VOCALS-SouthEast Pacific Regional Experiment (REx)

SCIENTIFIC PROGRAM OVERVIEW

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VOCALS-Regional Experiment (VOCALS-REx) Scientific Program Overview

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Project Summary: VOCALS (VAMOS[1]Ocean-Cloud-Atmosphere-Land Study) is an international CLIVAR program the major goal of which 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 The program is ultimately driven by a need for improved numerical model simulations of the coupled climate system in both the SEP and over the wider tropics and subtropics.

The SEP climate is a tightly coupled system involving poorly understood interactions between clouds, aerosols, marine boundary layer (MBL) processes, upper ocean dynamics and thermodynamics, coastal currents and upwelling, large-scale subsidence, and regional diurnal circulations, to the west of the Andes mountain range. The VOCALS **R**egional **Ex**periment (VOCALS-REx) is an international field campaign that will provide detailed and targeted observations of those processes during a month long period. The intensive field program has been carefully designed to complement a suite of enhanced long-term observations. Modeling activities, which are the other major thrust of VOCALS, have provided the context and will directly benefit from the intensive observations in a poorly known region where coupled ocean-atmosphere models exhibit strong biases in sea surface temperature and rainfall. The coordination through VOCALS of observational and modeling efforts will lead to acceleration in the rate at which field data can be used to improve simulations and predictions of the tropical climate variability..

Multi-disciplinary intensive observational datasets will be obtained during VOCALS-REx from several platforms including aircraft, research vessels, and a surface land site. These datasets will be used to test a coordinated set of hypotheses that are organized into two broad themes: (1) improved understanding of aerosol-cloud-drizzle interactions in the marine boundary layer (MBL) and the physicochemical and spatiotemporal properties of aerosols; (2) improved understanding of the chemical and physical couplings between the upper ocean, the land, and the atmosphere. The intensive observational period will be a month long and will take place during November 2008, chosen because it is the month during which the coverage of stratocumulus over the SEP is at its greatest, the southeast trade winds are at their strongest, and the coupling between the upper ocean and the lower atmosphere is at its tightest.

Intellectual merits:

The proposed work involves making state of the art field measurements of the atmosphere and ocean in a climate regime that is poorly explored but that has important consequences for the regional and global climate system. Few previous observational programs have been designed with such a strong multidisciplinary focus, and the simultaneous and collocated ocean and atmosphere dataset will allow an unprecedented examination of how mesoscale ocean variability impacts the chemical and aerosol properties of the lower atmosphere. These measurements will have a broad impact upon current knowledge in the fields of atmospheric science and oceanography which will ultimately lead to improved predictions of future climate.

Broader impacts:

The field and subsequent analysis phases will involve and foster considerable international collaboration and provide important training for a number of scientists and graduate students. The datasets generated in the field will stimulate the development of a broad range of numerical process models, and provide invaluable constraints that will accelerate the improvement of regional and global climate models.

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[1] VAMOS – Variability of the American MOnsoon Systems, a CLIVAR sponsored program to study the American monsoons in the context of the global climate. Additional information at *http://www.clivar.org/science/vamos.htm*

D. PROJECT DESCRIPTION

1. Introduction

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 continuity of the Andes Cordillera forms a sharp barrier to zonal flow, resulting in strong winds (coastal jet) parallel to the coasts of Chile and Peru (Garreaud and Muñoz 2005). This, in turn, drives intense oceanic upwelling along these coasts, bringing cold, deep, nutrient/biota rich waters to the surface. As a result, the coastal SEP sea-surface temperatures (SSTs) are colder along the Chilean and Peruvian coasts than at any comparable latitude elsewhere (Fig. 1). The cold surface, in combination with warm, dry air aloft, is ideal for the formation of marine stratocumulus clouds, and supports the largest and most persistent subtropical stratocumulus deck in the world (Klein and Hartmann 1993, see also Fig. 1). The presence of this cloud deck has a major impact upon the earth's radiation budget (Fig. 1) by reflecting solar radiation. This helps maintain the cool SST, resulting in tight couplings between the upper ocean and lower atmosphere in this region. The unique climate of the SEP has been very sparsely observed, yet has great economic impact, with fishing in the Humboldt Current system representing 18-20% of the worldwide marine fish catch (source: UN LME report).

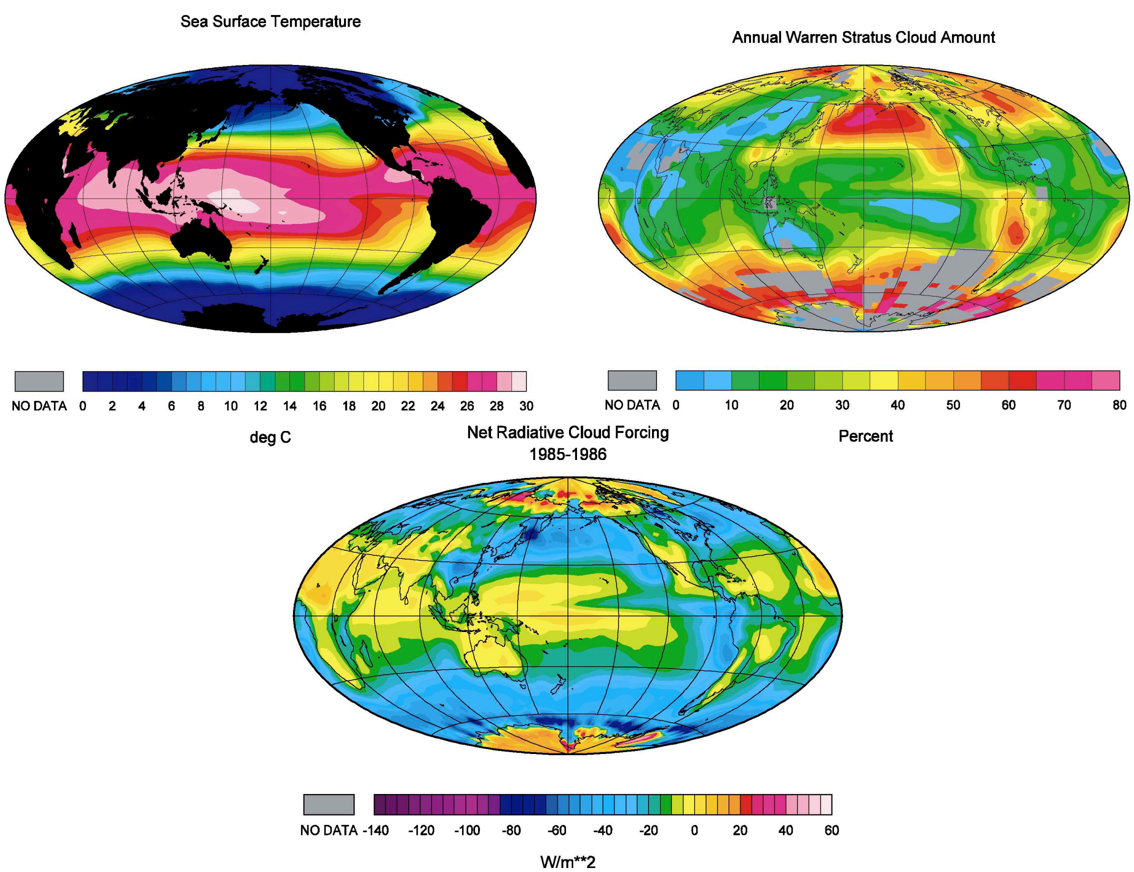

Figure 1: Annual-mean climatological SST (top left), stratus cloud amount from ship observations (top right), and ERBE-derived TOA net cloud radiative forcing (bottom).

Three fundamental issues that impede our understanding of the weather and climate system are: (a) our current lack of understanding and quantification of the indirect effect of aerosols upon cloud radiative properties (e.g. Haywood and Boucher 2000, Lohmann and Feichter 2005); (b) biases in tropical rainfall, SST, and winds that repeatedly occur in coupled ocean-atmosphere models, which several studies have traced in part to errors simulating ocean dynamics in the low-latitude coastal upwelling zones, and errors in simulating of boundary layer clouds and their radiative properties (e.g. Mechoso et al. 1995, Ma et al. 1996); (c) our inability to make consistently accurate regional weather predictions, especially in coastal areas dominated by low cloud. The SEP is a region where these fundamental issues all have a demonstrable and major impact upon our ability to make accurate predictions of the weather and climate system.

VOCALS (VAMOS[2] Ocean-Cloud-Atmosphere-Land Study) is an international CLIVAR program the major goal of which 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. Overall VOCALS science and implementation plans have been developed by a VOCALS Science Working Group, and can be found at www.eol.ucar.edu/projects/vocals/. In this Scientific Program Overview we summarize those overall aspects of VOCALS germane to the proposed intensive field experiment. The overall goal of the VOCALS field experiment is to investigate interactions between clouds, aerosols, marine boundary layer (MBL) processes, upper ocean dynamics and thermodynamics, coastal currents and upwelling, large-scale subsidence, and regional diurnal circulations, to the west of the Andes mountain range. Understanding these linkages is an essential step towards improving our model simulations and therefore our climate predictions.

The different components of the coupled climate system of the SEP operate on a large range of time and space scales from minutes to decades, and meters to thousands of kilometers. Under VOCALS, modeling, extended-time observations (including a wealth of new satellite sensors, buoy, island and coastal measurements), and a suite of ship-based observations on annual buoy maintenance cruises to the Southeast Pacific are coordinated over the period 2003-2010[3]. While these observations are rapidly improving our understanding of this sparsely-observed region, they have raised a set of interconnected scientific questions better addressed by a process study involving in-situ atmospheric and oceanic measurements.

For this purpose, we propose an intensive observation period (IOP) named VOCALS-REx (VOCALS-Regional Experiment). It comprises enhanced observations for a month long period during November 2008 using a number of platforms which are described in detail in this document and in the accompanying Experimental Design Overview (EDO). The IOP will combine resources from South American countries, the United States, and Europe.

The VOCALS-REx intensive observations are a vital component of the VOCALS program and have been carefully designed to complement a suite of enhanced long-term observations. The long-term observations provide important context for the intensive observations. Modeling activities, which are the other major thrust of the VOCALS, have provided the context and will benefit from the intensive observations. A summary of the modeling work associated with VOCALS is given in Section 4 below, with a more detailed Modeling Plan available on the VOCALS website[†]. The coordination through VOCALS of observational and modeling efforts will lead to an improved pull-through for climate and regional forecasting agencies.

The November time frame is chosen because it is the month at which the coverage of stratocumulus over the SEP is at its greatest (approximately 70%) and the southeast trade winds are at their strongest, which means that the coupling between the upper ocean and the lower atmosphere is at its tightest. This period will also provide continuity with the recent annual buoy maintenance cruises which have taken observational data during the austral spring season (2001, 2003-2005, with a further cruise planned for

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[2] VAMOS – Variability of the American MOnsoon Systems, a CLIVAR sponsored program to study the American monsoons in the context of the global climate. Additional information at *http://www.clivar.org/science/vamos.htm*

[3] Detailed science, implementation and modeling plans for VOCALS can be found on the web at *www.eol.ucar.edu/projects/vocals/*

2006). Observations (e.g. Park and Leovy 2004) indicate that the impact of ENSO on clouds and the lower atmosphere in the study region is actually quite limited, with the majority of the ENSO impact further to the north. Thus, we do not expect the success of VOCALS-REx to be compromised by ENSO.

