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Title: **Coupled Ocean-Atmosphere Model System for Studies of Interannual-to-Decadal Climate Variability over the North Pacific Basin and Precipitation over the Southwestern United States**

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Coupled Ocean-Atmosphere Model System for Studies of Interannual-to-Decadal Climate Variability over the North Pacific Basin and Precipitation over the Southwestern United States

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Abstract

This is the final report of a one-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). The ultimate objective of this research project is to make understanding and predicting regional climate easier. The long-term goals of this project are (1) to construct a coupled ocean-atmosphere model (COAM) system, (2) use it to explore the interannual-to-decadal climate variability over the North Pacific Basin, and (3) determine climate effects on the precipitation over the Southwestern United States. During this project life, three major tasks were completed: (1) Mesoscale ocean and atmospheric modeling over the west coast: built a coupled mesoscale ocean and atmospheric model; (2) global-coupled ocean and atmospheric modeling: completed the coupling of LANL POP global ocean model with NCAR CCM2+ global atmospheric model; and (3) global nested-grid ocean modeling: designed the boundary interface for the nested-grid ocean models.

Background and Research Objectives

The precipitation (and hence the water supply) in the Southwestern US has a great variability from year to year. Major variations are well evidenced by the last two decades of precipitation and runoff in the California Sierra Nevada and New Mexico Rio Grande—from the extremely high flows of 1983, 1986, and 1993, to the severe droughts of 1976-1977, 1987-1992, and the more recent extremely dry winter of 1994-1995. Some of these extremes are related to El Niño events, some are not. Why?

Virtually all the water supply for the region west of the Rocky Mountains is provided by North Pacific winter storms. Seasonal total precipitation (snow, rain) in the Southwest is crucial to agriculture, bio-habitat, recreation, and many other sectors. Extreme events (such as floods, multi-year wet spells, and droughts inherent in the climate system) are linked to upstream atmospheric circulation. This is because the ocean surface conditions within the tropics, the eastern North Pacific, as well as the US coastal ocean, have great influence on the path and intensity of cyclones that bring the region's water supply.

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Some fraction of climate variability over the North Pacific on interannual-to-decadal time scales is predictable . This predictability is associated with ocean dynamics and its interaction with the atmosphere (Davis, 1976; Namias, 1979; Wallace and Jiang, 1987). Recent studies (Jacobs et al., 1994; Speich et al., 1995) suggest that the intrinsic variability of North Pacific major currents may modulate and interact with the sea surface temperature (SST) anomaly signals on a decadal time scale. This may give a background of the fluctuation of precipitation. Therefore, examining the dynamical processes of the propagation of anomalous SST areas, using a coupled ocean-atmosphere model (COAM), may help improve the predictability of large-scale atmospheric weather regimes influenced by El Niño (Dettinger and Cayan, 1995).

However, precipitation over the Southwestern US is also strongly affected by the coastal ocean and atmospheric circulations and the orography (Rocky Mountains). Thus, an ocean model of a COAM should be eddy-resolving in major current ocean general circulation model (GCM); this is the most logical choice for the study. So far, the only oceanic application of the nested-GCM concept has been nesting the Gulf of Mexico regional model (see Fig. 2 for the result of a simulation of Loop Current and Eddy—a collaborative research with university colleagues) into a north-Atlantic-basin ocean general circulation model (OGCM). Nevertheless, there are a few atmospheric nested GCMs in operation at the National Weather Service and the Navy.

Mesoscale ocean-atmosphere interactions are known to exist in the tropical Pacific. Over the western equatorial Pacific, the evaporation-wind feedback theory has been used to explain the eastward propagation of cloud clusters related to the Madden and Julian oscillation. The mesoscale interaction of ocean and atmosphere over the eastern Pacific Ocean in relation to precipitation events in the Southwestern US has not been studied extensively. Over California and the ocean to the west, strong south or southwest wind will bring warm ocean water to the coast. It tends to create a surface low-pressure center, enhanced evaporation, more clouds, and precipitation. On the other hand, strong north or northwest wind will produce significant upwelling near the coast and cold ocean temperature. This cold ocean temperature will produce a surface high-pressure center and clear weather. Therefore, coastal mesoscale air-sea interaction has a major influence on the path and the moisture contents of winter cyclones and eventually the precipitation events in the Southwestern US.

Therefore, the ultimate objective of this research project is to make understanding and predicting regional climate easier. This objective cannot be reached without achieving three goals of this project: (1) to construct a COAM system, (2) use it to explore the interannual-

to-decadal climate variability over the North Pacific Basin, and (3) determine climate effects on the precipitation over Southwestern United States.

