g. Garreaud 1999). Do the Altiplano convection and the associated circulation anomalies affect the SEP on synoptic timescales? One mechanism might be modulation of subsidence over the SEP (Gandu and Silva Dias 1998). In addition, Altiplano convection is associated with moist air advecting westward over the Andes crest, producing a midlevel tongue of moist air over the SEP (Fig. 17). The resulting water vapor greenhouse effect may affect stratocumulus clouds by interfering with the cloud-top longwave radiative cooling that sustains them.

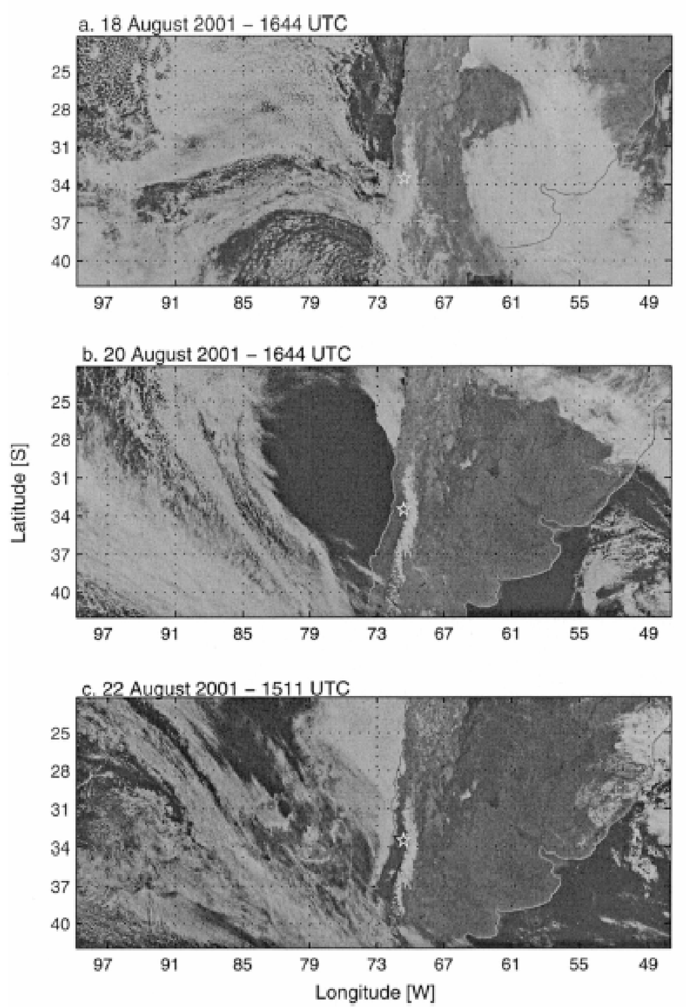

Figure 16: Sequence of GOES-8 visible images (date and time atop of each panel) during a coastal low episode in central Chile, illustrating the synoptic-scale stratocumulus clearing during these episodes (Garreaud and Rutllant 2003).

Synoptic and diurnal variability in winds along the coastal strip affect upwelling as well as cloud incidence. A shallow low-level wind jet (LLJ) often develops along the coast, especially in the onset stage of coastal lows (Rutllant 1993, 1997), and interacts with with capes and headlands to focus upwelling foci are located. Primary productivity driven by upwelling in this area could be an important factor in generating primary CCN through DMS degassing and further transformation into sulfate aerosols. Several SO_2 anthropogenic sources are also located in northern Chile (copper smelters and power plants) that are periodically transported into the ocean both within and above the MBL in connection with regional-scale easterly wind events (Huneeus et al. 2005). VOCALS is anticipating that

South American research groups will take the lead in both atmospheric and oceanic measurements of synoptic-scale variability in the coastal zone, including extended-time measurements and ship-based intensive sampling of the coastal strip in coordination with the VOCALS-RF experiment.

