VOCALS

The VAMOS Ocean-Cloud-Atmosphere-Land Study

Improving understanding, model simulations, and prediction of the Southeast Pacific Climate System

PROGRAM SUMMARY

June 2007

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1. The Southeast Pacific Climate System

The Southeast Pacific (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 (Fig. 1). This unique system is very sparsely observed, yet its variations have important impacts on the global climate. There are also great economic impacts, with the regional fisheries representing almost one-fifth of the worldwide marine fish catch.

The great height and extent of the Andes Cordillera are barriers to zonal flow in the South Pacific, resulting in strong winds parallel to the coasts of Chile and Peru (Garreaud and Muñoz 2005). These winds drive intense coastal upwelling, bringing cold, deep, nutrient/biota rich waters to the ocean surface. As a result, sea-surface temperatures (SSTs) are colder along the Chilean and Peruvian coasts than at any comparable latitude elsewhere. The cold SSTs, in combination with warm and dry air aloft helped by orographic effects of the Andes (Richter and Mechoso, 2006), support the largest and most persistent subtropical stratocumulus deck in the world. The presence of this cloud deck has a major impact upon the earth's radiation budget.

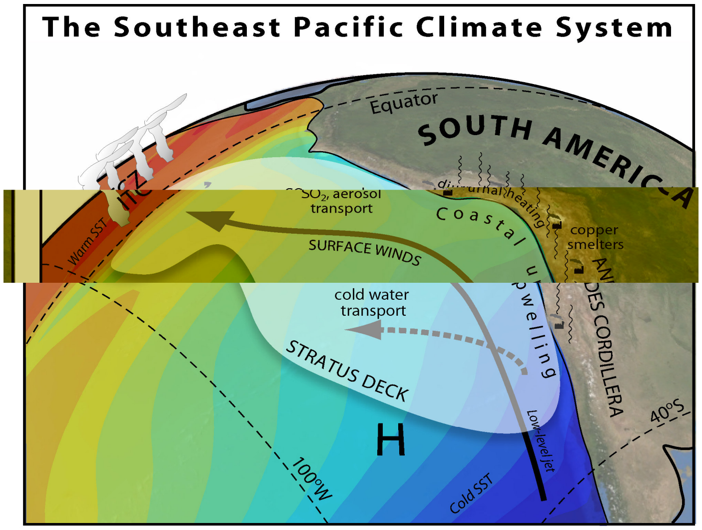

Figure 1: Key features of the SEP climate system.

Several fundamental problems are barriers to the understanding of SEP's weather and climate:

- Difficulties in the quantification of the indirect effect of aerosols upon cloud radiative properties (e.g. Lohmann and Feichter 2005);
- The existence of systematic errors in coupled atmosphere-ocean general circulation models (CGCMs), which in the SEP include (Fig. 2) too warm SSTs and too little cloud cover (e.g. Mechoso et al. 1995, Ma et al. 1996);
- Our inability to make accurate regional weather predictions in coastal areas dominated by low cloud.

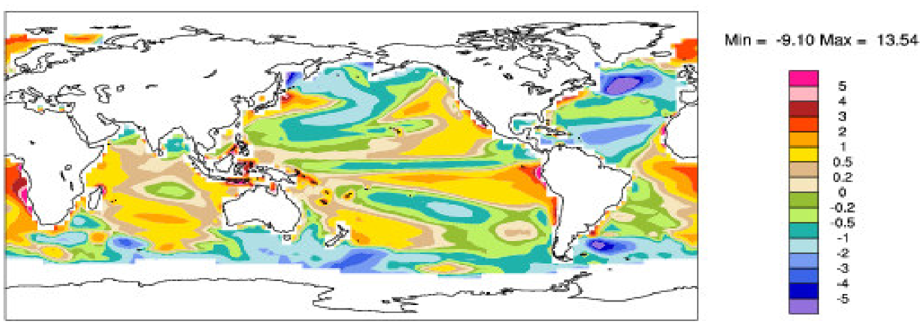

Figure 2: Annual mean sea-surface temperature biases in CCSM3 1990 control run (Collins et al. 2006)

2. The VOCALS Program

VOCALS (VAMOS* 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 of the SEP coupled ocean-atmosphere-land system on diurnal to inter-annual timescales**. The principal program objectives are: 1) the improved understanding and regional/global

* 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.eol.ucar.edu/projects/vamos/*

model representation of aerosol indirect effects over the SEP; 2) the elimination of systematic errors in the region of coupled atmospheric-ocean general circulation models, and improved model simulations and predictions of the coupled climate in the SEP and global impacts of the system variability. Program documents and information can be found at *www.eol.ucar.edu/projects/vocals/*.