2. Scientific issues and hypotheses to be tested

The climate of the SEP is dependent upon important interactions and feedbacks between the upper ocean, the Andes mountains, and the lower troposphere. Studies using coupled ocean-atmosphere general circulation models (Ma et al. 1996, Gordon et al. 2000) have clearly demonstrated that the accurate prediction of the optical properties of low clouds over the SEP is an essential requirement for simulating strong trade winds and producing the observed SST distribution. Richter and Mechoso (2005) demonstrate that the great height and extent of the Andes mountains markedly increases the lower tropospheric static stability over the SEP, enhancing the cloud cover. The Andes mountains also encourage the formation of a near-coastal jet in the marine boundary layer (MBL) that enhances the oceanic upwelling of cold water (Garreaud and Muñoz 2005). Mountain effects on the monsoon circulations over the continents drive stronger subtropical gyres, which increase the evaporative cooling of the surface and further reduce SST (Kitoh 2002). The coastal upwelling associated with the Humboldt Current system is not only important in the coastal zone, but also impacts the SST much further offshore through ocean transport processes that include mesoscale eddy transport (Penven et al. 2005, Colbo and Weller 2006). **The climate of the SEP region is therefore a tightly coupled system involving interactions between the ocean, the atmosphere, and the land.** The SEP climate system is unique in that its ocean current system is directly connected with the tropical ocean (Lukas 1986) and so can interact with ENSO. In addition, there is modeling evidence that global climate and particularly tropical precipitation is affected by the western boundary of subtropical South America. The SEP is poorly explored observationally, and our ability to make accurate predictions of the tropical climate is strongly sensitive to its representation in numerical models (Yu and Mechoso 2001).

In addition to responding to large scale dynamics, cloud optical properties over the SEP are also affected by atmospheric aerosols (Bretherton et al. 2004), with contributions from both natural and anthropogenic sources. Figure 2 shows that cloud droplet effective radii are low off the coast of Northern Chile, implying elevated concentration of cloud droplets. These elevated concentrations are directly downwind of major copper smelters whose combined sulfur emissions total 1.5 TgS yr^{-1}, comparable to the entire sulfur emissions from large industrialized nations such as Mexico and Germany. The smaller droplet effective radii increase the reflected solar radiation, and estimates of the component of the TOA solar radiation due to geographic variability in effective radius alone are as high as 10-20 W m^{-2} or 15% of the mean (Fig. 2). The magnitude of these estimates is such that the indirect effects of aerosols on clouds could lead to significant decreases in the amount of solar radiation entering the ocean, with significant implications for the ocean heat budget.

There is also evidence from the recent East Pacific Investigation of Climate (EPIC) field study (Bretherton et al. 2004) that drizzle formation, enhanced by the depletion of aerosols in the clean MBL, can drive remarkably rapid transitions which drastically reduce cloud cover (Stevens et al. 2005). It is clear therefore that **low clouds and the dynamical and microphysical processes controlling their thickness and coverage are a cornerstone of the climate of the SEP.** However, our knowledge of clouds in this region is so far limited to surface and spaceborne remote sensing. There are no *in-situ* observations of these clouds with which to test hypotheses concerning their physics and chemistry.

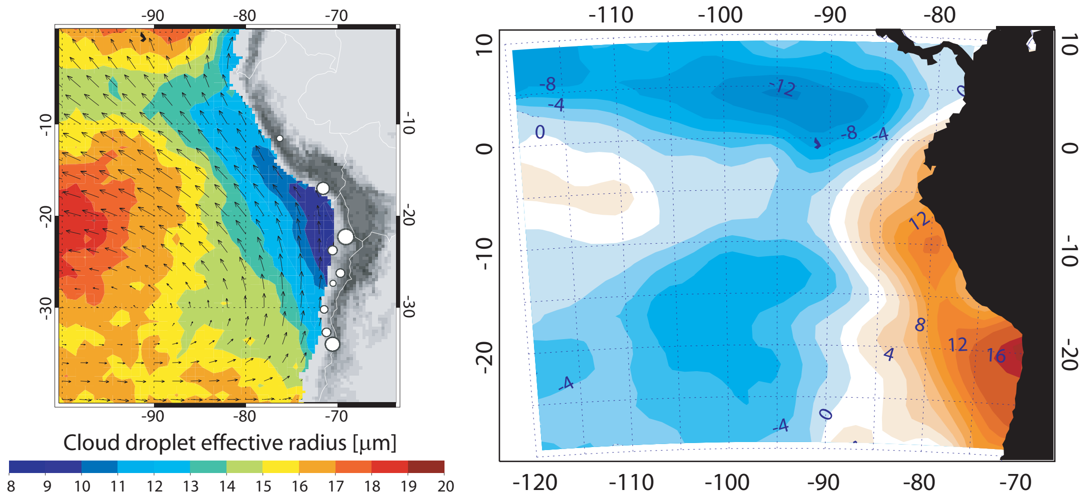

Figure 2: Left: Austral spring season (SON) mean cloud droplet effective radius from MODIS; mean surface winds from Quikscat. Locations of the major copper smelters in the region are shown as white circles (relative area proportional to their expected sulfur emissions). Right: Component of SON shortwave cloud forcing [W m^{-2}] due to geographic variations in effective radius, inferred from MODIS.

The maintenance of the SST over the SEP, and the eastern ocean basins in general, is an important unresolved problem (Xie 1994). In this region, as evidenced by the oxygen minimum layer and the strong density gradient found at the base of the upper ocean mixed layer associated with northern flow of cool, fresh intermediate waters, the surface layer of the ocean is a distinct layer with slow (only several cm s^{-1}) mean horizontal advection. As such, it readily accumulates and expresses locally the influences of interaction with the atmosphere, lateral fluxes associated with eddies (Holland 1978, Penven et al. 2005), and vertical mixing events associated with transients in the atmospheric forcing (Wijesekera and Gregg 1996). Satellite altimetry, SST maps, and regional ocean model studies all reveal that mesoscale ocean eddies 50-200 km across can affect SST well offshore by fluxing cold water out from the coastal upwelling regions. Through their nutrient content, eddies could also impact the ocean-atmosphere flux of dimethylsulfide (DMS), an important aerosol precursor gas. The heat flux divergence by mesoscale eddies may account for roughly 40 W m^{-2} net heat flux into the ocean over the remote SEP. At the same time, regions of enhanced vorticity and shear within the eddies may locally enhance response to the wind forcing and vertical mixing. Mesoscale eddies are poorly observed and understood, and are barely resolved in coupled ocean-atmosphere climate models (see Canuto and Dubovikov 2005 for discussion of mesoscale eddy modeling). Another source of vertical mixing at the base of the upper layer is the shear associated with near-inertial oscillations. If present, this mixing would entrain fluid from the cool, fresh intermediate water below. Observations at the IMET buoy (20°S, 85°W) show that variability in the magnitude of the trade winds generates near-inertial oscillations; because that variability is not seen in the winds from numerical weather prediction models, this mixing, like the eddy lateral fluxes, may not yet be well-represented in coupled ocean-atmosphere models.

VOCALS-REx will provide intensive observations of key processes contributing to the climate of the SEP. The observations will be used to test a coordinated set of hypotheses, to help validate satellite retrievals, and to evaluate our ability to model the important physical and chemical processes in the SEP. The VOCALS-REx hypotheses are organized into two broad categories: (1) testing hypotheses related to the impacts of aerosols upon the microphysical and structural properties of stratocumulus clouds and drizzle production; (2) testing hypotheses related to the coupled ocean-atmosphere-land system. The hypotheses are as follows:

1) **TESTING AEROSOL-CLOUD-DRIZZLE HYPOTHESES**

   a) *Variability in the physicochemical properties of aerosols has a measurable impact upon the formation of drizzle in stratocumulus clouds over the SEP.*

   b) *Precipitation is a necessary condition for the formation and maintenance of pockets of open cells (POCs) within stratocumulus clouds.*

   c) *The small effective radii measured from space over the SEP are primarily controlled by anthropogenic, rather than natural, aerosol production, and entrainment of polluted air from the lower free-troposphere is an important source of cloud condensation nuclei (CCN).*

   d) *Depletion of aerosols by coalescence scavenging is necessary for the maintenance of POCs.*

2) **TESTING COUPLED OCEAN-ATMOSPHERE-LAND HYPOTHESES**

   a) *Oceanic mesoscale eddies play a major role in the transport of heat and fresh water from coastally upwelled water to regions further offshore.*

   b) *Upwelling, by changing the physical and chemical properties of the upper ocean, has a systematic and noticeable effect on aerosol precursor gases and the aerosol size distribution in the MBL over the SEP.*

   c) *The diurnal subsidence wave ("upsidence wave") originating in northern Chile/southern Peru has an impact upon the diurnal cycle of clouds that is well-represented in numerical models.*

   d) *The entrainment of cool fresh intermediate water from below the surface layer during mixing associated with energetic near-inertial oscillations generated by transients in the magnitude of the trade winds is an important process to maintain heat and salt balance of the surface layer of the ocean in the SEP.*

An additional key VOCALS-REx goal is to use the observational datasets to critically evaluate the accuracy of current and future satellite cloud microphysical retrieval algorithms. These measurements are central to our understanding and quantification of the indirect effects of aerosols upon clouds and the climate system. The following sections detail the scientific rationale behind the hypotheses and describe how they will be tested using the intensive field observations.

2.1 Aerosol-cloud-drizzle interaction hypotheses

Shipborne remote sensing observations over the SEP made during the 14 day EPIC 2001 field campaign (Bretherton et al. 2004) provide some evidence that drizzle production may be stronger during periods of reduced cloud droplet number concentration. Precipitation, even the low rates associated with drizzle, exerts a powerful influence on the structure, thickness, and coverage of stratocumulus, and is hypothesized to be a powerful mechanism by which aerosols can impact the radiative balance of the earth (Albrecht 1989). Observations and theory suggest that variability in cloud droplet concentration in marine stratocumulus is largely driven by variability in the concentration of accumulation mode aerosol particles (e.g. Twomey and Warner 1967, Martin et al. 1994, Breon et al. 2002). There are reasons to believe that both natural and anthropogenic sources of aerosols are important in the SEP. Few *in-situ* measurements of SEP aerosol physical and chemical properties exist. A few exploratory flights conducted as part of the NASA PEM Tropics campaigns (Hoell et al. 1999) made such measurements, and these demonstrated the importance of continental plumes of aerosols in the north of the VOCALS study region (Moore et al. 2003). More recent measurements from recent buoy maintenance cruises (Tomlinson et al. 2006) reveal that aerosols in the MBL are predominantly soluble, and are strongly bimodal in nature with an accumulation mode concentration that is highly variable in time and space (Fig 3). As far as 1000 km from the coast concentrations vary from 20-300 cm^{-3} with even higher values of up to 500 cm^{-3} nearer the Chilean coast. This suggests that the MBL over the SEP experiences periods of extremely clean *and* quite heavily polluted air. This, coupled with the extensive cloud coverage during the Austral spring, indicates that the SEP is an ideal test-bed for investigating the indirect effects of aerosols on clouds. Investigation of the influences of aerosol physicochemical properties on cloud microphysics and drizzle production is a key goal of VOCALS-REx.

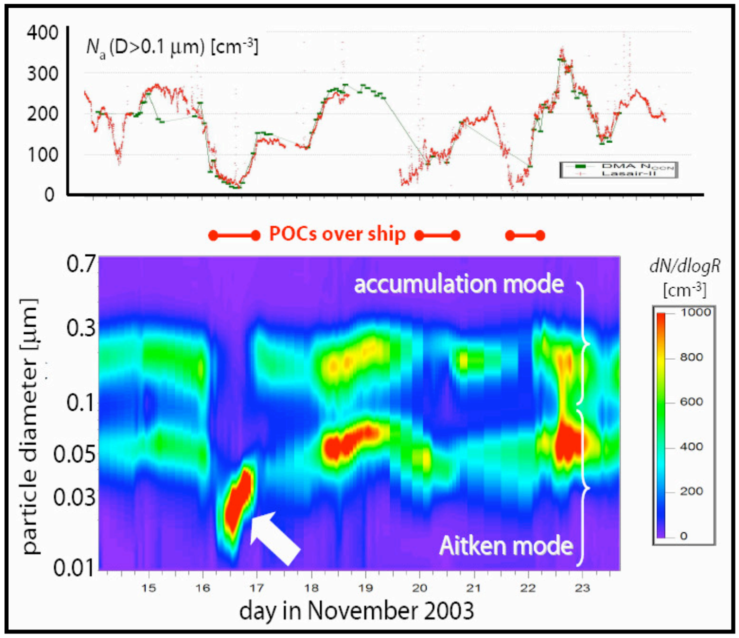

Figure 3: Accumulation mode aerosol concentration (top), and aerosol size distribution (bottom) measured on the R/V Roger Revelle over the SEP during November 2003. The red horizontal bars indicate periods where satellite imagery revealed pockets of open cells (POCs) over the ship. At these times there is strong reduction of the accumulation mode aerosol concentration, and on the 16th (white arrow) there is evidence of new particle formation.

