Modeling of the South Eastern Pacific Climate: Progress and Challenges

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- Motivation

- Our recent work on the simulation of the coupled atmosphere-ocean system with CGCM

- Challenges and Hypotheses

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

- Summary
Major features of SEP climate

- Cold SSTs, coastal upwelling
- Cloud-topped ABLs
- Influenced by and influential on remote climates (ENSO)
- Unresolved issues in heat and nutrient budgets
- Important links between aerosol and clouds
- Poorly simulated by atmosphere-ocean GCMs
Ocean Salinity Section at 88W
The CFS model has significant errors in the SEP.

There is a meridional shift in ITCZ (top), a warm SST bias (middle), and insufficient stratocumulus cloud cover (bottom).

These errors adversely affect the skill of CFS climate forecasts (ENSO).

What model developments are required to alleviate these errors, which are common to most CGCMs?
Work at UCLA on the Simulation of the coupled atmosphere-ocean system with CGCM

Akio Arakawa (1): AGCM; Cabriel Cazes-Boezio (1, 7): AGCM PBL, Coupled GCM;

C. Roberto Mechoso (1): P. I.;

Chris Hill (3): MIT OGCM; Phil Jones (4): POP;

Dimitris Menemenlis (5): MIT OGCM, ECCO; George Philander (2): Coupled GCM;

Joseph A. Spahr (1): ESMF; Slujia Zhou (6): ESMF

(1) Department of Atmospheric and Oceanic Sciences, University of California Los Angeles
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(3) Department of Earth, Atmospheric and Planetary Sciences, MIT
(4) Theoretical Fluid Dynamics Group, Los Alamos Natural Laboratory
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Sponsor: NASA Earth Science Tech. Off. (ESTO), NOAA PACS
Coupled Atmosphere-Ocean Application in ESMF- Superstructure

- **AGCM Driver**
  - Initialize
  - Run
  - Finalize
  - Import/Export States

- **OGCM Driver**
  - Initialize
  - Run
  - Finalize
  - Import/Export States

- **Atmos to Ocean Coupler Driver**
  - Import/Export States

- **Ocean to Atmos Coupler Driver**
  - Import/Export States

*Infrastructure*
Vertical Structure of UCLA (and CSU) AGCMs

- The PBL top is explicitly defined, and its depth is predicted from a mass budget equation, with parameterizations of the mass source due to entrainment and the mass sink due to cumulus mass flux.
- The treatment of processes near the PBL top (clouds, radiative cooling near PBL top) is more tractable in this framework.
- The variable-depth PBL model is incorporated as an integral part of the GCM vertical structure. "Horizontal" differencing taken along a coordinate surface does not have to cross the PBL top.
- Profiles within the PBL can be well-mixed (traditional formulation) or deviate from well mixed structure (new formulation).
PBL Regimes in UCLA-AGCM

Clear deepening PBL

Collapsing PBL

Nighttime PBL

Cloud-topped PBL

Different Regimes
Hybrid approach to determine turbulence fluxes

- Effects of large-scale convective eddies are represented by a bulk PBL parameterization. Their fluxes are determined by interpolating conserved quantities such as moist static energy and total water mixing-ratio from surface to PBL top.

\[
F_\psi \equiv a \left( F_\psi \right)_S + (1 - a) \left( F_\psi \right)_B
\]

**Bulk formulation determines the surface and PBL-top fluxes,**

- Effects of small scale diffusive eddies are represented through a K-closure formulation

\[
\tilde{F}_\psi \equiv -\rho K \left( \frac{\partial \psi}{\partial z} \right)
\]
Main Components of bulk parameterization

- **Bulk TKE** ($e_{PBL}$) is predicted through a budget equation.
- **Surface fluxes** are given by

\[
F_v = \rho_s C_U C_U \max \left( u_M, \alpha_1 \sqrt{e_{PBL}} \right) v_M \\
F_\theta = \rho_s C_U C_T \max \left( u_M, \alpha_2 \sqrt{e_{PBL}} \right) (\theta_G - \theta_M) \\
F_q = \rho_s C_U C_T \max \left( u_M, \alpha_2 \sqrt{e_{PBL}} \right) (q_G - q_M) \ k
\]

- **Entrainment** is parameterized as function of TKE ($e_{PBL}$) and the jumps at PBL top of radiation, virtual dry static energy, and critical virtual static energy.
• Simulations capture the precipitation maximum in early afternoon.
Figure 6 - Mean diurnal cycle of rainfall for networks 1-4 (full thick line), average of the westerly regime (thin full line), and easterly regime (thin broken line). Values are in mm/hour and time is LST.

