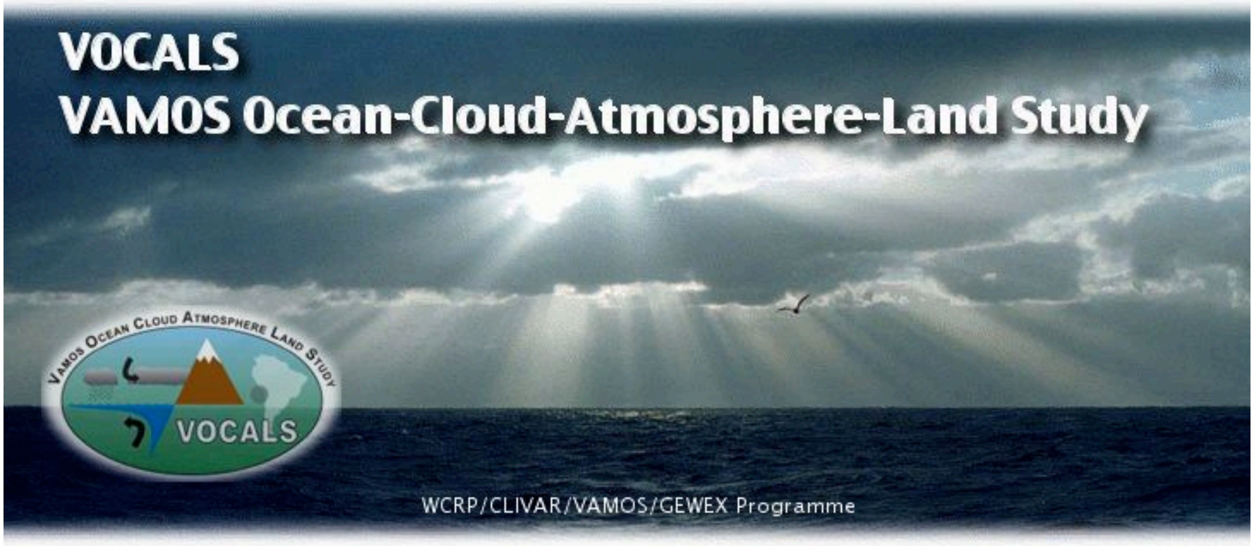

VOCALS Modeling Plan

VOCALS Science Working Group

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VOCALS Modeling

1. Introduction

The **V**AMOS **O**cean-**C**loud-**A**tmosphere-**L**and **S**tudy is an international program designed to better understand the physical and chemical processes central to the climate system of the Southeastern Pacific (SEP). VOCALS is organized as two major efforts: 1) VOCALS **R**egional **Ex**periment (VOCALS-Rex), and 2) VOCALS Numerical **Mod**eling (VOCALS-Mod). The VOCALS Science and Experiment Plans Overview can be obtained at the project's web site: www.eol.ucar.edu/projects/vocals.

VOCALS-Mod will contribute to the overall project's goals by 1) improving the understanding and simulation of the seasonal cycle and interannual as well as interdecadal variability in the SEP, 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.

The metrics for success of the VOCALS modeling component are the reduction of systematic errors in simulations of the SEP climate by regional and global numerical models of the coupled atmosphere-ocean system, and the improvement in the simulation and understanding of aerosol-cloud-drizzle interactions in the marine Planetary Boundary Layer (PBL).

2. Modeling issues in the SEP

There is a consensus that the numerical simulations of the SEP climate faces major issues and challenges:

- 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).
- A realistic simulation of the tropical stratocumulus by an AGCM (with prescribed SSTs) does not guarantee a single northern 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.
- The wind-driven oceanic circulation in the SEP develops a vigorous mesoscale and submesoscale eddy field that covers a much larger area than the coastal upwelling zone. The extent to which OGCMs capture this extension is unclear.
- Global OGCMs have difficulties with the simulation of eddy transports of heat, salinity, and nutrients in the SEP, most plausibly because they do not resolve well the regional upwelling currents and eddies.
- Mesoscale atmospheric processes, such as those at work for pockets of open cells (POCS),

influence cloud properties over the SEP. The PBL parameterization of AGCMs does not adequately consider those processes.

- 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. 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.
- Microphysical processes affect cloud properties in the SEP. The variability of those processes is strongly affected by aerosols, derived in varying degrees from natural (surface emissions) and anthropogenic (industrial emissions via the FT) sources. The aerosols impact clouds by enhancing cloud optical thickness and suppressing drizzle, while the clouds impact the aerosols through coalescence, loss by drizzle, and competition for precursor gases. CGCMs do not address the potentially important feedbacks associated with the effects of aerosol upon the SEP coupled ocean-atmosphere system.

There is also consensus that model difficulties in the SEP can imprint a signature in the simulation of large-scale fields via teleconnections:

- The CGCMs errors are consistent with a "double ITCZ bias" and the poor simulation of tropical variability (including ENSO). The interhemispheric asymmetry of the ITCZ is missed by practically all coupled atmosphere-ocean GCMs, which tend to produce either two ITCZs straddling the equator or a single one that migrates between the two hemispheres (Mechoso et al. 1995; Kirtman et al. 2002; Collins et al. 2005; Meehl et al. 2005). Previous work has provided indications that it and other features of tropical precipitation patterns are strongly influenced by the SEP (Ma et al. 1996; Large and Danabasoglu 2006).
- Deficiencies in ENSO simulation and prediction can affect remote climates, particularly over the Americas.
- 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).

3. VOCALS modeling hypotheses

- The CGCMs difficulties in capturing the effects on the SEP of an upstream region with strong coastal upwelling and high Sc incidence are crucial contributors to the model errors in the region.
- In the atmosphere, southeast trades from the South American coast flow from a cool and dry PBL over strong SST gradients and regions where trade cumuli form moistening the lower troposphere. These processes are not well represented by AGCMs.
- In the ocean, mesoscale eddies not captured by OGCMs play a major role in the transport of heat and fresh water from coastally upwelled water to regions further offshore.

- An approach based on regional and high-resolution ROAM embedded within the seasonally and interannually varying global climate is the methodology with the highest potential to overcome climate model difficulties in the region within the VOCALS time frame.

4. VOCALS models and modeling approach

VOCALS will establish links among operational centers (NCEP), research laboratories (NCAR, GFDL) and universities (CSU, UCLA, UCSD, UH, UW, UCH). The combined expertise will be directly applied to improving seasonal forecasting with global models developed for operational numerical weather prediction and climate studies. 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 the realization of hypothesis-testing experiments.

The collaborations established will assure the availability of the hierarchy of numerical models needed to address the broad range of space and time scales of processes in the VOCALS region. The numerical models in the hierarchy will 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.

The research methodology in VOCALS modeling will be organized as the following activities, of which the realization will be tightly coordinated among VOCALS modeling projects:

1) Diagnosis of simulations of the SEP climate and oceanic circulation using both model output and observational data, including data assimilation.
2) Simulation and/or prediction with different model types for the austral spring, including the VOCALS-Rex season, analysis of the predictions, and comparison with the observations.
3) Assessment of the impact of VOCALS-Rex enhanced observations on predictions through data assimilation.
4) Model development for error alleviation, including parameterizations of PBL, microphysical, and oceanic-eddy processes.
5) Organized modeling activities, such as the community-wide "Correcting Tropical Biases Workshops" and the GCSS/WGNE Pacific Cross-section Intercomparison (GPCI) project.

5. VOCALS Modeling Tasks

a. Downscaling to the VOCALS Rex-Region

One of the major contributions to VOCALS from its modeling component will be the downscaling of atmospheric (re-) analysis and oceanic datasets to the VOCALS-Rex region. The project's RAMs and ROMs forced on the lateral boundaries by products such as the NCEP (re-) analysis are expected to reproduce not only the large-scale circulation of the atmosphere but also synoptic disturbances sampled by VOCALS observations. The three-dimensional and time-varying perspective provided by the simulation will help interpret field observations made of a few transects and stations for a limited time. The output of the the regional models will be critically compared with the observation, especially the horizontal and vertical structures of wind, temperature, vapor and liquid water, and their diurnal and synoptic variations. For the ocean, in particular, the scientific strategy uses data gathered in VOCALS-REX to establish eddy and frontal structures and assess model verisimilitude, and then uses the models to establish the eddy heat flux consequences. A pilot project will be done before VOCALS-Rex to gain experience and physical insights to refine the design of the field experiment as necessary.

Real-time forecast for the VOCALS-Rex will also be performed. These coupled real-time forecasts will provide a) a complete definition of atmospheric flows in the region, which will be used in subsequent analyses such as investigation of mesoscale structure, evaluation of modeled MBL structure and cloud distribution and LES simulation studies; b) SST distribution in the region, ocean flow and temperature profiles in the water for study of physical processes that regulate SST.

Immediately after completion of VOCALS-Rex, a dataset will be produced by the method of data assimilation using a 4D-variational data assimilation system for high-resolution basin-wide and coastal oceanic flows.

b. Modeling and analysis of stratus buoy maintenance cruises

VOCALS Rex builds on a series of annual cruises to the SEP in austral spring starting in 2000. The primary purpose of these 2-3 week cruises is to maintain the WHOI stratus buoy, but during the EPIC stratocumulus experiment in 2001, a broad suite of NOAA surface flux and cloud remote sensing instrumentation was taken (Bretherton et al. 2004). An integrated 6-day long dataset[1] has produced from the portion of this data taken at the stratus buoy (Caldwell et al. 2005) is being used by the modeling community to examine the ability of AGCMs run in single-column or weather –forecast modes to accurately simulate the diurnal cycle of low clouds over the SEP. Experience at the University of Washington has been that it is even challenging for an LES to simulate the diurnal cycle of cloud cover and drizzle in this EPIC dataset. Similar measurements (with the addition of some aerosol characterization) have been made on subsequent cruises since 2003, sampling a broader range of cloud regimes, and we plan to gather these into additional integrated datasets and compare them similarly with models. These efforts are building VOCALS modeling expertise and infrastructure needed to best use the Rex data, as well as being valuable in their own right.

c. Diagnostic Studies of the Climate System

VOCALS will conduct a series of diagnostic studies using simulated, observed and model-assimilated datasets. The coupling between atmosphere and ocean in the SEP is sensitive to the stratocumulus cloud cover, PBL structure including a strong diurnal heating cycle modulated by the cloud cover, orographically and thermally patterned wind forcing, and mesoscale eddy modulation of the boundary layer depth (e.g., Chelton et al. 2001; Capet et al. 2004). There is evidence that decreased SST caused by mesoscale ocean variability encourages the formation of low clouds (Hashizume et al. 2001; O’Neill et al. 2005).