Hypothesis 1a: Variability in the physicochemical properties of aerosols has a significant impact upon the formation of drizzle in stratocumulus clouds over the SEP

Testing strategy: Data from two platforms will be used to test H1a: the NOAA R/V Ronald H Brown (RHB) and the NSF C-130 aircraft. Both the RHB and the C-130 will be equipped with instrumentation necessary to provide a comprehensive suite of rapid size-resolved aerosol and physicochemical measurements. The C-130 will characterize cloud and drizzle microphysics using *in-situ* measurements and the Wyoming Cloud Radar (WCR) will be flown to remotely sense drizzle. The C-130 will also carry: a time of flight aerosol mass spectrometer (ToF-AMS) that will characterize non-refractory size-resolved composition from 50-2000nm with 1Hz to 0.1Hz resolution depending upon sampling mode; size spectra for volatile (eg. sulfate) and refractory (eg. sea-salt, soot) measurements over 120 – 5,000nm (30 s resolution); DMA and volatility DMA size measurement (10 – 500nm) made on 15s grab samples, continuous spectral light scattering and light absorption, CN and Ultrafine CN concentrations all at 1Hz. Together these provide rapid inferred size resolved compositional information that can be constrained by slower measurements of bulk chemisty A new fast size spectrometer (UHSAS) will provide 1Hz sizing over the dominant CCN size range (50-1,000 nm) to provide context for changes in CCN during the slower volatility and composition measurements. A new external cloud droplet probe (CDP) will also provide 1Hz data on cloud droplet distributions. The RHB will make continuous remotely sensed measurements of cloud physical properties including cloud base, cloud top and liquid water path, in addition to a set of *in-situ* aerosol microphysical measurements similar to those on the C-130. Cloud microphysical measurements will be obtained from the RHB using transmissivity-based retrievals. The RHB C-band scanning radar will provide essential measurements of the horizontal and vertical drizzle structure, while a combination of vertically pointing 35 GHz radar and lidar will provide estimates of the drizzle size distributions using variations of the methodologies that have already proven successful (Frisch et al. 1995, Comstock et al. 2004, O'Connor et al. 2005). Collocated C-130 and RHB measurements will provide an unprecedented characterization of the microphysical and macrophysical structure of drizzling stratocumulus.

The essence here is to build from the various VOCALS-REx ship and aircraft measurements a database containing collocated observations of cloud base precipitation rate P_{cb}, cloud thickness h and/or liquid water path *LWP*, cloud droplet concentration N_d, aerosol properties above the inversion, and subcloud aerosol properties (particularly the Aitken and accumulation mode size distributions that give rise to the aerosol concentration N_a). We will then determine the degree to which variability (both temporal and spatial) in P_{cb} is correlated with variability in these sizes as they relate to N_a.. If these relationships are weak, or it is clear that P_{cb} is much more closely correlated with the cloud macrophysical properties (h or *LWP*), then this would constitute a falsification of H1a.

Tantalizing observational evidence suggests 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 that tends to be organized in the form of closed mesoscale cellular convection. These regions have been termed POCs, or "pockets of open cells" (Stevens et al. 2005); the satellite image in Fig. 4 includes some examples.

The formation of POCs occurs most frequently at night (Wood et al. 2006), and can occur with surprising rapidity. Following the initial formation, the POC can grow, but the basic open cellular structure within it tends to persist for several days. This supports the notion that there are two relatively stable states for the structure of low cloud over the SEP (e.g. Fig. 4). Theoretical work suggests that such bistability may be microphysically driven (Baker and Charlson 1991), but this is untested observationally. Qualitative observations using satellites suggest that a large fraction of the subseasonal variability in SEP cloud cover can be explained by the transition from closed to open cellular convection; this strongly motivates the need to determine the dynamics of POC formation and maintenance. Recent work using a synthesis of satellite observations and reanalysis data suggests that large scale meteorological factors may not be the driving force behind the transition (Wood and Hartmann 2006), and that processes internal to the MBL may be responsible. The few case studies to date suggest that POCs are often associated with low aerosol concentration (Petters et al. 2004, Sharon et al. 2006, Wood et al. 2006), and intense drizzle production (Stevens et al. 2005, VanZanten et al. 2005, Comstock et al. 2005. Figure 3 demonstrates that near-total depletion of accumulation mode aerosols occurs quite regularly over the SEP and coincides with the presence of POCs.

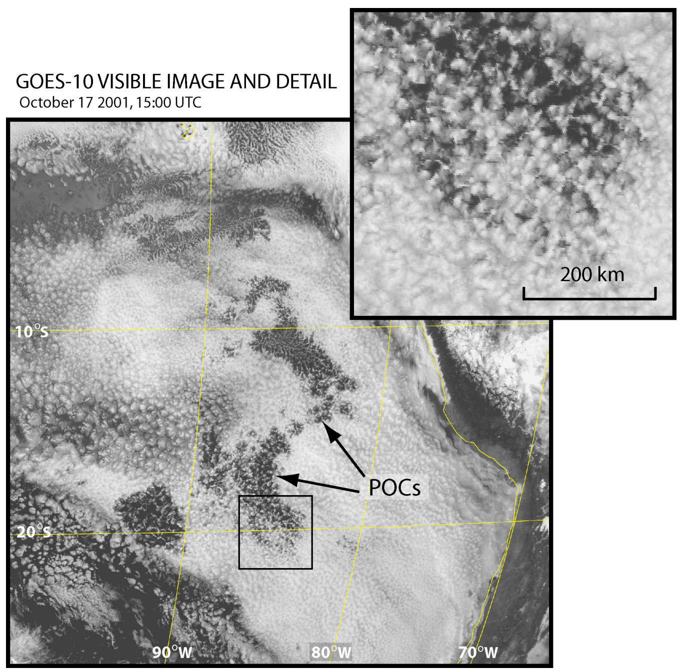

Figure 4: GOES visible-wavelength satellite image showing extensive stratocumulus cloud cover over the SEP, with embedded regions of broken cloud cover called 'pockets of open cells' (POCs). The inset zooms in on the black square, which includes one such POC (from Bretherton et al. 2004). Are these two states evidence of microphysical bistability in the MBL?

Further evidence that cloud microphysical changes are associated with POCs emerges from analyses of satellite-derived 3.9-11 m brightness temperature difference (BTD). For cloudy regions at night, BTD is a good discriminator of cloud droplet size (Perez et al. 2001, Stevens et al. 2005). Low BTD values indicate large cloud droplet sizes which are required to initiate collision-coalescence leading to drizzle. Satellite observations (Wood et al. 2006) indicate that POCs tend to form preferentially in low BTD regions, consistent with the hypothesis that precipitation and POCs are intimately connected.

There is currently no complete conceptual model that satisfactorily describes the POC formation process. In addition, the existing observational datasets have sampled POCs rather serendipitously which has not resulted in an optimal observing strategy. By direct aircraft observation of the POCs and the surrounding overcast stratocumulus, we hope to gain an understanding of the role of precipitation in forming and maintaining the structure of POCs, as described below:

Hypothesis 1b: Precipitation is a necessary condition for the formation and maintenance of pockets of open cells (POCs) within stratocumulus clouds.

Testing strategy: Dedicated C-130 'POC-drift' missions (see the EDO) will be conducted to study the dynamical and microphysical cloud and precipitation in marine stratocumulus. Stacks of flight legs that span the boundary between a POC and the surrounding unbroken stratocumulus will be used to contrast cloud and drizzle microphysics in the two regions. At night, the favorable time for POC formation, satellite 3.9-11 m BTDs from GOES will be used to locate regions of cloud that are susceptible to POC formation. Flights will be directed according to these forecasts. Ideally, observation of the POC formation process itself is a goal, but much will be learned about their structure by studying existing POCs over an extended time period, and efforts will be made to sample the same POC on two flights, or to fly in a POC region that will ultimately advect over the ship. **If POCs are observed that do not contain drizzle heavier than a few tenths of a mm day^{-1} then we can rule out precipitation as being a necessary condition, and consider H1b as falsified.** Based upon our findings from recent cruise data, we expect that drizzle will accompany POCs. If this is the case, then a key goal is to learn the mechanisms by which precipitation affects the mesoscale cloud structure.

Scanning C-band radar observations from EPIC indicate that drizzle cells frequently develop a complex layered mesoscale structure with extensive 5-10 km wide regions flowing into the center of the cells roughly at cloud base with outflow above this. It is an untested possibility that these mesoscale inflow regions are necessary to maintain the moisture supply to the cloud that would otherwise precipitate out within 30 minutes or less. The role of evaporating precipitation is also likely to be important, but evidence linking this with the mesoscale dynamics is so far lacking. The cloud radar on the C-130 will be used in conjunction with the aircraft-derived flight level winds to determine the mesoscale dynamics of the individual cells within the POC and help elucidate the mechanisms responsible for their maintenance and longevity. The scanning C-band radar on the RHB will also provide important information on the horizontal and vertical structure of the POCs, and we plan to obtain at least one POC case where the C-130 and RHB C-band radar will sample the same structures.

The small cloud droplet effective radii observed off the Northern Chilean coast are suggestive of high concentrations of CCN in the MBL, and indeed, aerosol observations (Don Collins, personal communication) from a single cruise leg that passed through this region found a near-coastal peak in accumulation mode aerosols. Volatility measurements on the cruise indicate that the aerosol is primarily composed of sulfur species but this information alone is insufficient to determine the aerosol source. The biologically productive coastal waters that are an important component of the coupled ocean-atmosphere-land climate system in the SEP, are a strong source of dimethylsulfide (DMS, Andreae 1985, Kettle et al. 1999), a critical aerosol precursor gas with a short residence time that oxidizes via two main pathways to form SO_2 and then sulfate anion (S(VI)) in the MBL (Charlson et al. 1987, Hobbs 2000, Chen et al., 2000). At the same time, emissions inventories (GEIA) indicate strong sulfur sources, primarily from copper smelting, in Northern Chile and Southern Peru. An important aspect is that a significant fraction of these emissions are in the Andean foothills, well above the subsidence inversion. Trajectory analyses and model studies (Gallardo et al. 2002) indicate that this air often moves westward, subsides, and is incorporated into the MBL within a couple of days. This gives us an additional opportunity to attribute high droplet concentrations to aerosols sources using aircraft observations in the free troposphere in conjunction with trajectory analyses. New particles for refilling POCs with CCN could either arrive in this subsiding polluted air (Raes 1995) or could be nucleated in the drizzle-scavenged air from the products of DMS oxidation. Evidence for the former has been demonstrated in the equatorial Pacific (Clarke et al., 1999). However, during the same PEM-T experiment nucleation in the boundary layer was observed in very clean recently-scavenged air just to the north of the VOCALS study area Clarke et al. (1998).

Hypothesis 1c: The small effective radii measured from space over the SEP are primarily controlled by anthropogenic, rather than natural, aerosol production, and that entrainment of polluted air from the lower free-troposphere is an important source of cloud condensation nuclei (CCN).

Testing strategy: Vertical profiles of aerosol size distributions, chemistry and optical properties on the C-130 will establish altitude variability in effective radius and the air masses that contribute most to column integrated satellite measurements. Coupled with size resolved chemistry and observations, in both the MBL and the free-troposphere, of the important aerosol precursor species including DMS, SO_2 and MSA, the DMS flux from the ocean surface, in conjunction with the physicochemical aerosol measurements including combustion influence light absorption, it will be possible to estimate the relative importance of different pathways for aerosol formation and growth in the MBL, and to attribute the aerosol to specific anthropogenic and/or natural sources. Aerosol size and composition measurements on the RHB and above and below the inversion on the C-130 platforms will be used, together with DMS/SO_2 measurements, to estimate entrainment rates and assess the potential contribution of free-tropospheric aerosol/precursor sources. Airborne profiles of the SO_2 flux will be used to separate entrained vs surface DMS-derived SO_2 and associated particles. Aerosol and cloud chemistry measurements will also be made at an elevated land site in the Chilean coastal range downwind of smelters in Northern Chile to determine characteristics of this air before it flows over the SEP, and C-130 flight legs will be dedicated to sampling the characteristics of elevated pollution layers in the free troposphere, marine boundary layer, and close to land.

