VOCALS: A Program for Studies of the Southeastern Tropical Pacific Climate

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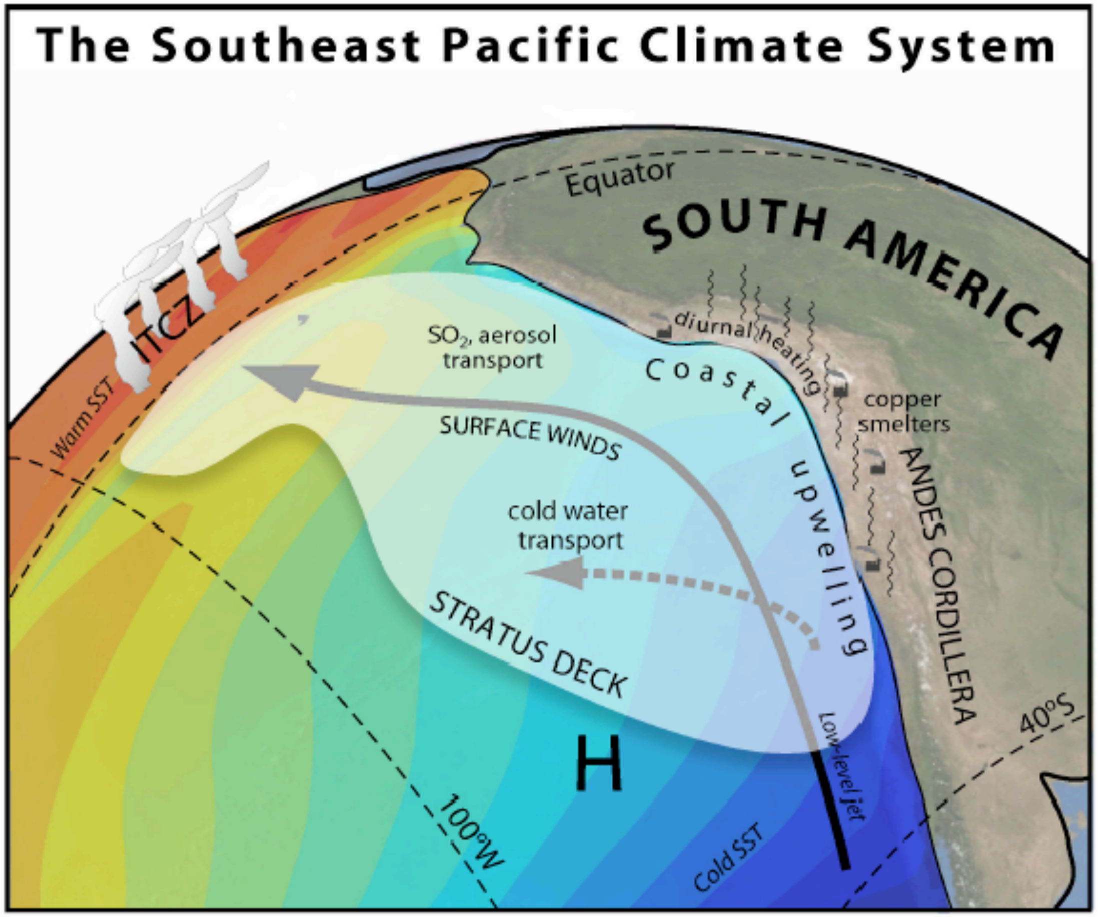
- *The climate of the Southeastern Tropical Pacific (SEP)*
- *Challenges to its Understanding, Modeling and Predicting*
- *Hypotheses*
- *VAMOS Ocean-Cloud-Atmosphere-Land Studies (VOCALS)*

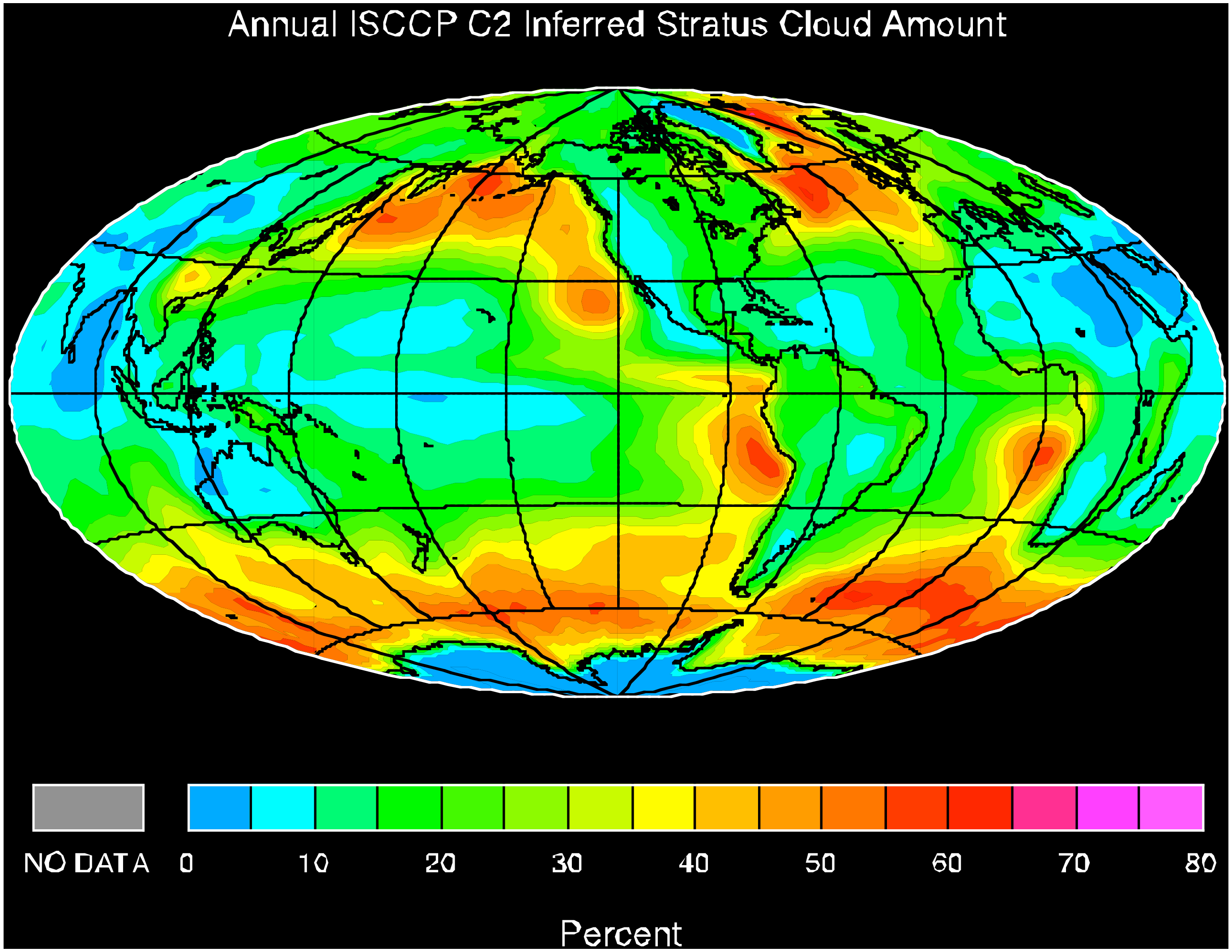
www.atmos.ucla.edu/~mechoso/esm *GFDL March 27, 2006*

UCLA



- Cold SSTs, coastal upwelling
- Cloud-topped ABLs
- Influenced by and influential on remote climates (ENSO)
- Poorly simulated by atmosphere-ocean GCMs
- Unresolved issues in heat and nutrient budgets
- Important links between clouds and aerosol

Low-level Cloud Incidence

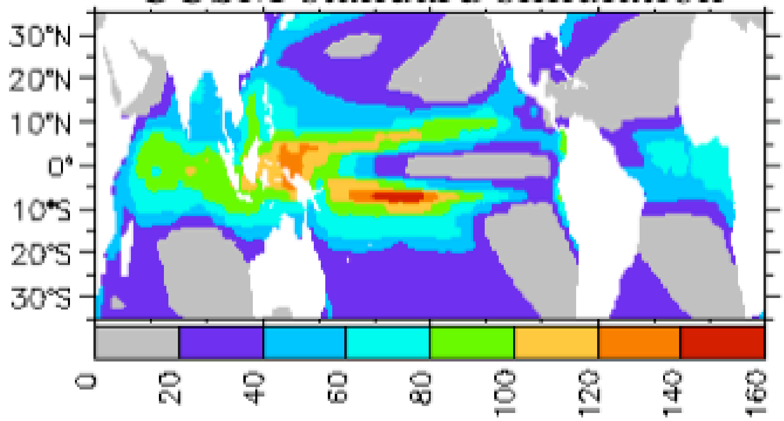


Courtesy of: Dennis L. Hartmann

University of Washington Climate Processes Research Group

UPSCALING EFFECTS FROM SUBTROPICAL EASTERN BOUNDARY OCEANS

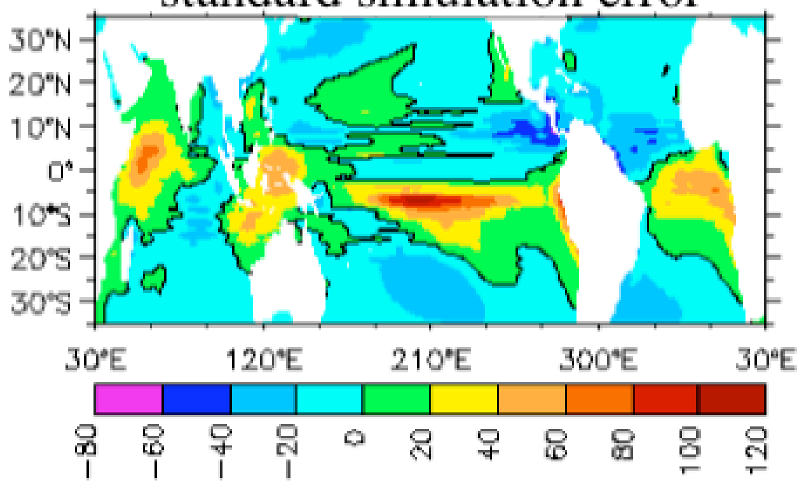
CCSM standard simulation



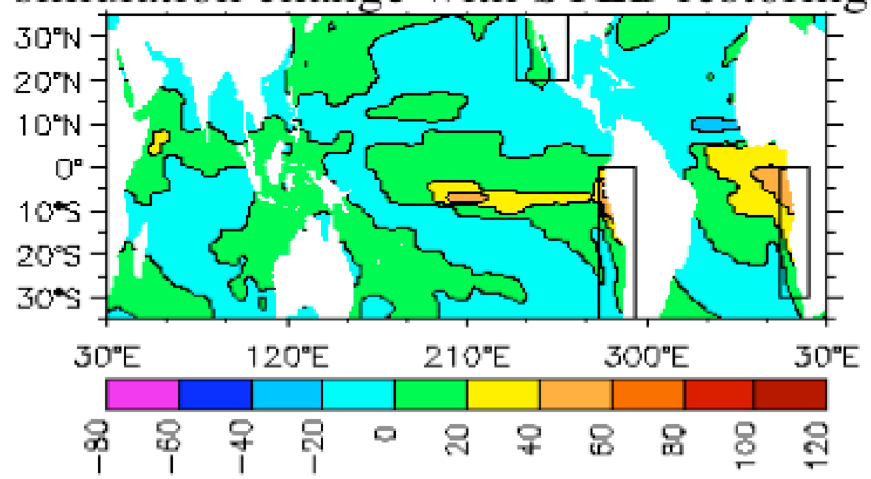
Mean precipitation [mg/m^2/s] in coupled model and its change with restoring of T & S in upper subtropical Eastern Boundary regions in N. & S. Pacific and S. Atlantic.

(Large & Danabasoglu, 2006)

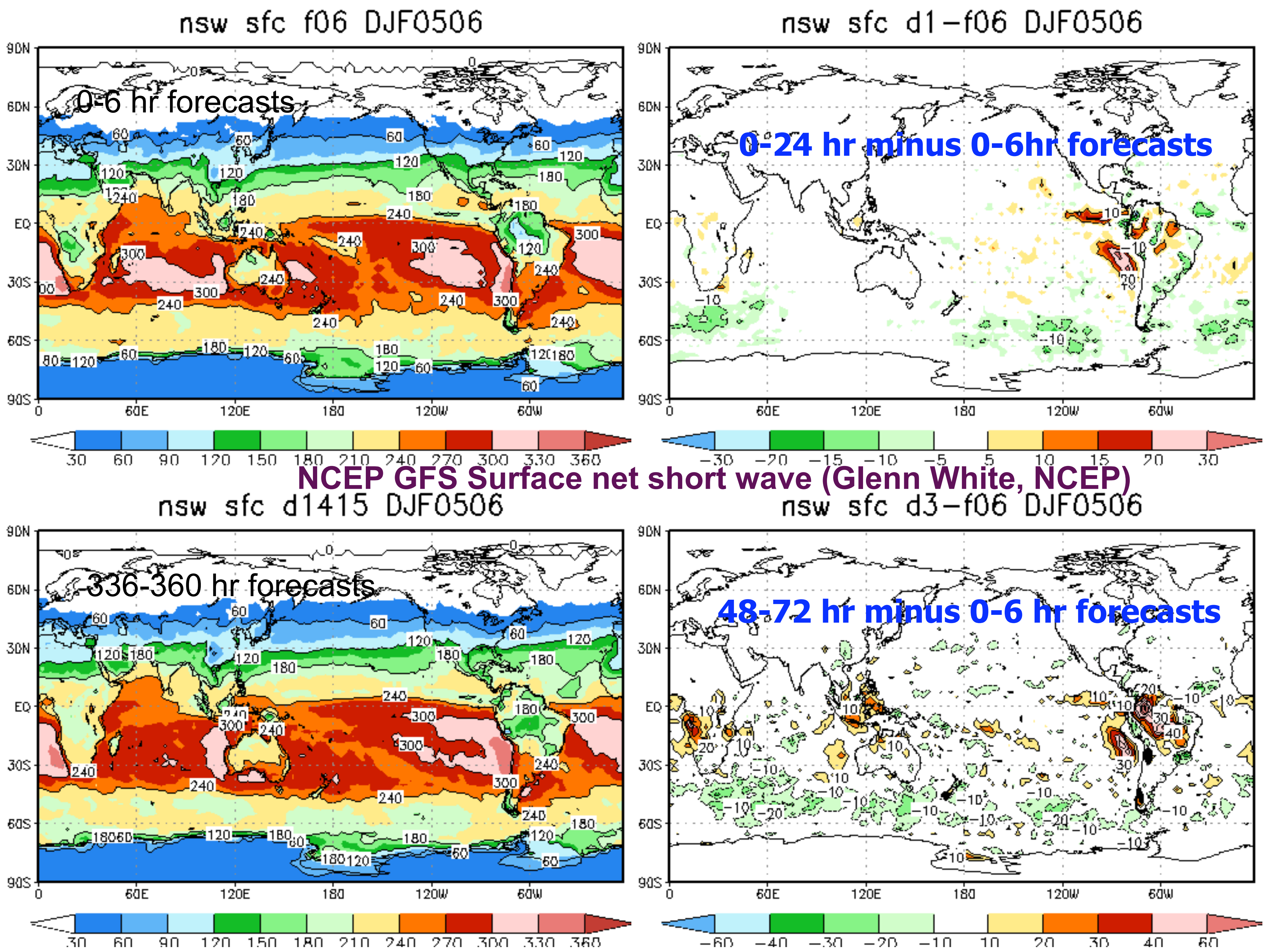
standard simulation error



simulation change with STEB restoring



NCEP GFS Surface net short wave (Glenn White, NCEP)

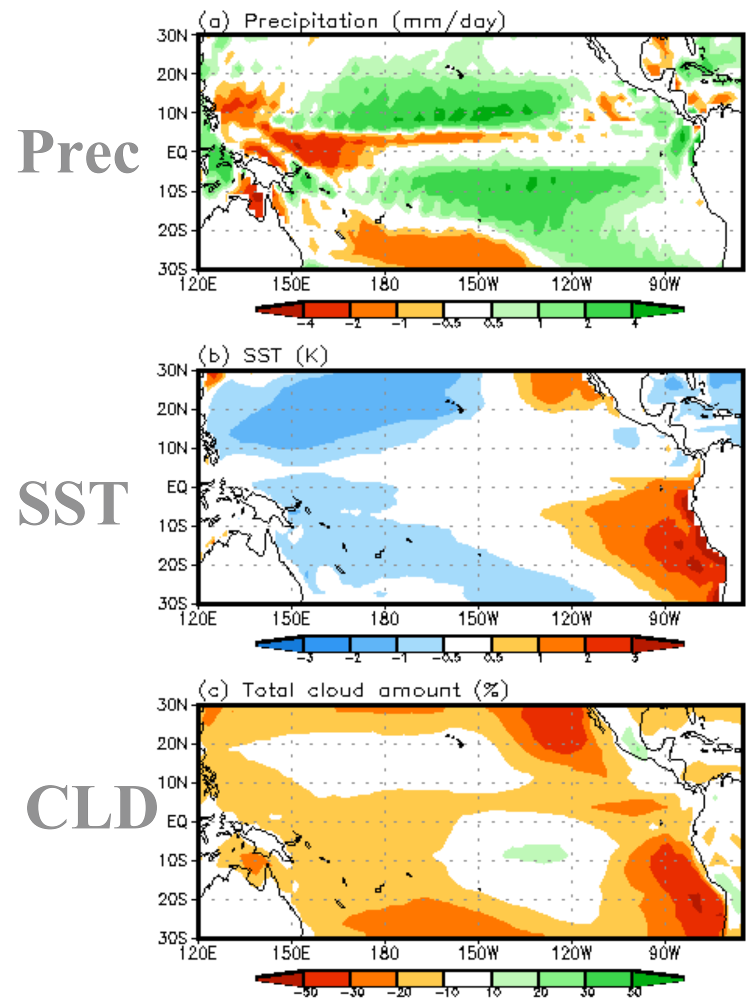


CGCM Problems: NOAA CFS Model

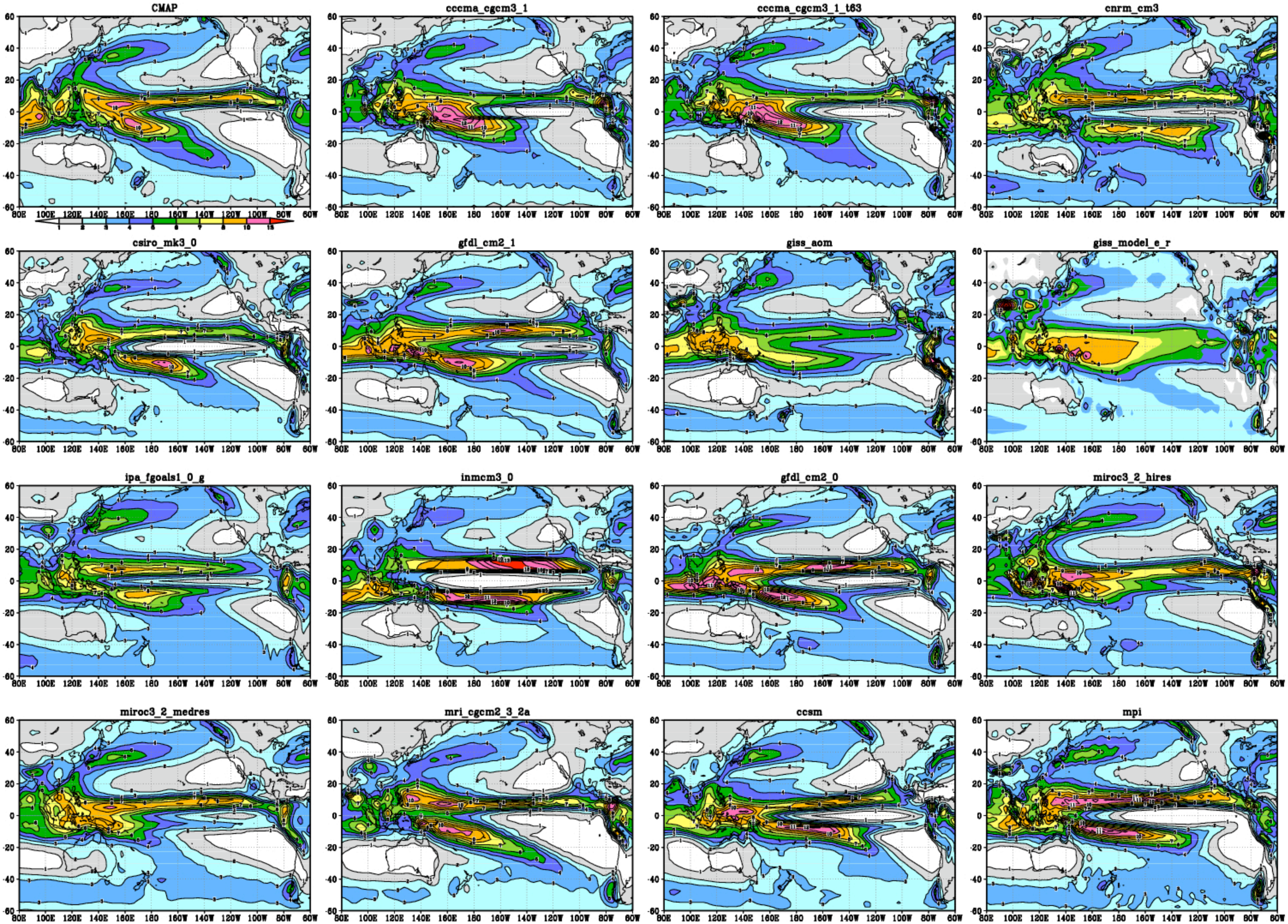
- The CFS model has significant errors in the SEP
- There is a meridional shift in ITCZ (top), a warm SST bias (middle) and insufficient stratocumulus cloud cover, (bottom)
- These errors adversely affect the skill of CFS climate forecasts (ENSO).