In the atmosphere, diagnostic studies will address the extent to which the effects of cold and dry conditions near the coast of South America extend westward in the atmosphere of the SEP.

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[1] *www.atmos.washington.edu/~caldwep/research/ScDataset/sc_integ_data_fr.htm*

Southeast trades from flow from a cool and dry PBL over strong SST gradients and regions where trade cumuli form moistening the lower troposphere. The studies will include detailed analysis of the momentum, vorticity, moisture, and moist static energy budget budgets. The importance of moisture and moist static energy advection has been emphasized in several studies of the circulation in the tropics (Sobel and Bretherton 2000; Neelin and Zeng 2000).

In the ocean, diagnostic studies will address the extent to which the effects of upwelling along the South American coast act on the SEP and are captured by CGCMs, and whether rectification of ocean eddy effects plays an important role on basin scale atmosphere-ocean interactions in the SEP. Recent observations at the WHOI stratus buoy suggest that the SST advection by mean flow is insufficient to explain the offshore cooling over the Southeast Pacific. Mesoscale eddies, therefore, can play an important role in closing the ocean mixed layer budget by providing shoreward heat and material transport that balance the upwelling supply of cold water and the air-sea heat exchange. A source of eddies in the SEP is the instability of the Peru Current, which comprises an equatorward surface geostrophic flow and a poleward undercurrent that is strongest in summer. There are also standing eddies associated with alongshore coastline and bathymetric irregularities (e.g., Barth et al. 2000 for the northeastern Pacific).

d. Aerosol-Cloud-Drizzle-Ocean Interactions

A central goal of VOCALS-REx is to take a comprehensive set of coordinated saircraft, ship, and satellite measurements of aerosol-cloud-drizzle-ocean interaction. The emphasis will be on drizzle production, mesoscale organization of cloud structure and the impact of large/meso-scale conditions such as vertical motion and horizontal winds/advection. Statistics derived from these will be used to constrain and refine parameterizations of aerosol scavenging, cloud fraction and cloud microphysics processes used in participating AGCMs and RAMs, building on results from the EPIC stratocumulus cruise (Bretherton et al. 2004, Comstock et al. 2004).

Since POCs appear to be a particularly striking form of aerosol-cloud-drizzle-ocean interaction in the SEP and will be heavily studied in REx, they are also a key VOCALS modeling challenge. 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.

Conceivably, a multiscale approach based on a moving LES grid nested within a regional coupled atmosphere-ocean modeling system could be used to simulate the entire lifecycle of a POC, including the supporting synoptic conditions. This 'grand challenge' modeling problem would truly test that we can quantify all the microphysical and aerosol processes involved in POC evolution.

e. Biogeochemical Processes

The potential link between ocean and atmosphere, and between biogeochemical and physical system components, is a major focus of VOCALS and the VOCALS-Rex campaign. DMS emissions may play a major role in controlling the distribution of cloud condensation nuclei (CCN) and hence the optical properties of stratocumulus cloud. VOCALS, therefore, will develop the capability to simulate DMS fluxes from ocean to atmosphere. There are relatively simple models of DMS production that could be easily added to ROMS (Aumont et al. 2002; Kloster et al. 2006), and the resulting fluxes can then be validated against published climatologies (e.g. Belviso et al. 2004) as well as direct measurements of both DMS-producing biota and fluxes.

f. Regional and Global Model Development

VOCALS will use knowledge gained from the VOCALS-Rex campaign to improve and develop parameterizations for regional and global models. For example, VOCALS-Rex will measure mesoscale POCs and drizzle, which are being recognized as influencing statistical-mean properties of low cloud. The field campaign will also provide a unique dataset to test aerosol activation parameterizations. Data collected during VOCALS-Rex will be used to evaluate and improve boundary layer and cloud physics packages as well as next generation parameterizations being developed.

The participating SCMs and ROAMs will be used as test beds for these new parameterizations, and to refine and constraint parameterizations for PBL turbulence and cloud microphysics. Important requirements include a favorable comparison with VOCALS-Rex data as well as a successful reproduction of large-scale, monthly/seasonal-mean state of the SEP climate, which will be monitored from satellite and (re-) analysis products. The observation-model comparison is a two-way iterative process to help interpret observations on one hand and constrain the simulation and model physics on the other.

The ultimate goal is the elimination of the systematic errors of CGCMs in the eastern part of the tropical oceans. VOCALS researchers will target several key model components such boundary layer and stratiform cloud parameterizations. Work will be also performed to include aerosol activation in the current framework in order to study anthropogenic aerosols and cloud interaction. There is a need to develop new formulations that will provide a consistent framework for the parameterization of clouds and boundary layer turbulence transport, which in turn will enable a more realistic treatment of the aerosol activation process.

e. Development of a Multi-Scale Simulation and Prediction (MUSSIP) System

The oceanic structure in the SEP, budgets, and biases in global coupled models, is strong motivations for a Multi-Scale Simulation and Prediction (MUSSIP) approach. VOCALS plans to investigate one possible approach, based on a RAM and an eddy-resolving ROM embedded within a global climate model or forced by reanalysis data (see Fig. 1). The focus will be on the eastern tropical Pacific and adjacent areas of the South American continent, from approximately

5N to 30S, and 65W to 90W, which comprises the area of VOCALS-Rex. The regional approach facilitates much higher resolution, allowing for important effects of complex topography and bathymetry on atmospheric and oceanic solutions. Typical length scales of topography and bathymetry in the SEP are on the order of a few km, roughly comparable with the model resolution possible given current computational limits.

The MUSSIP approach is predicated on the importance of climate interactions across scales, i.e., that global changes are manifested in their regional details by downscaling effects (e.g., wind and cloudpatterns adjacent to the Andes and coastal upwelling zone) and that global changes themselves occur through important upscaling effects of the regional climate (e.g., teleconnection consequences for precipitation changes throughout the tropics due to Southeast Pacific surface temperature changes). While the present suite of models span all the requisite functional categories, but as yet there is little experience in their cross-scale coupling either in the atmosphere or ocean. The strategy in VOCALS is to first secure the downscaling and the regional air-sea couplings and then to extend toward upscaling coupling capabilities for both AGCM-RAM and OGCM-ROM. This has considerable algorithmic, software, and physical challenges. In VOCALS this will be approached in stages, first demonstrating the upscaling impact of the downscale-coupled solutions with ad hoc couplings while proceeding towards a more comprehensive MUSSIP system.

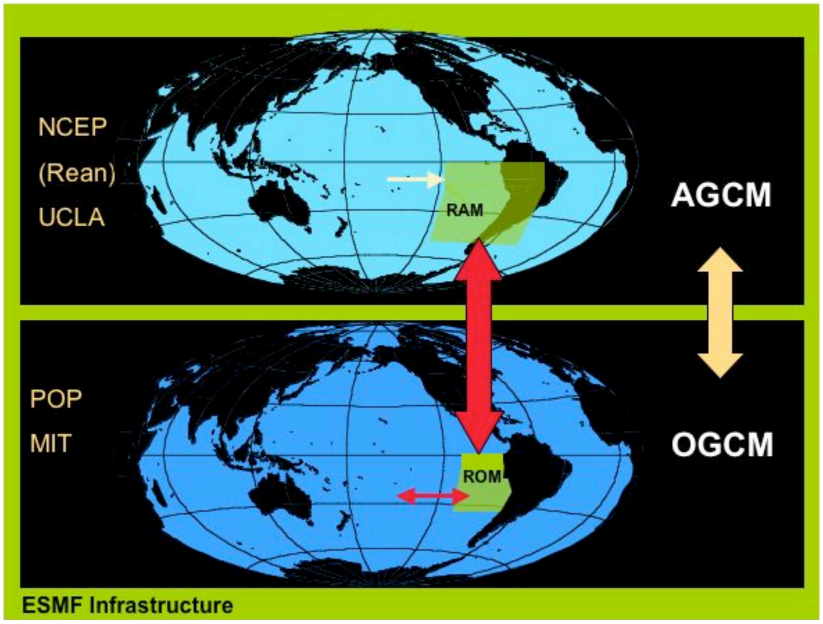

Figure 1. A multi-scale approach to seasonal prediction

The leading candidate for RAM in the MUSSIP system is the NCEP version of the Weather Research and Forecast (WRF) model in the NCEP and/or NCAR versions. The leading candidate for ROM is the Regional Ocean Modeling System (ROMS; Haidvogel et al., 2000; Marchesiello et al., 2003; Shchepetkin and McWilliams, 1998, 2003, 2004). The ROAM system will be coupled to the NCEP CFS for predictability and prediction research, and eventually to other GCMs in VOCALS for basic research on specific aspects of the climate system.

Several scientific and technical issues will have to be addressed before the MUSSIP system can be applied in real time. Extensive testing and analysis of the WRF will be required to assess whether the model can produce a successful simulation of stratocumulus clouds with prescribed SSTs. Similarly extensive tests will have to be performed with ROMS to assess whether the model captures the coastal upwelling and associated oceanic eddy field. Once these assessments are accomplished and the regional coupled system produces a realistic simulation of stratus, winds, and SSTs, is obtained the scientific focus will be to assess 1) the magnitude of errors in surface wind and surface energy budgets in the global models due to inadequate resolution and 2) the extent to which the large errors in tropical climate in the global models would be reduced if they were subject to the improvements in fluxes and winds of the regional simulation. Finally, the regional and global models will have to be coupled and tested in climate simulations.

VOCALS has assembled a team of researchers that are addressing all of these concerns and will coordinate their work for a much faster achievement of the project goals. For development and research, MUSSIP will have a highly modular structure based on the Earth System Modeling Framework developed under NASA/NSF funding. In this way, individual institutions will benefit directly from model improvements resulting from VOCALS, while simultaneously contributing to a new and more skillful national system for climate simulation and prediction.

6. Organization

A VOCALS Modeling Council (VMC) will coordinate efforts of participating teams and develop the bridge between observations and modeling needed to translate the knowledge and parameterization gains from observations into tangible improvements in both regional and global numerical models. The VMC will be appointed by the VOCALS Science Working Group.

It is envisioned that modeling projects will start at least one year before VOCALS-Rex. PIs of modeling projects will meet on a semi-annual basis before the field campaign and with less intensity afterwards to report on their progress towards VOCALS objectives.