We will attempt to falsify H1c by carrying out aerosol-CCN-cloud microphysical closure studies using in-situ data from the NSF C-130. These will center around determining correlations, both spatially and from flight-to-flight, between cloud droplet size distributions and concentration (and hence effective radius) and accumulation mode aerosol size distributions (and number concentrations) and physicochemical properties. Using measurements of anthropogenic tracers such as CO and DMS tracers such as MSA, and by measuring the concentration of SO_2 we will attempt to determine the anthropogenic impacts on the air in the MBL. Size resolved information on ionic and organic constituents in sizes from 50 to 1,000nm will provide indications of aerosol types from diverse sources and their mixtures likely to be effective as CCN. Falsification of H1c would require poor correlations between accumulation mode concentration and anthropogenic indicators. Aircraft remote sensing (lidar, radar, and imaging radiometer) and simultaneous satellite overpasses will also be used to broaden the context of the aircraft dataset.

Numerical models of the aerosol indirect effects (Lohmann and Feichter 1997, Lohmann et al. 2000, Ghan et al. 2001) rely on parameterizations of microphysical processes that are poorly constrained using observations (Lohmann and Feichter 2005). In most of these models, aerosol number concentration is derived chiefly from the aerosol mass. It is becoming evident that even light precipitation can have a marked impact upon the accumulation mode aerosol concentration even if this precipitation evaporates before reaching the surface as recent observations suggest (Comstock et al 2004). Collision-coalescence of cloud and drizzle drops can remove aerosol number concentration ("coalescence scavenging") without affecting aerosol mass, which can have a major impact upon cloud microphysics in subsequent cloud formation. Simple calculations (Wood 2006) suggest that coalescence scavenging in aerosol rich plumes in the cloud-topped MBL is independent of the CCN concentration and may deplete CCN on a timescale comparable to the timescale for dilution by entrainment of free tropospheric air if the pollution is confined to the MBL. These results suggest a potentially important role for coalescence scavenging in limiting the geographical extent over which pollution in the oceanic boundary layer can travel over the oceans when low cloud is present. This needs to be accurately parameterized if the regional indirect effects of aerosols on the climate system are to be predicted with confidence.

Hypothesis 1d: Depletion of aerosols by coalescence scavenging is a major sink term for cloud condensation nuclei over the SEP.

Testing strategy: We will use C-130 observations to determine the magnitude of the CCN scavenging loss for stratocumulus, using (i) the cloud layer droplet concentration (N_d) budget and (ii) the subcloud layer accumulation mode aerosol budget. Theoretical estimates (e.g. Wood 2006) suggest that loss rates in stratocumulus topped MBLs can be in the range 10-200 cm^{-3} day^{-1}, and increase with precipitation rate. This is large enough to be estimated with reasonable accuracy over the course of 6-8 hour Lagrangian-type flights. For (i), the total eddy-covariance N_d flux will be evaluated for in-cloud flight legs using aircraft-measured vertical wind and cloud microphysics. DMS tracer measurements made in-cloud and above-cloud will be used to estimate the total water deficit due to entrainment, and when combined with a microphysics-entrainment model will give the deficit of cloud droplets due to entrainment-evaporation. Finally, the CCN scavenging rate will be evaluated by combining the rate of change of N_d measured during the flight with the total eddy-covariance droplet flux and the flux attributed to entrainment-evaporation. **Falsification of H1d would require derived CCN loss rates not to exceed 10-20 cm^{-3} day^{-1} even when substantial drizzle (~1 mm day^{-1}) is present.** These data will be used to develop improved parameterizations of the two way interactions between aerosols and warm clouds.

2.2 Coupled ocean-atmosphere-land hypotheses

Coupled ocean-atmosphere models exhibit large SST biases in the SEP (Fig. 5), which are believed to stem both from errors in the surface heat budget and in ocean heat transport (Collins et al. 2005). Hence a central goal of VOCALS is to improve parameterizations of atmospheric cloud-topped boundary layers and lateral ocean mixing by mesoscale eddies. A major goal of VOCALS-REx is to gather intensive SEP observations and use them to compare with both regional and global coupled model simulations of the ocean heat budget, to identify and quantify the key processes regulating SST and cloud cover across the SEP.

The maintenance of the SST distribution over the SEP is an important problem. The WHOI stratus buoy (85°W, 20°S) 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 (Fig. 6), Rossby waves, and coastally-trapped Kelvin waves playing an important role as in the Northeast Pacific (e.g. Kelly et al. 1998), but much less is known about these processes in the SEP.

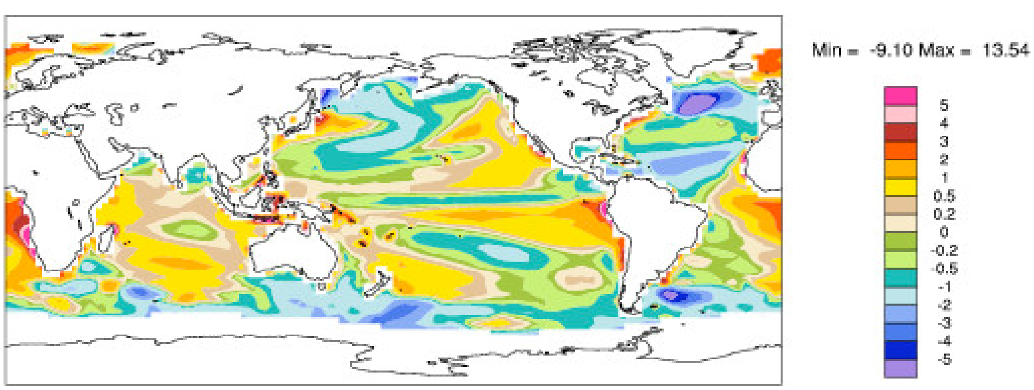

Figure 5: Annual-mean SST biases in CCSM3 1990 control run (Collins et al. 2005)

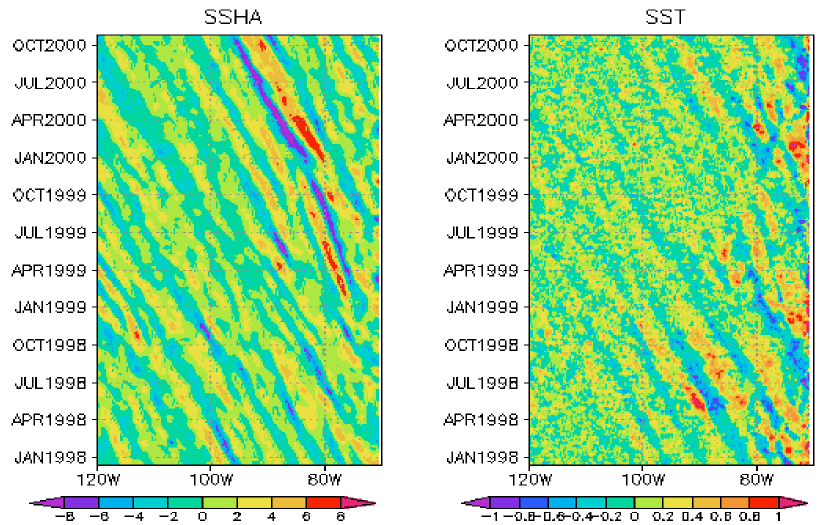

Figure 6: Bandpassed satellite-derived sea-surface height and temperature meridionally averaged from 18-22°S. Note anomalies propagating westward at 5-10 cm s^{-1} (S-P Xie).

A scientific issue that VOCALS-REx 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.

A single measurement location provides an important anchor point, but is inadequate for understanding (i) what eddy or wave scales and structures dominate the eddy heat flux convergence; (ii) if this heat flux convergence is in fact as large as 20-40 W m^{-2}; (iii) how far offshore the eddy heat flux convergence is significant; (iv) and how this affects the regional SST distribution. VOCALS-REx will provide detailed measurements of the mesoscale variability of the upper ocean eddy field to determine their importance in the regional climate of the SEP.

Hypothesis 2a: Oceanic mesoscale eddies play a major role in the transport of heat and fresh water from coastally upwelled water to regions further offshore.

Testing strategy: The NOAA R/V Ronald H Brown (RHB) will be used to conduct two mesoscale surveys consisting of butterfly patterns 500 km on a side centered on 20°S, 77.5°W and 20°S, 85°W. While executing the butterfly patterns the RHB will tow the SeaSoar platform (Pollard 1986) which will be instrumented with a range of sensors to sample thermodynamics and nutrients and will drop XBTs at hourly intervals when transiting. An ADCP will be used to determine kinematics of the eddies. Mapping the horizontal velocity and temperature fields will allow estimation of the advective transports associated with the mesoscale variability at the two sites, of the water mass characteristics of eddies, and of the change in water mass characteristics as the eddies move offshore. That change is an indicator of the amount of mixing with the surrounding water. Mapping of nutrient concentrations as well as heat and salinity will provide additional insight into relevant mixing and transport processes and into the strong productivity of the waters offshore. 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. These blooms may also contribute to biological production of aerosols. Drifters, with thermistor chains extending below the mixed layer base, will be deployed to examine horizontal homogeneity and resolve smaller scale features and Lagrangian transports in the eddy field. Microstructure observations might provide useful constraints on the role of vertical mixing processes at selected locations within the eddy and current field. Strong vertical gradients in salinity and oxygen, with fresh, low oxygen water below the surface layer of the ocean, point to a good signal to noise ratio in observing vertical mixing. Altimetry will be used to put the SeaSoar and XBT sections into better spatial context. Through partnership with colleagues in Chile or through proposals written to NSF, investigators are working to bring a second research vessel to participate in VOCALS-REx. The presence of a second vessel would greatly enhance the ability to sample the mesocale eddies. This would provide a rich context for understanding the long-term buoy time series and altimetry data**. Falsification of the hypothesis will require the observations to be placed into the broader context by comparison with long term data and eddy-resolving ocean simulations from which quantitative flux transport estimates will be obtained**. Coupled and regional ocean model simulations will also be used to understand the role of lateral ocean mixing and eddy transports in setting the regional SST distribution of the SEP.

Coastal upwelling occurs on spatial scales smaller than those typically resolved in coupled ocean-atmosphere GCMs. High resolution regional ocean models (e.g. Penven et al. 2005) broaden the context of the limited observations (e.g. Huyer 1980, Conkright et al. 2002) in suggesting that the depth and offshore extent of the northward flowing Humboldt current and the coastal upwelling varies markedly from location to location along the South American coast in response to varying bathymetry and coastal shape. Certainly, the upwelling regions in the NE Pacific exhibit strong geographic features that would be difficult to resolve with coupled ocean-atmosphere GCMs (Barth et al. 2000). There is also expected to be strong temporal variability in the upwelling strength, particularly along the Chilean coast in response to a transient southerly coastal jet (Garreaud and Muñoz 2005). As shown in Fig. 5, coupled ocean-atmosphere models exhibit biases in SST in regions of strong upwelling (Collins et al. 2005), and it is yet unclear to what extent these biases stem from poorly resolved coastal upwelling in these models. Observations from other important upwelling regions (Andreae et al. 1994) suggest that ocean productivity and biogenic aerosol precursors such as upper oceanic DMS are strongly tied to variability in local coastal upwelling, and so their production may therefore be poorly estimated in chemical transport climate models, which almost all assume fixed DMS sources (e.g Koch et al. 1999). This variability certainly impacts seawater DMS concentrations (Andreae 1985) and probably the sea-air DMS fluxes, although the relationship between DMS and satellite-observed chlorophyll is poorly understood (Matrai et al. 1993, Kettle et al. 1999). Over the SEP, there is considerable small scale variability in the upper ocean (e.g. Fig. 6), particularly in the coastal zone, but there are few measurements of DMS fluxes and their mesoscale variability over the SEP. There are few studies anywhere that have attempted to examine how variability in DMS fluxes might impact the mesoscale microphysical structure of aerosols and clouds.