What model developments are required to alleviate these errors?

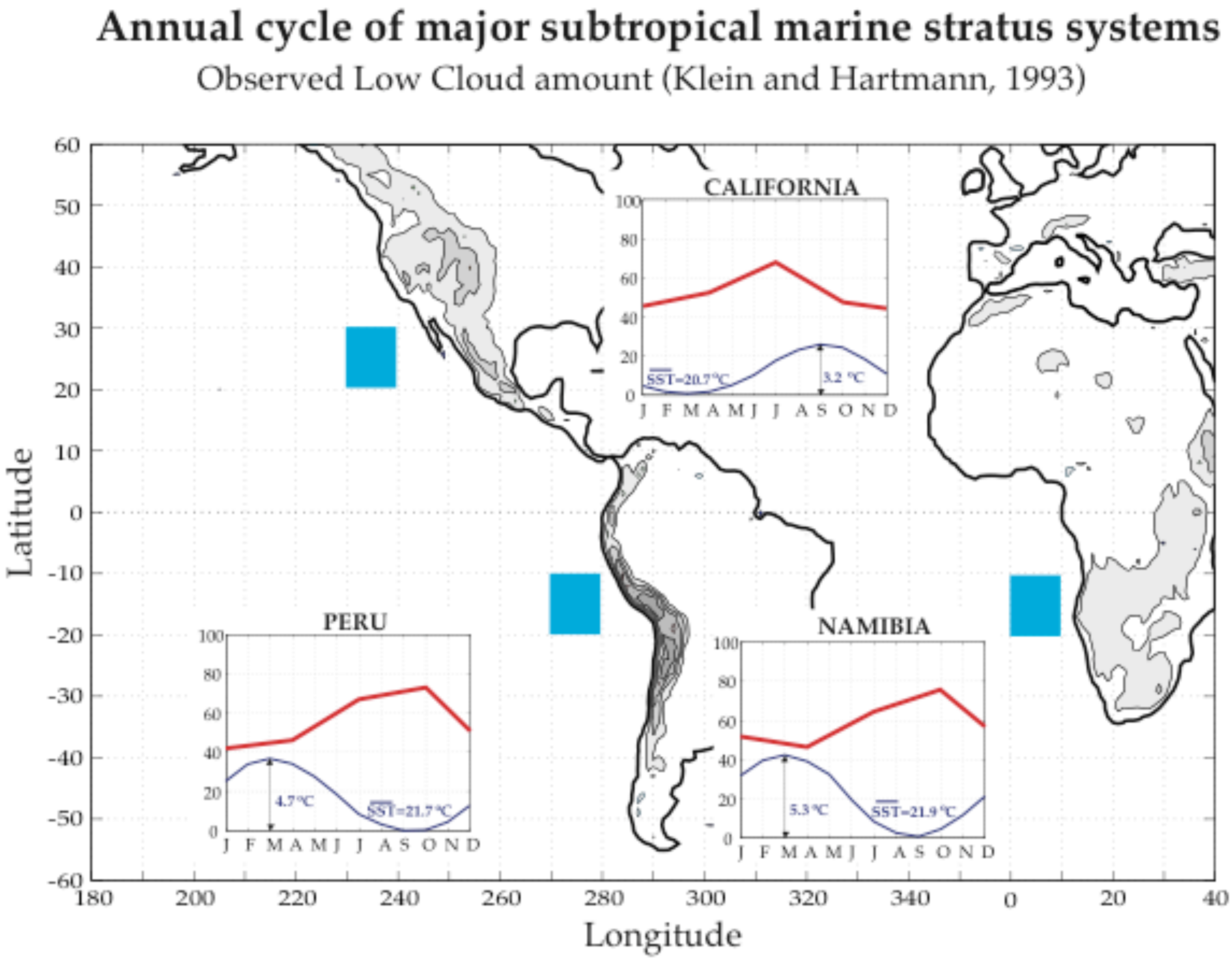
CFS Errors



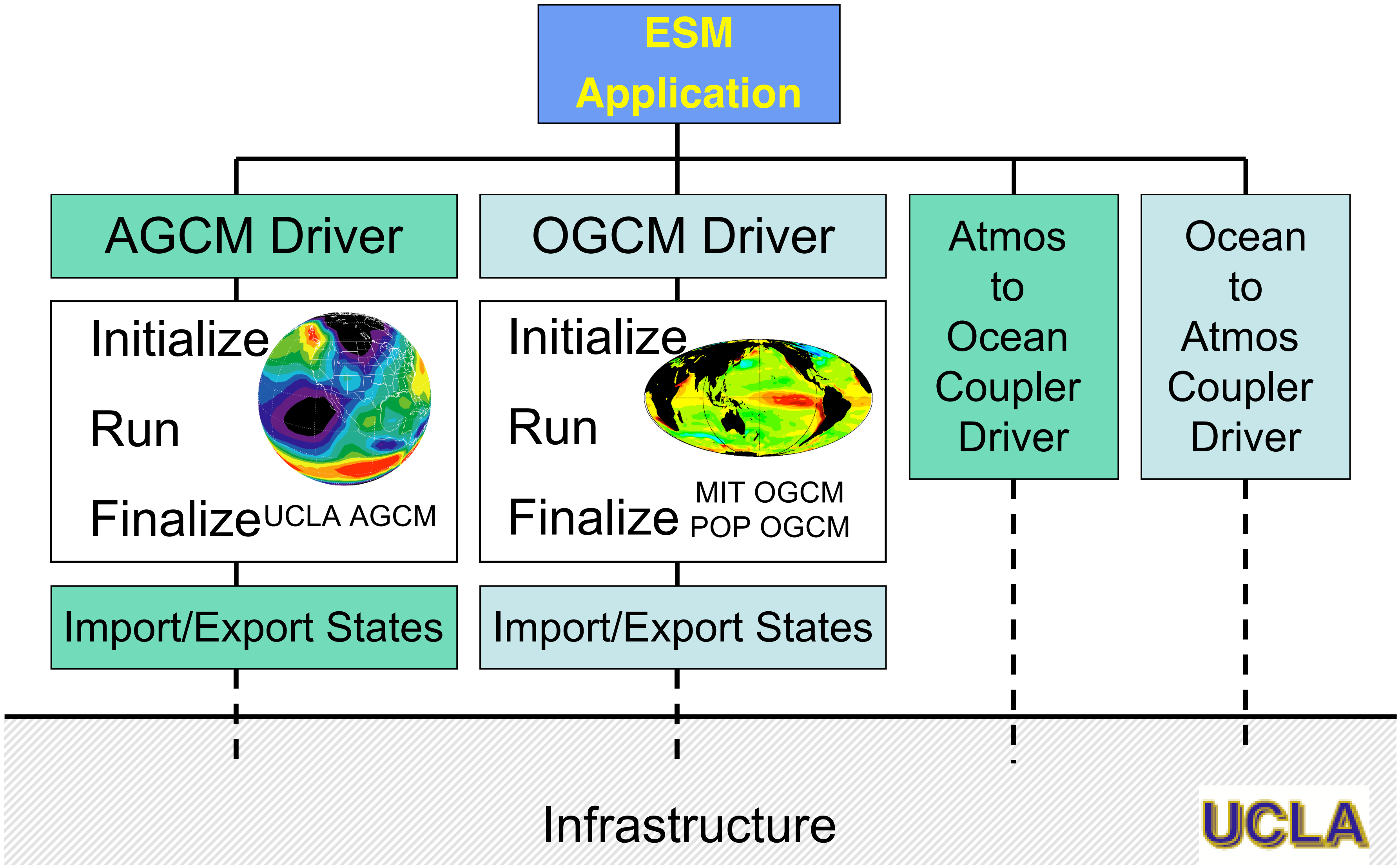
Annual Mean Precipitation - IPCC Models



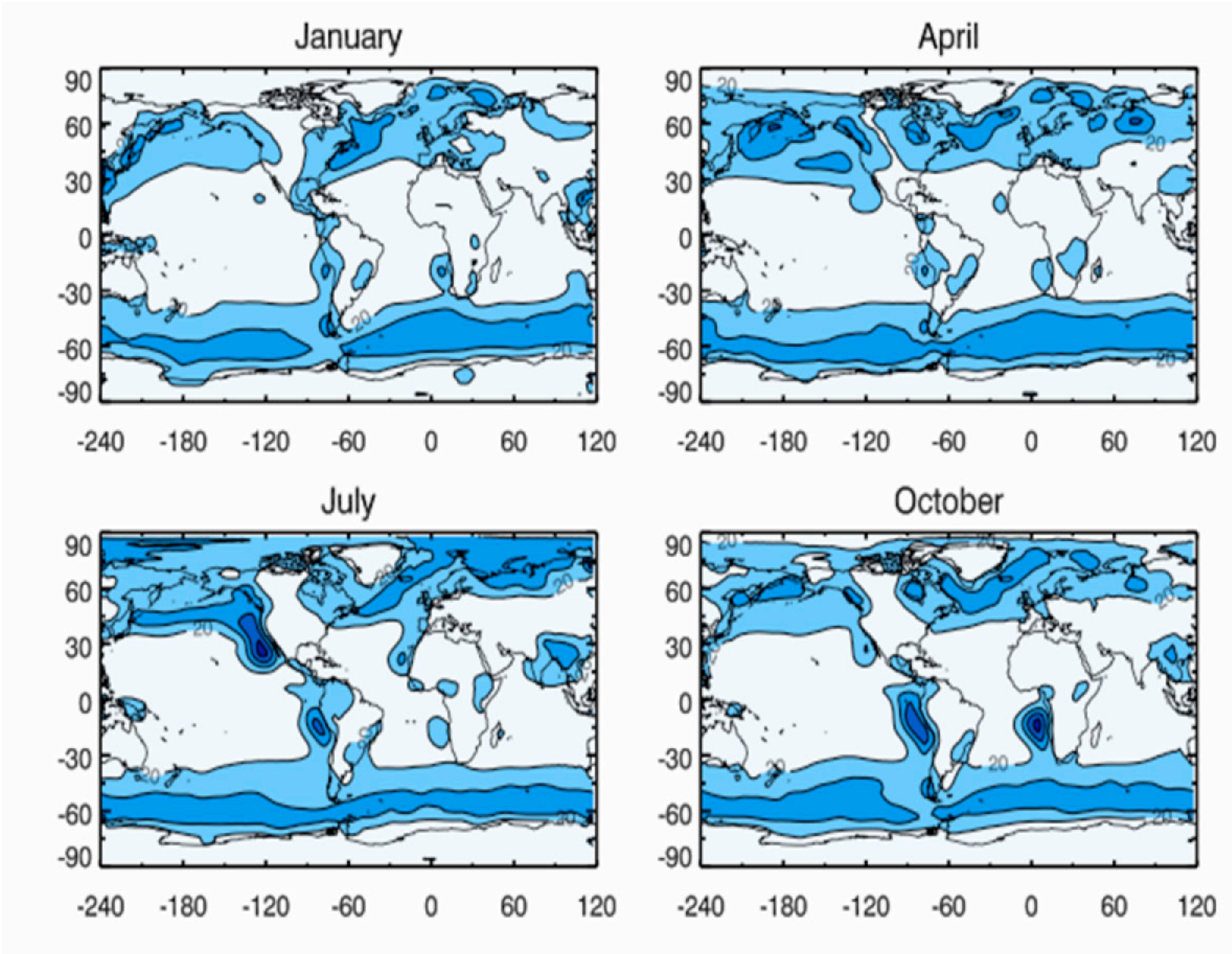
Role of stratus on double ITCZ bias



Coupled Atmosphere-Ocean Application in ESMF- Superstructure

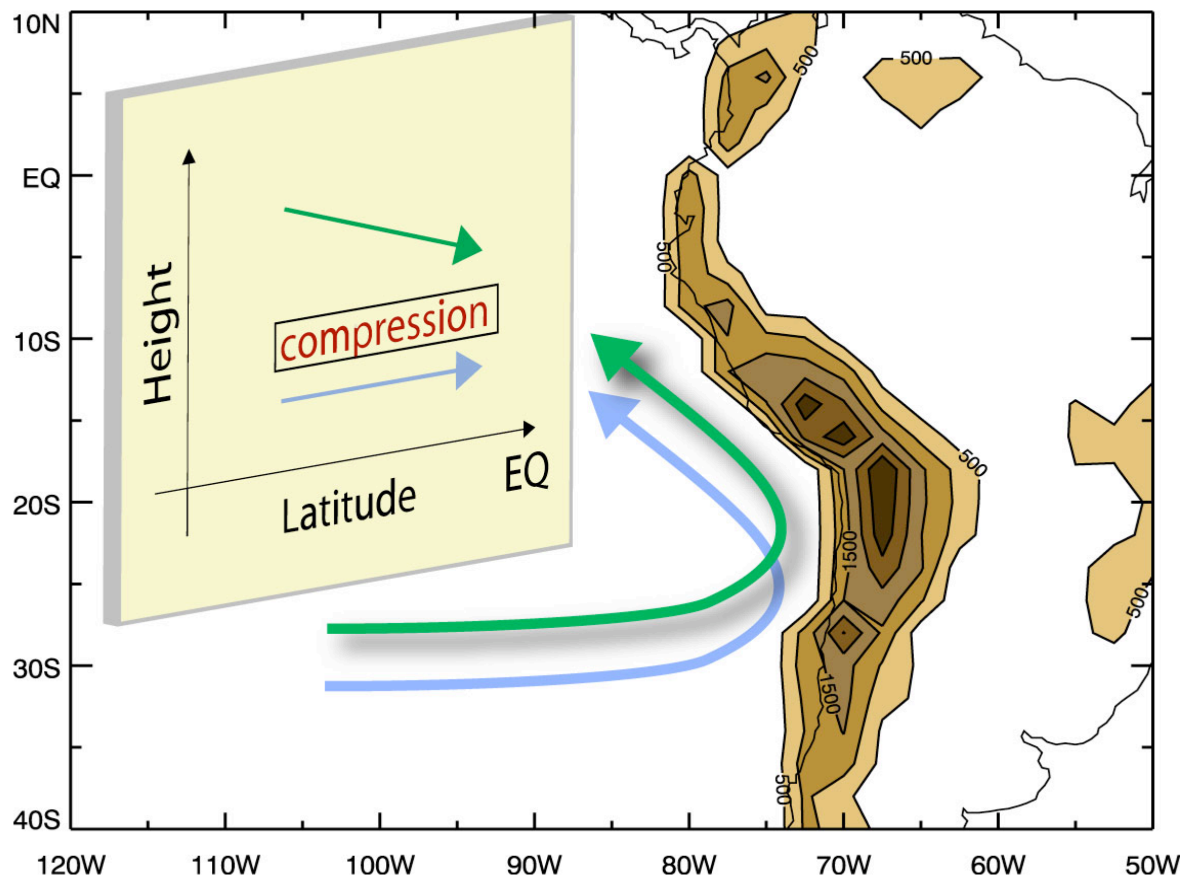


Stratocumulus Incidence by UCLA AGCM



AGCM v7.1 2.5x2x29L

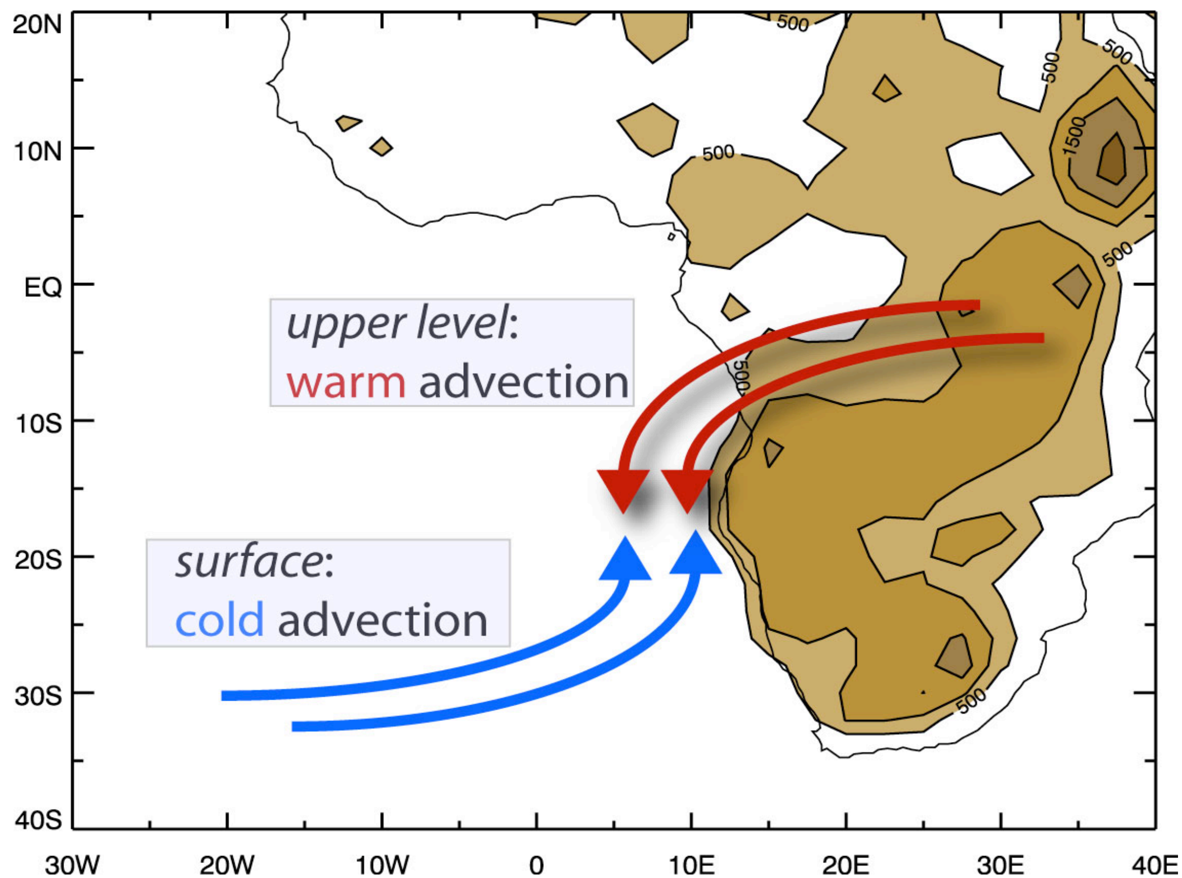
Orographic Effects on Peruvian Stratus



UCLA

(Richter and Mechoso, JAS 2006)