VOCALS regularly report to CLIVAR and GEWEX through VAMOS.

7. Links to other programs

The VOCALS modeling activities have several important linkages to the international global climate modeling and prediction communities. As such, an important integrating element of this VOCALS modeling strategy is to examine the global scale coupled simulations made available through PCMDI and coupled prediction made available through CLIVAR-WGSIP and the COPES task force for seasonal prediction (TFSP) activities to assess how well the model capture the relevant physical phenomena. The importance of a local analysis of the global models cannot be overstated. The collaboration with CLIVAR-WGSIP and COPES-TFSP provides the relevant global modeling and prediction expertise and the VOCALS modeling community provides the focus expertise in the southeastern Pacific. Moreover, the VOCALS modeling community will continue to work with both the International (e.g., WGCM, WGSIP) and US CLIVAR (e.g., PPAI, PSMIP) communities to design numerical experiments to define model sensitivities that can then be used to improve the simulation in the southeastern equatorial Pacific.

Appendix A

VOCALS Models

1. Large-Eddy Simulation and Single Column models

Large eddy simulation (LES) models explicitly simulate the largest and most energetic eddies in a moist turbulent boundary layer using a three-dimensional grid. LES of subtropical stratocumulus typically employs a grid spacing of 10-100 m in the horizontal and 5-25 m in the vertical, and a time step of a few seconds, run over periods of hours to a few days. Radiative transfer, cloud microphysics, and subgrid turbulence must still be parameterized at each grid point, but LES produce realistic representations of the vertical structure and turbulence statistics of cloud-topped boundary layers. These models still have difficulty accurately simulating the entrainment into subtropical stratocumulus layers due to the extreme sharpness of the capping inversion, which is poorly resolved even by an LES grid. Despite this, LES represents the most realistic and complete method to simulate the response of low clouds to changes in atmospheric aerosols and the large-scale circulation. Continuing advances in computer power are stretching the maximum practical horizontal domain size for LES of subtropical stratocumulus, allowing grids of up to 1000 points (100 km) in the horizontal to be simulated for periods of a few days, as required for simulating the development of a small POC.

The University of Washington (UW) group uses the System for Atmospheric Modeling (Khairoutdinov and Randall 2003), developed at Colorado State University. It runs highly efficiently on Linux clusters, is simply coded and therefore easily customized, and has been extensively tested against observations and other LES models as part of GCSS Boundary-Layer Cloud and Deep Convection Working Group intercomparisons. It includes sophisticated radiation and bulk microphysical schemes. Other core VOCALS groups (e.g. NRL at Monterey) also have similarly sophisticated LES models, and in addition have capabilities for bin-resolved microphysical modeling, a more fundamental (but much more computationally expensive) approach for simulating the size distribution of cloud droplets at each grid point.

Single-column models (SCMs) emulate a single column of an AGCM, but with specified horizontal advection and vertical motion. They are useful for testing the realism of the AGCM physical parameterizations against observational datasets or similarly forced LES models, and for exploring model sensitivity to changes in vertical resolution and time step. GFDL and NCAR support SCM versions of their AGCM. The NCAR SCM (called the SCAM) is openly available to the scientific community. The UW group has considerable experience using the SCAM for testing of their moist turbulence and shallow convection parameterizations implemented in the current development version of CAM.

2. Regional models

Regional models, which afford high resolutions with downscaling skills, are very useful tools for study of the processes important for the mean state, seasonal and interannual variability of the atmosphere-ocean system. The models provide a bridge between field observations, parameterization development, and global climate models.

a. UCH-MM5/WRF

The Mesoscale Model of the 5th Generation (MM5) and the Weather and Research Forecast (WRF), two widely-used, regional atmospheric models, have been used at Department of

Geophysics – Universidad de Chile, to study several features of the weather/climate of the South-east Pacific (SEP) region. Particular emphasis has been put on the adequate simulation of the stratocumulus-capped marine boundary layer (MBL) in the SEP, since the distribution of low level coastal clouds, the intensity and direction of coastal winds and the amplitude of coastal temperatures are strongly modulated by the dynamics of this MBL. Past and ongoing research includes:

- Atmospheric gravity waves propagating from the coast of southern Perú – Northern Chile into the SEP, and their effect on the diurnal cycle of the stratocumulus (Garreaud and Muñoz 2004)
- Structure, variability and dynamics of the coastal jet off central-Chile (Garreaud and Muñoz 2005; Muñoz and Garreaud 2005)
- Structure and dynamics of the so-called coastal lows, coastally trapped disturbances often observed in North-central Chile (Garreaud and Rutllant 2003).
- Trajectory analysis over the SEP, in which we assess the oceanic/continental origin of air masses arriving to different locations (ongoing research)
- Juan Fernandez Island Wakes (ongoing research)

The regional models have been typically integrated with relatively high horizontal resolution (10-30 km), over domains on the order of 1000x1000 km2, and forced at their lateral boundaries by NCEP-NCAR reanalysis. While MM5 and WRF were initially designed for weather (short) simulations, increasing computing power has allow us to extend the integration periods up to a few months, getting close to regional climate simulations.

The "operational" vertical grid of MM5 has typically 30 sigma vertical levels, with a grid spacing of about 100 m in the lowest 2 km. Even with such high resolution (compared with most GCMs), key elements of this MBL are usually not well reproduced, including the boundary layer height and the cloud cover extent. Reasons for these deficiencies may lay in low spatial resolutions, poor initial conditions, limitations of the physical parameterizations of the model, or in a combination of these factors.

In some research applications significant increase of the vertical and horizontal resolution of model domains has proven valuable to produce a better match between model results and the limited observations available for specific periods. Currently, sensitivity analysis of model results to initial conditions, spatial resolutions and physical parameterizations are carried out in order to better understand the main physical processes controlling the different phenomena, and at the same time improving the skill of the models (MM5/WRF). In particular, we investigate now the sensitivity of the MBL depth to parameters of one of the turbulence schemes present in MM5 that control the partition between dissipation and buoyancy destruction of TKE in stable conditions. Preliminary results show that the entrainment rate at the top of the MBL in the model is indeed quite sensitive to this partition.

Within the context of VOCALS, we envision a major synergy among regional modeling, global modeling, and field observations. First, the available data on the 3-D dynamic and thermodynamic structure of the MBL in the SEP is generally too limited to be able to diagnose the regional model results, and identify the sources of important model errors. Until now, for lack of in-situ data, satellite-derived data (GOES images, QuikScat data) are amply used in the model validation efforts. During VOCALS field campaign, in-situ observations will give us an unprecedented dataset, with temporal and spatial resolution comparable with (or better than) those obtained from regional modeling, and hence allow a detail inter-model, inter-parameterization comparison and validation. Secondly, a suite of regional models will be run over the SEP region on real during (as well as a few months before/after) the VOCALS field campaign. Outputs from these regional models can serve as guidance for field operations. Finally, regional models can serve as a bridge between high-resolution field observations and coarse-resolution GCMs, as well as a test-bed for physical parameterizations used in GCMs.

b. WRF

Details of WRF-NMM can be found at "http://www.dtcenter.org/wrf-nmm/users".

c. RAMS

RAMS, the Regional Atmospheric Modeling System, is a highly versatile numerical code developed by scientists at Colorado State University for simulating and forecasting meteorological phenomena, and for depicting the results. Its major components are:

1. An atmospheric model, which performs the actual simulations,
2. A data analysis package, which prepares initial data for the atmospheric model from observed meteorological data, and
3. A post-processing model visualization and analysis package that interfaces atmospheric model output with a variety of visualization software utilities.

The atmospheric model is constructed around the full set of primitive dynamical equations with optional parameterizations for turbulent diffusion, solar and terrestrial radiation, moist processes including the formation and interaction of clouds and precipitating liquid and ice hydrometeors, sensible and latent heat exchange between the atmosphere, multiple soil layers, a vegetation canopy, surface water, the kinematic effects of terrain, and cumulus convection. RAMS is fundamentally a limited-area model, but may be configured to cover an area as large as a planetary hemisphere for simulating mesoscale and large scale atmospheric systems. There is no lower limit to the domain size or to the mesh cell size of the model's finite difference grid: microscale phenomena such as tornadoes and boundary layer eddies, as well as sub-microscale turbulent flow over buildings and in a wind tunnel, have been simulated with this code. Two-way interactive grid nesting in RAMS allows local fine mesh grids to resolve compact atmospheric systems such as thunderstorms, while simultaneously modeling the large-scale environment of the systems on a coarser grid. RAMS is most strongly supported for execution under the UNIX operating system, but is also supported to some degree on computers for employing COS, VMS, or CTSS. The code is written almost exclusively in FORTRAN 77 with some common extensions, although some C code is used to facilitate I/O procedures and dynamic memory allocation. In order to utilize the standard graphics capability of RAMS, the computer installation should have the GKS Version 3.0 of NCAR Graphics.

The planning, design, and construction of the RAMS code has been conducted primarily by Drs. Robert L. Walko and Craig J. Tremback under the supervision of Drs. William Cotton and Roger Pielke. This effort has been carried out with a major emphasis given to uniformity of design of the code, and nearly all developments have involved cross-discussion and/or debate which we hope has resulted in the best of our ideas being incorporated. Many valuable ideas and experiences with RAMS have been shared by the students of Drs. Pielke and Cotton and by other users over the years, which has led to significant improvements in RAMS.

c. UCLA-RU ROMS

In recent years, the UCLA group has been systematically evolving the Regional Oceanic Modeling System (ROMS; Haidvogel et al., 2000; Marchesiello et al., 2003; Shchepetkin and McWilliams, 1998, 2003, 2004) with the North American West Coast region as the primary testbed. ROMS solves the hydrostatic, free-surface Primitive Equations in 3D curvilinear coordinates that exactly follow the bottom topography and sea level (i.e., a generalized S-coordinate) and the coastline approximately (i.e. with an irregular boundary mask for coastline fine structure). It contains innovative and accurate algorithms for the extremum-preserving advection, pressure-gradient force, seawater equation of state compressibility, and split-explicit time-stepping for the barotropic/baroclinic mode coupling. ROMS is efficiently parallelized for both shared- and distributed-memory computer architectures. The lateral boundary conditions for open-ocean sectors are designed for stable, long-time integration with a combination of nudging towards specified (large-scale, low-frequency) boundary data and radiation or advection of outgoing information (Marchesiello et al. 2001). A multi-level, fully coupled, embedded-gridding scheme of Blayo and Debreu (1999) has been adapted to achieve finer horizontal resolution in local nearshore sub-domains without losing the regional or basin-scale influences in an outer domain. This technique has been successfully tested in applications to the central upwelling region within the central California Current System (Capet et al. 2004) and the Southern California Bight, and presently it is configured with a Pacific basin model as its outer domain with embedded regional and littoral subdomains**.**

d. ROMS Data assimilation

Data assimilation of the VOCALS cruise time intervals can be achieved using the inverse Regional Ocean Modeling System (iROMS), a 4D-variational data assimilation system for high-resolution basin-wide and coastal oceanic flows (Di Lorenzo et al., 2006). IROMS makes use of the recently developed perturbation tangent linear (TL), representer tangent linear (REP) and adjoint (AD) models of the Regional Ocean Modeling System (ROMS) to implement a “representer”-based generalized inverse modeling system. This modeling framework is modular. The TL, REP and AD models are used as stand-alone sub-models within the Inverse Ocean Modeling (IOM) system described in Chua and Bennett (2001). The system allows the assimilation of a wide range of observation types and uses an iterative algorithm to solve nonlinear assimilation problems.