Hypothesis 2b: Upwelling, by changing the physical and chemical properties of the upper ocean, has a systematic and noticeable effect on aerosol precursor gases and the aerosol size distribution in the SEP.

Testing strategy: The primary test will be to examine the broad spatial and temporal variability of the aerosol physicochemical properties both in and above the MBL in combination with back-trajectory analyses from regional models. We will use correlations between the key aerosol precursor SO_2 and chemical tracers such as CO and methanesulfonic acid (MSA) to attempt to separate the anthropogenic contribution to the aerosol size distribution from the natural contribution. Surface DMS fluxes and gas phase SO_2 will be measured on both the C-130 and the RHB Relationships between these fluxes, the wind speed, and the thermodynamic and nutrient structure of the upper ocean will be assessed using shipborne upper ocean measurements from the RHB, and SST and ocean color measurements from the C-130 radiometers. These data will be used to assess the potential impact upon the aerosol size and concentration using complementary data such as satellite-derived upwind wind speed and SST (and hence upwelling) variability. Entrainment of aerosols from the free-troposphere will also be estimated (hypothesis 1c above). **Falsifiability of H2b would require evidence of dominance by anthropogenic sources or evidence of a dominant free-tropospheric source.**

Clouds over the SEP exhibit a much stronger diurnal cycle of cloud cover and liquid water path *LWP* (Rozendaal et al. 1995, Wood et al. 2002) than MBL clouds at comparable latitudes in the northern hemisphere. Regional model simulations (Garreaud and Muñoz 2004) suggest that a large-scale diurnal subsidence wave formed by the interaction of the coastal jet along the Chilean coast with dry convective heating over the western Andean slopes travels at least 1000 km over the SEP and leads to a strong diurnal cycle of subsidence at remote locations. The phase of the wave strengthens the existing diurnal cycle of MBL depth and *LWP*, with important potential impact upon albedo. Satellite wind observations (Wood, personal communication) provide some support for the model results, suggesting that the amplitude of the subsidence at 85°W, 20°S may be 40-60% of the mean. The wave is also clearly seen in ECMWF analyses (Fig. 7) as a response to the strong diurnal heating on the Andean slopes. In addition, because the relationship between precipitation and *LWP* is strongly nonlinear, the diurnal wave may impact the mean drizzle rate and its effects upon MBL structure and the rate of aerosol scavenging, but observations at higher temporal resolution and over a broader range of distances from the coast are required to demonstrate that the amplitude, phase, and vertical structure of the diurnal subsidence wave are accurately simulated by regional models.

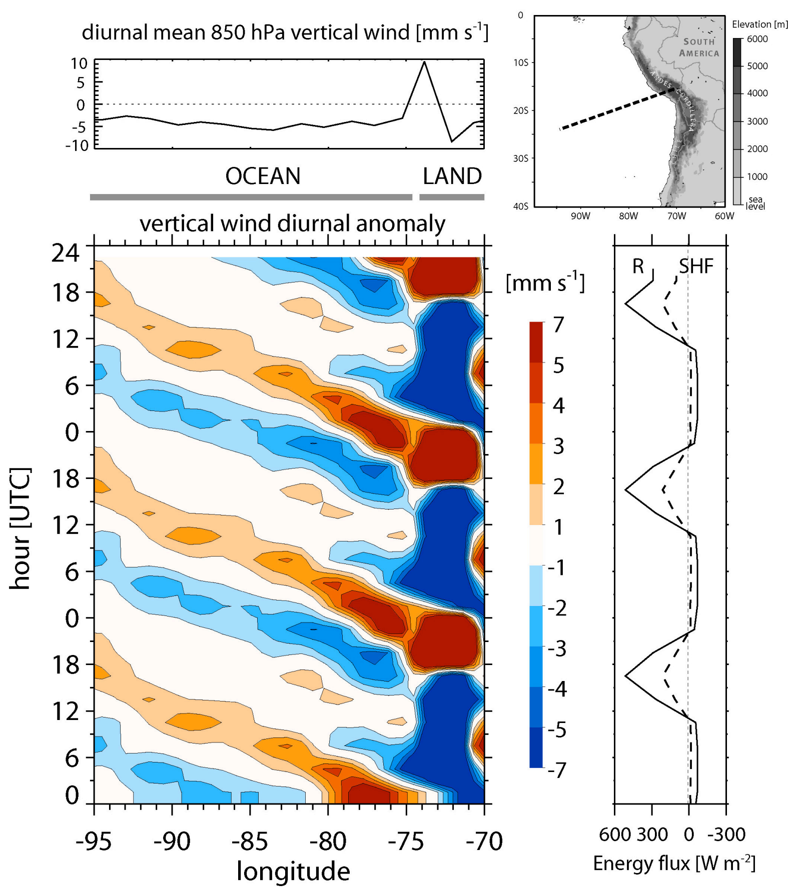

Figure 7 (right): Characteristics of the diurnal subsidence wave emanating from the Andean slopes. Bottom left panel shows a Hovmoller vertical wind diurnal composite anomaly diagram from ECMWF operational analyses (Jul-Oct 2003) along the section shown on the map. The periods of strong ascent follow periods of strong dry heating on the Andean slopes (bottom right shows suface net radiative flux R and sensible heat flux SHF). Data courtesy of Martin Kohler, ECMWF.

Hypothesis 2c: The diurnal subsidence wave ("upsidence wave") originating in northern Chile/southern Peru has an impact upon the diurnal cycle of clouds that is well-represented in numerical models.

Testing strategy: A key signature of the diurnal subsidence wave is the diurnal cycle of temperature in the lower free troposphere (z<5 km), reflecting the ascent and descent associated with the wave. Rawinsonde observations of the lower tropospheric structure will be taken either 4 or 8 times per day from the RHB at different locations along 20°S during the 35 day cruise and will be composited to determine the amplitude and phase of the diurnal cycle as a function of the distance from the coast by compositing potential temperature anomalies as a function of local time. In addition, vertically-resolved satellite temperature data from AIRS will provide longer-term constraints on the free-tropospheric diurnal cycle, and lower free tropospheric data will be provided by wind profilers and rawinsonde ascents on both the Chilean and Peruvian coastal cruises planned for October/November 2008 (see the EDO for additional information).

Estimating the impact of the wave upon the diurnal cycle of cloud and MBL properties is more challenging. We will primarily use the diurnal cycle of liquid water path, cloud top and cloud base from the RHB at two different distances from the coast (i.e. at 75°W and 85°W). Based upon our current knowledge of the upsidence wave, the diurnal cycles should be markedly different at these sites owing to the distance-dependent amplitude and phase differences between solar absorption and the subsidence wave. Assuming that significant differences are observed, the measurements will be used as strong constraints to test process, regional, and global model simulations.

We will also use the model results and observations to determine the primary factors controlling the wave amplitude and phase, and attempt to more broadly address its role in modulating the diurnal cycle of cloud over the SEP**. Falsification of the hypothesis will require either that no significant differences in the diurnal cycle of MBL and cloud properties are observed at the two locations, *or* that the models are unable to accurately predict the impact of the subsidence wave upon the diurnal cycle of clouds and the MBL.**

Over the annual cycle of the upper ocean, SST warms and shoals in the spring-summer and cools and deepens in the fall-winter (e.g. Gaspar 1988). Solar insolation and a relaxation of mechanical mixing in calmer winds are the primary reason for spring-summer warming and shoaling. Vertical mixing associated with convection of surface water made denser by cooling and/or evaporation and with shear-driven instabilities at the base of the surface layer are the primary means for cooling and deepening. Impulsive wind forcing of the surface layer initiates the resonant response - oscillations at the local inertial frequency . Energy from these oscillations enters the stratified fluid below in the form of downward propagating near-inertial internal waves. The shear associated with these oscillations and waves is large at the base of the surface layer and in the thermocline and is often the cause of the shear-instability that deepens the surface layer (Halpern 1974). Capturing this mixing in simulations requires accurate surface winds that do have the observed impulsive transients, good vertical resolution of density and velocity structures, and temporal resolution that well-resolves the forcing and response transients. In the SEP, while buoy data shows the transients in the wind and resultant near-inertial oscillations, there has not yet been an assessment of their importance in the overall evolution of SST and the heat budget of the upper layer. However, NCEP winds do not accurately capture the transients in the observed trade winds, and ocean model simulations to date for the SEP have not addressed the potential for this mixing to be important.

Hypothesis 2d: The entrainment of cool fresh intermediate water from below the surface layer during mixing associated with energetic near-inertial oscillations generated by transients in the magnitude of the trade winds is an important process to maintain heat and salt balance of the surface layer of the ocean in the SEP.

Testing strategy: The variability associated with events in which the trade winds die to 1 or 2 m s^{-1} for up to several days and the consequences of this variability will be observed. Wind data from the buoy, the NOAA R/V RHB, satellites, and the research aircraft will provide information about the space/time variability of the surface wind field. The buoy data has as yet shown the strong temporal variability, but the area over which this modulation in wind speed is observed needs to be defined. At the same the spatial structure of the ocean response will be documented by the buoy, by drifting buoys with thermistor chains suspended below, and by the the RHB. As the wind dies, the near-surface ocean re-stratifies, leaving a shallow, warm layer that is very sensitive to subsequent wind events. The strengthening wind accelerates the shallow layer, triggering near-inertial oscillations and, potentially, mixing with the fluid below. The mean vertical shear and the vertical temperature structure will be observed by the moored and drifting buoys. Microstructure profiling from the RHB will quantify the vertical mixing. These observations will quantify the contribution of this mixing term to the upper ocean heat budget during VOCALS-REx. Subsequent to the field work, modeling studies will be used to hindcast the evolution of the upper ocean layer with wind fields that both include and exclude the transients in the magnitude of the trade winds. This will further assess the importance of the mixing events generated by the temporal variability in the winds in the SEP. We anticipate that the observations will find strong near-inertial oscillations. **Falsification of H2d would require little significant correlation between the trade wind speed and the observed mixing into the shallow surface layers.**

2.3 Satellite retrieval evaluation

Satellite cloud observations are a key tool in assessing the magnitude of the indirect effects of aerosols on regional and global climate (e.g. Breon et al. 2002, Lohmann and Lesins 2002). Such assessments rely critically upon retrievals of cloud optical depth (τ) and cloud effective radius (r_e). Of these, τ estimates are the most widely used and well-characterized (Rossow and Garder 1993, Pincus 1995) and have been made routinely using geostationary and polar-orbiting satellites as part of the International Satellite Cloud Climatology Project (Rossow and Schiffer 1991). There has been a recent focus upon understanding and correcting errors in τ related to subpixel cloud variability, including methods to account for partially filled pixels (Coakley and Bretherton 1982, Coakley and Davies 1985, Loeb and Coakley 1998, Barker et al. 2004). However, problems in estimating r_e in heterogeneous and broken clouds are considerably more serious than for τ, are likely to have a more profound impact upon indirect effect estimates, and have received much less attention. This stems fundamentally from the retrieval methodology (termed the "visible-near infrared technique", Twomey and Cocks 1982, Nakajima and King 1990, Nakajima et al. 1991), which typically uses two channels: the first, in the visible portion of the spectrum, is at a wavelength that is scattered, but not absorbed, by cloud droplets; the second, in the near-IR, is absorbed by cloud liquid water. The combination of the two allows an estimate of the ratio of absorption to scattering which is used to determine an estimate of r_e. The scattering itself is used to estimate τ.

A key problem here is that because the sea surface is strongly absorbing whereas the cloud is weakly absorbing, a cloud that partially fills a satellite pixel can appear to be a strongly absorbing cloud leading to a considerable overestimate of r_e if the subpixel variability is not accounted for. Climatologies derived from satellite observations indicate a strong increase in r_e from the coastal regions to the trade wind regions further offshore (e.g. Fig. 2), which is interpreted as a reduction in the influence of continental aerosols upon clouds as they move away from land. However, morphological changes in the cloud structure from more overcast clouds near land to broken cumulus in the trades may introduce an important bias into the results which could cast doubt on conclusions concerning the extent of the anthropogenic influence upon clouds.