Importance to LANL's Science and Technology Base and National R&D Needs

Water resource has become one of the major national security issues. The impact of shortage of water and/or flood on the industries, society, and human life has become an increasingly urgent problem. However, it had been such a very complex scientific challenge that no one organization was able to make a significant contribution. The Laboratory's competency in high-performance computing has been a major contribution toward its science and technology base. Combining the advancement in ocean and atmospheric modeling techniques and the Laboratory's assets in computing, this project will be the first to prove the solvability of the problem.

No systematic study for the North Pacific Basin's dynamics as a COAM climate system has been performed so far. This project will be a pioneer work of "clearing house" of models and expertise on the climate system.

The emphasis of this project is to employ the nested-grid COAM in exploring how and to what extent the interaction between the ocean and atmosphere affects the ocean's internal variability and hence the climate, above and to the east of the North Pacific Basin. Investigations such as this are extremely exciting to the climate and hydrology research communities that have long awaited specific regional-scale physical models. Therefore, this project will have a major scientific and technical impact on the research of long-term regional climate modeling and prediction, both of which are the foundation for climate-related policy making.

Scientific Approach and Accomplishments

The scientific approach is first to build and test mesoscale and global COAM separately. The next step is then to embed the mesoscale COAM into the global COAM. Simulations of meso-scale/global COAMs are needed to study climate variability and precipitation. There are three major tasks. The first two (A & B below) are to build the research model: a nested COAM system (illustrated in Fig. 1). The third task (C below) is to explore the interannual-to-decadal climate variability over the North Pacific Basin and its effects on the

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precipitation over Southwestern US. These three tasks include the following work (technical details omitted):

A. Mesoscale ocean and atmospheric modeling over the west coast.

(1) Build a coupled mesoscale ocean and atmospheric model. This takes a few incremental steps:

(a) Configure and validate both ocean and atmospheric models [RAMS and Parallel Ocean Program (POP)] in a common domain. We need to (i) take care of spatial interpolation and temporal synchronization between ocean and atmospheric models; (ii) define a consistent interface boundary condition; and (iii) give/receive the vertical fluxes of heat, water vapor, and momentum, accordingly.

Because our goal is to simulate the precipitation over the Southwestern US and the moisture source in the Pacific, the domain will extend from approximately 165 degree W to 105 degree W and 15 degree N to 55 degree N.

(b) Couple the atmospheric model to a "dummy" ocean model that is simpler than the real ocean model but resembles it. This is to test out the scheme and algorithm or the exchange of information (fluxes). The ocean model can do vice versa.

(c) Complete a mesoscale COAM.

(2) Using this model, we investigate the mechanism of generation, transportation, and precipitation of water vapor across the domain (ocean and Southwestern US). This must be carried out with the North Pacific Basin nested COAM.

(a) Use the mesoscale COAM to study the physical processes involved in West Coast precipitation events.

(b) Use the mesoscale COAM to study the regional climate of the Southwestern US, including the change of precipitation patterns and snow accumulation during the dry and wet seasons.

(c) We start from simulating a normal climate condition with mean SST and atmospheric flows. We document (i) the budget of water vapor over the ocean, the coastal zone, and the mountain; (ii) the atmosphere; the transport, the precipitation areas, forms, and intensity; and (iii) and the atmospheric and ocean mean circulation and energy exchanges.

(d) We then select a few abnormal events and prepare a comprehensive archive of observations of atmospheric variables and precipitation. We thus begin simulating those special events, validating the results with observation. We must compare these abnormal events with mean climate in terms of the shifting of precipitation pattern, intensity, duration, and mechanism and atmospheric physics.

B. Global nested-grid ocean modeling.

  (1) Create nested-grid ocean models. The model has a twice-nested (or three-level) structure: the background GCM (first level) will be a low-resolution (1/2 degree) global(77 degree S - 77 degree N) POP whose entire Pacific basin will be replaced by an intermediate-resolution, "coarse-mesh" (CM: 1/4 degree) model (second level) for the Kuroshio; a north-eastern pacific region will be embedded

  (2) Model runs: four 10-year simulations:

      (a) Non-nested global POP control run without the coarse mesh (CM) or fine mesh (FM) models inside.

      (b) Non-nested CM model control run without the FM models inside.

      (c) FM regional model run with boundary condition provided by the CM control run.

      (d) Interactively nested model run (POP-CM-FM).