The assimilation can be performed either under the perfect model assumption (strong constraint) or by also allowing errors in the model dynamics (weak constraints). For the weak constraint case the TL, REP and AD models are modified to include additional (non-physical) forcing terms on the right hand side of the model equations. These terms are needed to account for errors in the model dynamics. Posterior error statistics, term balances and array assessment are computed using separate diagnostic tools provided by the IOM. Since we wish to diagnose physical balances during the VOCALS cruise survey period, we plan to use strong constraints in our assimilations of the BEST data.

Di Lorenzo et al. (2006) have tested IROMS in an idealized 3D double gyre circulation and in a realistic application for the geometry and bathymetry of the Southern California Bight (SCB), a region characterized by strong mesoscale eddy variability like the Bering Sea. Synthetic data for sea surface height, upper ocean (0-500m) temperatures, salinities and currents were assimilated over a period of 3 days. The model first guess, prior to assimilation, was initialized using climatological conditions. The assimilation solution for the strong constraint experiment successfully reduced the initial model observation misfit by 75% and improves the model fields also at locations where observations are not assimilated.

Associated with the data assimilation platform of ROMS is a suite of Generalized Stability Analysis tools (Moore et al. 2004), which allow the quantitative assessment of sensitivities of model solutions to various parameters. These include computation of the eigenmodes of the tangent linear model (standard linear stability analysis normal modes), eigenmodes of the adjoint model (optimal eigenmodes for exciting these normal modes), singular vectors (fasting growing modes over finite time intervals), stochastic optimals (patterns of stochastic forcing that account for the largest amount of stochastic response in the model solution) and forcing singular vectors (forcing patterns that maximize model variability over a specified region for a given time period).

e. IPRC ROAM (iROAM)

A ROAM has been developed at the International Pacific Research Center (IPRC), University of Hawaii in collaboration with Japan. This model (iROAM) has been implemented on Japan's Earth Simulator and extensively tested. The ocean and atmospheric components share the same 0.5° grid in horizontal but the resolution may be varied as necessary. The atmospheric component is a full-physics regional model of Wang et al. (2004), which has 28 sigma levels and covers one-third of the global tropics including the eastern Pacific and the entire tropical American continents (150°W-30°W, 35°S-35°N). The model physics include a mass flux parameterization scheme for shallow, midlevel, and deep convection; cloud microphysics; a radiation package interactive with cloud; a land surface model; and a nonlocal turbulence closure scheme for vertical turbulent mixing. The ocean component is the GFDL MOM2 with 35 vertical levels and covers the entire tropical Pacific basin within 35°S-35°N. The updating of the ocean component to MOM4 is in process.

The control simulation for 1996-2003 reproduces the salient features of eastern Pacific climate, including a northward-displaced ITCZ (which becomes double and symmetric about the equator for a brief period of March-April), the equatorial cold tongue and their seasonal cycle. In particular, iROAM simulates a low cloud deck in the Southeast Pacific that displays transitions between the coupled and decoupled cloud regimes both in time and space as it interacts with the underlying SST.

Encouraged by its realistic simulation, iROAM is been used to study eastern Pacific climate processes key to tropical biases of global model simulations (Xie et al. 2006). Results show that internal air-sea feedback, in particular that between stratus cloud and SST, is essential for the model to maintain a realistic climatology (de Soeke et al. 2006). The model has also been used to simulate and verify the EPIC2001 cross-equatorial aircraft transects with some success, leading to a reconsideration of the role of SST-induced pressure in atmospheric adjustment across the SST front north of the equator (Small et al. 2005).

f. NRL COAMPS

The Naval Research Laboratory Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®[2]) is a versatile modeling and data assimilation system that includes comprehensive cloud, precipitation, aerosol and ocean components. It was recently extended to perform as a LES model (Golaz et al. 2005). The COAMPS atmospheric model is a finite-difference approximation to the fully compressible, non-hydrostatic equations (Hodur 1997). Physical parameterizations are used to represent surface fluxes, boundary layer mixing, radiation, and moist processes including microphysical quantities. In particular, the aerosol microphysical model is fully embedded in COAMPS as described by Liu et al. (2003); the moist physics parameterization consists of the recently developed COAMPS® two-moment bulk cloud microphysics scheme, which includes bulk cloud microphysics scheme described by Rutledge and Hobbs (1983,1984) and the more recent drizzle parameterization by Khairoutdinov and Kogan (2000). The initial fields for the model are created from multivariate optimum interpolation analyses of upper-air soundings and surface, commercial aircraft, and satellite data that are quality controlled and blended with the COAMPS forecast fields. The data assimilation is accomplished through an incremental update procedure that enables mesoscale phenomena to be retained in the analysis increment fields. COAMPS is routinely run in nested mode, and is rapidly relocatable to any area of the globe. The lateral boundary conditions for the outermost mesh make use of Navy Operational Global Analysis and Prediction System (NOGAPS) forecast fields.

The COAMPS ocean model is based on the Princeton Ocean Model, a hydrostatic primitive equation model. It includes additional features such as a choice of mixing schemes and a hybrid sigma-z vertical grid (Martin 2000). The 3D ocean data assimilation system was designed to mirror the atmospheric data assimilation system. The outermost nest of the ocean model uses fields from a global version of the ocean model running operationally at the Naval Research Laboratory. When run as a coupled system, the ocean model receives momentum and heat fluxes from the atmospheric component. In turn, the ocean model supplies the atmosphere model with evolving sea surface temperature fields. Simulations of the coupled system using a nested implementation with highest atmosphere/ocean resolution of 4-km/2-km are evaluated in Pullen et al. (2006) and shown to produce superior forecasts.

g. UCSD SCOAR

The Scripps Coupled Ocean-Atmosphere Regional (SCOAR) model (Seo et al., 2006a) is designed admit air-sea feedbacks due to mesocale eddies while downscaling observed atmospheric large-scale flows. It consists of the ROMS and the Regional Spectral Model (RSM). Large-scale forcing is provided by NCEP/DOE reanalysis fields, which have physics consistent with the RSM. Coupling allows the sea surface temperature (SST) to influence the stability of the atmospheric boundary layer and, hence, the surface wind stress and heat flux fields.

The RSM is a primitive equation hydrostatic model on terrain-following sigma coordinates, and the large-scale (low-wavenumber) components of the flow are specified in the model by the NCEP/DOE Reanalysis (RA2) downscaling procedure or by any GSM simulation. Numerous sensitivity studies demonstrate the excellent performance of the RSM, which has a significantly greater freedom to respond to internal dynamics compared with other regional models. The RSM boundary layer physics employs a nonlocal diffusion concept (Hong and Pan, 1996). This

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[2] COAMPS® is a registered trademark of the Naval Research Laboratory.

scheme is strongly coupled to the surface layer physics. In the scheme, the turbulent diffusivity coefficients are calculated from a prescribed profile shape as a function of boundary layer height and scale parameters derived from similarity requirements. Above the mixed layer, a local diffusion approach is applied to account for free atmospheric diffusion. The parameterization for deep convection is based on Relaxed Arakawa-Schubert Scheme (Arakawa and Schubert 1974; Moorthi and Suarez 1992). Further details about the model physics can be found in Kanamitsu et al. (2002). ROMS has already been described. The flux coupler was developed by Seo et al. (2006a). The interacting boundary layer between RSM and ROMS is based on the bulk formula that is implemented in ROMS, which computes surface fluxes of momentum, sensible heat, and latent heat from near-surface meteorological variables based on Fairall et al. (1996), adapted from the COARE (Coupled Ocean-Atmosphere Response Experiment) algorithm.

The model has been successfully used by Seo et al. (2006b) in modeling tropical Atlantic climate, showing that fluctuations of tropical instability waves (TIW's) significantly perturb the ITCZ, weakening its sharp spatial peak near the equator and increasing rainfall up to 1500km away. Seo et al. (2006a) also show that it can reproduce many of the observed features of the strength and structures of air-coupling in the eastern tropical Pacific, due to TIW's and due to winds through the Central America mountain gaps. The model can easily be adapted to the VOCALS region for downscaling observed, large-scale atmospheric flows in the presence of air-sea feedbacks due to the mesocale eddies that arise along the Peru Humboldt Current.