VOCALS is organized into two tightly coordinated components: 1) a **R**egional **Ex**periment (VOCALS-REx), and 2) a Modeling Program (VOCALS-Mod). Extended observations (e.g. IMET buoy, satellites, EPIC/PACS cruises) will provide important additional contextual datasets that help to link the field and the modeling components. The coordination through VOCALS of observational and modeling efforts (Fig. 3) will accelerate the rate at which field data can be used to improve simulations and predictions of the tropical climate variability. VOCALS is a CLIVAR program sponsored by NSF and NOAA with contributions from ONR and DoE.

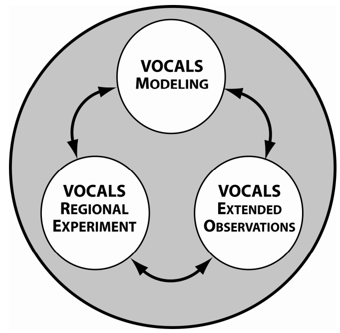

Figure 3: The VOCALS Strategy: Intensive field data (VOCALS Regional Experiment), extended observations (e.g. cruises, satellite, buoy), and numerical modeling (from process models to global models) are coordinated under the VOCALS program. This integrated approach ensures that the observational programs target the key issues required to improve large scale model simulations of the SEP climate system.

3. VOCALS Scientific Issues

a. Aerosol-cloud-precipitation interactions in the marine PBL

In addition to responding to large-scale dynamics, cloud optical properties over the SEP are also impacted by atmospheric aerosols (Huneeus et al. 2006), with contributions from both natural and anthropogenic sources. Cloud droplet effective radii are small off the coast of Chile and Peru (Fig. 3), implying enhanced cloud droplet concentration, particularly 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 (Source:GEIA). Regional changes in surface and TOA radiation caused by the enhanced effective radii are as high as 10-20 W m^{-2} (Fig. 4), with significant, but currently unknown, implications for the ocean heat budget.

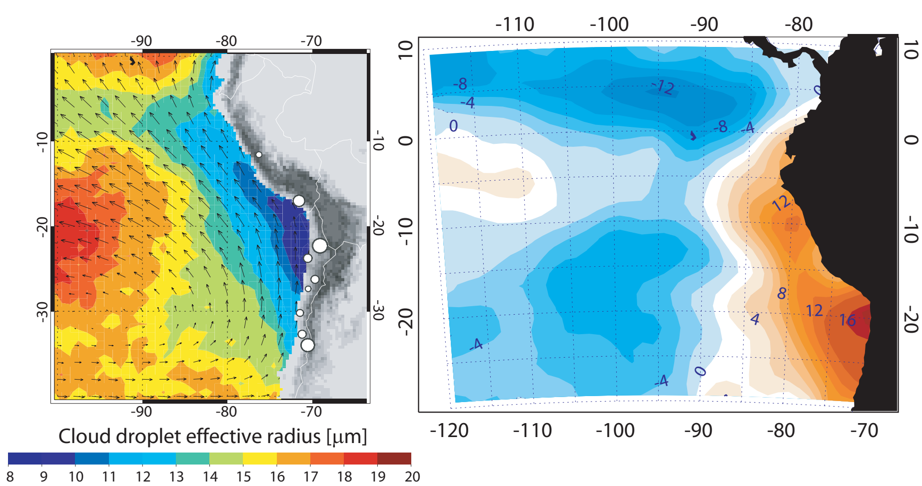

Figure 4: Left: Austral spring season (SON) mean cloud droplet effective radius from MODIS; mean surface winds from Quikscat. Locations of the major copper smelters in the region are shown as white circles (relative area proportional to their expected sulfur emissions). Right: Component of SON shortwave cloud forcing [W m^{-2}] due to geographic variations in effective radius, inferred from MODIS.