  (3) Validation and data analysis. Model output compared with archived oceanic data sets such as COADS and TOPEX for validation purposes.

C. Nested COAM system simulation studies.

These simulations represent atmospheric-ocean global/basin scale conditions and response to perturbation such as El Niño/Southern Oscillation phenomena. The work consists of the following three complementary activities:

  (1) Basin-scale climate study using double-gyre models for the ocean.

  (2) Eddy-resolving Kuroshio region study.

  (3) Relation to SST variability.

The three major tasks are closely linked and overlap. The time of emphasis for each is indicated in logical sequences, but research on all three proceeded (to some extent) in parallel, feeding at the same time essential guidance to the COAM study.

Major accomplishments during this project are as follows:

Mesoscale ocean and atmospheric modeling over the west coast.
We have successfully built a mesoscale coupled ocean and atmospheric model over the west coast region. This took advantage of an existing regional atmospheric model (Mesoscale Atmospheric Simulation -- MAS) from University of California at Davis (UCD) and an existing regional ocean model (DieCAST) from Mississippi State University (MSU). However, we had created an interface module which not only replaced the

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traditional "prescribed" interface boundary conditions (e.g., climatological sea surface temperature) with time-dependent values but also guaranteed the conservation of heat and momentum in the coupled models system. A series of model simulations of weather events in the winter of 1995, using MAS model alone and coupled models system, had been made. The results were compared to the observations. We found that the amount of precipitation (rain and snow) over the California simulated with coupled models system matched better with the observations than that simulated with MAS model alone. It is especially noticeable for the weather when there was southwesterly wind off the California coast. This is because the southwesterly wind could bring warm ocean water from south to the California coast and enhance the evaporation from ocean to atmosphere. That, in turn, enhanced the precipitation over the California. When the MAS model was used alone, the climatological value of the sea surface temperature was the only reliable bottom boundary condition from which the thermal forcing was calculated, just like all uncoupled atmospheric models did. Therefore, the MAS model was not correctly "informed" of the ocean condition. Our mesoscale coupled models system is the first one to demonstrate the significance of the air-sea interaction process in the coastal weather events.

Global coupled ocean and atmospheric modeling. We have completed the coupling of a global OGCM with a global atmospheric general circulation model (AGCM). We took advantage of the well-tested LANL Parallel Ocean Program and the Community Climate Model (CCM2+) of the National Center for Atmospheric Research (NCAR). This coupling of the two codes utilized the "flux coupler" package developed in the NCAR Climate System Modeling project funded by the National Science Foundation. A one-year coupled model simulation, starting with current climatology, gave satisfactory results in the global atmospheric and ocean temperature distributions and velocity fields. It proved that the "flux coupler" package conserved the heat and momentum of the coupled system. However, our detailed analysis of the model ocean data revealed that there was a significant bias of salinity in the Arctic ocean and near river delta areas. We had modified the "flux coupler" to conserve the water mass in the coupled system. In the coupled model system, water evaporates from ocean and land surface into the atmosphere. Water vapor condensed to form clouds and produced rain and snow over the ocean and land. In the original "flux coupler", there was no mechanism to collect the rain and melted snow over the land and put them back to oceans via rivers. That led to the loss of water mass in the oceans and the increase of salinity. Without the correction of ocean salinity, the model ocean thermohaline circulation will eventually be quite different from the reality. We had completed a 10-year coupled model simulation and found no drift in the temperature, salinity, velocity fields of the oceans. Some other global coupled models have conserved the heat and momentum

budget of the system, but our global coupled model is the only one which also conserves the water mass.

Global nested-grid ocean modeling. Unlike the coupling of ocean and atmospheric models in the vertical, this research dealt with the communication of information across the lateral interface between a global coarse-mesh (coarse-resolution) ocean model and an embedded fine-mesh ocean model. There is no standard way of designing the interface for this kind of nested-grid models. Our nested-grid models have a boundary interface that conserves the heat, mass, momentum and also their gradients across the interface. The ratio of grid size between coarse-mesh and fine-mesh is 3:1. We had embedded a fine-mesh DieCAST ocean model inside a coarse-mesh DieCAST model. The coarse-mesh DieCAST model, in turn, receives the boundary conditions from LANL POP model simulation results. This nested-grid DieCAST model had been applied to simulate the complicated currents off the California coast. The POP model simulation results provided the background North Pacific circulation and the California currents. The coarse-mesh DieCAST model had successfully simulated the narrow coastal current, while the fine-mesh DieCAST model had revealed the detailed mesoscale eddies triggered by the capes along the California coast and in the Santa Barbara Channel (off Long Beach, CA). This work has been in cooperation with the MSU's Gulf of Mexico simulation project. Our results will be applied to a cooperation with the University of California at Los Angeles (UCLA) in the study of the interannual-to- decadal variability of ocean currents in the North Pacific. Our ocean models are the first of few nested-grid models that used real ocean configuration and revealed a realistic ocean circulation.