2. Global Models

a. NCEP GFS

The GFS model uses a spectral triangular truncation of 62 waves (T62) in the horizontal (equivalent to nearly a 200 Km Gaussian grid) and a finite differencing in the vertical with 64 sigma layers. The model top is at 0.2 hPa. This version of the GFS has been modified from the version of the NCEP model used for the NCEP/NCAR Reanalysis (Kalnay et al. 1996; Kistler et al. 2001), with upgrades in the parameterization of solar radiation transfer (Hou, 1996 and Hou et al. 2002), boundary layer vertical diffusion (Hong and Pan 1996), cumulus convection (Hong and Pan 1998), gravity wave drag (Kim and Arakawa 1995). In addition, the cloud condensate is a prognostic quantity with a simple cloud microphysics parameterization (Zhao and Carr 1997, Sundqvist et al. 1989; Moorthi et al. 2001). The fractional cloud cover used for radiation is diagnostically determined by the predicted cloud condensate.

b. UCLA AGCM

Work with the UCLA AGCM has a long tradition; the model itself has been kept state of the art and development of new components and code upgrading have been a constant concern. The PBL parameterization has been discussed earlier in this proposal. The parameterization of cumulus convection in the UCLA AGCM is a version of the Arakawa-Schubert scheme (Arakawa and Schubert 1974) in which the cloud work function quasi-equilibrium is relaxed by predicting the cloud-scale kinetic energy (Pan and Randall 1998) and that includes the effects of convective downdrafts (Cheng and Arakawa 1997). In the version we use for climate studies, the parameterization of solar and terrestrial radiation follows Harshvandan et al. (1987 and 1989, respectively). The model has been coupled to the simplified Simple Biosphere (SSiB) in order to examine land-atmosphere interactions (Xue et al. 1991; Zhan et al. 2003). A radiation calculation based on the Fu-Liou scheme has been recently implemented in the model (Gu et al. 2003). In this scheme, a total of eighteen aerosol types are parameterized by using the Optical Properties of

Aerosols and Clouds (OPAC) database (Gu et al. 2005). Inhomogeneities in stratocumulus clouds over land due to sub-grid scale orographic effects are parameterized according to Terra (2004). The model code is fully optimized, parallelized and integrated into the Earth System Modeling Framework (ESMF).

c. GFDL MOM

GFDL Modular Ocean Model V.3 (MOM3; Griffies and Pacanowski 1998), which is a finite difference version of the ocean primitive equations under the assumptions of Boussinesq and hydrostatic approximations. MOM3 uses spherical coordinates in the horizontal with a staggered Arakawa B grid and the z-coordinate in the vertical. The ocean surface boundary is computed as an explicit free surface. The domain is quasi-global extending from 74°S to 64°N. The zonal resolution is 1°. The meridional resolution is 1/3° between 10°S and 10°N, gradually increasing through the tropics until becoming fixed at 1° poleward of 30°S and 30°N. There are 40 layers in the vertical with 27 layers in the upper 400 m, and the bottom depth is around 4.5 Km. The vertical resolution is 10 m from the surface to the 240-m depth, gradually increasing to about 511 m in the bottom layer. Vertical mixing follows the non-local K-profile parameterization of Large et al. (1994). The horizontal mixing of tracers uses the isoneutral method pioneered by Gent and McWilliams (1990) (see also Griffies et al. 1998). The horizontal mixing of momentum uses the nonlinear scheme of Smagorinsky (1963).

d. NCAR/LANL POP

The Parallel Ocean Program (POP) is a descendent of the Bryan-Cox-Semtner class of ocean models first developed by Kirk Bryan and Michael Cox at the NOAA Geophysical Fluid Dynamics Laboratory in Princeton, NJ, in the late 1960's. POP had its immediate origins in a version of the model developed by Bert Semtner and Bob Chervin at NCAR. Experience with this version led to a number of changes resulting in what is now known as POP. Articles by Smith et al. (1992), and Dukowicz et al. (1993, 1994) give details of these changes. The model has continued to develop to adapt to new machines, incorporate new numerical algorithms and introduce new physical parameterizations. The MIT OGCM is described in Marshall et al. (1997). The model employs the K-Profile Parameterization (KPP) vertical mixing scheme of Large et al. (1994) and the isopycnal mixing schemes of Redi (1982) and Gent and McWilliams (1990), with surface tapering as in Large et al. (1997). At the bottom and lateral boundaries no-slip and free-slip conditions are applied, respectively. At the top, a free surface condition is applied. The web site www.atmos.ucla.edu/~mechoso/esm gives more details on models and resolution.

e. MITogcm

The MITogcm uses a horizontal grid that has 360 zonal and 224 meridional cells. Zonal grid spacing is 1° of longitude. Meridional grid spacing is 0.3° of latitude within 10° of the Equator and increases to 1° latitude poleward of 22°N and 22°S. There are 46 levels in the vertical with thicknesses ranging from 10 m in the top 150 m, and gradually increasing to 400 m thickness near the bottom. The maximum model depth is 5815 m. Model bathymetry is based on ETOPO5 (Data Announcement 88-MGG-02, Digital relief of the Surface of the Earth, NOAA, National Geophysical Data Center, Boulder, Colorado, 1988). The model employs the K-Profile Parameterization (KPP) vertical mixing scheme of Large et al. (1994) and the isopycnal mixing schemes of Redi (1982) and of Gent and McWilliams (1990) with surface tapering as per Large et al. (1997). Laplacian diffusion and friction are used, except that horizontal friction is biharmonic. Lateral boundary conditions are closed. No-slip bottom, free-slip lateral, and free surface boundary conditions are employed. Surface freshwater fluxes are applied as virtual salt fluxes. Isopycnal diffusivity and isopycnal thickness diffusivity is 500 $m^2\ s^{-1}$. Vertical diffusivity is $5\times10^{-6}\ m^2\ s^{-1}$. Horizontal and vertical viscosities are $10^{13}\ m^4\ s^{-1}$ and $10^{-4}\ m^2\ s^{-1}$, respectively.

f. NCEP CFS

The Climate Forecast System (CFS) is a fully coupled ocean-land-atmosphere dynamical seasonal prediction system whose most recent version became operational at NCEP in August 2004. The atmospheric component of the CFS is the NCEP atmospheric GFS model, as of February 2003 (Moorthi et al. 2001). The oceanic component is the GFDL Modular Ocean Model V.3 (MOM3) (Pacanowski and Griffies 1998). The two components exchange daily averaged quantities, such as heat and momentum fluxes with no flux adjustment or correction. Because of the difference in latitudinal domain, full interaction between atmospheric and oceanic components is confined to 65°S to 50°N. Poleward of 74°S and 64°N, SSTs needed for the atmospheric model are taken from observed climatology. Between 74°S and 65°S, and between 64°N and 50°N, SSTs for the atmospheric component are the weighted average of the observed climatology and the SST from the ocean component of the CFS. The weights vary linearly with latitude, such that the SSTs at 74°S and 64°N equal observed climatology and the SSTs from 65°S and 50°N equal values from the ocean component. Sea ice extent is prescribed from the observed climatology. For the prediction of land surface hydrology, the CFS uses the two-layer model described in Mahrt and Pan (1984).

The NCEP CFS has stronger surface radiative fluxes, evaporation and precipitation than independent estimates. On-going experiments with higher horizontal resolution in the atmosphere (T126) suggest that surface stresses in the eastern equatorial Pacific are somewhat too weak. Also, surface fluxes and cloudiness appear to be sensitive to horizontal resolution. The sensitivity to vertical resolution is discussed in section 3.4.c.

The NCEP GFS captures the stratocumulus in the operational analysis cycle, but these clouds quickly decrease in the forecasts. The model also tends to have the highest incidence of stratocumulus too far away from the coast. Consistently, long model runs of the CFS indicate a substantial (3-4 K) warm bias in the east Pacific near the coasts of North and South America. Convection and precipitation over the Andes are too strong, which is likely associated with deficiencies in the subsidence and stratocumulus formation over the Southeastern Tropical Pacific (SEP). Xie et al. (2005) examined the consistency in the CFS between the lack of stratus clouds, warm SST biases in the SEP (and southeastern Atlantic), and shifts in the ITCZ.

g. GFDL CGCM

The GFDL CGCM (CM2, Delworth and Coauthors 2006) is composed of separate atmosphere, ocean, sea ice, and land components. The atmospheric component (AM2, GFDL Global Atmosphere Model Development Team 2004) includes a finite volume dynamical core (Lin 2004).

AM2 offers the capability to be run as a SCM using the complete column physics suite. The AM2 SCM can be run in a variety of configurations ranging from idealized to full AM2 model derived forcings. The AM2 boundary layer scheme is based on Lock et al. (2000). Its stratiform cloud parameterization is from Tiedtke (1993) and is coupled with the Rotstayn (1997) and Rotstayn et al. (2000) microphysics.

h. UCLA CGCM

Using the ESMF framework, the model has been coupled to global versions of LANL parallel Ocean Program (POP) and MIT OGCM.

In the UCLA CGCM, the simulated tradewinds and associated surface stress are too weak even with the high resolution version of the atmospheric component (2.5 lon by 2 lat with 29 levels). The net surface fluxes of heat and fresh water are simulated reasonably well due to partial cancellation between slightly overestimated evaporation and short wave flux into the ocean (Cazes-Boezio personal communication). The annual mean distribution of SST along the equator shows a very realistic west-east gradient, but has a cold bias of about 1.5 K.

The UCLA AGCM and CGCM are very successful in the simulation of stratocumulus and their annual cycle (Richter and Mechoso 2006). Consistently, SST errors along the Peruvian and Namibian coasts are negligible. The double ITCZ bias, however, remains in the simulation.

i. NCAR CGCM

The NCAR CCSM3 CGCM is summarized by Collins et al. (2006) and extensively documented in a special issue of the 1 June 2006 issue of the *Journal of Climate*. The atmospheric model component, the CAM3, can be run with three dynamical cores (spectral Eulerian, semi-Lagrangian, and finite-volume. Current model development is focusing on the finite-volume dycore with a control resolution of roughly 2 degrees in latitude and longitude, with ambitious efforts to combine new boundary layer, shallow and deep convection, microphysical and cloud fraction schemes in the next version of CAM.

CAM3 with specified climatological SST produces a fairly realistic distribution of boundary layer cloud radiative forcing over the East Pacific with a clear SEP stratocumulus regime. However, the boundary layer is much too shallow compared to SEP observations (Bretherton et al. 2004). The coupled CCSM3 still has a stratocumulus regime, but has a large coastal warm bias and a strong double-ITCZ bias (Collins et al. 2006).

EPIC and VOCALS datasets are already beginning to play a role in the development and testing of the new CAM. Thanks to the DOE CAPT (CCSP-ARM Parameterization Testbed) and the low-latitude cloud Climate Process Team, the CAM3 can be run in weather forecast mode initialized with state-of-the-art analyses and reanalyses. C. Hannay of the low-latitude cloud Climate Process Team has investigated the short-range forecast biases of this system with various parameterization choices vs. the EPIC stratocumulus integrated dataset. This type of comparison is an efficient approach for comparing an AGCM with limited time series of field data, and will be continued with other VOCALS integrated datasets from buoy maintenance cruises and REx.