Orographic Effects on Namibian Stratus



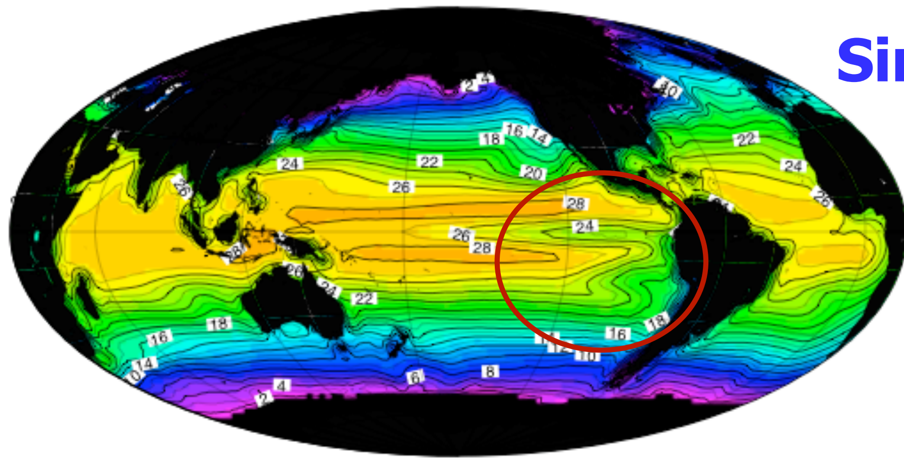
UCLA

(Richter and Mechoso, JAS 2006)

UCLA-AGCM globally coupled to MIT-OGCM

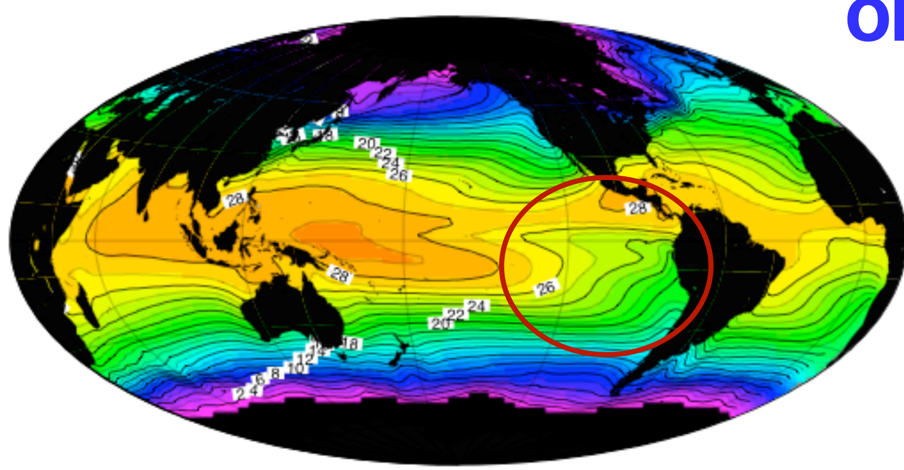
Low-atmospheric resolution (5X4)

UCLA AGCM 6.98, new PBL, coupled with global MIT OGCM



Simulated annual mean SST

Reynolds SST analysis

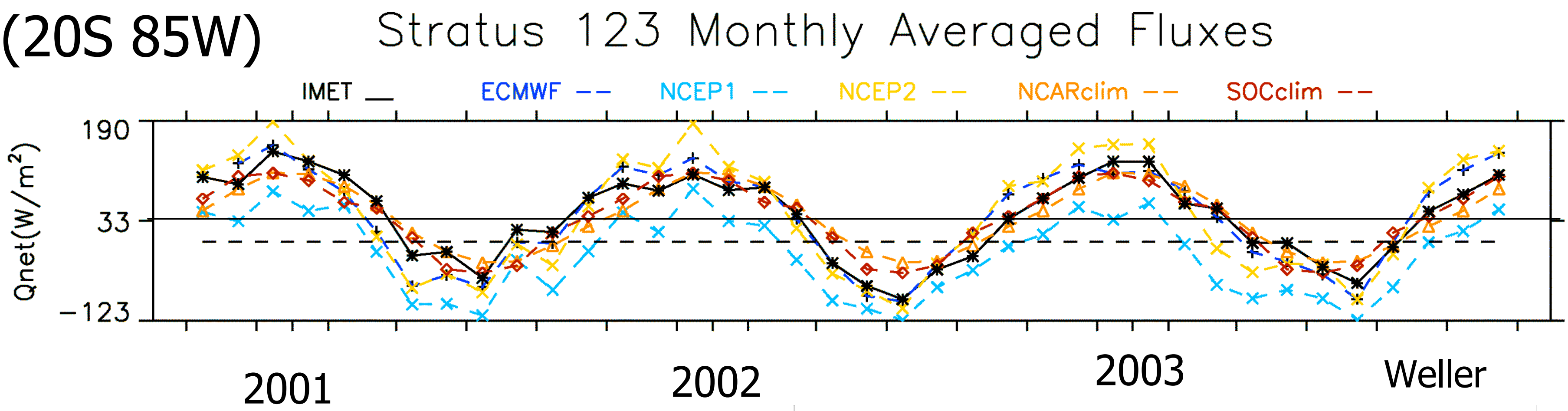


Observed annual mean SST

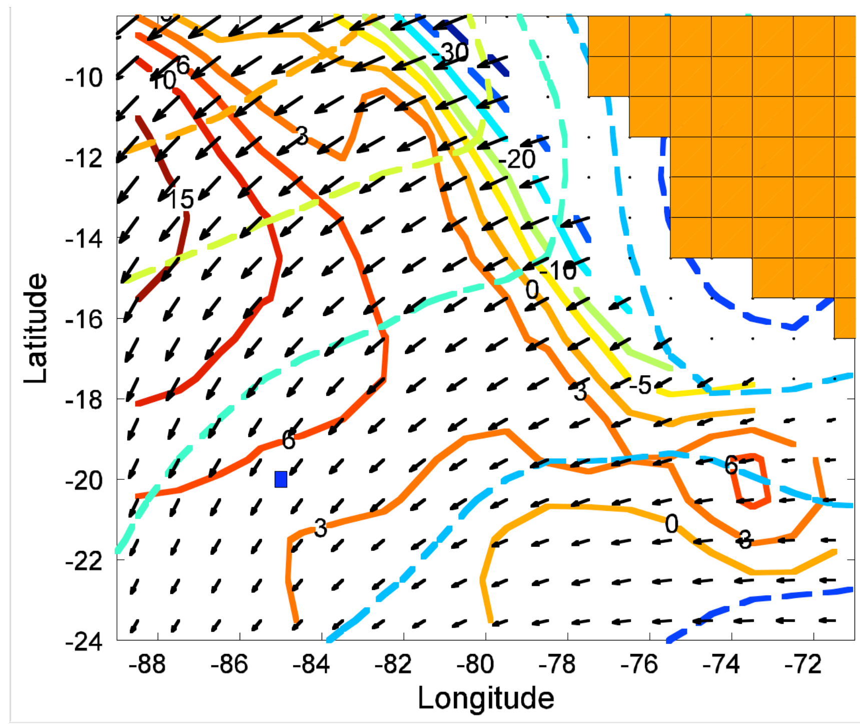
- Cold tongue is asymmetric relative to the Equator. Equatorial West-East SST gradient is realistic.
- Double ITCZ in both Pacific and Atlantic Oceans.

Issues in ocean transports

(20S 85W)



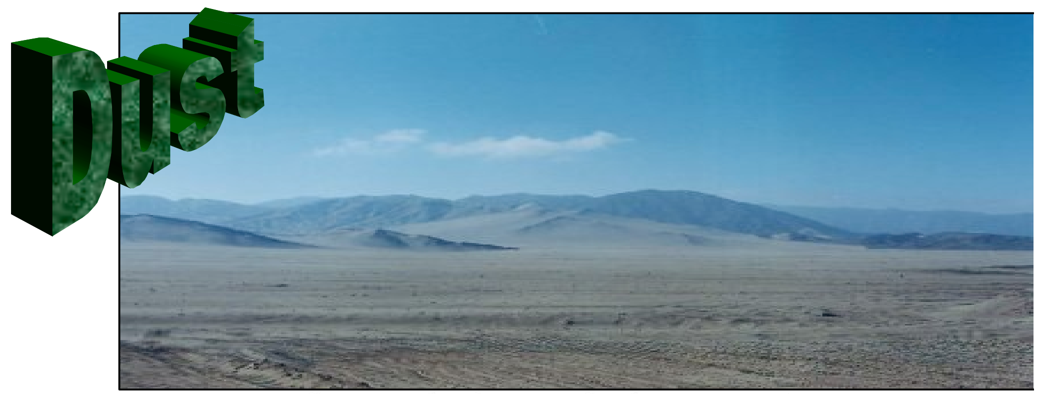
Annual-mean heat flux **into** ocean ~ 30 W m^{-2} at 1500 km offshore under persistent low cloud!

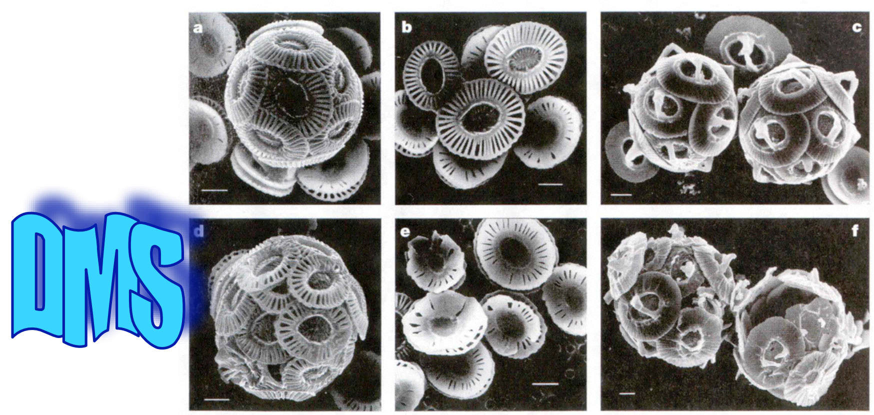


How is this net warming at the surface balanced by ocean heat transports?

Aerosol issues in SEP

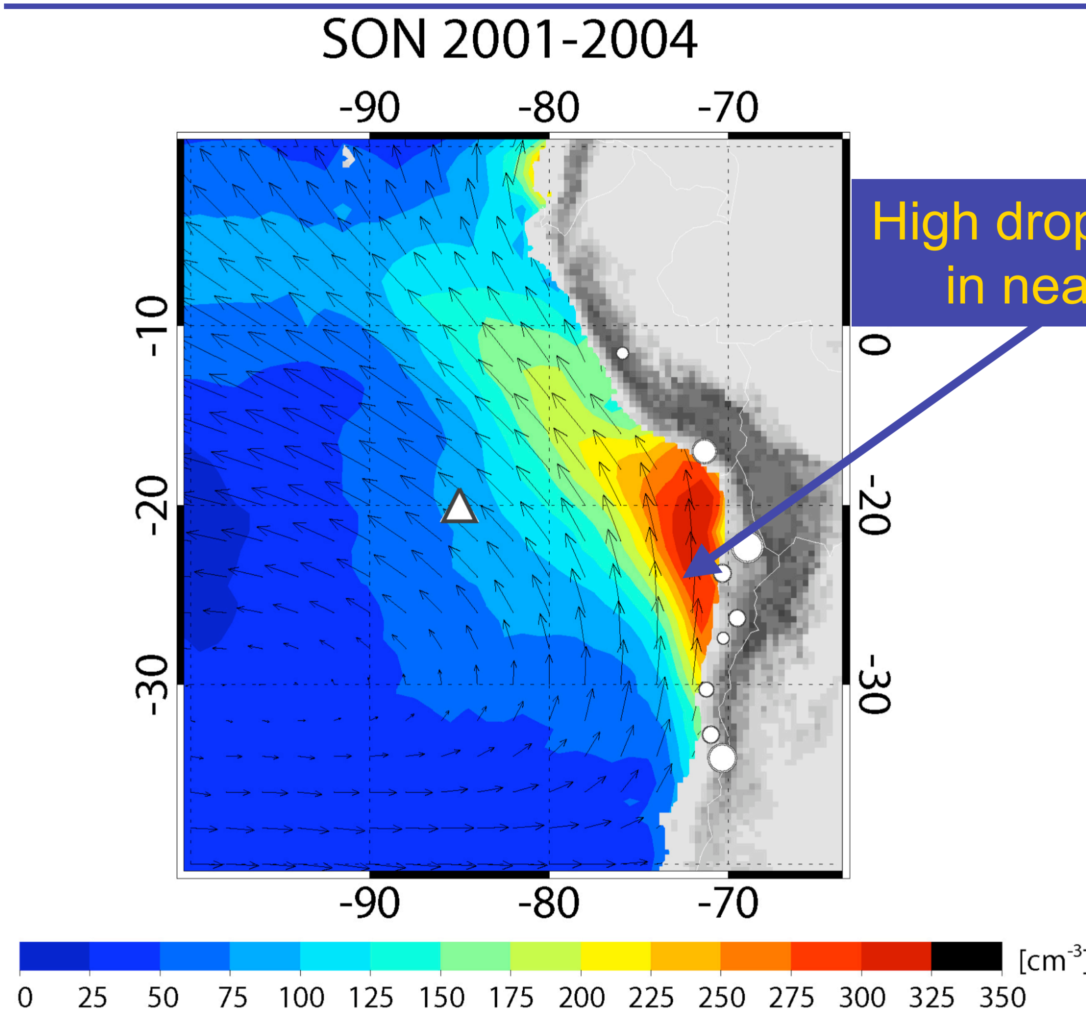
- Locations and strengths of sources of natural and anthropogenic aerosols and precursors
- Regional distribution of aerosol. Relative contribution of anthropogenic and natural sources
- Effects of aerosol on micro and macrophysical cloud properties





High droplet concentrations in near coastal clouds

Ship aerosol measurements (November 2004)