The East Pacific Investigation of Climate (EPIC) field study (Bretherton et al. 2004) found evidence that drizzle formation, enhanced by the depletion of aerosols (Wood 2006) in the clean MBL (Fig. 5), 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.

b. Systematic biases in atmosphere-ocean GCMs

CGCMs have difficulties in simulating marine stratocumulus clouds (Ma et al. 1996; Kiehl and Gent 2004; Wittenberg et al. 2006). This is attributable, in part, to the inadequate representation of MBL processes (turbulence, drizzle, mesoscale organization) in large and regional scale atmospheric models, and to a poor representation of cloud microphysical processes (i.e. aerosol processes, including their transport from continental sources and their removal by drizzle). Studies using CGCMs (Ma et al. 1996, Gordon et al. 2000) demonstrate that the accurate prediction of the optical properties of low clouds over the SEP is required in order to simulate the strong trade winds and the observed SST distribution.

The OGCM components of CGCMs also have difficulties with coastal upwelling, and the offshore heat and nutrient transport by the associated mesoscale eddy field (Penven et al. 2005, Colbo and Weller 2006).

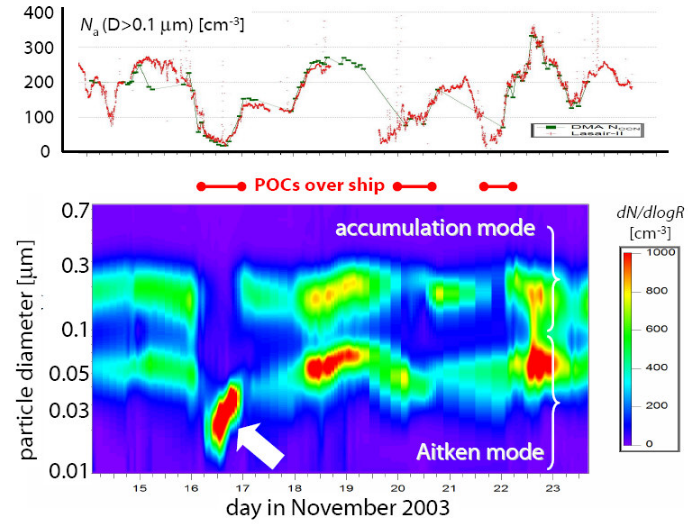

Figure 5: Accumulation mode aerosol concentration (top), and aerosol size distribution (bottom) measured on the R/V Roger Revelle over the SEP during November 2003. The red horizontal bars indicate periods where satellite imagery revealed pockets of open cells (POCs) over the ship. At these times there is strong reduction of the accumulation mode aerosol concentration, and on the 16th (white arrow) there is evidence of new particle formation.

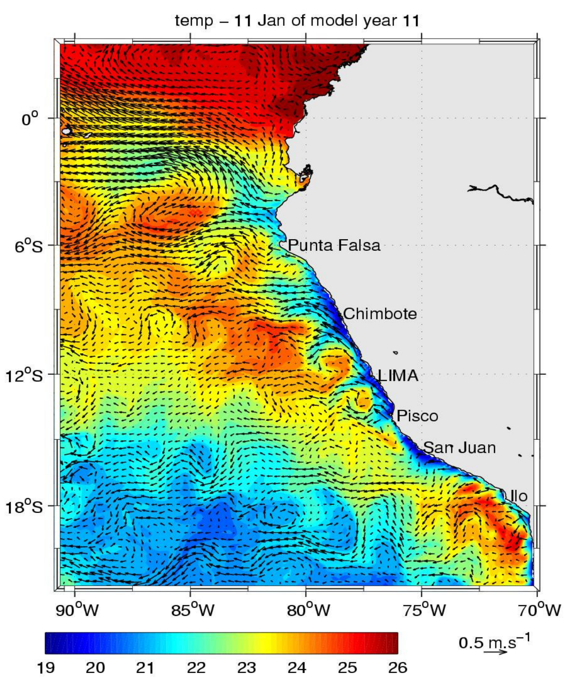

Figure 6: SST and surface current variability associated with the mesoscale ocean eddy field in a regional ocean model.