Appendix B
VOCALS Modeling Teams – CORE Project

#	Team	PIs	Science	VOCALS Modeling Goals
Mod-1	IPRC	Y. Wang/S. Xie	Regional ocean-atmosphere modeling	Regional coupled modeling of SEP climate
Mod-2	NCAR/UCLA	W. Large/ J. McWilliams	Multi-scale ocean-atmosphere modeling	Regional coupled modeling of SEP climate embedded in the global system
Mod-3	NCEP/UCLA	H. Pan/Mechoso	Global ocean-atmosphere modeling and prediction	To improve modeling, simulation and prediction of the tropical climate with coupled GCMs
Mod-4	U Washington	R. Wood/C. Bretherton	Large eddy simulation and microphysical process modeling	Stratocumulus and cloud/PBL parameterization challenges in the SEP
Mod-5	SCRIPPS	Miller	Eddy resolving ocean modeling and regional coupled ocean-atmosphere modeling	Regional ocean data assimilation and atmospheric downscaling in the SEP
Mod-6	NRL	Shouping Wang/Pullen	Regional ocean-atmosphere prediction	Predictions for the SEP during VOCALS-Rex

Simulations and analysis of aerosol/cloud/drizzle interactions in marine stratocumulus

Principal Investigators: William R. Cotton and Gustavo Carrió, CSU

The region to the west of Chile is an ideal natural laboratory for studying aerosol-cloud-drizzle interactions in marine stratocumulus clouds. In this region very clean air characterized by clouds with large effective radii occur to the south while other regions to the north are contaminated by pollutants advecting over the marine boundary layer from industrial sources at higher elevations in Chile. We therefore propose to participate in the VOCALS field campaign to acquire case studies to perform simulations and analysis to investigate aerosol/drizzle cloud interactions including possible feedbacks such as POCs (Stevens et al, 2005). In addition the selected case studies will be used to evaluate an aerosol retrieval model developed under NASA funding deploying an ensemble Kalman filter (EKF) technique to retrieve concentrations of CCN, GCCN, and IFN from satellites. The algorithm is adapted from an EKF algorithm developed by Zupanski (2005) and Zupanski and Zupanski (2006) that is used in the cloud resolving version (CRM—see Carrio et al., 2005) of RAMS.

The proposed research will involve performing mesoscale and LES simulations with RAMS (see Cotton et al., 2003) of marine stratocumulus clouds off the coast of Chile in both clean and contaminated air masses. We have performed similar LES simulations in RAMS of entrainment of polluted aerosols into the marine boundary layer (Jiang et al., 2002). In each region simulations will be performed using the observed concentrations of cloud nucleating aerosols as well as sensitivity studies varying those aerosol amounts. The results of those simulations will be compared with observed cloud structures during VAMOS. In addition we will apply and test the EKF aerosol retrieval algorithm in the clean and contaminated regimes to evaluate its performance against aircraft measured aerosol concentrations. We anticipate this study will further quantify aerosol/cloud/drizzle interactions and their impacts on cloud albedo.

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Integrating the VOCALS Data with the Improvement in the Treatment of Marine Boundary Layer Clouds and Turbulence in the NCEP CFS03 and NCAR CCSM3

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The PIs have analyzed radiosonde, radar, ceilometer, and surface measurements over the eastern Pacific in order to document the temporal and spatial variability of MABL height (h) and evaluate the model parameterization of h in CCSM3 (Zeng et al. 2004). A similar evaluation of the CFS03's parameterization was also done. More recently, we have used the CPPA/EPIC data and aircraft data from other field experiments to document the probability distribution function of cloud base, top, thickness, and liquid water path (LWP). The relationship of stratus/stratocumulus cloud fraction and depth with LWP has also been established (Zhou et al. 2006).

Our bulk algorithm for computing ocean surface flux has been implemented in the CFS03. We have made contributions (both in model physics and global data) to the NCEP Noah land model, which will become the land component of the CFS03 in the near future. Xubin Zeng coordinated the development of the earlier version of the land component of the CCSM3, and we are currently working with Bill Large at NCAR on the implementation of our ocean skin temperature prognostic scheme into the CCSM3.

We propose to analyze the relationship among marine boundary layer (MBL), cloud microphysics, and cloud fraction based on observational data from VOCALS and other sources.

We also propose to perform a detailed budget analysis of the cloud microphysics prognostic equation in the CFS03 and CCSM3 over various stratus and stratocumulus regions. These model output will also be compared with the VOCALS and other observations. These analyses will enable us to better understand the relationship among MBL, cloud microphysics, and cloud fraction and how this relationship over the VOCALS regions differs from other regions.

Through these analyses, better treatments of MBL, cloud microphysics, and cloud fraction will be developed, and their impact on CFS03 and CCSM3 modeling will be assessed.

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Using VOCALS to Develop and Evaluate Stratiform Cloud Parameterizations Incorporating Sub-grid Vertical Velocity Variability

Principal Investigators: Leo Donner and J. –C. Golaz, NOAA/Princeton U/GFDL

GFDL's participation in VOCALS will be dedicated towards improving the representation of low level stratiform clouds in the AM2 GCM (GFDL Global Atmosphere Model Development Team 2004) using VOCALS-Rex collected data. The research will focus on two specific goals:

- Improve AM2's climatology of low-level clouds in the SEP region. AM2 currently suffers from a negative cloud cover bias in the coastal regions of the SEP. The goal is to obtain more realistic cloud properties, such as geographical distribution of cloud cover and liquid water path.

- Implement a more physically based treatment of CCN activation in the stratiform cloud parameterization. Currently, CCN activation is linked to the average grid box vertical velocity and cloud top radiative cooling. Because the grid box velocity is substantially smaller in magnitude than, and actually often of opposite in sign to the cloud scale motions that activate CCN, AM2 tends to underestimate cloud droplet number concentration in stratiform clouds. An accurate and physically based CCN activation is particularly important in order to simulate the effect on climate of anthropogenic aerosols.

Work on these scientific goals will proceed on two parallels tracks. The first one will be for the current boundary layer and stratiform cloud parameterizations in AM2. Because the next round of IPCC simulations is likely to rely on these schemes, even modest improvements regarding the two areas mentioned above would be beneficial. We recognize, however, that there will be a limit to the improvements that can be achieved. For this reason, GFDL is also proceeding on a separate track with the development of a next generation parameterization. This new parameterization will make use of a multi-variate probability density function to represent the subgrid-scale variability in vertical velocity, temperature and moisture. The methodology will be based on the work of Larson et al. (2002) and Golaz et al. (2002). This formulation offers a consistent framework for the representation of clouds and boundary layer turbulence transport. Furthermore, the availability of a sub-grid vertical velocity distribution enables a more realistic treatment of CCN activation.

We anticipate that a majority of the parameterization development can be performed using a SCM framework initially, followed by an evaluation in the full GCM. GFDL also has modeling capabilities to perform LESs that can serve as reference for the SCM. LES will be used in support of the parameterization development when appropriate.

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Role of the Southeastern Pacific Marine Stratus and Convection Parameterization in Double ITCZ Formation in a Coupled GCM

Principal Investigator: Guang Zhang, Scripps Institution of Oceanography

A recent CGCM study by Zhang and Wang (2006) using the NCAR Community Climate System Model CCSM3 shows that the double ITCZ in boreal summer can be eliminated by using an improved version of the Zhang-McFarlane (1995) convection parameterization scheme. In association with the changes in ITCZ, SST biases both in the cold tongue and at the latitudes of the double ITCZ location are reduced by as much as 1 K.

In this proposed research, we will investigate the role of the Southeastern Pacific marine stratus and convection parameterization in the formation of double ITCZ in the NCAR CCSM3. We plan to carry out the following multi-year simulation experiments:

1. Control simulation (CLD0) using the standard CCSM3 configuration. This will be used as a baseline experiment. The shortwave cloud radiative forcing (SWCRF) over the observed climatological stratus region in the SE Pacific will be calculated to produce an annual cycle of SWCRF at each grid point in this region for use in the next simulation.
2. CLD1 with the same configuration as in (1), except prescribing the SWCRF annual cycle at each grid point in the SE Pacific stratus region with values calculated from (1). The difference between CLD0 and CLD1 shows the effect of coupling between the marine stratus and SST.
3. CLD2 is the same as CLD1, except with the SWCRF annual cycle over the same region specified from the observed values. The difference between CLD2 and CLD1 shows the impact of increased marine stratus on SST simulation. The effect of the feedback between the stratus and SST is not included since both are run with prescribed SWCRF. Therefore, comparison of CLD1 and CLD2 isolates the impact of increased SE Pacific stratus.
4. Repeat the simulations in (1) through (3) using the improved Zhang-McFarlane convection parameterization (denoted CON0, CON1 and CON2, respectively).

The difference between CON0 and CLD0 gives the effect of convection parameterization on the ITCZ and SST simulation when the Peruvian marine stratus is under-predicted. The comparison between CON2 and CLD2 gives the effect of convection in the presence of realistic marine stratus cloud radiative forcing on SST. CON2 would provide an estimate on what we would expect of the ITCZ and SST simulation if the Peruvian stratus were simulated realistically.

An equally important scientific issue is to understand the mechanisms through which convection and clouds interact with SST to affect the SST and ITCZ simulation. We will carry out extensive analysis of the model simulations, including upper ocean heat budget and atmospheric analyses in the stratus region and ITCZ region.

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Upper ocean variability in the southeast Pacific and its role in the maintenance of stratus clouds

Principal Investigators: Toshiaki Shinoda (NOAA-CIRES Earth System Research Laboratory)
Jialin Lin (NOAA-CIRES Earth System Research Laboratory)

While there are still problems in reproducing stratus clouds in AGCMs, they could generally simulate stratus clouds better than coupled GCMs when they are forced by observed SSTs. Also, our results from the current NSF-funded project demonstrate that the OGCM is able to simulate SSTs under the stratus deck reasonably well when it is forced with satellite-derived surface fluxes. However, when the AGCM and OGCM are coupled, air-sea feedback processes can amplify the small errors caused by the model deficiency, which could result in unrealistic stratus clouds and SSTs. Hence, it is important to determine the sensitivity of upper ocean processes to changes in atmospheric forcing and that of atmospheric processes to changes in SSTs. In this proposed study, we will examine the former (sensitivity of ocean processes) using OGCM experiments with different surface forcings. Data collected from current and future observations in this region will be maximally utilized to validate the model performance. The output from AGCM and coupled GCM experiments will also be diagnosed to examine the impact of air-sea coupling on stratus clouds. Specific objectives of the proposed project are: 1) to determine the sensitivity of upper ocean processes to changes of surface forcings such as along shore winds and shortwave radiation, and 2) to describe the coupled GCMs' ability to reproduce stratus clouds and to identify the source of the deficiency in simulating stratus clouds. The proposed research is complementary to our current NSF-funded project that focuses on different aspects of oceanic processes in this region. Diagnoses of coupled GCM experiments One of the PIs have recently analyzed the output from experiments of 22 IPCC AR4 coupled GCMs and the available AMIP runs of 12 of them to examine the double ITCZ problem (Lin 2006). In this study, we will diagnose the atmospheric and oceanic variability in the stratus cloud region in these models. Specifically, the relation between stratus clouds, SSTs, and along shore winds near the coast of South America in each model will be thoroughly described. Impact of air-sea coupling on stratus clouds is identified by the comparison between coupled GCM and AGCM experiments. We expect that the deficiency of reproducing stratus clouds and SSTs is relevant to unrealistic along shore winds.