MODIS satellite measurements

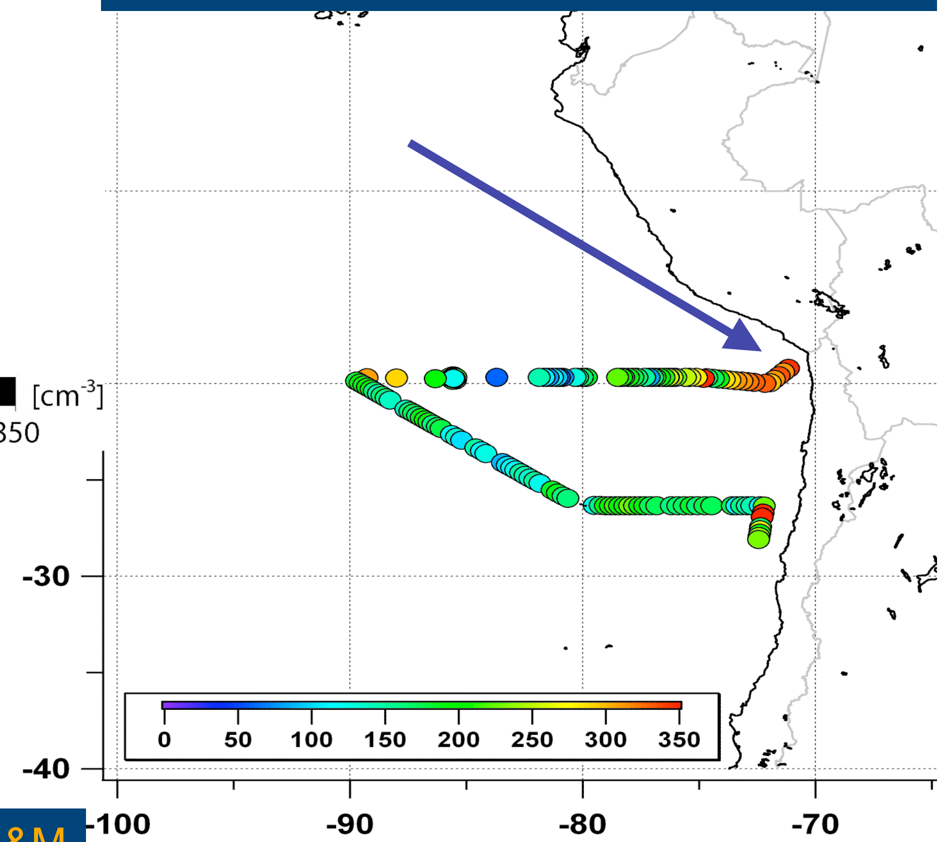
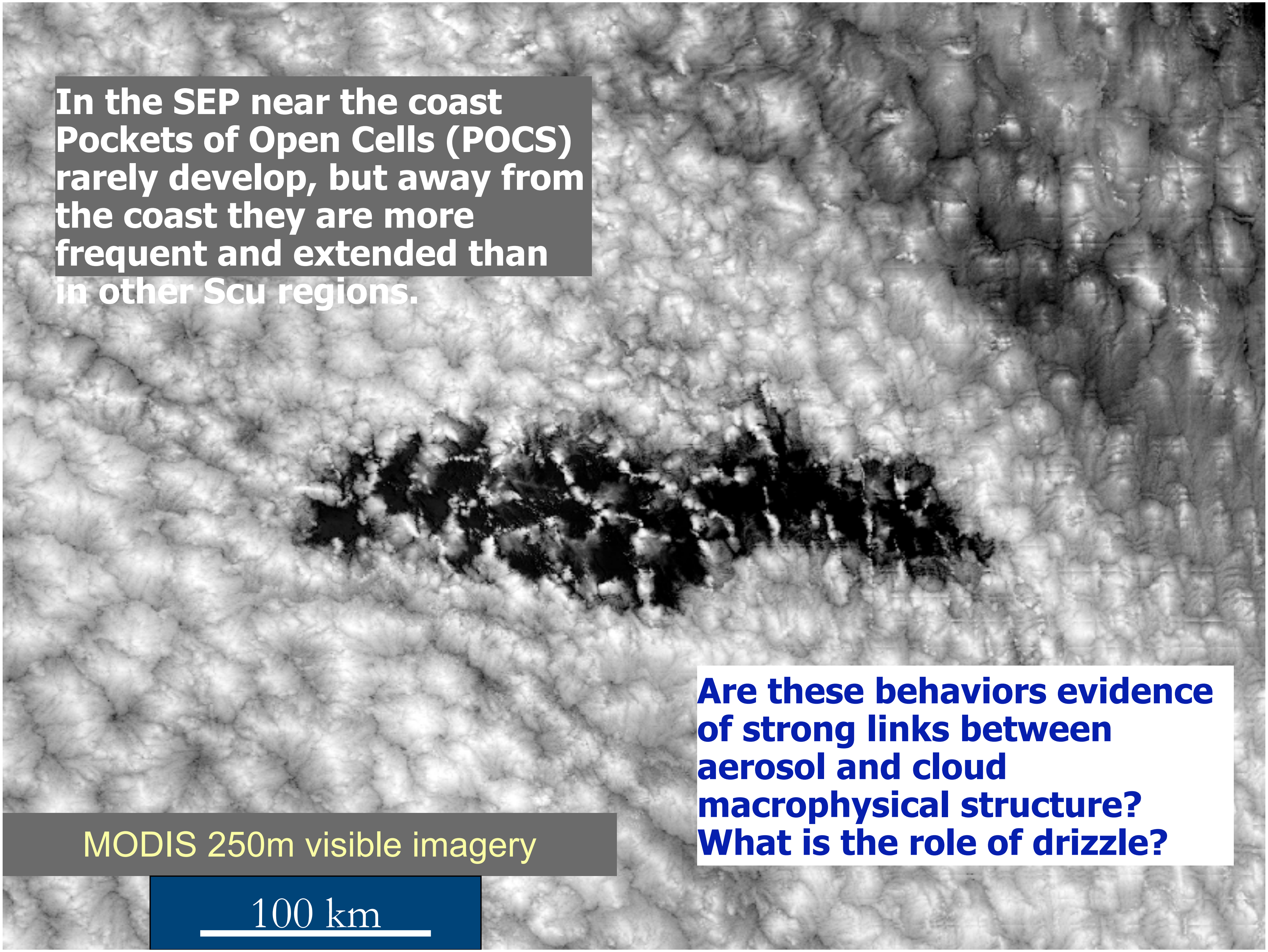
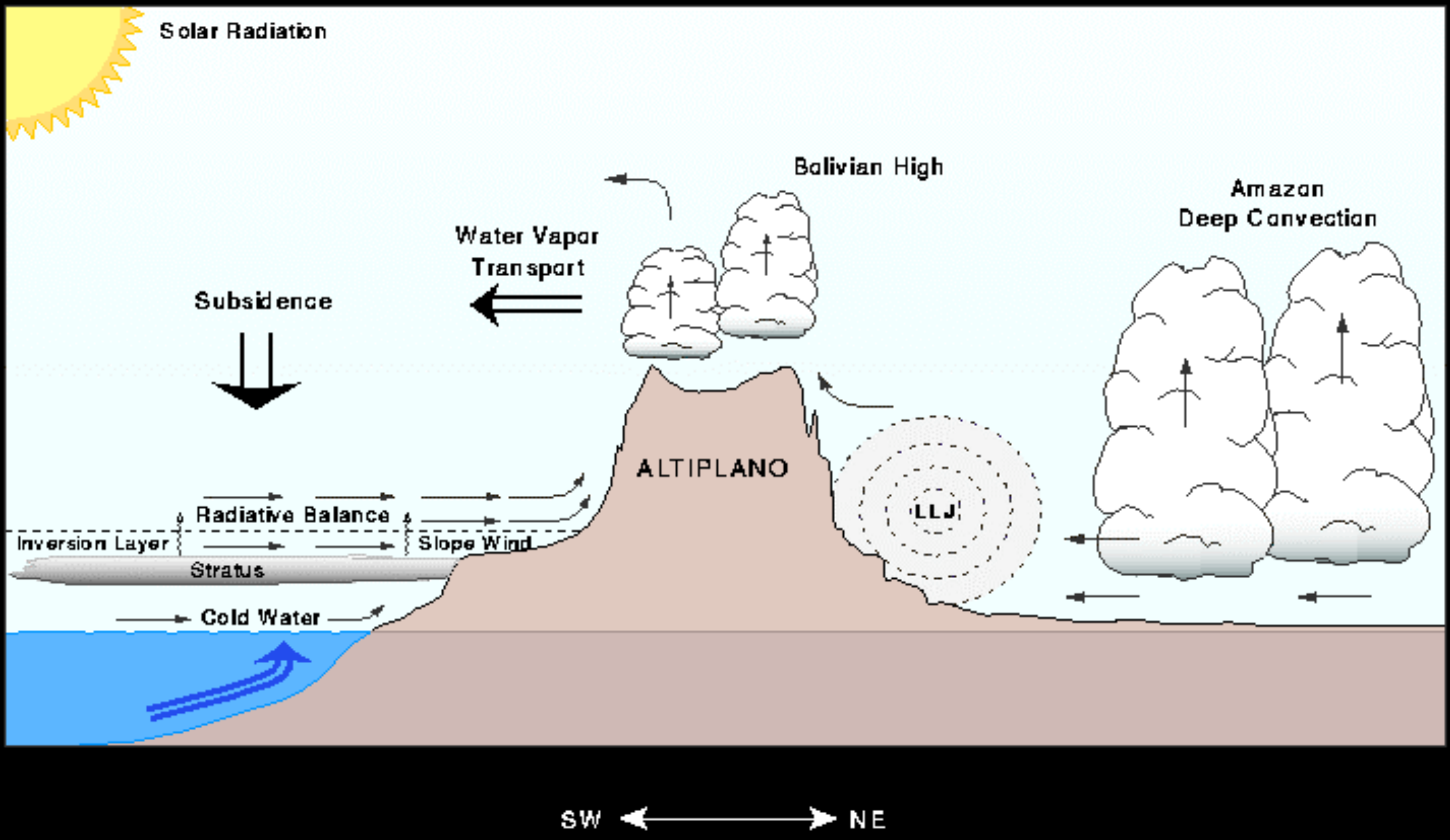


Image courtesy Jason Tomlinson, Texas A&M

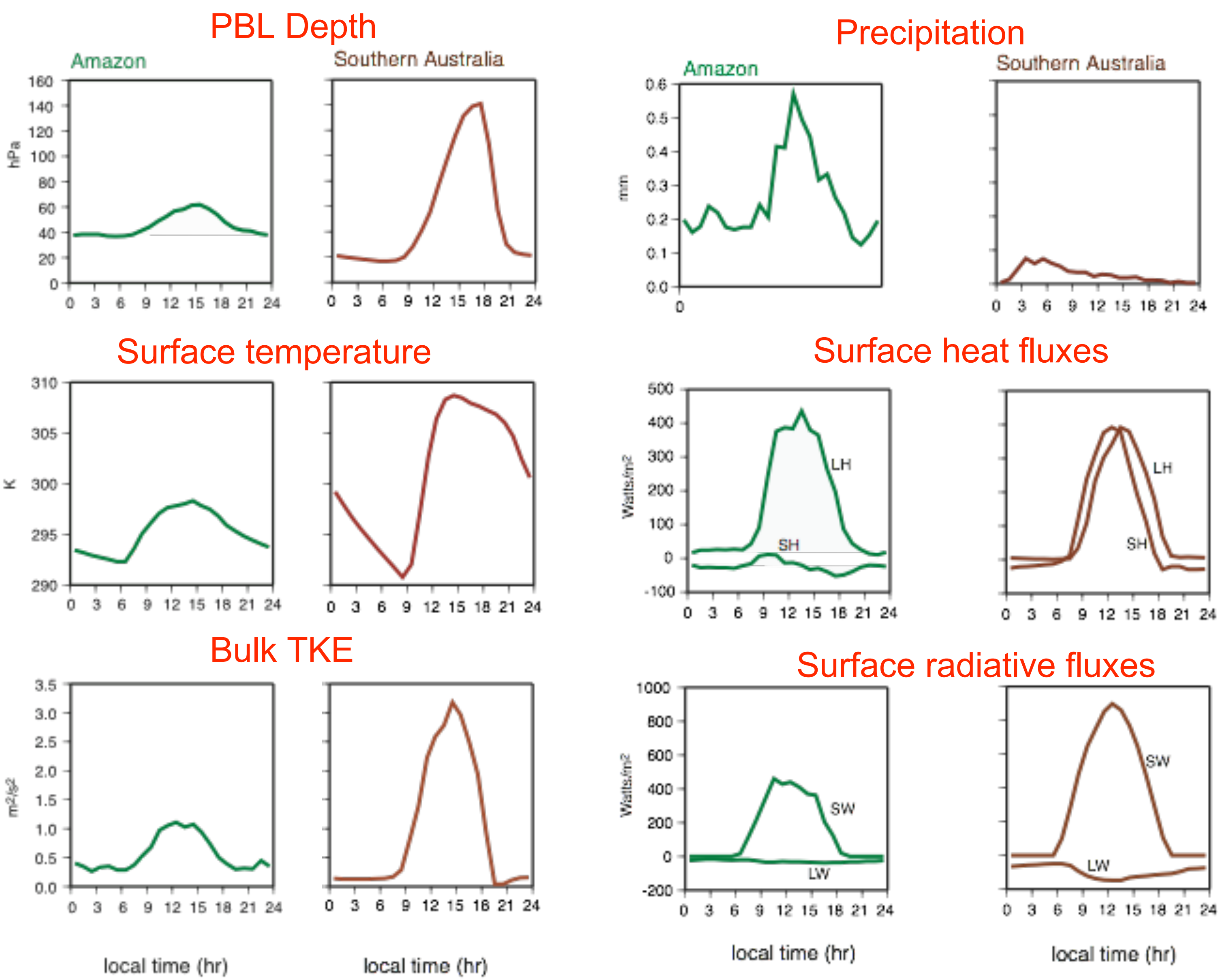

In the SEP near the coast Pockets of Open Cells (POCS) rarely develop, but away from the coast they are more frequent and extended than in other Scu regions.
Are these behaviors evidence of strong links between aerosol and cloud macrophysical structure? What is the role of drizzle?
MODIS 250m visible imagery
100 km

Connections with Land Processes

SEP Climate and South American Monsoon
Ascent to the east - Descent to the west



PBL Test - Composite diurnal cycle during January



- Simulations capture the precipitation maximum in early afternoon.

Diurnal Cycle of Precipitation in Rondonia, Amazonia

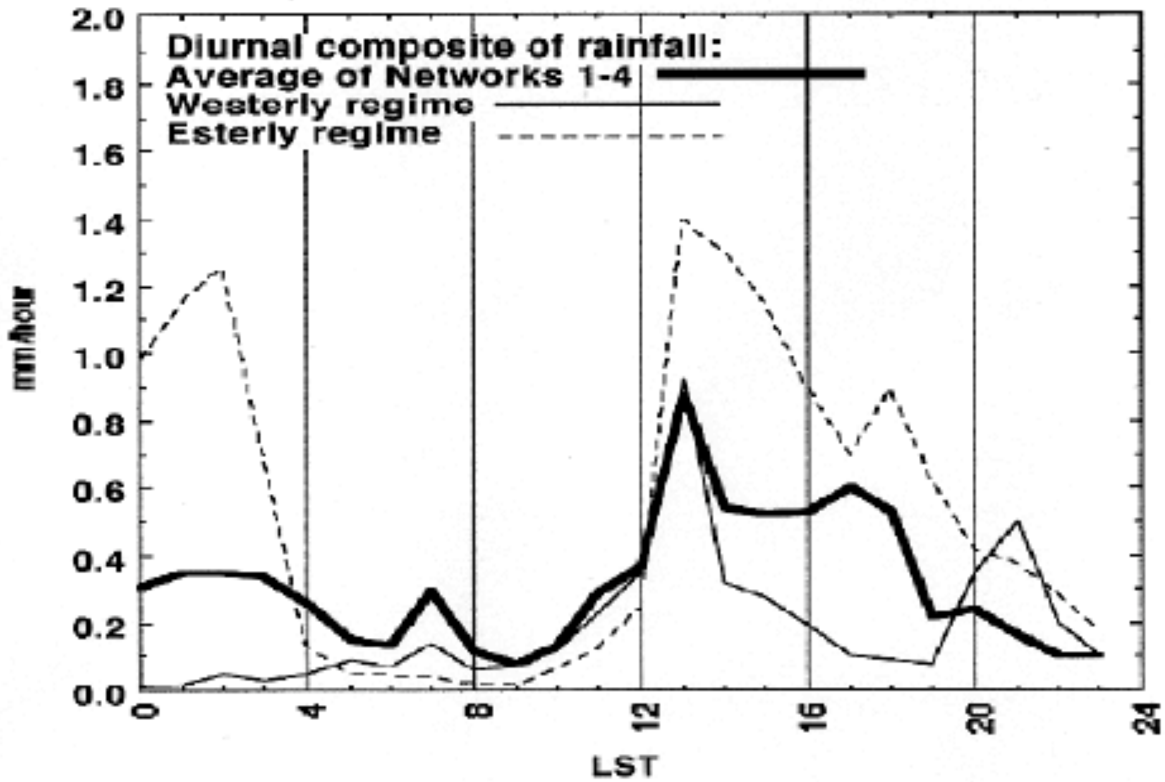


Figure 6 - Mean diurnal cycle of rainfall for networks 1-4 (full thick line), average of the westerly regime (thin full line), and easterly regime (thin broken line). Values are in mm/hour and time is LST.

Marengo et. al (2005)

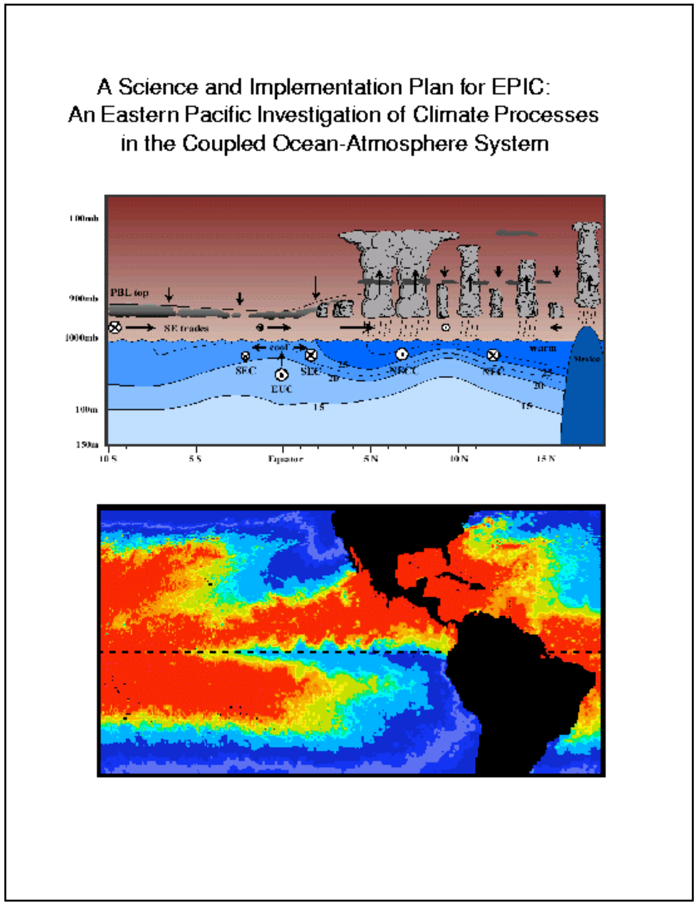
VOCALS

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:

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

A VOCALS Precursor: EPIC
Eastern Pacific Investigation of Climate



http://www.atmos.washington.edu/gcg/EPIC/

Also see:

http://www.physics.ntm.edu/~raymond/epic2001/epic2001.html

http://www.joss.ucar.edu/epic/

Scientific Objectives:

(1) To observe and understand the ocean-atmosphere processes responsible for the structure and evolution of the large-scale atmospheric heating gradients in the equatorial and northeastern Pacific portions of the cold-tongue/ITCZ complex.

(2) To observe and understand the dynamical, radiative and microphysical properties of the extensive boundary layer cloud decks in the southeasterly tradewind and cross-equatorial flow regime and their interactions with the ocean below.

EPIC2001 Stratocumulus Cruise exploration of SE Pacific stratus

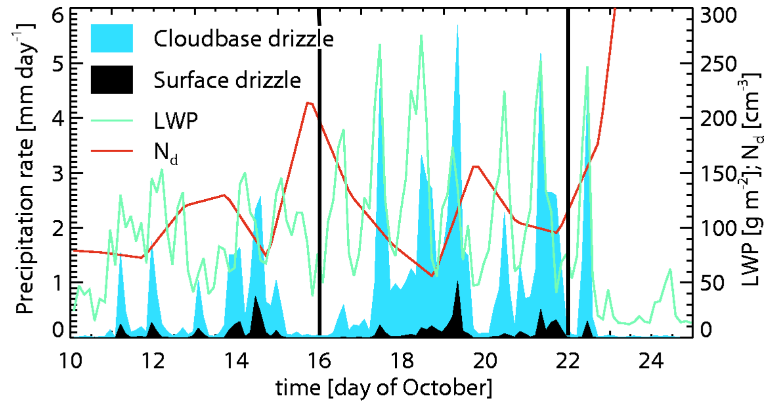
Surface mooring with 1-year turn-around starting October 2000

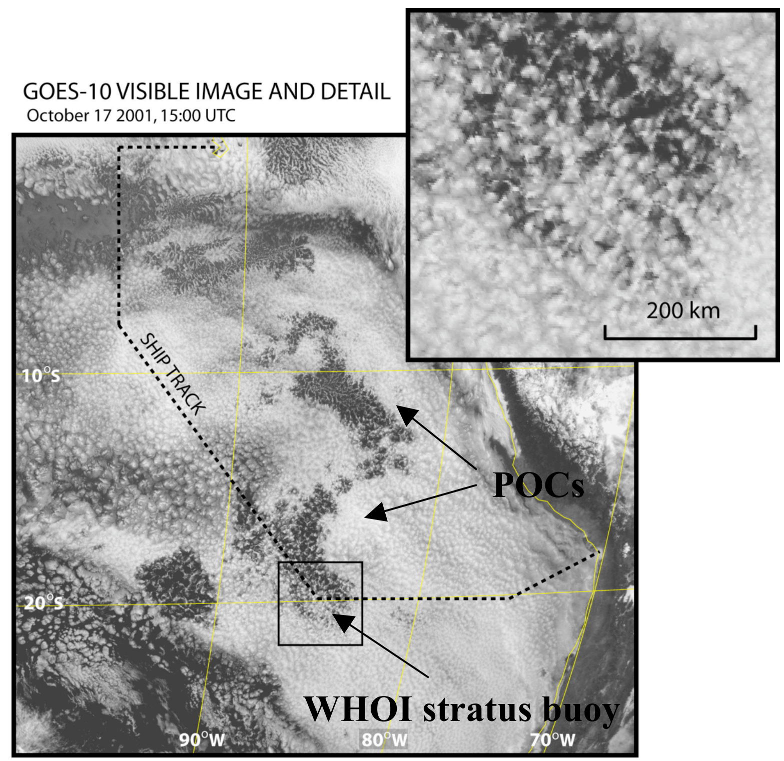
Meteorology: Wind spd and dir, air temp, SST, RH, BP, incoming SW and LW, precipitation. Two systems. Sampling: 1 minute

Ocean: Temperature, salinity, velocity in the upper 400 m, most above 250 m. Sampling: 7.5 to 60 minutes

Telemetry: Hourly surface met, not on GTS.