Marengo et. al (2005)
Low-level Cloud Incidence

Simulation

JJA

DJF

Klein-Hartmann analysis

JJA

DJF

UCLA-AGCM; 5lonx5lat, 17 layer
Simulations with CGCM
(UCLA-AGCM/MIT-OGCM)

- **AGCM** (Low-resolution): 5X4, 14+4 layers.
  (High-resolution): 2.5X2, 28+4 layers.
- **OGCM** 1X0.3 (near Eq.), 1X1 (mid and high lat), 46 layers.

Hindcasts with CGCM

- Initial conditions: March 5th, June 5th
- 5 - member ensemble over 9 years (1993-2002)
- 15 - month long runs; 180 runs
- Initial atmospheric states: From long AGCM run with clim. SST.
- Two initial ocean states: 1) JPL’s ECCO Project; 2) Long OGCM run with prescribed climatol. wind stress and SST.
Surface wind stress (Eastern Pacific)

January

- Observed
- Simulation
- Low-Resolution
- High-Resolution

July

- Observed
- Simulation
- Low-Resolution
- High-Resolution

- High resolution results very closely match COADS analysis.
SST and Zonal wind stress (4S-4N) anomalies

• ENSO like signal exists
DJF 1997 Forecast from March 5, 1996

DJF 1997 SST anomaly from March 5 initial conditions (ECCO)

Reynolds analysis

UCLA AGCM 8.0 2x2.5x29
MIT OGCM Global
DJF 1997 Forecast from June 5, 1996

DJF 1997 SST anomaly from June 5 initial conditions (ECCO)

Reynolds analysis

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Reynolds analysis

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MIT OGCM Global
Correlations with Nino 3.4

Forecasts from early March (top) and early June (bottom)
Standard Deviation of DJF Forecast Error
From Early March Initial Conditions

a) Using ECCO

b) No-ECCO

c) Persistence

UCLA AGCM 7.3 HighRes
MIT Global OGCM

Contour interval, 0.5°C
UCLA-AGCM coupled to MIT-OGCM
Low-resolution AGCM (5X4; 14+4 layers)

Simulated annual mean SST

Observed annual mean SST

- Cold tongue is asymmetric relative to the Equator. Equatorial West-East SST gradient is realistic.
- Double ITCZ in both Pacific and Atlantic Oceans.
**UCLA-AGCM coupled to MIT-OGCM**
**High-resolution AGCM (2.5X2; 28+4 layers)**

- Cold tongue is asymmetric relative to the Equator. Equatorial West-East SST gradient is realistic.
- Double ITCZ in both Pacific and Atlantic Oceans still exist, but SST errors are smaller.
Challenge: The doubled ITCZ bias  
A synthetic view of this problem is still elusive ...

The consensus is that the bias is at least partly due to the underestimation of stratocumulus cloud cover by the AGCM, which results in too warm SSTs in the eastern tropical oceans. Other strategies for improvement have shown to be AGCM-specific, with different effects in different models:

- **Increasing cumulus friction**
- **Changing the cumulus parameterization**
- **Increasing the re-evaporation efficiency**
- **Improving the advective transport of water vapor above the PBL**
- **Increasing both horizontal and vertical resolution**
Surface wind stress

January

July
How to approach the doubled ITCZ bias?

Since the double ITCZ bias is common to most CGCMs, one approach is to narrow down on large-scale aspects such as improving the too weak trades in the simulations.

1. The simulated zonal momentum budget in the tropics has errors. Westerly momentum gained by the atmosphere through surface easterlies must be removed at some level above, otherwise the vertically integrated atmosphere tends to become more dominantly westerly until the easterly surface stress vanishes.

2. It is possible that this removal is not well simulated due to: (a) too weak simulated standing waves, and/or (b) too weak or missing momentum redistribution from the surface to upper levels.

In this regard, a more drastic improvement may require substantial model development. This has to be guided by the results of an in-depth analysis of model performance, particularly of the mechanisms for maintenance of zonal momentum.
Hadley circulation: momentum and heat transports

- Latent heating in convective rain
- Trade winds
- Ocean heat transport
- Moisture transport
- Evaporation
- Heat transport by transients
- Westerly momentum transport (eddies)
- Radiation solar down infrared up
- Dynamical warming by subsidence
The increased severity of the ITCZ bias in coupled models suggests that the OGCM contributes to it.

The Peru Current is one of the major eastern-boundary, subtropical upwelling regimes. There is an equatorward surface geostrophic flow and a poleward undercurrent that is strongest in summer. This circulation pattern of the ocean is baroclinically unstable and develops mesoscale eddies that extend the current system several hundred km offshore.