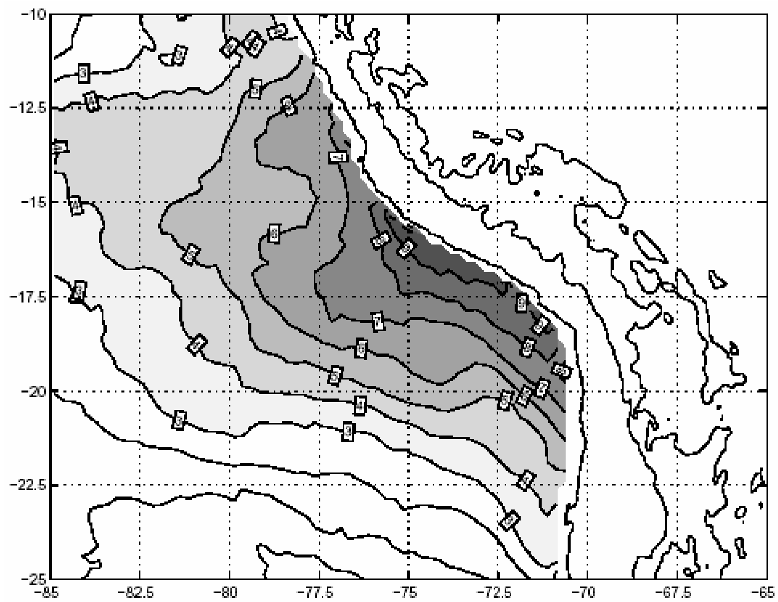

Figure 17: Mean difference of MODIS-derived precipitable water [mm] between wet and dry episodes over the Altiplano during the austral summer.

From the climate perspective, we need to accurately predict how the cloud radiative properties and surface fluxes respond to this synoptic variability. Klein (1997), using ocean weather ship observations from the 1950s-1970s in the NEP, showed that strong cold advection and high lower tropospheric stability were correlated with daily-mean cloud cover. Xu et al. (2005) have recently found similar correlations at the SEP stratus buoy. However, to date there has been little study of whether AGCMs and forecast models can reproduce these correlations, as well as anticipated correlations with subsidence, free-tropospheric humidity, etc. As mentioned in Sec. 3.1, VOCALS plans to undertake such comparisons using a variety of models with the goal of identifying biases and improving model parameterizations.

3.4.4 Summary scientific questions:

- How do topography and deep convection over South America affect the seasonal cycle of eastern Pacific stratus and SST in a coupled atmosphere-ocean model?
- Do the depth, phase speed, and vertical structure, of the diurnal subsidence wave ("upsidence wave") originating in northern Chile/southern Peru agree with regional model simulations?
- How large are the boundary layer cloud variations on synoptic timescales compared to longer timescales in the different parts of the SEP (including the coastal zone)? What

synoptic-scale features dominate the variability in the low-latitude SEP?

- Which of the following are dominant controls on synoptic variations in SEP boundary layer cloud - variations in subsidence, horizontal advection in the boundary layer, moisture variability above the boundary layer, or aerosol variability?
- How important is synoptic-scale atmospheric variability in forcing the coastal oceanography and influencing the eddy and current field further offshore?

4. Summary of VOCALS Implementation Plan

VOCALS is currently led by Robert Weller (WHOI, USA) and Chris Bretherton (U. Washington, USA), under the oversight of the CLIVAR VAMOS program. VOCALS currently is organized by a Scientific Working Group, which has met annually since 2000. Current active participants come from the USA, Chile and Ecuador.

VOCALS combines three main elements, described at length in the VOCALS Implementation Plan:

(a) Diagnosis and advancement of coupled, atmosphere-only, and ocean-only regional and global model simulations of the SEP, with a focus on improving physical parameterizations relevant to boundary layer cloud and ocean mixing. This includes high resolution coastal oceanographic models and will be supported by high-resolution large-eddy simulation of the atmospheric cloud-topped boundary layer.

(b) Diagnostic studies of existing and targeted new observations in the SEP, coordinated between several research groups and feeding into the modeling activities. New observations initiated by VOCALS are:

- The WHOI stratus buoy at 20S, 85W, which is providing continuous surface and subsurface meteorological and flux measurements and a profile of subsurface measurements since October 2000,
- Extensive surface-based remote sensing, surface meteorology and fluxes, and limited aerosol sampling by NOAA-ETL from annual maintenance cruises to the WHOI buoy in austral spring.
- Automated surface meteorological measurements from San Felix Island (27S 80W) since December 2002.