Weller et al.



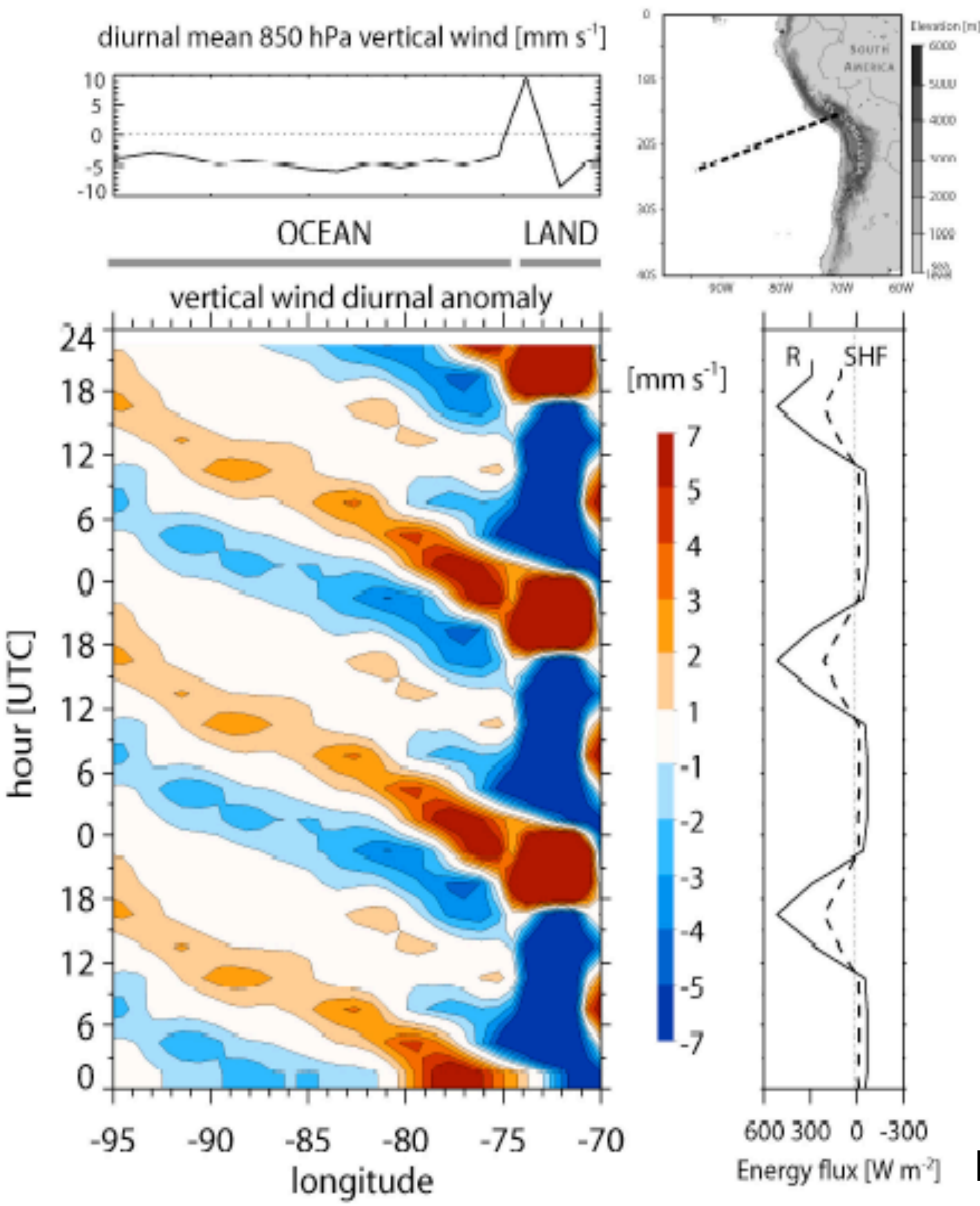


Issues: Control of cloud fraction, albedo

Findings:

- Extensive evaporating drizzle drives low-albedo patches of POCs in aerosol-poor air masses.
- Strong diurnal cycle of cloud thickness amplified by Andes-induced subsidence wave

Diurnal subsidence wave



What is the role of this wave in modulating the diurnal cycle of cloud over the SEP?

ECMWF Analysis. Courtesy M. Kohler

EPIC Contributions

- Much was learned on ITCZ variability and the cross-equatorial flow in the eastern Pacific.
- A new parameterization of oceanic solar absorption based on satellite color and chlorophyl concentration was developed by using radiative flux profiles from EPIC. This is used derive surface fluxes from the TAO buoy network.
- The simulation of PBL height over the eastern Pacific by NCAR CCSM2 was evaluated by using EPIC data.
- The methodology to obtain ship-based liquid water path (LWP) estimates in marine stratus was improved and a new probabilistic approach for the relationship between cloud LWP and cloud fraction (CF) was developed.
- The data motivated a lot of work with cloud ensemble, regional and global models.
- **But……the major problems in the southeastern Pacific, which in some ways motivated EPIC, remain largely unsolved.**

Chile
Peru
USA

UCLA
U. Wash.
U. Hawaii
U. Chile
U. Concepcion
IMARPE-Peru
GFDL
NCAR NCEP
NOAA
WHOI

Chair of SWG: C. Roberto Mechoso

C. Bretherton, R. Garreaud, B. Huebert J. McWilliams, B. Weller, H. Wijeskera, S.P. Xie

Field Experiment (US): C. Fairall, R. Wood

Field Experiment (Chile): J. Rutllant, O. Pizarro

VAMOS Project Office: J. Meitin

www.joss.ucar.edu/vocals

COUPLED OCEAN-ATMOSPHERE-LAND ISSUES/HYPOTHESES

a) Since the double ITCZ bias is common to most CGCMs, one approach for solution would be to reduce model errors in the large-scale circulation.

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

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

The doubled ITCZ bias
A synthetic view of this problem is still elusive …

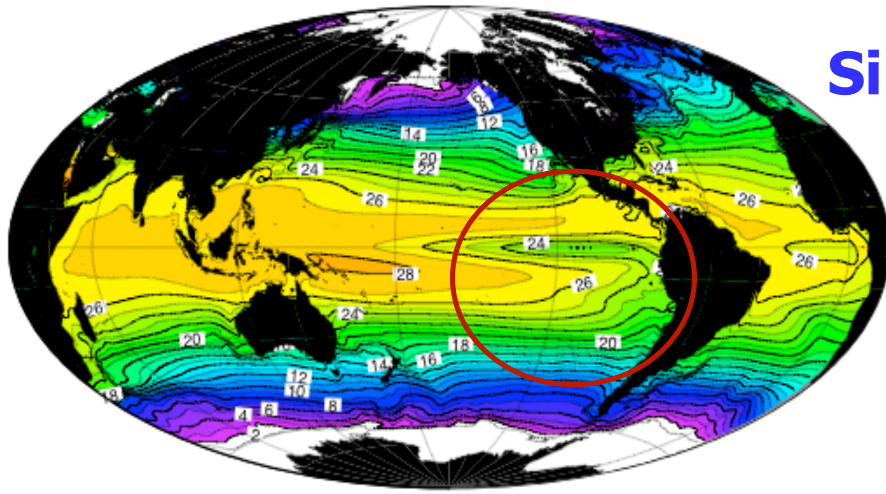
The consensus is that the bias is at least partly due to the underestimation of stratocumulus cloud cover by the AGCM, which results in too warm SSTs in the eastern tropical oceans. Other strategies for improvement have shown to be AGCM-specific, with different effects in different models:

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

UCLA-AGCM globally coupled to MIT-OGCM

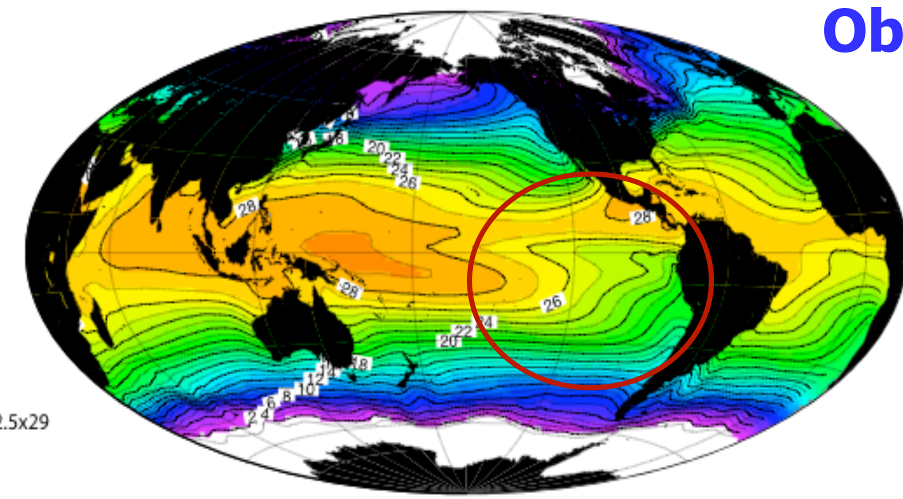
High-atmospheric resolution (2.5X2)

Annual Mean SST Simulation



Simulated annual mean SST

Annual Mean SST: Reynolds analysis

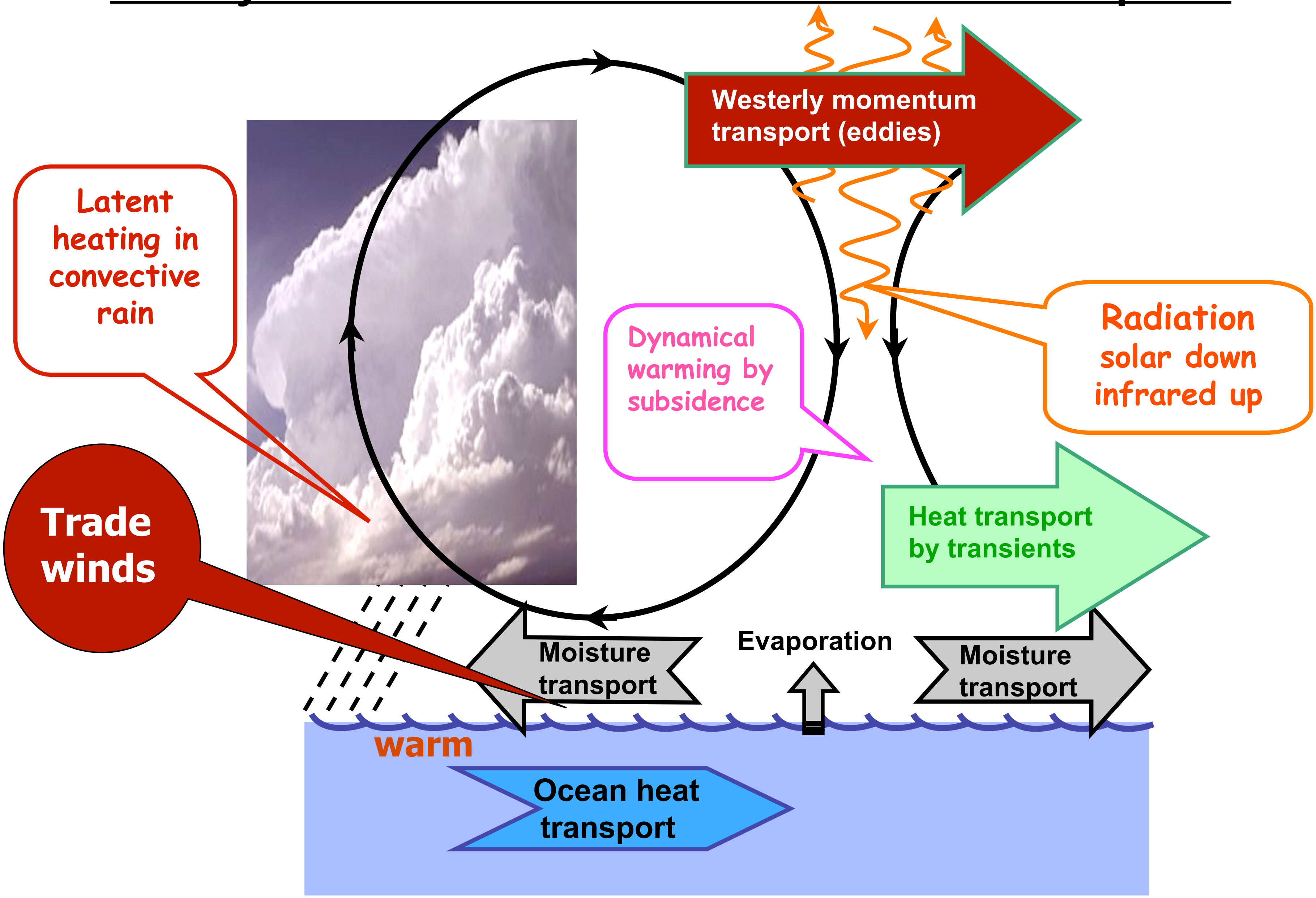


Observed annual mean SST

UCLA AGCM 8.0 2x2.5x29
MIT OGCM Global

- 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.

Hadley circulation: momentum and heat transports



A possible approach to the doubled ITCZ bias?

Revisiting the AGCM simulation of the large-scale circulation:

1. 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.

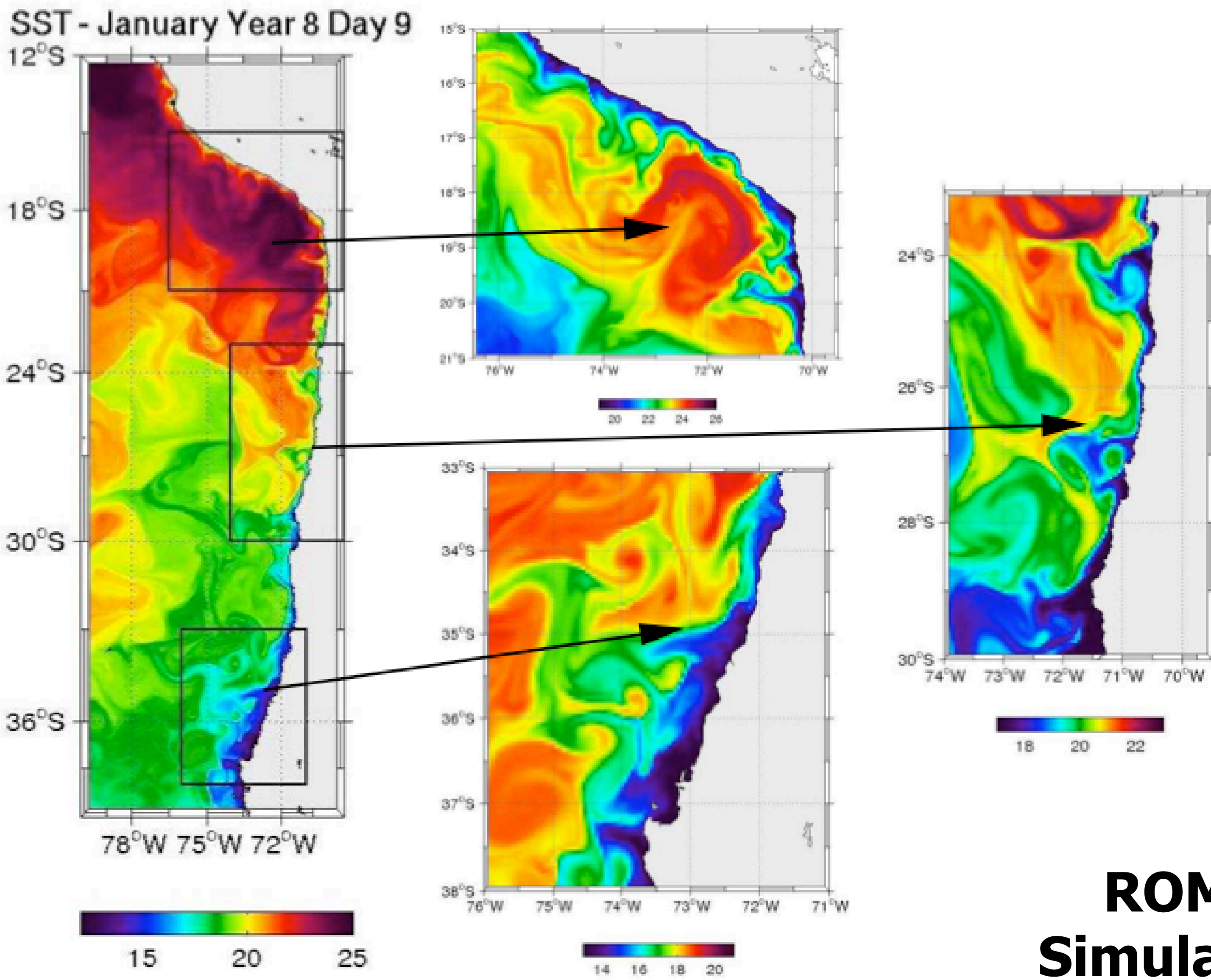
   In this regard, a more drastic improvement may require substantial model development to be guided by the results of an in-depth analysis of model performance.

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.

Is the “right” ocean temperature been upwelled in the SAP?