The eddies provide shoreward heat and material transport that balance the upwelling supply of cold water and the air-sea heat exchange. These structures are reinforced by standing eddies associated with alongshore coastline and bathymetric irregularities.
Annual-mean heat flux into ocean $\sim 30$ W m$^{-2}$ at 1500 km offshore under persistent low cloud!

How is this net warming at the surface balanced by ocean heat transports?
Hypotheses and Challenges

H: AGCMs have difficulties in maintaining the zonal momentum budget of the vertically integrated atmosphere over the tropical oceans.

C: Can these difficulties be overcome?

H: Oceanic mesoscale eddies play a major role in the transport of heat, and biogenic species, from coastal upwelling regions to further offshore.

C: Can numerical models of the ocean simulate such transports?

Upwelling, by changing the physical and chemical properties of the upper ocean, affect aerosol precursor gases and aerosol size distribution in the PBL. Variability in aerosol and cloud droplet concentration affect the variability in cloud cover and albedo on timescales of days and lengthscales of a few hundred kilometers.

C: Can numerical models of climate simulate such variability?
The overall goal of VOCALS is to develop and promote scientific activities leading to improved understanding, model simulations, and predictions of the southeastern Pacific (SEP) coupled ocean-atmosphere-land system, on diurnal to interannual timescales.

The science objectives of VOCALS include:

- Improving the understanding and simulation of aerosol-cloud-drizzle interactions in the marine PBL.
- Improving the understanding and simulating of the ocean budgets of heat, salinity, and nutrients in the SEP.
- Characterizing, determining, and alleviating the systematic biases of atmosphere-ocean GCMs in the SEP.
- Elucidating and understanding interactions between the SEP climate and remote climates.
Elements of VOCALS in the SEP

- SEP has research-grade buoys and strategic island
- Strong gradients in the climate system
- Imprints of aerosol and mesoscale ocean variability in the structure of PBL clouds
- Highly committed regional partners, primarily in Chile but also in Peru and Ecuador
- Possible European presence: PRIMO
VOCALS Program

**VOCALS - REX**

Airborne: NCAR C-130 (and others)
SHIP: Ron Brown (and others)

**VOCALS - Modeling**

GCMs: NCEP, NOAA, GFDL, UCLA
RCMs: WRF, ROMS
VOCALS-REX

Aircraft: NCAR C130

Ships: 1. NOAA Ron Brown 2. Chilean

October 2007
**VOCALS:** Regional Coupled Modeling

- 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.

- The aim is to provide the appropriate framework for understanding regional, small-scale processes and heat budgets.

(From A. Miller)
VOCALS aims to develop a Modeling Framework for Interannual Climate Predictions

AGCM: Atmosphere General Circulation Model

OGCM: Ocean General Circulation Model

ESMF Infrastructure
SUMMARY

• The CGCM shows skill in ENSO hindcasts from months in advance. The skill is higher for the UCLA AGCM/MIT OGCM combination with ECCO initial conditions for the ocean. Cases from early June have substantially higher skill than form early March.

• Biases such as the double ITCZ are reduced but not eliminated in the CGCM simulation. Higher resolution in the ocean helps.

• Approaches to further reduction of the biases are proposed, for both the AGCM and OGCM.

• The broader problem of the tropical Pacific climate, including the effect of aerosol, motivate VOCALS. This is an international program with a field component scheduled for October 2007 and supported by a modeling component that emphasizes regional coupled models.

• Upgrades in the PBL parameterization of the UCLA AGCM have improved simulation of fluxes at the ocean’s surface and stratocumulus. The model has been coupled to the MIT OGCM and LANL POP using ESMF services.
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Structural differences between PBL implementations

**Vertical Structure of GCMs (e.g., NCAR, ECMWF, NCEP)**

- Vertical coordinate surfaces are fixed
- Profiles may deviate from well mixed ones.
- Processes near the PBL top are difficult to simulate properly (even with moderately high vertical resolution).
- It is difficult to keep track of budget of PBL quantities.
- Thus, a realistic simulation of PBL cloud incidence may be difficult.
- It is difficult to simulate PBL-free atmosphere exchange realistically.
Two DJF Forecasts with Different Success
From Early March Initial Conditions

DJF1994 SST anomaly - forecast

DJF2002 SST anomaly - forecast

DJF1994 SST anomaly - Reynolds Analysis

DJF2002 SST anomaly - Reynolds Analysis

UCLA AGCM 7.3 HighRes
MIT Global OGCM
a) ECCO temperature anomaly at vertical section, March

b) Baseline temperature anomaly at vertical section, March

contour interval: 1°C