Mean advection velocities in the upper ocean in the SEP are weak (few cm s^{-1}). The upper ocean, therefore accumulates and expresses locally the influences of lateral fluxes associated with eddies (e.g. Penven et al. 2005), and vertical mixing events associated with atmospheric forcing transients (Wijesekera and Gregg 1996). Satellite altimetry, SST maps, and regional ocean models all reveal that mesoscale ocean eddies 50-200 km across can affect SST well offshore by fluxing cold water from the coastal upwelling regions (Fig. 6). Eddies could also impact the ocean-atmosphere flux of dimethylsulfide (DMS), an important precursor gas for cloud condensation nuclei. Eddy heat flux divergence may account for roughly 40 W m^{-2} net heat flux into the ocean over the remote SEP (Colbo and Weller 2006). In addition, increased vorticity and shear within eddies may enhance the response of the oceanic mixed layer to the wind forcing and convective overturning. Mesoscale eddies are poorly observed and understood, and are barely resolved in coupled ocean-atmosphere climate models (Canuto and Dubovikov 2005). Observations at the IMET buoy (20°S, 85°W) show that another challenge for OGCMs is vertical mixing at the base of the upper layer by near-inertial oscillations, which can entrain fluid from the cool, fresh intermediate water below.

VOCALS-Mod posits that alleviation the difficulties with the simulation of stratocumulus and coastal upwelling will result in major improvements in GCM performance. These improvements include the alleviation/elimination of the double-ITCZ biases that characterizes contemporary CGCMs. There is evidence that this bias has a negative effect on the CGCM performance in the prediction of ENSO and its remote impacts.

c. Interactions between the SEP with remote climates

There is consensus that climate variability in the SEP can imprint a signature in large-scale fields via teleconnections. Previous work has provided indications that features of tropical precipitation patterns are strongly influenced by the SEP (Ma et al. 1996; Large and Danabasoglu 2006). The pronounced annual cycle in the equatorial cold tongue is also considered to originate from the SEP (Mitchell and Wallace 1992; Xie 1994). Atmospheric disturbances in the SEP with an asymmetric structure propagate westward in the form of Rossby waves (Xie 1996), and oceanic disturbances similarly propagate westward as Rossby waves and eddies (Chelton and Schlax 1994; Chelton et al. 2006). However, the mechanisms of interaction are not well understood.

4. VOCALS-REx

a. Goals and Hypotheses†

VOCALS-Rex will collect datasets required to address a set of issues that are organized into two broad themes: (1) aerosol-cloud-precipitation interactions in the marine boundary layer (MBL) and the physicochemical and spatiotemporal properties of aerosols; (2) chemical and physical couplings between the upper ocean, the land, and the atmosphere. These two sets of hypotheses are directly linked to the themes of the VOCALS Modeling Program (see Section 5). This strategy has been carefully designed so that the modeling makes best use of the REx data, and so that the models are used, from the outset, as an integral component of the field analysis at all stages from process studies through parameterization and model development. Figure 7 presents a graphical summary of the field sampling.

b. Aerosol-cloud-precipitation theme

The overarching goal for work in the first theme is a better understanding of processes that influence cloud optical properties (cloud cover, thickness, and particle size) over the SEP. We focus these goals using the following testable hypotheses:

[H1a] Variability in the physicochemical properties of aerosols has a measurable impact upon the formation of drizzle in stratocumulus clouds over the SEP.

[H1b] Precipitation is a necessary condition for the formation and maintenance of pockets of open cells (POCs) within stratocumulus clouds.

[H1c] 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).

[H1d] Depletion of aerosols by coalescence scavenging is necessary for the maintenance of POCs.

A comprehensive suite of in-situ and remotely sensed cloud and boundary layer measurements will be performed using the aircraft platforms (see Fig. 7 and strategy below) and the ships to address issues in this theme. It is becoming recognized that precipitation falling from stratocumulus clouds can have a profound impact upon the cloud structural, dynamical, and radiative properties (Stevens et al. 2005). Aircraft missions will focus upon understanding the processes that control precipitation, including the role of atmospheric aerosols, their transport from the land to the ocean, and their depletion by the clouds themselves. A key goal is to better link aerosol microphysical variability with the variability in the radiative properties of the clouds by performing closure studies that not only link cloud microphysics with aerosol microphysics, but also link the cloud optical properties (measured with aircraft and satellite remote sensing) to the underlying aerosol variability.

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† Strategies on the scientific background on the hypotheses and details about how VOCALS-REx will address them are given in the VOCALS Scientific Program Overview (see *www.eol.ucar.edu/projects/vocals/*). Only a brief summary is presented here.

c. Coupled ocean-atmosphere-land theme

The goals of the second theme aim to elucidate the roles that oceanic upwelling, mesoscale eddies and other transient upper oceanic processes, and the land play in determining the physical and chemical characteristics of the upper ocean across the SEP.