ROMS Simulation

(From J. McWilliams)

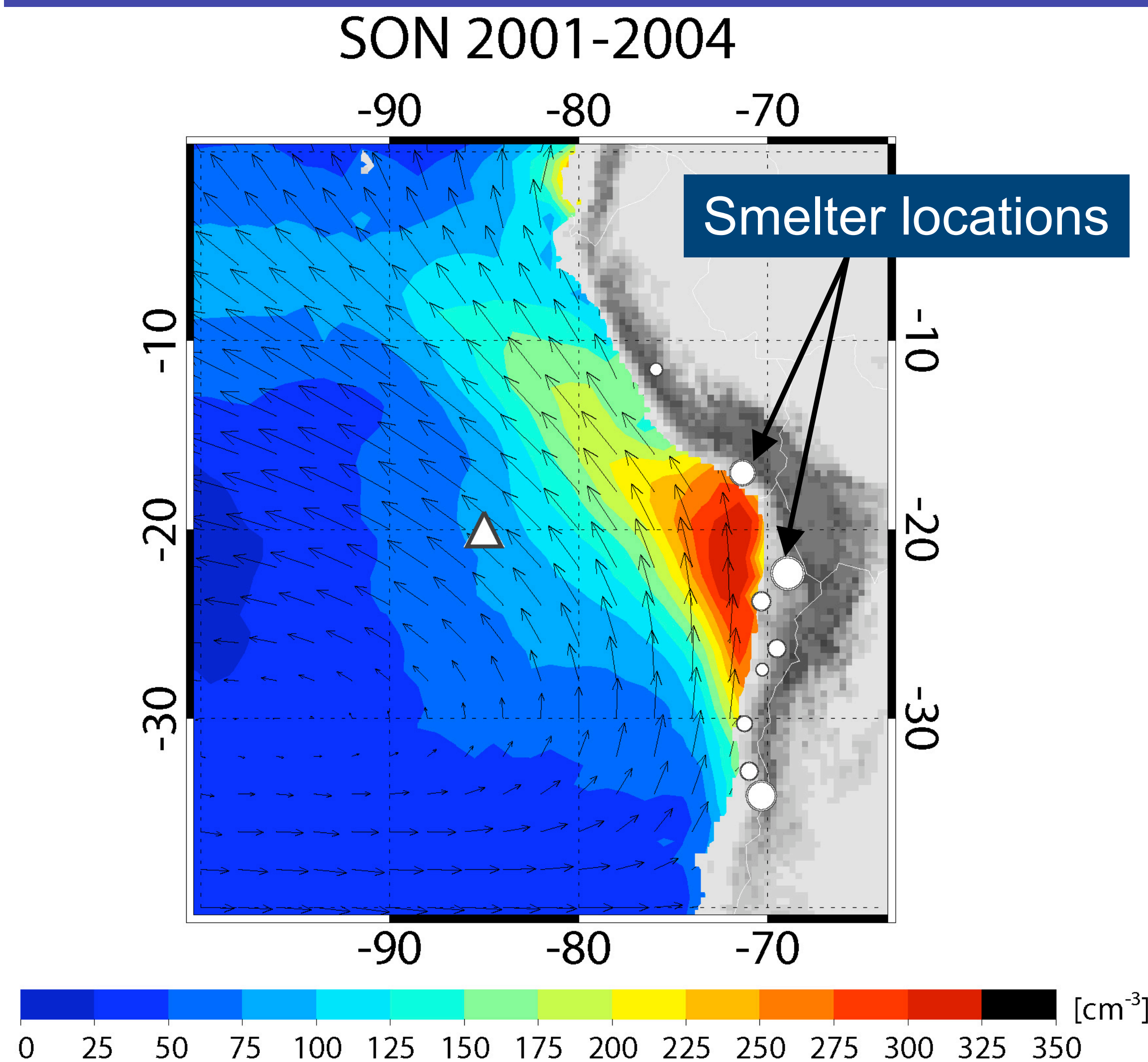
AEROSOL-CLOUD-DRIZZLE HYPOTHESES

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

b) Precipitation is a necessary for the formation of pockets of open cells (POCs) within stratocumulus clouds, and depletion of aerosols by coalescence scavenging is necessary for the maintenance of POCs.

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

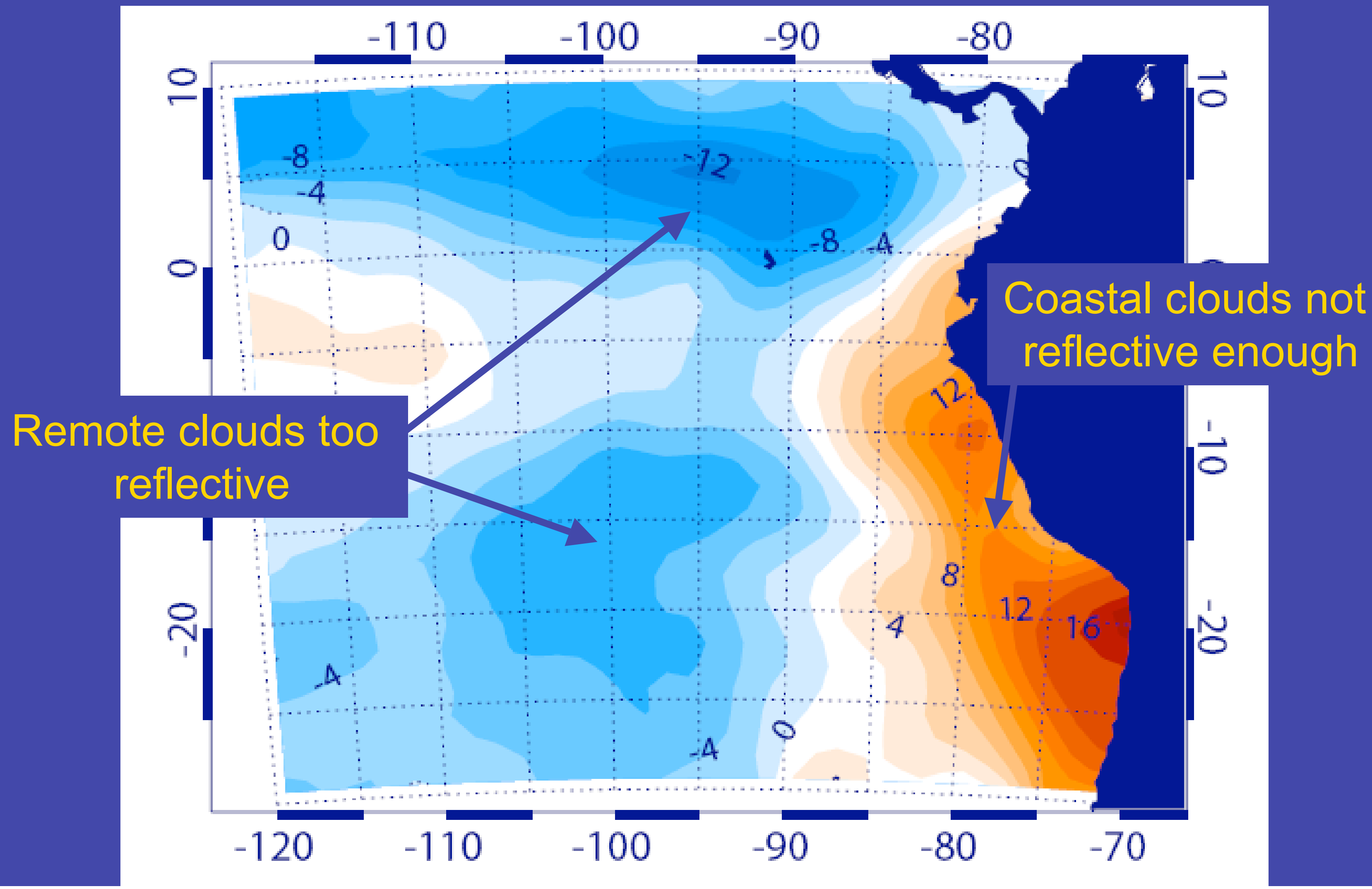
Pollution plumes in the SE Pacific



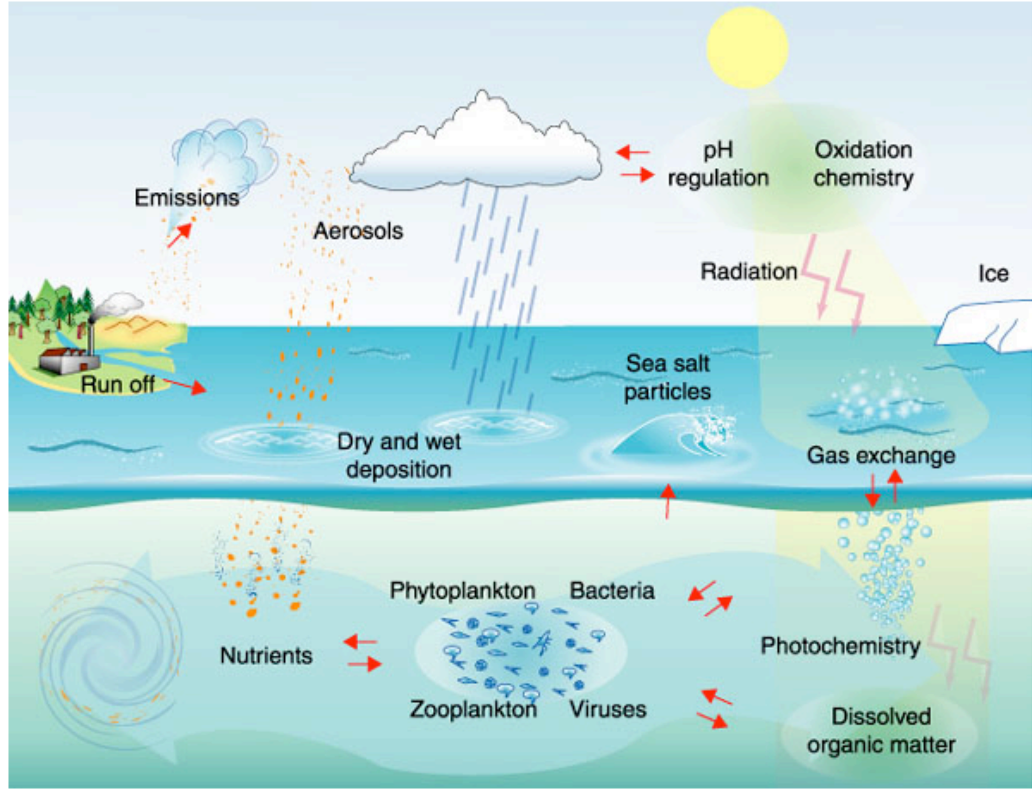
Cloud droplet concentration

- Chile is world's largest copper producer
- Copper smelting SO_2 emissions from Chile (1.5 TgS yr^{-1}) comparable to total SO_2 emissions in Germany
- 90% of Chilean SO_2 emissions from seven smelters!
- Andes mountains prevents eastward transport

Error in TOA net SW radiation (W m^{-2}) caused by assumption of constant cloud droplet effective radius (here assumed to be 15 microns)



IGBP's Surface Ocean Lower Atmosphere Study (SOLAS). http://www.uea.ac.uk/env/solas/



The surface fluxes of precursor gases (DMS and VOCs) grow the aerosols that control cloud properties. (DMS: dimethylsulfide). The supply of DMS and its oxidation mechanisms limit new particle nucleation and growth.

To what extent do these processes affect the re-filling of POCs with clouds, and what is the role of iodine, ammonia, and organics?

MODELING and SATELLITE RETRIEVAL VALIDATION GOALS

a) Improved simulation of the large-scale circulation in the atmosphere and mesoscale ocean eddy transports of heat and biogenic species offshore over the SEP

b) Improved representation of the aerosol indirect effects over the SEP by regional and/or global models

c) Detailed validation of techniques that provide satellite estimates of Scu microphysical properties (e.g. effective radius or cloud droplet number concentration from MODIS) and precipitation (from CloudSat or MODIS) under conditions that can be of broken cloudiness on the pixel scale

VOCALS Program

VOCALS - REX

Airborne: NCAR C-130 (and others)

SHIP: Ron Brown (and others)

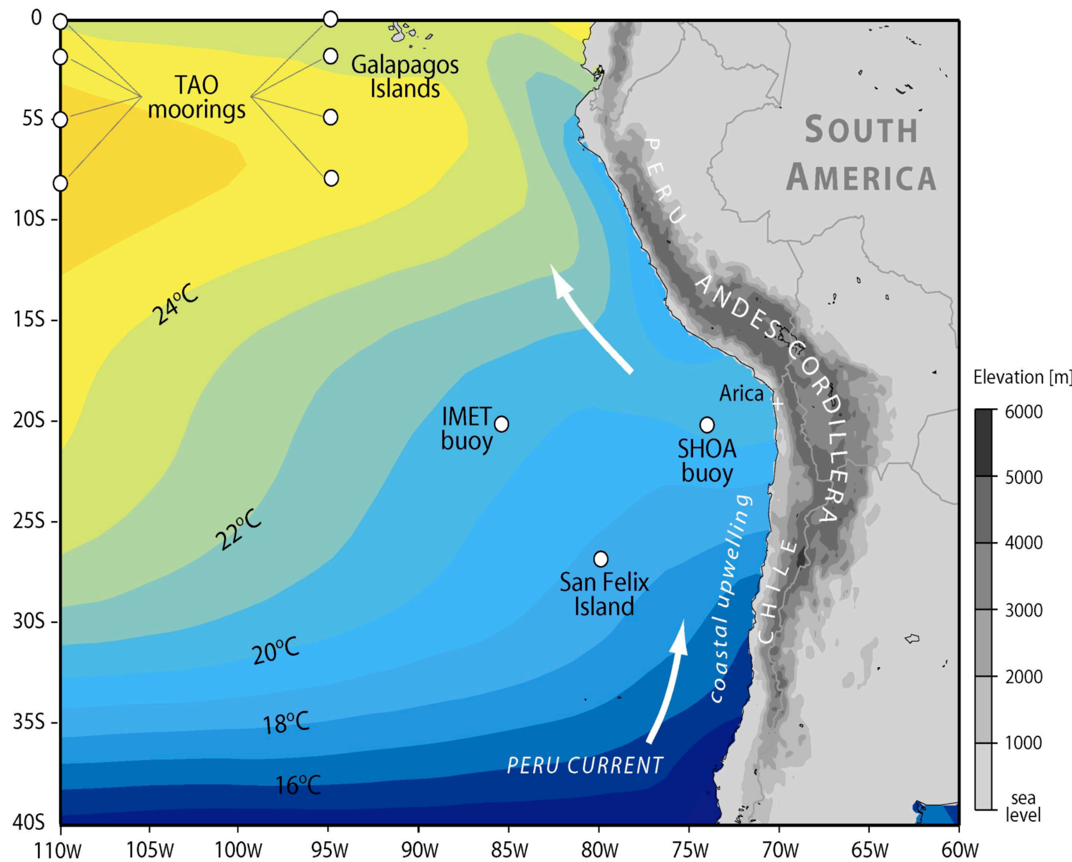
VOCALS - Modeling

GCMs: NCEP, NOAA, GFDL, UCLA

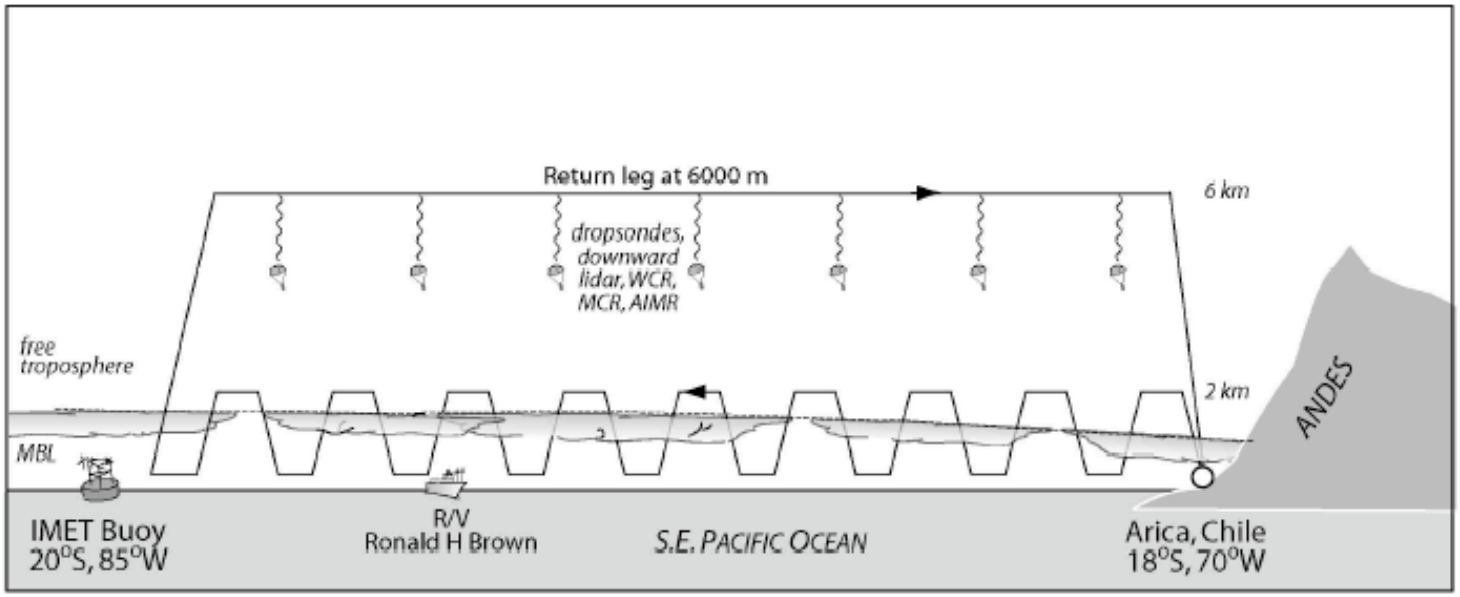
RCMs: WRF, ROMS

Elements of VOCALS-REX

- SEP has research-grade buoys and strategic islands
- Yearly maintenance cruises of the IMET buoy since 2000 have provided data along 20S. This cruises will continue until 2008
- Highly committed regional partners, primarily in Chile, Peru and Ecuador
- Possible European presence: PRIMO