VOCALS will also take advantage of the rapidly expanding suite of satellite measurements of boundary layer cloud and ocean surface properties over the SEP. Relevant ocean measurements include SST, altimetry, and wind stress, and ocean color. These will be intensively examined in coordination with near-shore in-situ measurements to better document the ocean eddy and current field off Peru and Chile. The CloudSat cloud radar/Calypso lidar combination to be launched in April 2005 will be used in conjunction with current measurements of cloud properties, global meteorological analyses, and chemical transport models for atmospheric model validation, understanding of cloud microphysical/aerosol feedbacks, and synoptic-scale boundary layer variability.

Lastly, there are annual hydrographic monitoring cruises jointly organized by the CPPS (Permanent Commission of the South Pacific), which is an intergovernmental organization of Colombia, Ecuador, Perú and Chile, as well as coastal zone buoy, current-meter and tide gauge measurements that will provide long-term context for the oceanographic measurements during the field experiment.

(3) The VOCALS-RF field experiment in October 2007, embedded in a three-month deployment of the Atmospheric Radiation Measurement (ARM) program's Mobile Facility at San Felix Island. The field experiment will take place in the region between the WHOI stratus buoy, San Felix Island, and the S American coast, in a region of strong gradients in cloud droplet size that we attribute to gradients in aerosol concentrations. This field experiment plays a vital role in the overall vision of VOCALS by extensive in-situ sampling of clouds and aerosol and ocean eddies. Measurement platforms will include an NCAR C-130 aircraft, an unmanned autonomous aircraft for better sampling of POCS and the diurnal cycle above POCS of the lower troposphere, the NOAA ship Ronald H. Brown (unique in having a scanning 5 cm precipitation radar) and a second Sea-Soar towing ship.

Complementary coastal oceanographic and atmospheric measurements, perhaps involving a third ship, will be made by research groups from Chile, Ecuador, the US, and possibly Peru (see Table 2 for potential participants). These measurements are critical to better understand, model, and remotely sense SEP aerosol-cloud-drizzle feedbacks, and to better understand and parameterize the role of ocean eddies in moving cold water offshore and thereby affecting SST over the entire SEP. The coastal component of VOCALS-RF is envisioned as part of a longer-term collaboration between the participating groups involving regional atmospheric, ocean, and biological modeling and analysis of the SEP coastal zone.

5. VOCALS Collaborations

VOCALS brings together a diverse group of atmospheric scientists and oceanographers. This connects VOCALS to several other important projects with which close collaborations will be maintained, ensuring that VOCALS results will quickly reach through a broad research community and benefit from the scientific feedback this brings.

VOCALS boundary-layer cloud research will tightly link into the Low-Latitude Cloud Feedback Climate Process Team (CPT, http://www.atmos.washington.edu/~breth/CPT-clouds.html), a three-year effort to reduce uncertainties in low-latitude cloud feedbacks on greenhouse-gas induced climate change by improving physical parameterizations, new approaches to model-observational comparison, and new modeling techniques such as 'superparameterization'. It is a NSF/NOAA funded component of US CLIVAR involving the NCAR, GFDL, and NASA-GMAO coupled climate model development groups, 8 external PIs, and an advisory panel. VOCALS scientist C. Bretherton is lead PI on this project, and four other VOCALS scientists are PIs or advisory panelists. Collaboration with VOCALS is ongoing. For instance, the WHOI stratus buoy site has already been chosen as a special CPT diagnostic column for analyzing model output.

C. Bretherton is also head of the Gewex Cloud System Study (GCSS) Boundary Layer Cloud Working Group (BLCWG, http://www.atmos.washington.edu/~breth/GCSS.html), an international group that performs intercomparisons of large-eddy simulations and single-column model versions of GCMs on selected case studies. B. Stevens of VOCALS is also a leading participant. A current focus is on intercomparison of drizzle in stratocumulus clouds, and the EPIC 2001 observations may be the basis of an upcoming intercomparison. The additional aerosol observations planned for annual VOCALS cruises and VOCALS-RF will make for even more attractive case studies for GCSS.

As mentioned in Section 3.1, VOCALS is developing links to the DOE CAPT and the NOAA Climate Testbed programs, both efforts designed to provide improved software infrastructure to facilitate the testing and development of new parameterizations in climate models by testing them in a short-term forecasting mode.

Since VOCALS include model developers active in the CCSM and UCLA coupled models, and the IPRC and MM5/WRF regional models, parameterization improvements stemming from VOCALS will have broad exposure across the U.S. modeling community.