> *[H2a] Oceanic mesoscale eddies play a major role in the transport of heat and fresh water from coastally upwelled water to regions further offshore.*
>
> *[H2b] 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.*
>
> *[H2c] The diurnal subsidence wave ("upsidence wave") originating in northern Chile/southern Peru has an impact upon the diurnal cycle of clouds and provides a useful framework for analysis of numerical model performance on diurnal time scales.*
>
> *[H2d] 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.*

To address the issues in this theme, a ship towing the SeaSoar platform will be used, in conjunction with the NOAA Ronald H Brown (RHB) to conduct surveys of the mesoscale eddy field both in the eddy genesis region close to the coast, and much further offshore. Detailed measurements of the microscale variability of the upper ocean will be used to explore the connections between the ocean mixed layer and the ocean beneath. Chilean and Peruvian coastal components are expected to provide key data on the nature of the upwelling and the initiation of the mesoscale eddies. Links between the variability in oceanic upwelling and the biogenic production of important aerosol precursor gases (e.g. DMS) will be explored using DMS flux measurements. In addition, the role of the land at modifying the diurnal cycle (Garreaud and Muñoz 2004) and synoptic variability of clouds and low level winds will be explored.

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. VOCALS-REx will offer an unparalleled combination of in-situ and remotely sensed cloud measurements, which will be used to tackle outstanding satellite remote sensing problems. Satellite measurements are the key to better global and regional quantification of the indirect effects of aerosols upon clouds and the climate system.

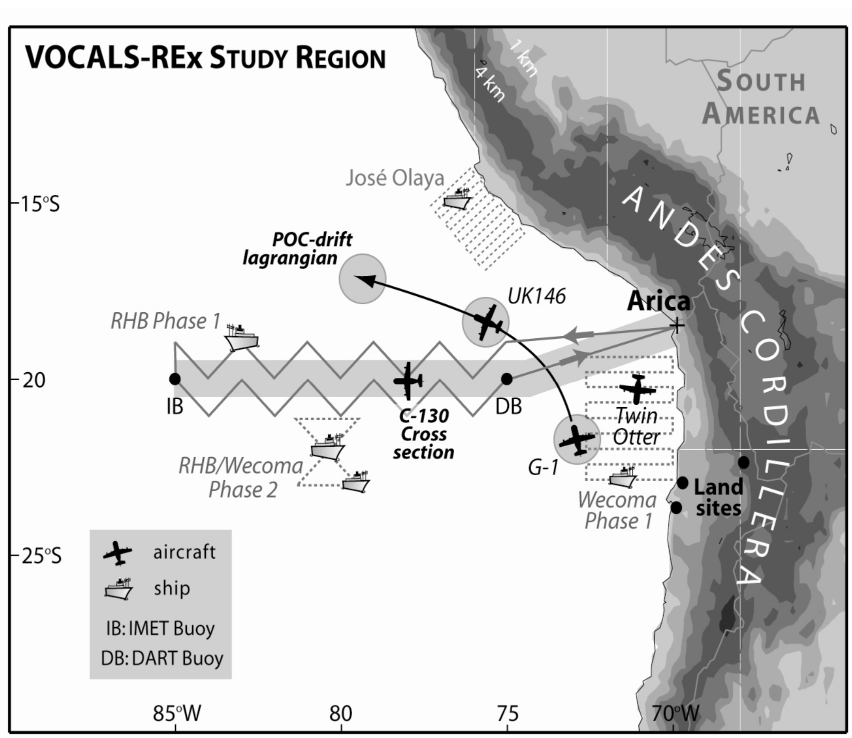

Figure 7: VOCALS-REx study region and key platforms/components

For Phase 1, the NOAA Ronald H Brown (RHB) will make measurements for 6 days at each of the IMET (20°S, 85°W) and DART (20°S, 75°W) buoys, transiting between the buoys with a concertina pattern to sample mesoscale ocean variability, while the Wecoma carries out a survey of the eddy-genesis region close to the coast.

For phase 2, the Wecoma will survey oceanic mesoscale variability (using SeaSoar) and its effects on the atmosphere around the RHB (one possible pattern is shown).

The NCAR C-130 will make cross-sectional measurements along 20°S out to 85°W, and will also conduct POC-drift and multi-day lagrangian flights (with other aircraft) to study the structure of POCs and the evolution of the MBL. The other aircraft (DoE G-1, CIRPAS Twin Otter, and the UK 146) will work mainly in the near-coastal zone to examine aerosol, cloud and precipitation variability.