Publications

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2. Lai, C.-C. A., "LANL global/regional coupled ocean-atmosphere modeling for climate research," Inter-Americas Institute, Regional Climate workshop, 18-20 September, 1996, San Miguel, Mexico.

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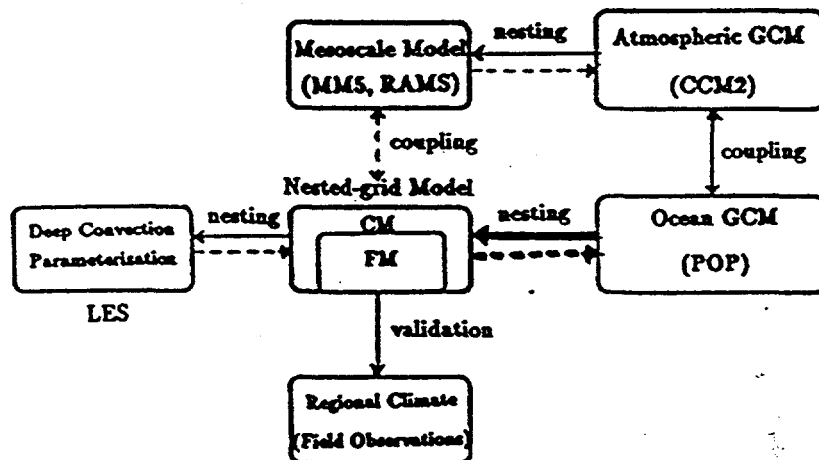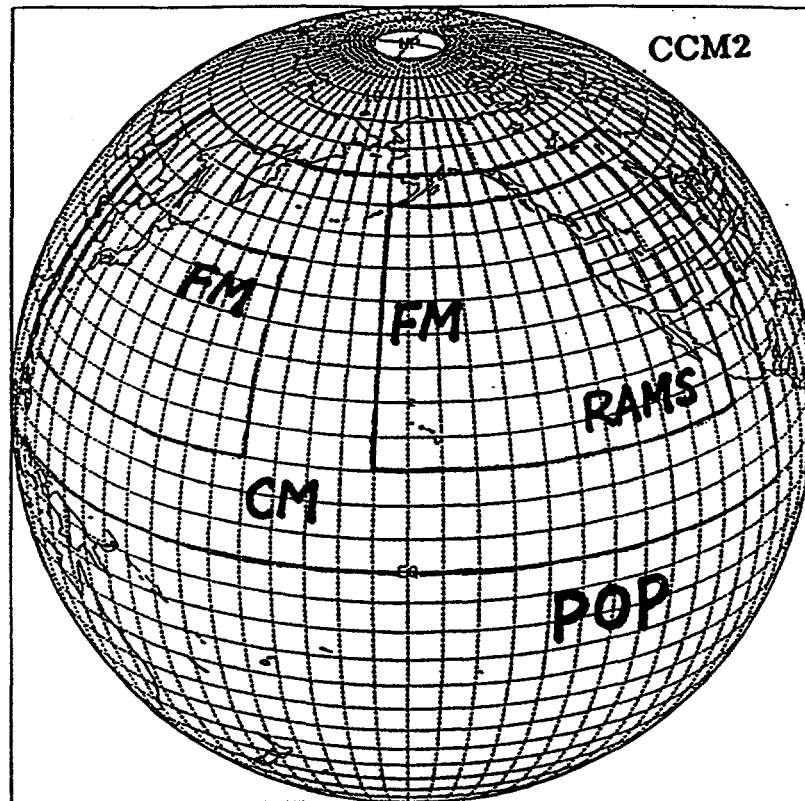
Fig. 1.   Domains and structure of the coupled and nested climate model system and its
          component models. Atmospheric and ocean models are vertically coupled.
          Global and regional models [coarse mesh (CM) and fine mesh (FM)] are
          horizontally nested. Regional nested-grid model can be validated with field
          observations.

This plot shows a new warm core eddy shedding from the Loop Current. and, an old warm core eddy interacting with its paired cold core counterpart. A narrow finger of Loop Current water has penetrated northward along the Florida shelfbreak.