We are entering an era where it is possible to make spaceborne radar estimates of drizzle precipitation in stratocumulus clouds via the NASA Cloudsat mission (Stephens et al. 2002) and, later, the European Space Agency Earthcare program. Cloudsat is expected to lead to great strides in understanding the importance of precipitation (and its suppression by anthropogenic aerosols) upon the coverage and lifetime of low clouds over the remote oceans. At present, there are major gaps in our basic understanding of the climatology of precipitation over the subtropical oceans.

It is critical therefore that we establish the extent to which satellites can credibly inform us about the microphysical and precipitating properties of warm clouds.

Can satellite estimates of stratocumulus cloud microphysical properties (e.g. effective radius or cloud droplet number concentration from MODIS) and precipitation (from CloudSat or MODIS) be refined to perform in a satisfactory manner even under conditions of broken cloudiness on the pixel scale?

Strategy: The C-130 aircraft will provide in-situ cloud microphysical and bulk liquid water profiles during both the Cross-section and POCS-drift missions. Additionally, level runs a few km above cloud will be used to obtain (i) passive multichannel radiometer (MCR) imagery in the visible, near and thermal infrared at high horizontal resolution (~30 m); (ii) microwave radiometer (AIMR) imagery at 37 and 90 GHz with ~200 m horizontal resolution; (iii) active millimeter radar measurements at high vertical and horizontal resolution (10 m and ~100 m respectively. The MCR, with wavelength bands similar to those used in passive satellite microphysical retrievals, will provide cloud spatial variability information at a resolution that considerably exceeds those available from space (e.g. MODIS, GOES, and AVHRR). The AIMR provides microwave radiances needed to estimate cloud liquid water path at a resolution also much higher than the spaceborne equivalents (SSMI, TRMM TMI, AMSR-E) Together with the vertical profile of cloud structure from the downward pointing cloud radar, and the in-situ microphysics, these data will be used to assess the efficacy of passive visible/near IR and microwave retrievals of microphysical and bulk properties of broken and thin clouds. Coordination of flights with satellite overpasses will also be made where possible.

3. VOCALS Partners

VOCALS is an international CLIVAR program with important participation from nations across the globe, both in the broader VOCALS program and in VOCALS-REx. Partners in South America, Europe, Canada, and the United States will continue to make important contributions to the depth and scope of the program, both in terms of their scientific participation in VOCALS-REx, and in their longer term interest in realizing the CLIVAR goal of understanding the coupled climate system and its variability.

VOCALS partners in Chile (Laura Gallardo, Rene Garreaud and Jose Rutllant from the Universidad de Chile, Oscar Pizarro from the Universidad de Concepcion, and scientists from the Hydrographic and Oceanographic Service of the Chilean Navy) and Peru (Ken Takahashi, IGP, Lima) are planning coastal cruises and associated field measurements to coincide with VOCALS-REx. These are detailed in the Experimental Design Overview (see www.eol.ucar.edu/projects/vocals/).

The UK Met Office, in collaboration with a consortium of UK universities, is preparing a cost-matched proposal (50% UK Met Office commitment) to the UK Natural Environment Research Council to bring the UK Facility for Airborne Atmospheric Measurements (FAAM) BAe-146 aircraft to VOCALS-REx to make detailed radiative measurements (Jon Taylor and Jim Haywood at the UK Met Office), an extensive suite of dynamical and cloud physics instruments (Alan Blyth and Alan Gadian, Leeds University; Phil Brown, The Met Office), a set of aerosol physicochemical measurements (Tom Choularton, University of Manchester), and state-of-the-art instrumentation for isotope speciation (Melanie Witt, University of Oxford).

Individual proposals to national funding agencies will be submitted by groups making coastal measurements of aerosol properties from Finland (Petri Vaattovaara, University of Kuopio) and Sweden (Radovan Krejci, MISU). Groups from Canada plan to study satellite measurements of oceanic primary productivity (Trevor Platt, Dalhousie) and sulfur isotope chemistry (Ann-Lise Norman, Calgary).

In addition to VOCALS international partners, NOAA's Atmospheric Composition and Climate Program (ACC) would like to support a comprehensive suite of aerosol measurements (coordinated by Tim Bates at PMEL) on the Ronald H. Brown. In addition, NOAA ACC is interested in deploying an aircraft instrumented with aerosol and trace gas physical and chemical measurements as part of VOCALS-REx. Bruce Albrecht at the University of Miami is seeking support through ONR to bring the CIRPAS Twin-Otter to the field. Finally, the University of Wyoming are in the process of submitting a DEPSCoR proposal to instrument the NSF C-130 with a Raman lidar that will greatly improve the scope of the airborne aerosol remote sampling.

4. Modeling strategy for VOCALS and VOCALS-REx

The VOCALS program has been envisaged from the outset as a means for integrating activities focusing upon the advancement of model simulations with new observational datasets from satellites, buoys, reanalysis, and field measurements over the SEP region. This integration aims to focus resources upon the overall VOCALS goals as laid out in the Science and Implementation Plans, to bring the modeling community into closer contact with observationalists, and to improve the design of observational programs by addressing the key issues that are poorly understood and resolved in climate models. VOCALS will blend diagnostic studies of existing observations, mesoscale and global model studies, new observations, and periodic meetings organized through VAMOS for exchange of scientific information.

The VOCALS program is motivated by the need to improve global simulations of low-latitude cool-ocean physical processes in coupled ocean-atmosphere models. As discussed in the Introduction, inadequate representations of these processes limit our current ability to simulate tropical SST, wind and rainfall biases (including ENSO and the seasonal cycle), cloud feedbacks on climate sensitivity, and aerosol indirect effects on climate. The overall VOCALS strategy is to tightly integrate model advancement activities spanning a hierarchy of space/time scales with new observational analyses over the SEP region. This includes not only REx, but also extended datasets from satellites, buoys, reanalysis, and past and ongoing field measurements. The VOCALS SWG has drafted a VOCALS Modeling Plan (www.eol.ucar.edu/projects/vocals/VOCALS_Modeling_Plan.pdf) that describes ongoing and planned VOCALS modeling work. Here, we will summarize that plan and especially focus on the coordination of VOCALS modeling (VOCALS-Mod) with REx.

4.1 Modeling challenges in the SEP

Numerical simulations of the SEP climate face major issues and challenges, some of which were alluded to in the introduction:

1) In the SEP, as well as in the southeastern tropical Atlantic, coupled atmosphere-ocean models have difficulties in simulating stratocumulus clouds and produce large sea surface temperature (SST) and surface wind errors (Ma et al. 1996; Kiehl and Gent 2004; Wittenberg et al. 2006).
2) A realistic simulation of east Pacific boundary layer cloud cover by an AGCM (with prescribed SSTs) does not guarantee a single ITCZ in the coupled mode. Also, a CGCM can produce a weak double ITCZ and yet obtain a very symmetric SST distribution in the eastern Pacific. The OGCMs, therefore, provide their own contribution to a double ITCZ bias.
3) The oceanic wind-driven circulation in the SEP develops a vigorous mesoscale and submesoscale eddy field that covers a much larger area than the coastal upwelling zone (Penven et al. 2005). Global OGCMs and even coarse-resolution ROMs must parameterize the impacts of this eddy field, e.g. through isopycnal diffusion.,but we have almost no observations of the vertical structure of the eddies, especially outside the coastal zone.
4) Global OGCMs do not adequately reproduce the budgets of heat, salinity, and nutrients in the SEP ocean mixed layer, e. g. as observed at the WHOI stratus buoy (Colbo and Weller 2006). This contributes to regional SST biases when these models are coupled to an AGCM. We hypothesize that a substantial contributor to this problem is poor representations of the lateral eddy transports, current systems and regional upwelling.
5) Key elements of the PBL, including its height and cloud cover/albedo are usually not well reproduced even in regional models with relatively high resolution in the vertical and horizontal (Bretherton et al. 2004). These problems are exacerbated in the near coastal strip. The large

diurnal cycle of cloud cover and height, due in part to interactions with the Andes, adds to this challenge, but does seem to be qualitatively correctly simulated in some AGCMs/RAMs (e.g. Rasch et al. 2006).

6) Recent in-situ and satellite observations show that mesoscale atmospheric processes enhanced by stratocumulus drizzle, such as those at work for pockets of open cells (POCS), influence cloud properties over the SEP and in other stratocumulus regimes (Stevens et al. 2005, Wood et al. 2006). The PBL parameterizations of most current AGCMs do not account for the impact of evaporating drizzle on the intensity of stratocumulus turbulence and entrainment, and the cloud fraction parameterizations do not allow for a feedback of drizzle that enhances the subgrid horizontal variability of cloud thickness (Stevens et al. 1998, Mechem et al. 2003). We need to better understand the sensitivity of simulated AGCM clouds are to better representation of drizzle feedbacks.

7) Microphysical processes affect cloud properties in the SEP (Bretherton et al. 2004, Wood et al. 2006). The variability of those processes is strongly influenced by the dispersal of continental aerosols, which can enhance cloud optical thickness and influence cloud liquid water through suppression of drizzle. CGCMs do not address the potentially important feedbacks associated with the effects of aerosol upon the coupled ocean-atmosphere system.

Challenges 1 and 2 are broad; the remaining modeling challenges helped motivate the need for additional observations to be taken in VOCALS-REx. The mission of VOCALS-Mod is to address these challenges.

4.2 Goals and approach of VOCALS-Mod

VOCALS-Mod has the following four broad goals: 1) improving the understanding and simulation of the seasonal cycle and interannual as well as interdecadal variability in the SEP, including the reduction of climate model biases in the seasonal cycle of clouds, SST, winds and rainfall in the region. 2) improving the understanding and simulation of oceanic budgets of heat, salinity, and nutrients in the SEP and their feedbacks on the regional climate, 3) developing the capability for simulation of the effects on cloud properties of aerosols emitted in the region, and 4) elucidating the interactions between the SEP climate and remote climates. In addition, VOCALS-Mod will provide modeling support for VOCALS-REx by downscaling atmospheric and oceanic datasets, performing real-time forecasts and assimilating data collected.

An important feature of VOCALS-Mod is the active involvement and comparison of a hierarchy of models that span a broad range of scales. This hierarchy includes 1) Atmospheric General Circulation Models (AGCMs, Δx = 50-300 km), 2) Oceanic General Circulation Models (OGCMs, Δx = 50-300 km), 3) Coupled Atmosphere-Ocean General Circulation Models (CGCMs), 4) Regional Atmospheric Models (RAMs, Δx = 5-50 km), 5) Regional Ocean Models (ROMs, Δx = 5-50 km), 6) Coupled ROM-RAM Models (ROAMs), 7) Large-Eddy Simulation Models (LESs, Δx = 25-100 m), and 8) Single Column Models (SCM) for clouds and aerosols. This hierarchy represents an equally broad spectrum of modeling interests from climate and seasonal forecasting to numerical weather prediction to ocean physics/biology to cloud/aerosol interaction, linking operational centers, research laboratories and universities. Research modeling systems will facilitate the realization of hypothesis-testing experiments. These are complemented by forecast experiments are directly comparable with a broad suite of observations and provide insight into the time evolution of errors and their dependence on model physics and initialization.

This hierarchy of models provides a powerful tool for understanding model errors and allows us to use the full range of scales over which VOCALS-related data is being collected. For instance, LES has demonstrated the role of drizzle in enhancing mesoscale cellularity, while decreasing PBL depth and area-averaged cloud albedo (Stevens et al. 1998), feedbacks that AGCMs and RAMs do not yet adequately include. Fine-resolution ROMs qualitatively reproduce the complex SEP mesoscale eddy field and are readily compared with ship-based and satellite observations of this eddy field, while OGCMs must parameterize the mesoscale eddy transports. A ROAM simulation of the East Pacific does not have the double-ITCZ bias that plagues CGCMs (Xie et al. 2006), though perhaps this is because the west Pacific ocean conditions are specified in this model.