The R/V José Olaya coastal cruise will sample oceanic upwelling and the MBL structure.

The land sites will be used to examine the chemical and physical properties of airmasses advected from Chile over the SEP.

d. Strategy

VOCALS-REx will have an intense observing period during October-November 2008. The observational platforms during the period will comprise aircraft (chiefly the NSF C-130, the CIRPAS Twin Otter, the DoE G-1, and possibly the UK BAe-146), research ships (the NOAA Ronald H Brown (RHB), and a second ship, most likely the R/V Wecoma or similar), a land site in Chile, and Peruvian and Chilean coastal cruises. Figure 7 shows a map of the VOCALS-REx study region and platforms involved. VOCALS-Rex activities have been carefully designed to complement and enhance a suite of enhanced long-term observations in the SEP. These include an uninterrupted six year record from the IMET instrumented surface buoy (85°W, 20°S), annual buoy maintenance cruises (in 2001 and then in 2003-2006 as part of the EPIC/PACS program), and regionally-subsetted satellite data (coordinated through JOSS), have been used extensively to provide important context for modeling activities and to aid our understanding of the physical processes occurring in the SEP.

5. The VOCALS Modeling Program (VOCALS-Mod)

a. Goals: A principal goal of VOCALS is to improve model‡ simulations of key climate processes using the SEP as a testbed, particularly in coupled models that are used for climate change projection and ENSO forecasting. VOCALS-Mod, therefore, provides the context for VOCALS and will directly benefit from the observations collected in the field campaign. The goals of VOCALS-Mod reflect the two overlapping themes of VOCALS, coupled ocean-atmosphere-land interaction and cloud-aerosol-drizzle interactions. These goals are:

(1) Understanding and reducing the warm SEP SST bias near the coast and excessive interhemispheric symmetry in the eastern tropical Pacific present in most CGCMs.

(2) Using the SEP as a testbed for better simulation of boundary-layer cloud processes and aerosol-cloud interaction, including the relative roles of natural and anthropogenic aerosol sources and their impact on cloud optical properties (coverage, thickness, and droplet size).

(3) Improving the understanding and simulation of oceanic budgets of heat, salinity, and nutrients in the SEP and their feedbacks on the regional climate.

(4) Elucidating interactions between the SEP and other parts of the earth's climate system, including the South American continent, the Pacific circulation and ENSO.

VOCALS-Mod will also provide modeling support for VOCALS-REx through real-time forecasts and data assimilation.

b. Multiscale modeling hierarchy: The VOCALS modeling vision is based on the concept of a multiscale hierarchy of models. This is motivated by the multiscale nature of processes in the SEP and the multiscale hierarchy of VOCALS observations, including REx, extended in-situ and satellite data. To implement this vision, VOCALS-Mod will coordinate activities carried out at operational centers (NCEP), research laboratories (NCAR, GFDL) and universities, using VOCALS observational datasets both to evaluate model performance and to inform physical parameterization development. Use of the operational modeling systems will provide insight into the time evolution of errors and their dependency on the analysis employed for initialization; use of research modeling systems will facilitate hypothesis-testing experiments.

c. Modeling Strategy: Cloud-Aerosol-Precipitation Themes

1. Chemical and aerosol transport modeling

Regional and global atmospheric models will be used to test our understanding of natural and anthropogenic aerosol sources in this region and understand what determines aerosol and cloud droplet concentrations and their variability over the SEP and. Models will be tested by comparing aerosol

‡ The numerical models to be used include 1) Large-Eddy Simulation Models (LESs), 2) Regional Atmospheric Models (RAMs), 3) Regional Ocean Models (ROMs), 4) Coupled ROM-RAM Models (ROAMs), 5) Atmospheric General Circulation Models (AGCM), 5) Oceanic General Circulation Models (OGCMs, 6) Coupled Atmosphere-Ocean General Circulation Models (CGCM), and 7) Single Column Models (SCM) for clouds and aerosols.

concentrations in and above the boundary layer, and satellite retrievals and REx observations of aerosol and cloud microphysical parameters.