ABOVE	26.0
25.5 -	26.0
25.0 -	25.5
24.5 -	25.0
24.0 -	24.5
23.5 -	24.0
23.0 -	23.5
22.5 -	23.0
22.0 -	22.5
BELOW	22.0

Loop Current Finger

Loop Current

New Warm Core Eddy

Paired Cold Core Eddy

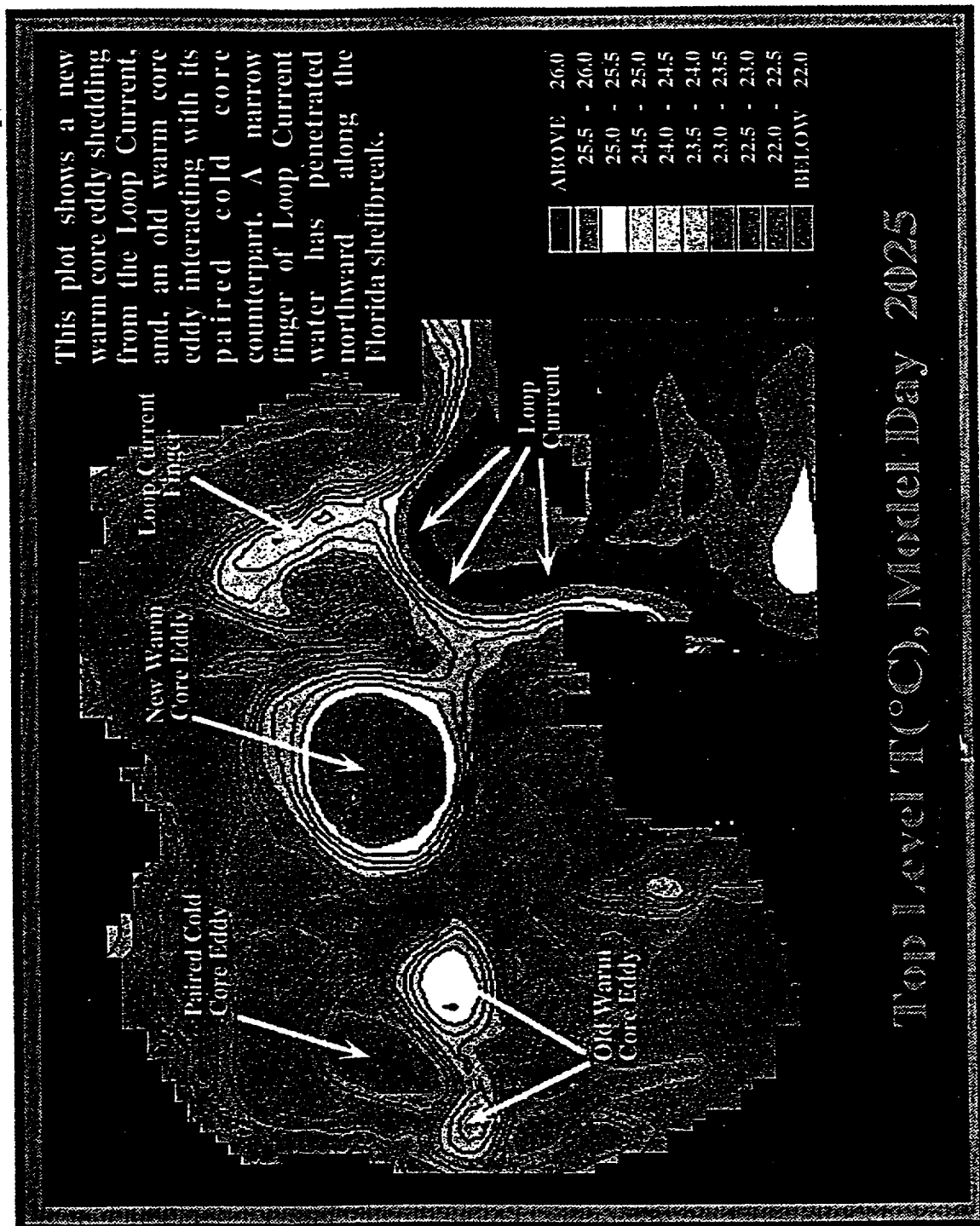Old Warm Core Eddy

Top Level T(°C), Model Day 2025

Fig. 2.   The simulation of Loop Current and Eddy by the Gulf of Mexico regional ocean model.

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