Sensitivity of upper ocean and SSTs to changes of along shore winds will be examined by OGCM experiments. The along shore winds induce coastal upwelling and horizontal advection that influence SSTs under the stratus deck on various time scales. The model will be first integrated with and without along shore winds. Also, the different strength of along shore winds that covers the range of those in coupled GCMs will be used to force the OGCM. The diagnosis of the OGCM output will focus on examining what upper ocean processes are most sensitive to the changes of along shore winds. Other experiments that investigate the sensitivity of the upper ocean to changes of stratus clouds (thus surface shortwave radiation) and horizontal resolution of the model will also be conducted.

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Collaborative Research: VOCALS: Coupled Ocean–Atmosphere Modeling and Synoptic Ocean Data Assimilation

Principal Investigator: Art Miller, Scripps/UCSD

Two related modeling studies will aid in the diagnosis of the VOCALS observations. 1) Large-scale atmospheric forcing fields from NCEP will be downscaled, allowing air-sea feedback processes, using a regional coupled ocean-atmosphere model to diagnose the importance of mesoscale air-sea feedbacks. 2) Observed mesoscale oceanic surveys of the VOCALS observations will be used in data assimilation experiments to diagnose the dynamics and sensitivities of the ocean circulation fields.

The Scripps Coupled Ocean-Atmosphere Regional (SCOAR) model was developed by Seo, Miller and Roads (2006) and consists of the Regional Spectral Model (RSM) coupled to the Regional Ocean Modeling System (ROMS). It is designed to admit the air-sea feedbacks arising in the presence of an oceanic mesoscale eddy field, such as exist in the VOCALS region. Coupling allows the sea surface temperature (SST) to influence the stability of the atmospheric boundary layer and, hence, the surface wind stress and heat flux fields. Downscaling of the large-scale atmospheric fields to the VOCALS domain will be done throughout the VOCALS observational periods as well as for key retrospective periods. The retrospective downscaling will provide an understanding of what controls the intraseasonal through interannual variability in the VOCALS environment and will constitute a baseline for comparison with current conditions

The inverse ROMS (iROMS) is a 4D-variational data assimilation system for high-resolution basin-wide and coastal oceanic flows that makes use of the recently developed perturbation tangent linear (TL), representer tangent linear (REP) and adjoint (AD) models of ROMS to implement a “representer”-based generalized inverse modeling system. The system allows the assimilation of a wide range of observation types and uses an iterative algorithm to solve nonlinear assimilation problems. Since we wish to diagnose physical balances during the VOCALS cruise survey period, we plan to use strong constraints in our assimilations of the VOCALS data. Data assimilation “fits” of the VOCALS hydrographic surveys (and concomitant data) will provide crucial dynamically consistent diagnostics of the circulation for interpreting the relation between physical variables, atmospheric variables and biology. Associated with the data assimilation platform of iROMS is a suite of Generalized Stability Analysis tools which allow the quantitative assessment of sensitivities of model solutions to various parameters, such as upstream ocean forcing, topography, winds, heat fluxes, etc.

The results will help us to understand the mechanisms that control the interactions of the variability of the ocean eddy fields, the coastal winds, heat fluxes, and clouds in the VOCALS domain.

This research has broader impacts in that it is relevant to commercially important fisheries management (which must deal with interannual and decadal variations in fish populations) and to the societal impacts on the livelihoods of subsistence fishermen of South America.

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Multi-Scale Coupled Interactions in the Southeastern Pacific

Principal Investigators: B. P. Kirtman and V. Misra. George Mason University/COLA

A well-known systematic error in all comprehensive coupled general circulation models (CGCMs) is that the simulated and predicted southeastern Pacific SSTs are too warm compared to observations. These warm biases are also strongly related to the so-called double ITCZ problem endemic to all coupled GCMs. These errors seriously impact our ability to predict seasonal-to-interannual variability associated with El Nino and the Southern Oscillation (ENSO) and our confidence in climate change projections. There are two working hypotheses/strategies for addressing this model error. The first hypothesis argues that the errors are due to inadequacies in the physical parameterizations in the coupled GCMs. The second strategy has been to argue that current coupled models fail to adequately resolve the relevant dynamics.

Here we suggest a different approach to examining the scale interaction issue, which can easily be implemented within the context of the current coupled GCMs. We argue that current coupled GCMs have variability due to internal atmospheric and oceanic dynamics that occurs on space-time scales that are too large. In other words, because to the relatively low resolution, the coupled GCMs alias the internal dynamics "noise" on space and time scales that are too large compared to nature, which leads to erroneous coupled variability, and ultimately, a biased mean state. In order to test this conjecture, we propose to use the interactive ensemble approach (e.g. , Kirtman et al. 2005) to remove the aliases atmospheric and oceanic "noise" at the air-sea interface in the NOAA Coupled Forecast System (CFS) model (the interactive ensemble version of CFS has already been implemented). We will examine how this noise removal procedure impacts the mean and variability in the Southeastern Pacific. Moreover, we will perform numerical experiments with the interactive ensemble adding back in the "observed" noise how the observed noise impacts the mean and variability.

The observed variability in the surface fluxes of heat, momentum and fresh water due to internal atmospheric dynamics can only be approximated. Similarly, the observed SST variability due to internal ocean dynamics can only be estimated. There are various possible approaches with different strengths and weaknesses. Here we propose to use a two-pronged approach, which relies on both purely statistical analysis of the observations and model/observational strategies. Model-based approaches for estimating the noise have the advantage of relaxing the time scale separation assumed in the filtering approaches. However, model deficiencies can impact the estimates of both the signal and noise. The model-based approach is to use ensemble simulation to define the signal and difference from the observed time series as estimates of the noise.

Based on the model simulations we intend to answer the following questions: (a) How much of the observed variability is controlled by the noise? (b) How does the poorly resolved internal dynamics noise impact the mean state? and (c) How do the observed noise statistics impact the simulation of the mean state?

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Evaluation and Improvement of NOAA Climate GCM Air-Sea Interaction Physics: An EPIC/VOCALS Synthesis Project"

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Proposal Submitted to NOAA/CPPA
Research Period: March 1, 2007 – February 28, 2010

This is a proposal for a joint NOAA/ESRL and University of Hawaii effort to synthesize recent CPPA-funded research to promote its application in the NOAA Coupled Forecasting System (CFS) model. Our plan is to work within the Climate Testbed structure with NOAA scientists involved with CFS. Our approach will combine three key sources: 1) data obtained in several CPPA field studies, 2) the International Pacific Research Center (IPRC) Regional Ocean Atmosphere Model (IROAM), and 3) the rapidly emerging scientific literature from CPPA field programs. Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System (EPIC) was an intensive field study of convection and air-sea interactions in the East Pacific ITCZ and the equatorial upwelling zone conducted in the fall of 2001. The EPIC2001 monitoring program consisted of detailed surface flux, atmospheric boundary layer profiles, and cloud observations made during the twice-a-year maintenance cruises to the TAO buoy lines at 110° and 95°W from the fall of 1999 through fall 2004 plus four cruises to the Chilean Stratus region with more planned in the future. The high-resolution regional model will be the IPRC Regional Ocean-Atmosphere Model (IROAM). The IROAM is configured as a tropical Pacific Ocean general circulation model coupled to the IPRC Regional Atmospheric Model (IRAM) of the eastern Pacific. The ocean model will be spun up for 5 years before coupling in 1996. The model climatology will be the average of the nine years 1998-2006 plus periods selected to match the observations.

The first task will be to work with the EPIC Science Working Group (SWG) to produce a synthesis review paper on the EPIC project related to ocean-atmosphere interaction physics. The initial research focus will be to compare the IROAM and CFS climatologies with the observations with an emphasis on surface fluxes (turbulent, radiative, and precipitation), marine boundary layer structure, and cloud properties. Besides the EPIC field data, additional sources (reanalyses, satellite, buoys) will be used to provide the most credible and comprehensive climatology. We will also examine parameterizations of these processes in the CFS. The IROAM will play a key role by providing important detail not available in the observations and by reconciling the mismatch of time/space averaging between the observations and the CFS. This will allow us to evaluate possible improvements of the representation of subgrid processes; for example, accounting for mesoscale variability in surface flux parameterizations, treatments of shallow convection, planetary boundary layer mixing, cloud-top entrainment, and drizzle.

To improve modeling, simulation and prediction of the tropical climate with coupled GCMs

Principal Investigators: C. R. Mechoso (UCLA) and Hualu Pan (NCEP)
Collaborators: Akio Arakawa (UCLA) and Steve Lord (NCEP)
Proposal Submitted the NOAA CPPA.
Research Period: May 1, 2007–April 30, 2010

UCLA and NCEP scientists have teamed to carry out work that will directly contribute to NOAA's vision. The common objectives are to improve the modeling, simulation and prediction of the tropical climate with the NCEP Climate Forecast System (CFS) and the UCLA coupled atmosphere-ocean General Circulation Model (CGCM). The metric for success is the elimination of the models' systematic errors in the simulation of 1) eastern tropical Pacific climate, and 2) diurnal and intraseasonal variability of American monsoon systems.

The methodology will be based on two tasks, of which the realization will be tightly coordinated at NCEP and UCLA: 1) The careful diagnosis of both prediction and simulations with the coupled systems, 2) model upgrade for performance improvement. Use of an operational model will allow working in prediction mode; use of a research model will facilitate working on model development and hypothesis-testing simulations. The research proposed centers on the validation of the following hypotheses: (1) An important contribution to the double ITCZ bias is generated by the CGCMs difficulties in capturing the westward extension of the effects of coastal upwelling and persistent stratocumulus that develop along the South American coast, and (2) The low frequency variations in the South American Monsoon System (SAMS) provide an excellent framework for designing and testing model improvements aimed to a better simulation of the diurnal cycle in regions of strong convection.