Some exploratory VOCALS-related modeling is going on with the full hierarchy of models, but these efforts are mainly not funded to focus on the SEP or make good use of present or future VOCALS datasets. As a result, these efforts are currently only loosely coordinated and are only slowly moving toward realizing the VOCALS modeling goals.

We therefore proposed that the VOCALS-REx program be coordinated with interagency funding for a VOCALS modeling component coordinated around the following activities:

1) Diagnosis of simulations of the SEP climate and oceanic circulation by comparing model output and observational data, including data assimilation and fundamental sensitivity studies to orography, resolution, feedbacks from specific physical processes, etc.
2) Improvement of GCM physical parameterizations, especially PBL, microphysical, and oceanic-eddy processes, for reduction of east Pacific biases in SST, rainfall, and boundary-layer clouds.
3) Detailed analysis of realistically initialized and forced simulations with different model types for the austral spring over the core SEP stratocumulus region, especially the VOCALS-REx season, and comparison with the observations. This includes LES studies over small domains.
4) Participating in and organizing relevant community-wide modeling activities, such as the "Correcting Tropical Biases Workshops" and the GCSS/WGNE Pacific Cross-section Intercomparison (GPCI) project.

Activities 1 and 2 are broader than VOCALS-REx, but in addition to being important in their own right, they provide the modeling context necessary to apply the scientific findings of VOCALS-REx to the overall improvement of global and regional climate models. Activity 4 acknowledges the need to cross-fertilize VOCALS modeling advances and datasets with the broader scientific community. Among a variety of other community groups that have expressed interest in VOCALS, we mention here the GEWEX Cloud System Study (GCSS) and the International Global Atmospheric Chemistry (IGAC) project of IGBP, which would like the atmospheric chemistry/aerosol components of the VOCALS-REx field campaign to become an IGAC Task. They have indicated they would be able to provide logistical and financial support for workshops on these components of the project. In particular we plan to leverage IGAC's expertise in the areas of regional and global chemical transport modeling and in observational and modeling studies of the aerosol indirect effect.

We propose to hold annual 2-day VOCALS Modeling Workshops over the next five years. These workshops will especially be aimed at large-scale and regional ocean and coupled ocean-atmosphere models, but will also coordinate cloud-scale SEP modeling activities such as single-column and large eddy simulation. The workshop goals will be to coordinate the activities and compare results of groups with diverse modeling approaches, to optimize the observational syntheses from VOCALS-REx and other VOCALS datasets so that they are of maximum utility to the modeling community, and to critically examine the performance of the various participating models by developing suitable case studies and observational metrics.

Table 1 lists the modeling groups that have been involved to date in VOCALS planning, including their proposed research area, types of models being used or developed, which of the modeling challenges in Section 3 they are addressing, the anticipated funding source, and whether the proposal has been submitted (S) or is still to be submitted (TBS). The VOCALS Modeling Plan included more information on their individual models and projects. This table is included to show that VOCALS-Mod has attracted the interest of top-notch modelers with the requisite breadth of interests and range of scales. VOCALS-Mod is an open project. In some cases there is substantial overlap between work proposed by different groups. We anticipate that all of these groups may not be fully funded, and other modeling groups may also develop an interest in VOCALS.

Table 1: VOCALS Modeling Teams

PI	Institution	Research Area	Challenge	Model Type¶	Funding Agency	Status
Wood/Bretherton	U Washington	Stratocumulus-drizzle-diurnal cycle interaction and simulating POCs	5,6,7	LES, SCM, AGCM,	NSF Clim.	TBS
Miller	Scripps	High resolution ocean modeling and assimilation	3, 4	ROM, ROAM	NSF OCE	TBS
Garreaud/ Gallardo/ Ruttland	Universidad de Chile	Coastal atmospheric circulations, aerosol transport, and mesoscale ocean coupling	3,5,7	RAM, ROAM	Fondecyt (Chile)	Submitted
Shinoda/Lin	NOAA-CIRES	Upper ocean variability and its role in the maintenance of stratus	1	OGCM, CGCM	NOAA CPPA	TBS
McWilliams/ Hall/Gruber/ Large	UCLA/NCAR	Nested multiscale simulation of SEP coupled with WRF/MOM inside CCSM.	1,3,4,5	CGCM, ROAM	NOAA CPPA	TBS
Mechoso/Pan	UCLA/NCEP	Simulation and prediction of the tropical climate with a coupled GCM	1,2	CGCM	NOAA CPPA	Submitted
Wood/Thornton/ Zaveri	U Wash/ PNNL	Lagrangian observations and modeling of aerosol-cloud interaction	7	AGCM with chemistry	NOAA ACC	S
Y. Wang /Xie/ deSzoeke/Fairall	U.Hawaii/ ESRL	Comparison of iROAM and CFS simulations of SEP climate	1,2,5	CGCM, ROAM	NOAA CPPA	S
Cotton/Carrio	CSU	Simulations and analysis of aerosol/cloud/drizzle interactions in marine stratocumulus	7	LES	NOAA ACC	TBS
Donner/Golaz	GFDL	Cloud scheme development/ application to aerosol-cloud-climate over the SEP	6,7	AGCM	NOAA ACC	TBS
S. Wang/Pullen	NRL	Interactions of aerosol-cloud-precipitation-ocean effects in marine boundary layers	6,7	ROAM, LES	NASA	S
Zeng/Brunke	U Arizona	Improved treatment of MBL clouds in NCEP CFS03 and NCAR CCSM3	5	AGCM	NOAA CPPA	TBS
Kirtman	GMU	Multi-scale coupled interactions in the SE Pacific	1,2,4	CGCM	NOAA CPPA	TBS

¶Model types: ROAM (Regional Ocean Atmosphere Model), ROM (Regional Ocean Model), RAM (Regional Atmospheric Model), OGCM (Ocean General Circulation Model), CGCM (Coupled General Circulation Model), LES (Large Eddy Simulation), AGCM (Atmospheric General Circulation Model), SCM (Single Column Model)

4.3 Modeling component of VOCALS-REx

The modeling component of VOCALS-REx will concentrate on the following three broad thematic questions, for which data from the field program will be essential:

1) *Can ROMs and OGCMs accurately simulate the mesoscale ocean eddy transports of heat and biogenic species offshore over the SEP?*
2) *Can regional and global atmospheric models, forced by our best estimates of aerosol sources, reproduce the observed geographical variability in cloud droplet concentration, and if so, what are the implications for the magnitude of the aerosol indirect effects over the SEP?*
3) *Can a large-domain LES simulate the evolution and structure of a SEP POC? If so, what cloud-aerosol feedbacks are required?*

These three questions can be regarded as critical tests of the skill of our hierarchy of models to address the REx coupled ocean-atmosphere-land and aerosol-cloud-drizzle hypotheses introduced in Section 2. Below, we discuss our modeling strategies for addressing them.

1. Mesoscale ocean eddy transports

In OGCMs, mesoscale ocean eddies are parameterized, and the relevant ocean mixing parameterizations cannot easily be tested with the kind of localized ship sampling that can be done in REx. Hence, our core modeling strategy for better understanding the mesoscale ocean eddy field is to explicitly simulate it with ROMs and compare the vertical and horizontal eddy structures of temperature, salinity, nutrients and other biogenic tracers (in a statistical composite sense) with REx ship-towed SeaSoar profiles, satellite-derived altimetry, IMET buoy measurements, and SST measurements from the Ronald H Brown, from satellites. If this comparison is satisfactory, ROM-derived statistics and fluxes will be used to illuminate the feedback of the eddies on the large-scale climate. The VOCALS groups at NCAR/UCLA and Scripps have already run ROM simulations of the SEP with grid spacings of O(5 km), which appear sufficient to generate a realistic-looking pattern of mesoscale eddies and coastal currents.

As a preliminary task before VOCALS-REx, the heat and salt budgets from ROM/ROAM simulations like this (as well as with CGCMs) will be carefully analyzed to see how consistent they are with existing measurements in this region, e. g. inferences from the multiyear times series at the WHOI stratus buoy. This will test whether a more realistic simulation of the ocean eddy field seems to lead to more realistic ocean mixed layer budgets. This task will involve all of the large-scale and mesoscale modeling groups within VOCALS-Mod. The Scripps group (and perhaps some other ROAM groups) plans to use ocean and atmosphere data assimilation to generate a ROAM simulation in which the ocean mesoscale eddy field remains at all times close to observations. This would be particularly useful for comparison of this ROAM with VOCALS-REx ocean data.

The UCLA/NCAR group will use a multiscale modeling strategy, with the WRF RAM coupled to the MOM ROM over a SEP domain, nested inside the NCAR CCSM3 CGCM. Comparison of this nested simulation with a control CCSM3 simulation will directly test the extent to which much better resolution of SEP mesoscale ocean and atmospheric processes changes the simulated climate, locally and remotely.

2. Aerosol transport and cloud droplet concentration

The aerosol indirect effect is a leading uncertainty in climate models (Lohmann and Feichter 2005). From the modeling perspective, it is necessary to model the aerosol sources, transport/aging (including entrainment into the cloud-topped PBL), sensitivity of cloud droplet number and size to the in-situ aerosol, aerosol processing by cloud, and the second indirect effect of aerosols on cloud thickness and lifetime through precipitation feedbacks (Albrecht 1989). The second VOCALS-REx modeling question involves all but the final step in this chain (which will be the main subject of the third modeling question). Satellite retrievals give us estimates of the space-time variability of cloud droplet size and cloud thickness over stratocumulus regions, except where the cloud becomes too broken. Hence, they provide a metric for testing AGCM simulations of aerosol transport and its effect on cloud droplet size. The NCAR and GFDL AGCMs both include aerosol source and transport models, and are capable of making wind forecasts when initialized from reanalyses. Both AGCMs are currently implementing cloud microphysical schemes that allow the cloud droplet concentration respond to aerosol variations. Hence, within a year or so both AGCMs will be able to plausibly predict the cloud droplet concentration in marine stratocumulus layers. The GFDL Donner/Golaz initiative will test this approach in the SEP against satellite and REx data. We are working to foster a similar effort at NCAR. The Universidad de Chile will also explore this approach in a regional atmospheric model.

3. LES simulation of POC formation and evolution

LES can convincingly simulate both stratocumulus-capped boundary layer dynamics and its interaction with drizzle processes (e.g. Rand 1997; Stevens et al. 1998). Hence, it is our most realistic modeling tool for examining cloud-drizzle-aerosol interactions in POCs. The UW and NRL groups are already using LES models (SAM and COAMPS, respectively) to simulate stratocumulus layers including drizzle,but specified cloud droplet concentration. They both hope to add rudimentary parameterizations for cloud-aerosol interactions, treating both nucleation and scavenging, which will give them the necessary modeling capability to examine POC evolution. Expanding computer capabilities will allow LES simulations with 50-100 m horizontal grid spacing to encompass domains of 100 km, large enough to try to simulate the development and evolution of a POC occupying part of the computational domain, and which interacts with unbroken stratocumulus is the remainder of the domain. Relevant questions include whether POCs can be formed by a local minimum in ambient aerosol concentration, a local synoptically induced maximum in cloud thickness or above-PBL humidity, whether POCs can be sustained in a simulation through a diurnal cycle, and how quickly a simulated POC modifies the aerosol concentrations within it. These questions map directly onto the REx observational objectives for POCs, and the REx observations will form the principal metric for evaluating LES POC simulations that appear to be successful. Ideally, LES models will provide context for the REx POC observations that will allow them to be better carried over to improved cloud, PBL and microphysical parameterizations in global models.

5. VOCALS Complementary Observational Datasets

The range of temporal and spatial scales being addressed under the VOCALS program is broad, and must therefore be met with a corresponding breadth in our observational capability. As part of the ongoing VOCALS program, the SWG has sought to draw together an expansive set of complementary observational datasets. These aim to provide (a) invaluable context for the VOCALS-REx field measurements by extending the range of temporal and spatial scales that can be addressed; (b) valuable assistance in the development and evaluation of modeling efforts under VOCALS-Mod.