VOCALS-REX: Flight-plan for C-130 Cross-section missions

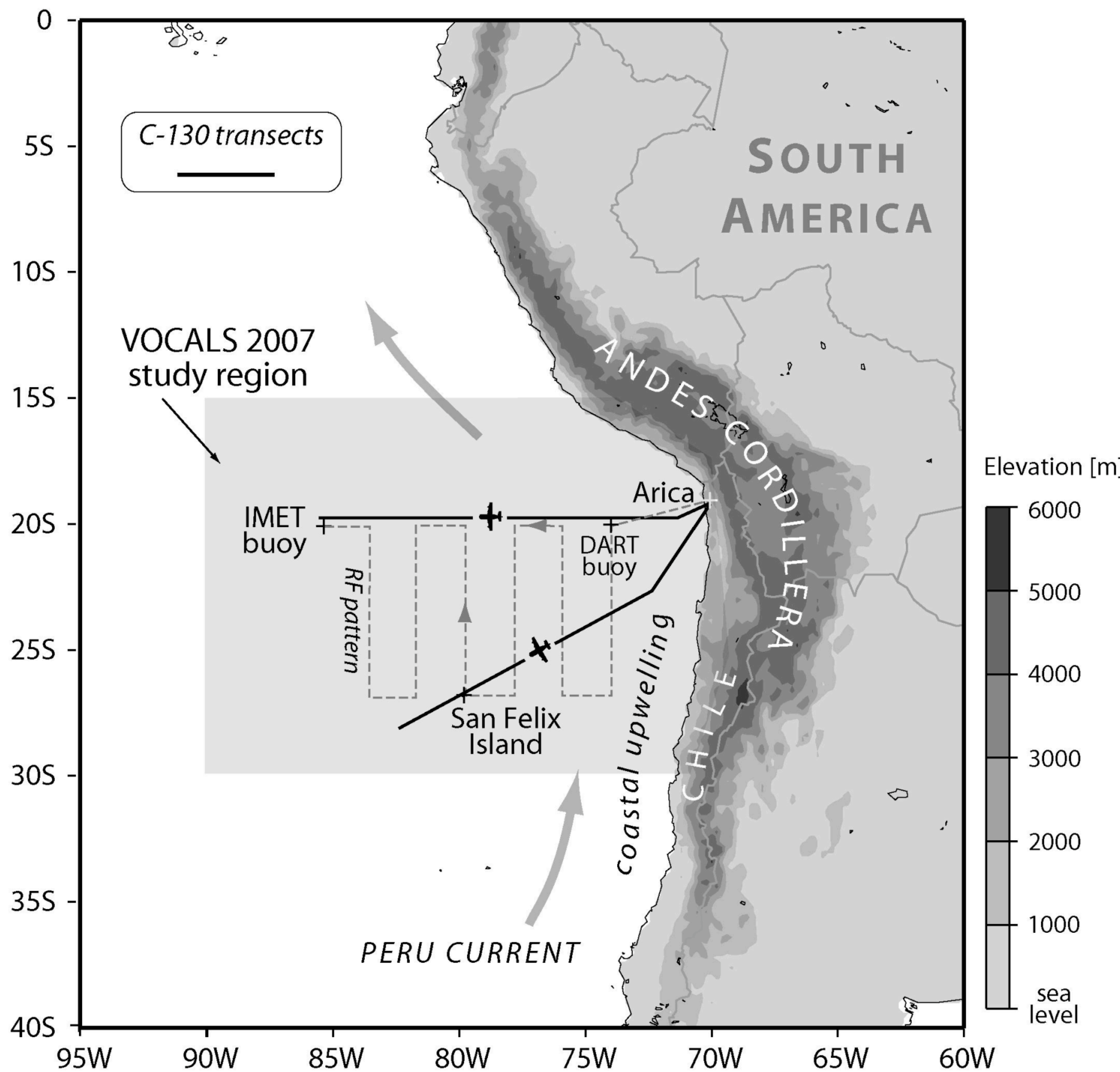


VOCALS-REX

Aircraft:
NCAR C130

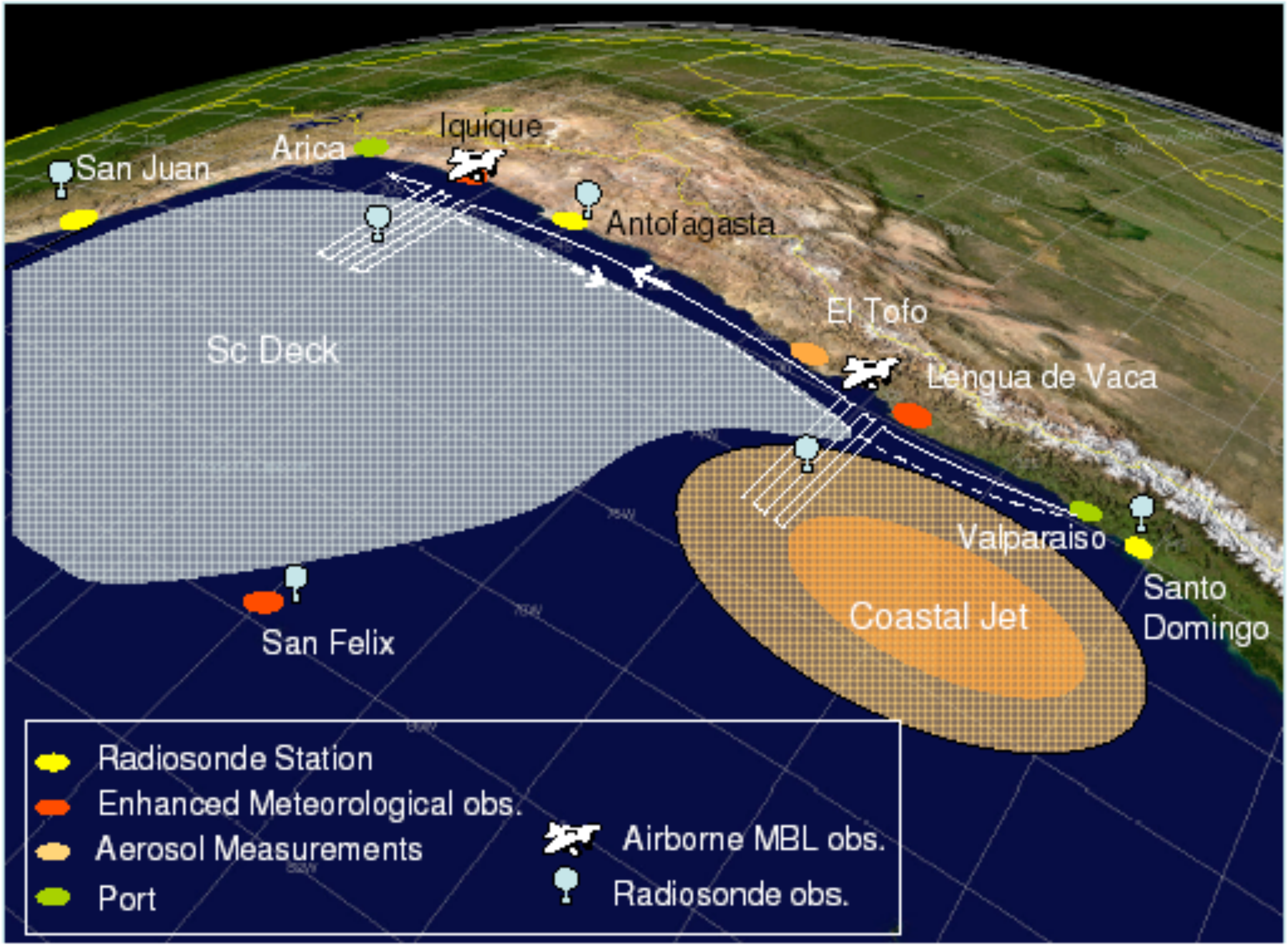
Ships:
1. **NOAA Ron Brown**
2. **Chilean**

October 2007



Chile VOCALS October/2007

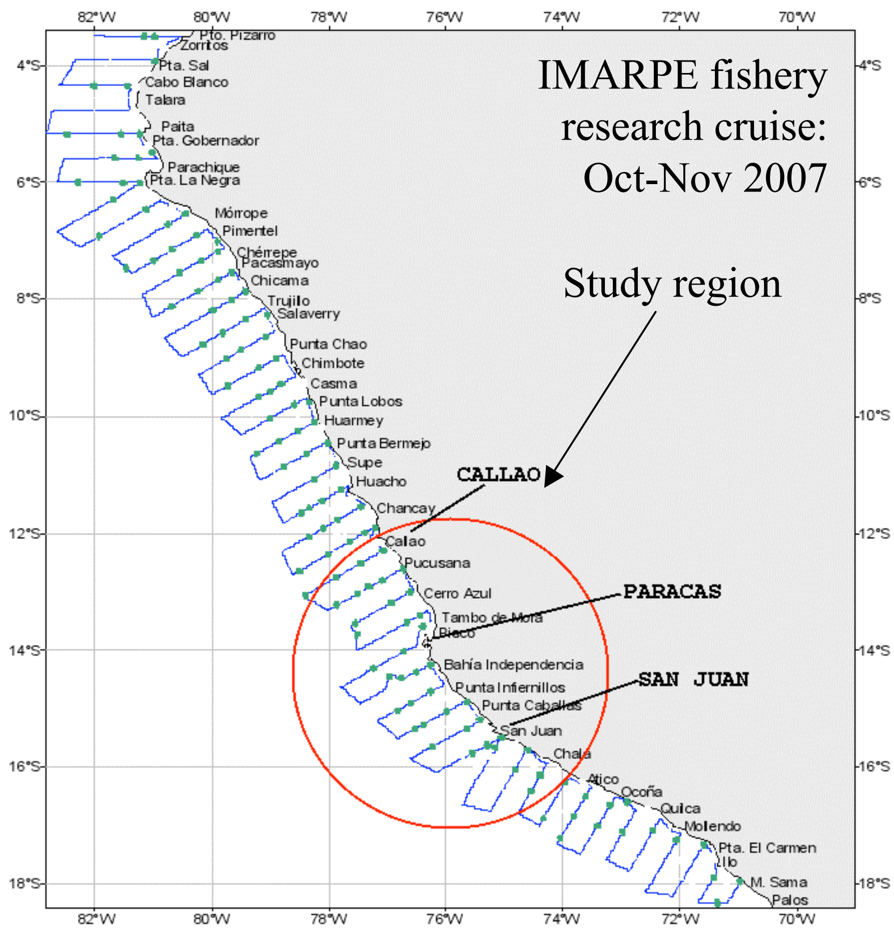
- SHOA 20-day oceanographic cruise along northern Chile. Onboard radiosonde observations will be made.
- Enhanced radiosonde observations at Santo Domingo (34°S), and Antofagasta (23°S).
- Flights with a twin-engine small airplane equipped with a meteorological package (e.g. AIMMS 20) to sample the AMBL and capping subsidence inversion within the 0- 250 km offshore area at 30°S.
- Coastal automatic weather stations at 30°S and 23°S and a laser ceilometer at 30°S (La Serena airport).
- Possible coordination with CPPS joint southern spring cruises and PRIMO (France-CNRS) cruise.



Chilean Component of VOCALS-REX ($250K)

International Partners - Peru

Field experiment: October-November 2007



Cost ~ $70K (Peru)

Main goals *(main instruments)*:

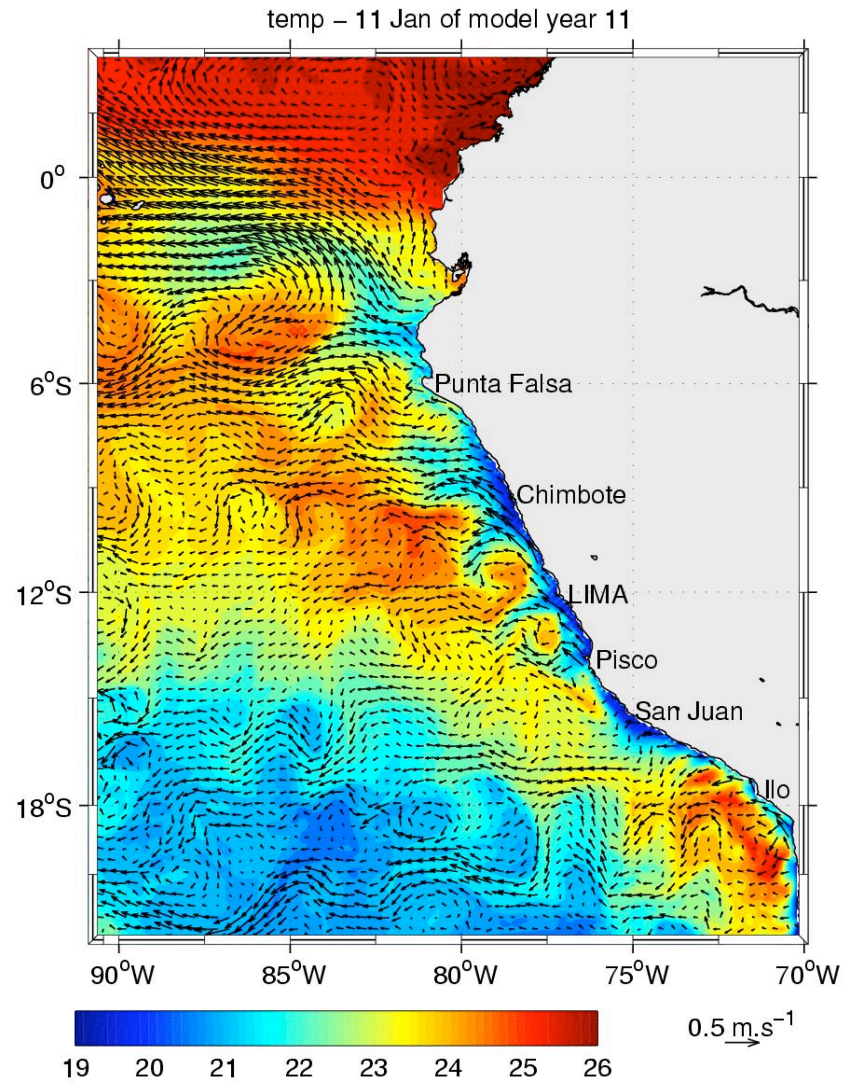
1. Characterize the near-coastal 3D wind structure *(ship-borne wind profiling radar)*.
2. Assess the relation between the wind and mesoscale ocean processes (upwelling and eddies) *(wind profiler, CTDs and ADCP)*
3. Determine the dynamical and thermodynamical structure associated with the coastal clearing *(ship-borne radiosoundings)*.

Cruise supplemented with land observations (surface met and radiosoundings)

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.

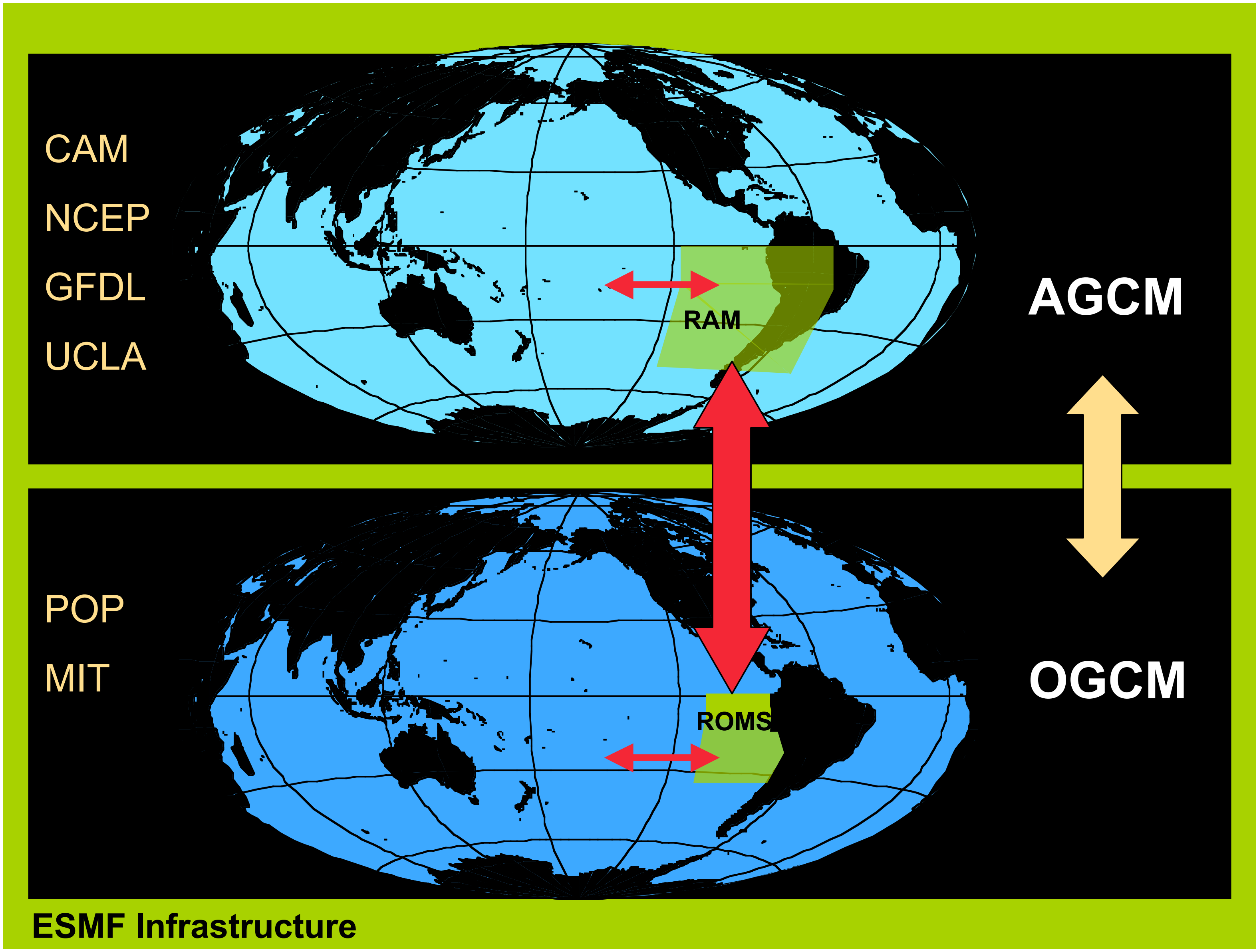


(From A. Miller)

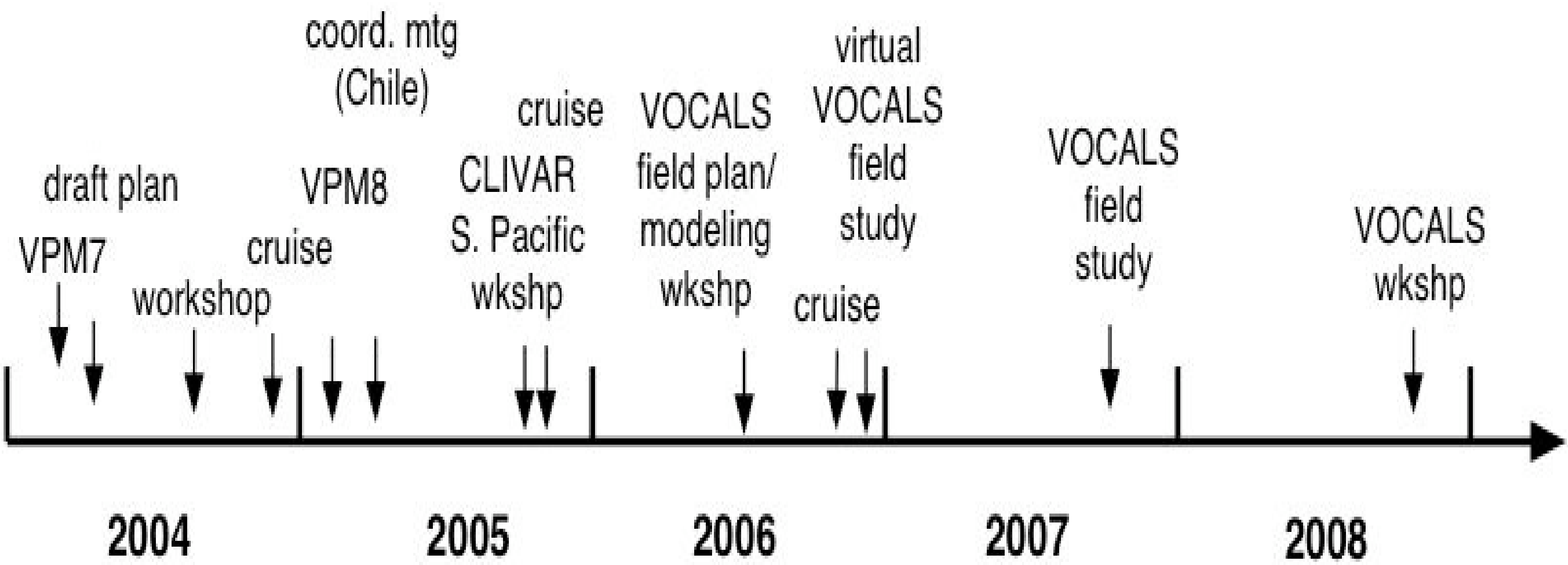
VOCALS aims to develop a Modeling Framework for Interannual Climate Predictions

AGCM:
Atmosphere
General
Circulation
Model

OGCM:
Ocean
General
Circulation
Model



VOCALS Timeline



VOCALS is in NOAA's Books; negotiations with NSF, NASA and US Navy are under way. Chilean and Peruvian programs are funded.

What VOCALS needs from GFDL

- Participation in setting up basic frameworks (e.g., for the “double ITCZ bias”)
- Contribution from modeling groups in model development, operation and validation.
- Assistance in developing the modeling framework for interannual climate predictions.