The work to be performed in addressing hypothesis (1) will consist of the analyses of heat transport by ocean eddies to the region offshore from that of coastal upwelling and of moisture and moist static energy transport by the trade winds from the stratocumulus region. The potential of a multi-scale approach for seasonal prediction from the perspective of regional coupled models embedded within the seasonally and interannually varying global climate will be explored. The work to be performed in addressing hypothesis (2) will consist of investigating the mechanisms at work for the existence of the different low-frequency wind regimes observed during SAMS, and of the different diurnal cycles observed during the regimes. An upgrade in the PBL parameterization will be relevant to the two hypotheses since it has the potential for a more successful simulation of the diurnal cycle and the stratocumulus decks in the tropical oceans.

The proposal goals support those of the VAMOS Ocean-Cloud-Atmosphere-Land-Studies (VOCALS), which is a major international, multi-agency program under WCRP/CLIVAR.

Interactions of Aerosol-Cloud-Precipitation-Ocean Effects in Marine Boundary Layers

Principal Investigator: Shouping Wang, NRL at Monterey
Proposal Submitted to NASA in Response to
NASA ROSES-2006, NNH06ZDA001N-IDS subelement 5
"Aerosol Impact on Clouds, Precipitation and Hydrology Cycle"
Research Period: 3/1/2007 – 3/1/2010

Proposal Summary

One of the most challenging issues in understanding the long term impacts of the clouds on the climate is aerosol indirect effects. Recent observations suggested that the aerosol-cloud-drizzle feedback and interaction may be responsible for the observed significant reduction in cloud cover in the marine boundary layers in the Northeast and Southeast Pacific. The objective of the proposed research is two fold: 1) to investigate the link between the observed mesoscale cloud variability and the aerosol-cloud-drizzle interaction; 2) to gain insight in the roles that the ocean-atmosphere coupling plays in regulating the cloud distribution and the interaction mechanism.

We intend to combine our unique capability in satellite retrieval and a sophisticated coupled ocean-atmosphere modeling/data assimilation system with *in situ* measurements to advance the understanding of the linkages of cloud, precipitation and ocean effects and their interaction with aerosols in marine boundary layers. Our research efforts will focus on the area off the west coast of Chile/Peru in the Southeast Pacific where the upcoming international VOCALS field program is located. The field experiment also provides a framework to integrate our various expertise to address highly interdisciplinary scientific questions.

Satellite-retrieved cloud properties will be analyzed to establish the link between passively-retrieved cloud top effective particle radii and drizzle conditions for the VOCALS area. Constrained by both the satellite retrieval data and the VOCALS *in situ* measurement, Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) analyses and forecasts will be performed to understand the mesoscale cloud distribution and the aerosol-cloud-drizzle effects in the marine boundary layers, as well as the impact of the relevant large-scale dynamics on the cloud processes. COAMPS®-Large-Eddy-Simulation will also be used to investigate at very high resolution the cloud dynamics associated with the aerosol-cloud-drizzle interaction mechanism.

This research bears immediate relevance to NASA's Earth Science Enterprise by addressing long-standing questions concerning aerosol/cloud interactions through a comprehensive analysis of multi-sensor satellite, *in situ*, and high-resolution modeling resources. Considering this problem in the context of a fully coupled air/sea/coastal system (accounting for sensible/latent heat fluxes and mesoscale dynamics) allows for a better isolation of the role of aerosols in both altering cloud microphysics and modifying the lifetime of these clouds. Lessons learned from this study will provide critical guidance leading to improved explicit moist physics in short term weather forecast models and more representative parameterization of cloud/aerosol processes in global climate models.

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Regional coupled ocean-atmosphere model in support for VOCAL-Rex

Principal Investigators: J. McWilliams, Alex Hall, Niki Gruber (UCLA), Bill Large (NCAR)

First, we propose a modest model development program to ensure the regional coupled ocean-atmosphere model will provide the maximum possible support for VOCAL-REx. A major concern here is whether WRF can produce a successful simulation of stratocumulus cloud. Preliminary results with the shallow cumulus parameterization by McCaa and Bretherton (2004) incorporated into a 6-km regional atmospheric model (MM5) of the Southern California region show significantly better agreement of simulated stratus coverage with satellite observations. Based on this initial success with MM5, we will incorporate this parameterization into WRF, and do the necessary testing and analysis to achieve realism in stratus coverage. In addition, we will incorporate a module for DMS production into ROMS. Modifications must also be made to WRF to keep track of DMS distributions given the DMS fluxes, and to incorporate empirical estimates of the effect of aerosols on cloud albedo (e.g. Schwartz et al. 2002) in WRF's radiative transfer subroutines.

Having completed these modifications to WRF and ROMS, we propose the following experiments using the regional coupled framework: (1) A retrospective simulation covering the month-long VOCALS-REx campaign. The short length of the simulation will allow for super high resolution (roughly 2km in the atmosphere, and 500m in the ocean). This will facilitate meaningful comparison with VOCAL-Rex point measurements, which will be basis for our validation of the coupled model. The simulation will also provide highly detailed information about both the atmosphere and ocean in the unsampled portions of the SEP. This will be vital in interpreting VOCALS-REx measurements. The lateral boundary forcing for this experiment will come from the NCEP reanalysis, in the case of the atmosphere, and a coarse resolution ROMS simulation forced by the NCEP reanalysis winds and surface fluxes, in the case of the ocean. (2) A retrospective simulation covering the last 50 years. Analysis of this experiment will put the VOCAL-Rex campaign in the context of interannual variability in the SEP. The resolution here will be coarser because of the length of the simulation (roughly 12 km in the atmosphere, and 2km in the ocean), though we will likely embed higher resolution nests in coastal areas where resolution is critical. (3) A regional simulation embedded within a global coupled ocean-atmosphere model. Comparison with the global coupled solution in the SEP region will allow us to assess a) the magnitude of errors in surface wind and surface energy budgets in the global models due to inadequate resolution and b) the extent to which the large errors in tropical climate in the global models would be reduced if they were subject to the improvements in fluxes and winds of the regional simulation. We anticipate needing a few decades of data to achieve stable statistics, and so the resolution here will be comparable to experiment (2) above.

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Acronyms

AD	Adjoint model
AGCM	Atmospheric General Circulation Model
AM2	GFDL Atmospheric Model version 2
AMIP	Atmospheric Model Intercomparison Project
AR4	Fourth Assessment Report
CCN	Cloud Condensation Nuclei
CCSM3	Community Climate System Model version 3
CFS	Climate Forecast System
CGCM	Coupled Atmosphere-Ocean General Circulation Model
CLIVAR	Climate Variability Programme
CM2	GFDL Coupled GCM version 2
COAMPS	Coupled Ocean/Atmosphere Mesoscale Prediction System
COLA	Center for Ocean, Land, Atmosphere interactions
COPES	Coordinated Observation and Prediction of the Earth System
CPPA	NOAA Climate and Prediction Program for the Americas
CRM	Cloud Resolving version of RAMS
CSU	Colorado State University
DOE	Department Of Energy
EKF	Ensemble Kalman Filter
ENSO	El Niño/Southern Oscillation
EPIC	Eastern Pacific Investigation of Climate
ESMF	Earth System Modeling Framework
ESRL	Earth Science Research Laboratory
ETL	Environmental Technology Laboratory
ETOPO5	5-minute Earth Topography
GCCN	Giant Cloud Condensation Nuclei
GCM	General Circulation Model
GCSS	GEWEX Cloud System Study
GEWEX	Global Energy and Water cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GOES	Geostationary Operational Environmental Satellites
GPCI	GCSS Pacific Cross-section Intercomparison project
IFN	Ice Forming Nuclei
IOM	Inverse Ocean Modeling
IPCC	Intergovernmental Panel on Climate Change
IPRC	International Pacific Research Center
IROAM	inverse Coupled ROM-RAM Model
iROMS	inverse Regional Ocean Modeling System
ITCZ	Intertropical Converge Zone
KPP	K-Profile Parameterization
LANL	Los Alamos National Laboratory
LES	Large-Eddy Simulation Model
LWP	Liquid Water Path
MBL	Marine Boundary Layer

MIT	Massachusetts Institute of Technology
MM5	Mesoscale Model of the 5th generation
MOM3	Modular Ocean Model V.3
MUSSIP	Multiscale Simulation and Prediction
NASA	National Aerospace and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NOGAPS	Navy Operational Global Analysis and Prediction System
NRL	Naval Research Laboratory
NSF	National Science Foundation
OGCM	Oceanic General Circulation Model
OPAC	Optical Properties of Aerosols and Clouds
ONR	Office of Naval Research
PBL	Planetary Boundary Layer
PCMDI	Program and Climate Model Intercomparison
POCS	Pockets of Open Cells
POP	Parallel Ocean Program
PPAI	Predictability, Prediction, and Applications Interface
PSMIP	Process Study and Model Improvement Panel
RA2	NCEP/DOE Reanalysis
RAM	Regional Atmospheric Model
RAMS	Regional Atmospheric Modeling System
REP	Representer tangent linear
Rex	Regional Experiment
ROAM	Coupled ROM-RAM Model
ROM	Regional Ocean Model
ROMS	Regional Ocean Modeling System
RSM	Regional Spectral Model
SAMS	South American Monsoon System
SCB	Southern California Bight
SCM	Single Column Models
SCOAR	Scripps Coupled Ocean-Atmosphere Regional model
SEP	Southeast Pacific
SSiB	Simplified Simple Biosphere
SST	Sea-Surface Temperature
SWCRF	Shortwave Cloud Radiative Forcing
TFSP	Task Force for Seasonal Prediction
T62	Triangular truncation of 62 waves
TIW	Tropical Instability Wave
TKE	Turbulent Kinetic Energy
TL	Tangent Linear
UCH	University of Chile
UCLA	University of California Los Angeles
UCSD	University of California San Diego
UH	University of Hawaii
UW	University of Washington
VAMOS	Variability of American Monsoon Systems

VOCALS	VAMOS Ocean-Cloud-Atmosphere-Land-Study
VOCALS-Mod	VAMOS Ocean-Cloud-Atmosphere-Land-Study Modeling
VOCALS-Rex	VAMOS Ocean-Cloud-Atmosphere-Land-Study Research Experiment
WCRP	World Climate Research Programme
WGCM	Working Group on Coupled Models
WGNE	Working Group on Numerical Experimentation
WGSIP	Working Group on Seasonal-to-International Predictions
WHOI	Woods Hole Oceanographic Institution
WRF-NMM	Weather and Research Forecast model