The key complementary observational datasets include

- A five year record from the IMET Buoy at 20°S, 85°W which includes high time resolution measurements of the upper ocean, surface meteorology and radiation.
- Regular buoy-maintenance cruises as part of the East Pacific Investigation of Climate (EPIC) and Pan American Climate Studies (PACS). So far cruises, with a range of surface meteorology, remote sensing, and limited aerosol measurements, have taken place during fall 2001, 2003-2005.

Satellite measurements including visible and near IR cloud and aerosol properties (GOES, MODIS), microwave radiometry (TMI/AMSR) altimetry data.

The complementary VOCALS datasets are archived in the distributed VOCALS long-term data archive (*www.eol.ucar.edu/projects/vocals/dm/dm_index.html*) which is managed by NCAR's Earth Observing Laboratory (EOL).

6. Relationship of VOCALS-REx to prior field campaigns

There have been no *major* field campaigns with dedicated focus upon the SEP climate system. The EPIC (East Pacific Investigation of Climate) Stratocumulus cruise (Bretherton et al. 2004), a 14 day cruise which took place during October 2001, represents the most comprehensive dataset to date, documenting the cloud, marine boundary layer, and upper ocean structure over the SEP. Despite the short duration of the cruise, the cruise has revealed a considerable amount about lower atmospheric processes in the region, including the strong diurnal cycle in cloud thickness and liquid water path; the abundance of drizzle in the region and evidence of its modulation by variations in cloud droplet concentration; the most comprehensive dataset to date on the cellular structure of the pockets of open cells (POCs). The cruise, together with the longer-term buoy measurements at 85°W 20°S, has revealed the importance of mesoscale oceanic eddies in transferring heat and freshwater from the coastal upwelling regions to the remote Pacific ocean.

More recent buoy-maintenance cruises to the SEP (2003, 2004, and 2005) and one by the Chilean National Oceanographic Committee (Garreaud et al. 2001) have added additional valuable information such as the first detailed aerosol physical and chemical measurements (Don Collins, Texas A&M University) and further measurements of the cloud and MBL structure that together reveal accumulation mode aerosol depletion and new nucleation during POCs. An earlier cruise (Andreae 1985, Kettle et al. 1999) revealed seawater DMS concentrations in the Peruvian upwelling region similar to values in other coastal upwelling regions, but values further south along the Chilean coast have not been measured.

There is a history of multi-platform chemistry and aerosol-cloud interaction studies in the stratocumulus topped boundary layer (STBL) over the subtropical eastern oceans. The First ISCCP Regional Experiment (FIRE) in the NE Pacific in 1987 provided comprehensive thermodynamic and turbulence measurements in the STBL. The Atlantic Stratocumulus Transition Experiment (ASTEX) in the NE Atlantic Ocean provided some of the first Lagrangian measurements to study the evolution of the MBL over several days. The concurrent Marine Aerosol Gas Exchange (MAGE) field program provided early exploration of the sulfur chemistry over the remote subtropical oceans in the subtropical Atlantic. A few exploratory missions to characterize physical and chemical properties of aerosols and precursors over the SEP were carried out during the NASA PEM Tropics missions, but simultaneous cloud measurements were limited. Aerosol-cloud interactions began to be explored in more detail with the Monterey Area Shiptracks Experiment (MAST) in 1994, with the first true aerosol-cloud droplet closure experiments taking place during the second Aerosol Characterization Experiment in 1997.

The ability to accurately characterize drizzle falling from stratocumulus clouds has improved dramatically with the development of millimeter radar technology in the past decade or so. This technology has been used with success to study drizzling MBL clouds from the ground during ASTEX, on ships during the the EPIC and recent Pan American Climate Studies (PACS) cruises (Bretherton et al. 2004, Kollias et al. 2004), and on aircraft to study drizzle in the NE Pacific by Vali et al. (1998) and more recently and extensively in the Dynamics and Chemistry of Marine Stratocumulus (DYCOMS-II) field program (Stevens et al. 2003). However, these studies have not focused directly upon the aerosol-drizzle interactions directly (how the physicochemical properties of aerosol affect, and are affected by, precipitation in the stratocumulus topped MBL).

The great advantages that VOCALS-REx offers over previous field programs to study aerosol-cloud interactions in other subtropical oceanic regions are that (a) the extensive ship dataset, with its comprehensive aerosol and cloud remote sensing suite, adds invaluable context that is impossible to obtain from an airborne campaign alone; (b) the more steady flow regime, stronger microphysical gradients, and simpler distribution of aerosol sources in the SEP make this region an excellent test bed.

From an oceanographic perspective, it has been known for several decades that mesoscale circulations in the ocean are important, and although experiments like California Cooperative Oceanic Fisheries Investigations (CalCOFI), the Coastal Ocean Dynamics Experiment (CODE), and the Coastal Transition Zone (CTZ) experiment have provided some insight, only recently has the surveying of mesoscale eddy systems been carried out with sufficient resolution to study mesoscale eddies. The Eastern Boundary Currents program in 1993 provided some early detailed three-dimensional eddy sampling in the California current, but this study has no equal in the SEP.

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Section I: Facilities, Equipment and Other Resources

Table 1: Field facilities requested, sponsors, status, costs estimates, personnel

Note: Additional detail about the range of instrumentation for the atmospheric chemistry measurements (shaded items) is presented in Table 2 (C-130 only). NOAA Climate Forcing Program plan to support chemistry/aerosol measurements on the Ronald H Brown.

FACILITY/INSTRUMENT	SPONSOR	REQUEST STATUS (TBS: to be submitted)	COST ESTIMATE (NSF only)	PI or CONTACT DETAILS
NCAR C-130 Base facility (cloud microphysics, dynamics, turbulence) Flight hours (90 hours research time)	NSF	TBS	$805K	Robert Wood (U Washington)
NCAR C-130 Dropsondes (150 sondes total)	NSF	TBS	$215K	Robert Wood (U Washington)
NCAR C-130 Multichannel radiometer (MCR)	NSF	TBS	To be determined	Mark Tschudi (NCAR EOL)
NCAR C-130 Airborne Imaging Microwave Radiometer (AIMR)	NSF	TBS	To be determined	Julie Haggerty (NCAR EOL)
NCAR C-130 PI Costs	NSF	TBS	$450K	Robert Wood, Chris Bretherton (U Washington)
NCAR C-130 High frequency gaseous phase chemistry measurements	NSF (SOLAS)	TBS	$500K	Alan Bandy, Donald Thornton (Drexel)
NCAR C-130 Aerosol growth and chemistry	NSF (SOLAS)	TBS	$570K	Steve Howell, Barry Huebert (U Hawaii)
NCAR C-130 WCR Radar analysis and CCN	NSF	TBS	$425K	Dave Leon, Jeff Snider (U Wyoming)
R/V Ronald H Brown 45 cruise days: NOAA/ETL surface flux, cloud and drizzle remote sensing instrumentation	NOAA (CPPA)	Proposal submitted	n/a	Chris Fairall (NOAA ESRL)
R/V Ronald H Brown PI Costs	NOAA	TBS	n/a	Robert Weller (WHOI), Chris Fairall (ESRL), Sandra Yuter (NCSU)

Table 1 (continued):

FACILITY	SPONSOR	REQUEST STATUS (TBS: to be submitted)	COST ESTIMATE (NSF only)	PI or CONTACT DETAILS
R/V Ronald H Brown Radiosondes: 4 per day, 8 during IOPs = 200 overall at $200 each	NOAA	TBS	n/a	Chris Fairall (NOAA ESRL)
R/V Ronald H Brown Conductivity/temperature/depth sensors (CTDs)	Robert Weller (WHOI)	approved	n/a	Robert Weller (WHOI)
R/V Ronald H Brown Expendable bathythermographs (XBTs) – 200 total	NSF	TBS	$12K	Robert Weller (WHOI)
R/V Ronald H Brown Surface drifters and thermistor chains	NSF	TBS	$95K	Robert Weller (WHOI)
R/V Ronald H Brown High frequency gaseous phase chemistry measurements	NSF	Already funded by ATM-Chem	n/a	Byron Blomquist, Barry Huebert (U Hawaii)
R/V Ronald H Brown Aerosol growth and chemistry	NOAA ACC	TBS	n/a	Bates (PMEL)
R/V Ronald H Brown Ocean microstructure	NSF OCE	TBS	$750K	Michael Gregg (APL, U Washington)
UNOLS Ship Sea Soar	NSF OCE	TBS	$780K	Clayton Paulson (Oregon State U)
R/V Ronald H Brown SOLAS surface gas/water sampling	SOLAS	Approved	n/a	Barry Huebert (U Hawaii)
R/V Ronald H Brown Ocean near-surface profiler	NSF	TBS	$425K	Brian Ward (Old Dominion University)

Table 1 (continued):

FACILITY	SPONSOR	REQUEST STATUS (TBS: to be submitted)	COST ESTIMATE (NSF only)	PI or CONTACT DETAILS
NOAA P3 or other aircraft	NOAA ACC	Requires allocation	n/a	Graham Feingold (NOAA ESRL)
San Felix Island/Chilean R/V Wind profiler/ceilometer shipping/install	FONDECYT, NOAA	TBS	n/a	Chris Fairall (NOAA ESRL)
Peruvian coastal cruise	Peruvian agencies + Possible wind profiler from NSF deployment pool	TBS	$250K (profiler)	Ken Takahashi (University of Washington)
Logistical support (NCAR JOSS) Field operations	NSF	TBS	$200K	José Meitín
Logistical support (NCAR JOSS) Data archiving and integration, satellite datasets	NSF	TBS		José Meitín

Table 2: Atmospheric chemistry suite on the NSF C-130

INSTRUMENT **indicates lower priority*	MEASUREMENTS	FUNDING SOURCE	CONTACT
5 stage MOI impactor & APS on LTI	Size distributions of NSS, MSA, NH4, Na, K, Ca, Mg, NO_3, Cl, etc.	NSF- ATM	Barry Huebert (U. Hawaii)
Total Aerosol Sampler	Bulk NSS, MSA, NH4, Na, K, Ca, Mg, NO_3, Cl, etc.	NSF- ATM	Barry Huebert (U. Hawaii)
TOF Aerosol Mass Spectrometer	NSS, Organics, composition vs size	NSF-ATM	Howell and Clarke (U Hawaii)
Streaker on LTI, SEM, TEM	Sized dust, sea salt, sulfate, & pollution aerosol images	NSF-ATM	Jim Anderson (ASU)
TSI 3010, 3025	Total aerosol number, incl. nanoparticles	NSF- ATM	Howell & Clarke (U. Hawaii)
DMPS and APS	Number size distribution from 5 to 10,000 nm diameter	NSF- ATM	Howell & Clarke (U. Hawaii)
NCAR RCAD	Number size distribution, 8 – 120 nm (nucleation)	Deployment pool	NCAR RAF
PSAP	Light absorption	NSF- ATM	Howell & Clarke (U. Hawaii)
3 wavelength TSI nephelometer	Total and sub-micron (alternating) light scattering and backscattering by aerosols	NSF- ATM	Howell & Clarke (U. Hawaii)
*LWC collector	Cloud water chemistry	NSF- ATM	Jeff Collett (CSU)
CVI	CCN chemistry	NSF-ATM	Cindy Twohy (U. Oregon)
Giant Aerosol Impactor	Giant aerosol size distribution (1-1000 m)	NSF-ATM	Jorgen Jensen (NCAR)
APIMS	DMS concentration and flux	NSF- ATM	Alan Bandy (Drexel U.)
APIMS	SO_2 concentration and flux	NSF- ATM	Alan Bandy (Drexel U.)
UV Resonance fluorescence	CO	Deployment pool	Teresa Campos (NCAR)
*Licor IR	CO_2	Deployment pool	Teresa Campos (NCAR)
Dasibi or TECO	O_3	Deployment pool	Teresa Campos (NCAR)
*NO chemiluminescence	Fast O_3 concentration and flux	Deployment pool	Teresa Campos (NCAR)