2. Improving parameterizations of boundary layer clouds

REx and satellite observations of SEP cloud and boundary-layer properties will be used to improve the representation of boundary-layer clouds in participating AGCMs and RAMs, including parameterizations of turbulence, aerosol scavenging, cloud fraction and cloud microphysical (drizzle) processes, and turbulence, building on results from the EPIC stratocumulus cruise (Bretherton et al. 2004). Single-column modeling based on REx will be an important analysis tool.

3. LES of aerosol-drizzle-cloud interaction and POCs

LES models will be used to investigate the physical processes involved in the formation and maintenance of pockets of open cells (POCs) and compare with VOCALS observations. Particular modeling foci will be the simulation of POC formation, aerosol budgets, and mesoscale circulations at the edges of POCs, and on comparing POC and non-POC regions.

d. Modeling Strategy: Coupled Ocean-Atmosphere-Land Themes

1. Simulation and data assimilation of SEP ocean mesoscale structure from 0-2000 km offshore

The ability of high resolution eddy-resolving ocean models (horizontal grid spacing <10 km) to accurately resolve the SEP eddy structure will be critically tested using the VOCALS-REx oceanographic mesoscale survey and satellite data. VOCALS will use ROMs to simulate the horizontal and vertical eddy structure (including synthetic analyses for REx using ocean data assimilation), eddy heat/freshwater/tracer/nutrient transports from the coastal upwelling region to the remote SEP, and interactions between the eddies, the mixed layer and the deeper ocean.

2. Multiscale assessment of SEP ocean eddy transport, heat budgets, and SST biases in CGCMs

In large-scale coupled models, complex ocean mesoscale circulations must be parameterized. Nevertheless, in a few large-scale models, SEP SST biases have been reduced to as little as 1 K even with a horizontal grid spacing as coarse as 50-100 km or larger. We must understand whether this involves a physically correct balance of processes and how to generalize these improvements to other models. This requires a comparison of SEP mixed-layer heat budgets in large-scale ocean and coupled models with VOCALS observations and eddy-resolving ROMs, and systematic sensitivity studies to horizontal and vertical resolution of both ocean and atmosphere models.

3. Diagnostic studies of the SEP regional climate system (coupled patterns of variability)

VOCALS will use regional and global models to investigate the coupling between the atmosphere, ocean and land in the SEP region, including model skill in simulating the strong diurnal cycle and its forcing, as well as dominant coupled patterns of SEP cloud-topped boundary-layer, wind, SST (upwelling), and aerosol variability on day-to-week timescales.

4. Modeling feedbacks between SEP and global-scale climate biases (incl. ENSO).

To foster better understanding of how the SEP interacts with global climate, VOCALS-Mod will study the response of the global circulation in coupled models to regional changes in model physics over the SEP. One approach to this is a Multi-Scale Simulation and Prediction (MUSSIP) system based on a RAM coupled to an eddy-resolving ROM, both embedded within a global climate model. The MUSSIP hypothesis is that high-resolution simulation of the SEP can greatly reduce model biases in this region and thereby considerably improve the entire tropical circulation.

Coordinated Model Assessment: VOCALS-Mod will coordinate an assessment of how well atmospheric models can simulate and interpret the time-varying regional structure of clouds, winds, and aerosols during the REx period. Global reanalysis data will be used as forcings for RAMs and ROAMs. The model data will be compared directly with VOCALS-REx and VOCALS extended observations (e.g. mesoscale ocean eddies, satellite and ship-observed clouds). A pilot for this study, the Preliminary VOCALS Assessment (PreVOCA), is being carried out within the VOCALS modeling community.

VOCALS-Mod participants will also participate in organized modeling activities, such as community-wide tropical bias workshops, the GCSS/WGNE Pacific Cross-section Intercomparison (GPCI) project, and the GEWEX Cloud System Study (GCSS).

The VOCALS Legacy

VOCALS has been conceived with the overarching goal of improving large scale coupled ocean-atmosphere model simulations and predictions of the SEP climate system. This will be achieved with a coordinated modeling and observational program, in which datasets are identified, generated and shared through a VOCALS-wide data archive. Datasets generated will be made available to the broad modeling community as soon as quality control is completed. A multi-scale simulation and prediction system will be developed. This will offer a paradigm for use in the eastern part of the tropical oceans. VOCALS will pave the way for field campaigns in the stratocumulus regions in the eastern tropical Atlantic, which influence the western African summer monsoon. VOCALS will provide education and training for scientists in the international climate community in several areas of major current interest.

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