The NOAA Atmospheric Composition and Climate Program aims to make aerosol and cloud measurements directed at improving our understanding of the indirect effect of anthropogenic aerosol on cloud radiative properties. VOCALS does not presently have any link with this program, but will seek one.

The IGBP's Surface Ocean Lower Atmosphere Study (SOLAS, http://www.solas-int.org) will organize a variety of collaborative studies during VOCALS, especially involving aerosols and their precursors. SOLAS interests include both biogeochemical issues, such as the role of biogenic gases (DMS) in forming the aerosols that control marine cloud properties, and studies of the many physical factors that control air-sea exchange. In VOCALS, SOLAS scientists plan to study the ocean chemistry and biology that modulate DMS (and other trace gas) production, to measure DMS fluxes and exchange velocities by eddy correlation, and to characterize the natural and anthropogenic aerosols in the MBL. Many of these measurements will be made from the Ron Brown, with some duplicated on the NCAR C-130.

6. What VOCALS needs from U. S. and International CLIVAR

VOCALS is a vibrant and developing program to study stratocumulus clouds, aerosols, and ocean processes in the low-latitude Southeastern Pacific Ocean cool ocean regime. It is made timely by improving but still flawed coupled model simulations of the region, new satellite observations, unique in-situ measurements, and feedbacks with ENSO and the climate of the entire low-latitude Pacific and South America.

VOCALS is currently organized under the informal auspices of the VAMOS program of international CLIVAR. PIs are receiving funding for VOCALS-related work from several sources, but to realize the potential of VOCALS and ramp up a field program for October 2007, a more organized approach to funding and coordination is needed, both within the U. S. and internationally.

Hence, VOCALS seeks formal endorsement from both the U.S. CLIVAR Scientific Steering Committee as well as VAMOS to work with funding agencies and governments to carry out the companion VOCALS Implementation Plan that lays out the detailed strategy for achieving the objectives laid out in this Science Plan. It is hoped that readers of this plan are as compelled as VOCALS scientists by the intricate and interwoven small-scale processes in atmosphere and ocean that make the climate of this region special, and by solving the important modeling challenges they present.

Name	Affiliation	VOCALS expertise
Bruce Albrecht	U. Miami	Radar remote sensing of cloud microphysics
Chris Bretherton	U. Washington	CCSM cloud modeling, parameterization
Pilar Cornejo	ESPOL, Ecuador	Coastal oceanographic measurements
Steve Esbensen	Oregon St. U.	Unmanned aircraft for VOCALS-RF
Chris Fairall	NOAA/ETL	R/V *Brown* cloud/turbulence/radiation
Rene Garreaud	U. Chile	MM5/WRF mesoscale model; synoptics
Jim McWilliams	UCLA	Regional ocean modeling
C. Roberto Mechoso	UCLA	UCLA coupled model
Rodrigo Nunez	Chilean Navy	Coastal buoys; San Felix logistics
Jose Ruttland	U. Chile	Coastal ocean/met; San Felix met. obs.
Oscar Pisarro	U. Valparaiso, Chile	Coastal ocean dynamics
Bjorn Stevens	UCLA	Boundary layer cloud/microphysics
Robert Wood	U. Washington	Cloud microphysics/C-130 lead PI
Shang-ping Xie	U. Hawaii/IPRC	IPRC regional coupled model
Barry Huebert	U. Hawaii	Aerosols/DMS
Robert Weller	WHOI	WHOI stratus buoy; *Brown* ocean obs.

Table 1: VOCALS Scientific Working Group (subject to change)

Country	Participants/Institution
Ecuador	Pilar Cornejo (ESPOL) and Rodney Martinez (CIIFEN, INOCAR)
Chile	Rene Garreaud/Jose Rutllant (DGF-UCHILE), Oscar Pizarro/Samuel Hormazabal/Dante Figueroa (DEFAO-UCEP), Rodrigo Nunez (SHOA), Laura Gallardo (CMM-UCHILE)
Peru	Dimitri Gutierrez (IMARPE), Pablo Lagos (IGP)?
USA	Ted Strub, Roger Samelson, Eric Skyllingstad (COAS-OSU) Jim McWilliams (UCLA)?

Table 2: VOCALS Coastal Program Anticipated Participants

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