VOCALS-REx C-130 instrumentation

FACILITY/INSTRUMENT	PROVIDER
Standard cloud/aerosol microphysics (PCASP, FSSP, 2D-C, 260X) Winds/turbulence	NSF (RAF)
Wyoming Cloud Radar (WCR)	NSF/UWYO
Dropsondes	NSF (RAF)
SABL Lidar	NSF (RAF)
Multichannel radiometer (MCR)	NSF (RAF)
Airborne Imaging Microwave Radiometer (AIMR)	NSF (RAF)
Gas chemistry package (CO, CO_2, O_3)	NCAR
APIMS High frequency gaseous phase chemistry measurements (DMS, SO_2)	Drexel U

FACILITY/INSTRUMENT	PROVIDER
Chemically-differentiated aerosol size distriutbutions (MOI impactors, APS, Total aerosol sampler)	U Hawaii
Streaker, SEM, TEM (aerosol particle imagery)	ASU
TSI 3010/3025 (total aerosol number concentration)	U Hawaii
DMPS/APS (size distribution 5-1000 nm)	U Hawaii
PSAP/nephelometer (light absorption/scattering)	U Hawaii
LWC collector (cloud water chemistry)	CSU
Giant aerosol impactor (aerosol size distribution 1-1000 microns)	NCAR
Counterflow Virtual Impactor (cloud chemistry)	U Oregon

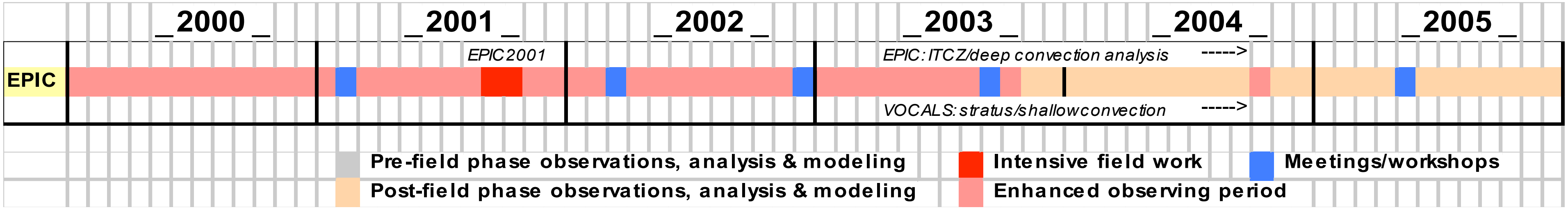
Instruments and measurements deployed by ESRL for the ship-based cloud/MBL monitoring project		
Item	System	Measurement
1	Motion/navigation package	Motion correction for turbulence
2	Sonic anemometer/thermometer	Direct covariance turbulent fluxes
3	IR fast H_2O/CO_2 sensor	Direct covariance moisture/CO2 fluxes
4	Mean SST, air temperature/RH	Bulk turbulent fluxes
5	Pyranometer/Pyrgeometer	Downward solar and IR radiative flux
6	Ceilometer	Cloud-base height
7	0.92 or 3 GHz Doppler radar profiler	Cloud-top height, MBL microturbulence
8	Rawinsonde	MBL wind, temperature, humidity prof.
9	23, 31 GHz :wave radiometer (ARM type) (MAILBOX)	Integrated cloud liquid water Integrated total water vapor
10	Riegl Laser wave sensor	Ocean surface wave height/period
11	DMT CIP Precipitation spectrometer	Drizzle droplet size spectra
12	Lasair-II aerosol spectrometer	Aerosol size spectra
13	BNL rotating shadowband radiometer	Direct/diffuse solar
14	94 GHz Doppler cloud radar	Cloud microphysical properties
15	20, 31, 90 GHz :wave radiometer (ETL) (MMCR)	Integrated cloud liquid water Integrated total water vapor
16	Upward pointed IR thermometer	Cloud-base radiative temperature
17	*Ronald H. Brown* C-band radar	Precipitation spatial structure

R/V Ronald H. Brown – SOLAS Observations

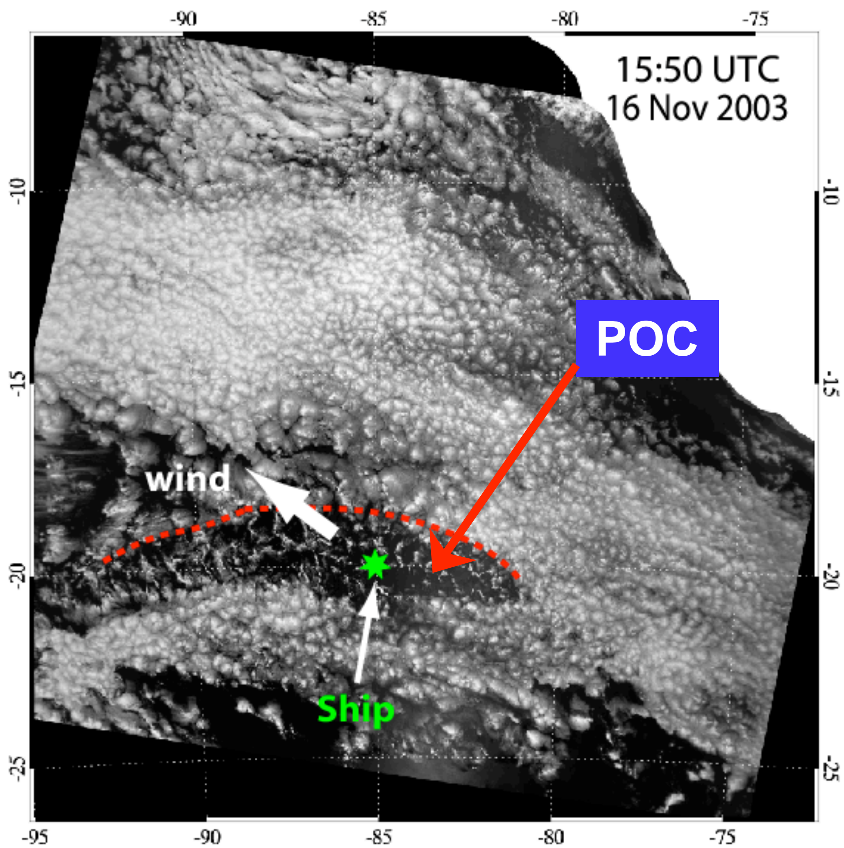
Instrument	Observations	Funding Source	Contact
Two 9 stage MOUDI impactors	Size distributions of NSS, MSA, NH4, Na, K, Ca, Mg, NO_3, Cl, mass, EC, OC, etc.	NSF-ATM	Barry Huebert (U. Hawaii)
Open filter Sampler	Bulk NSS, MSA, NH4, Na, K, Ca, Mg, NO_3, Cl, mass, EC, OC, etc.	NSF-ATM	Barry Huebert (U. Hawaii)
Semicontinuous OC/EC analyzer	Elemental and organic carbon aerosols	NSF-ATM	Barry Huebert (U. Hawaii)
TSI 3010, 3025	Total aerosol number, incl. nanoparticles	NSF-ATM	Howell & Clarke (U. Hawaii)
DMPS and APS	Number size distribution from 5 to 10,000 nm diameter	NSF-ATM	Howell & Clarke (U. Hawaii)
Aethalometer	7 λ light absorption	NSF-ATM	Barry Huebert (U. Hawaii)
3 wavelength TSI nephelometer – Ambient RH	Total and sub-micron (alternating) light scattering and backscattering by aerosols	NSF-ATM	Howell & Clarke (U. Hawaii)
3 wavelength TSI nephelometer - DRY	f(RH) for light scattering	NSF-ATM	Howell & Clarke (U. Hawaii)

Roadmap for EPIC

- Support continued and new EPIC empirical and model analyses
- Foster connections between modelers and observationalist (joint workshops, CPTs, ...)
- Foster connections between NAME and EPIC ITCZ work
- Support continued research on stratus deck region through VOCALS
- Support research on cold tongue dynamics/ thermodynamics through PUMP



Indirect effects of aerosol on climate



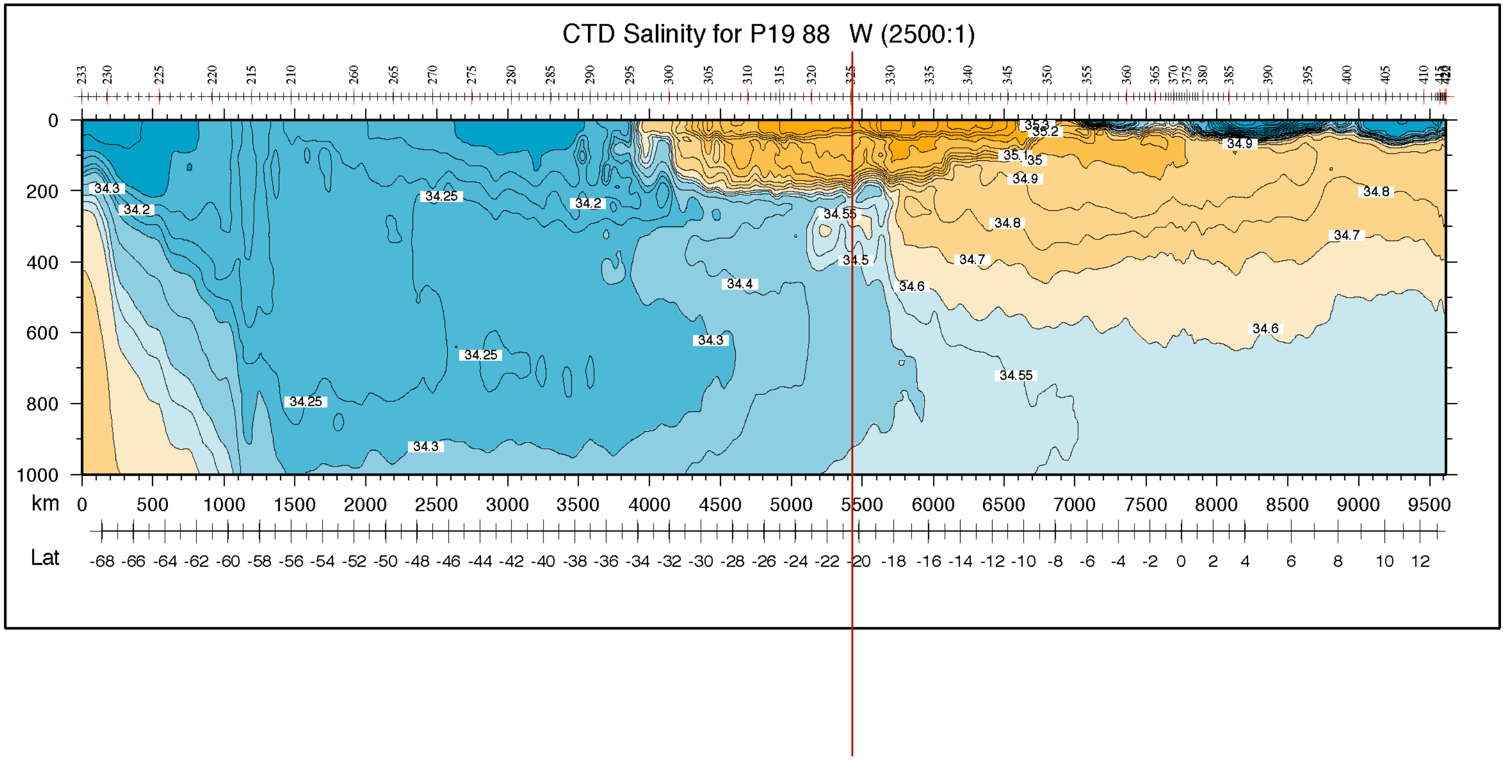
Pockets of Open Cells (POCs) are strongly drizzling and almost completely depleted of cloud forming aerosols

In the SEP near the coast POCS rarely develop, but away from the coast they are more frequent and extended than in other Scu regions.

Are these behaviors evidence of strong links between aerosol and cloud macrophysical structure? What is the role of drizzle?

To what extent do surface fluxes of precursor gases (e.g. DMS, dimethylsulfide) affect the re-filling of POCs with clouds, and what is the role of iodine, ammonia, and organics?

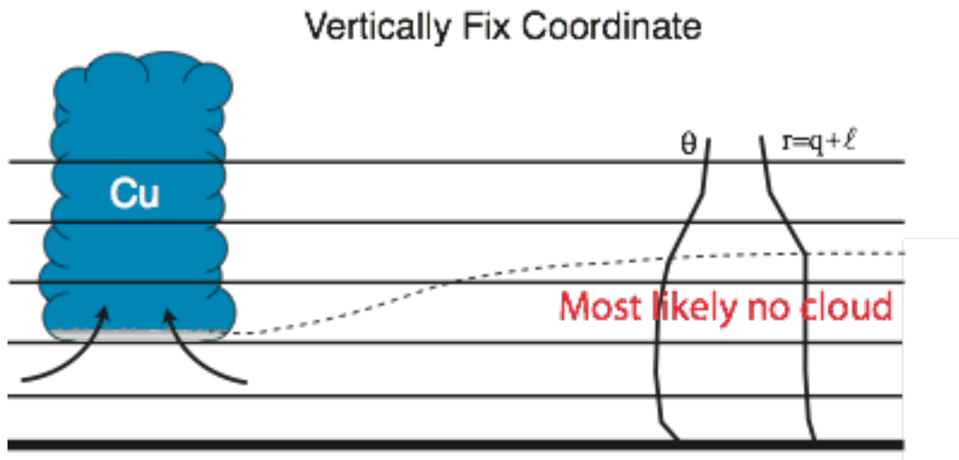
Ocean Salinity Section at 88W



20W

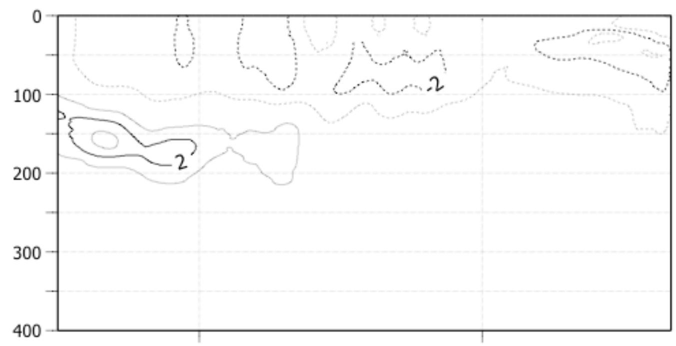
Structural differences between PBL implementations

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

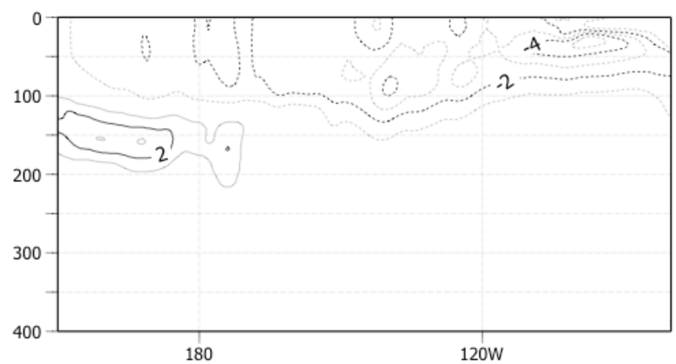


- Vertical coordinate surfaces are fixed
- Profiles may deviate from well mixed ones.
- Processes near the PBL top are difficult to simulate properly (even with moderately high vertical resolution).
- It is difficult to keep track of budget of PBL quantities.
- Thus, a realistic simulation of PBL cloud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

a) ECCO temperature anomaly at vertical section, March



b) Baseline temperature anomaly at vertical section, March



contour interval. 1oC

Simulations with CAGCM (UCLA-AGCM/MIT-OGCM)

- **AGCM** (Low-resolution): 5X4, 14+4 layers.

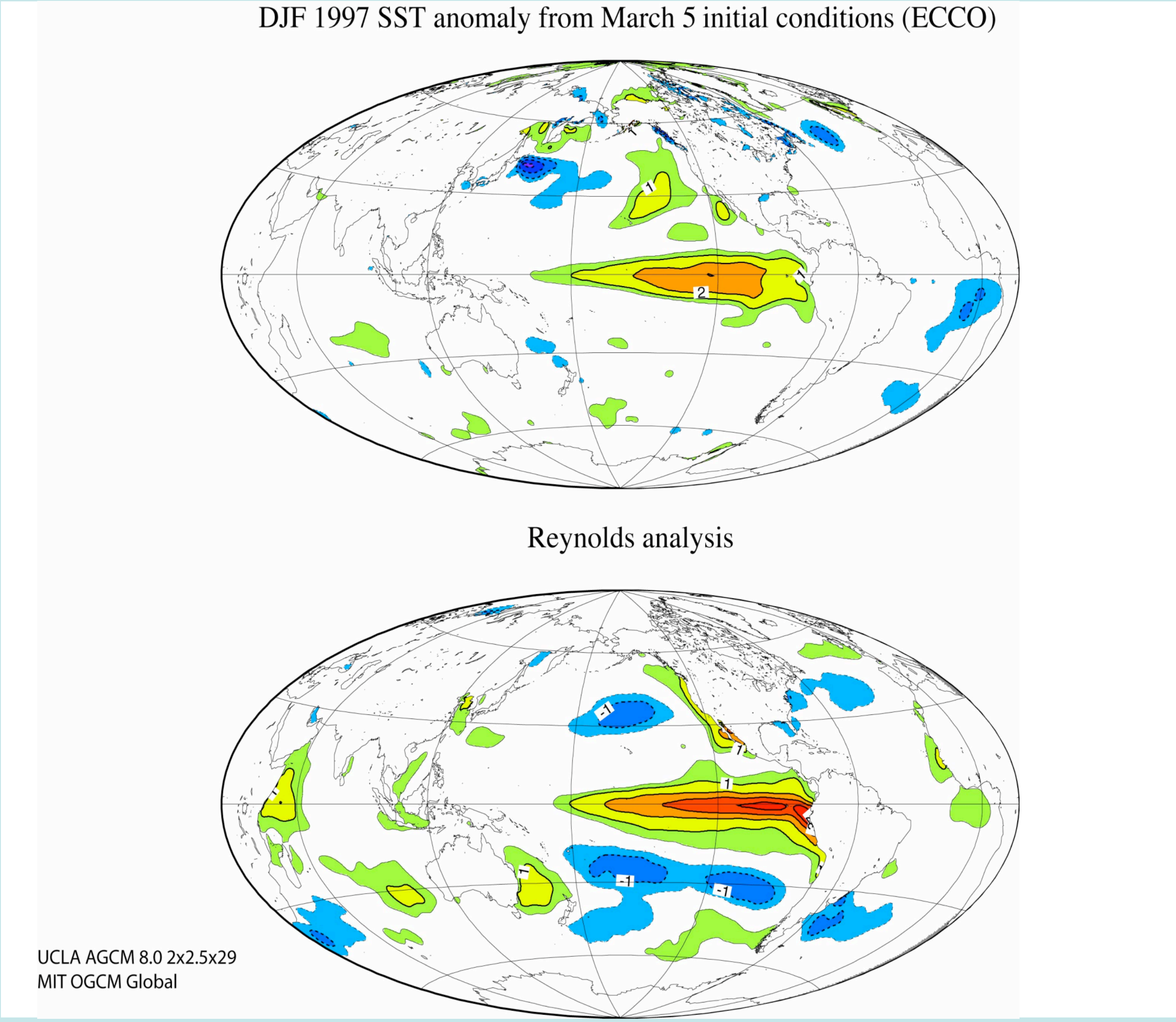
  (High-resolution): 2.5X2, 28+4 layers.
- **OGCM** 1X0.3 (near Eq.), 1X1 (mid and high lat), 46 layers.

Hindcasts with CAGCM

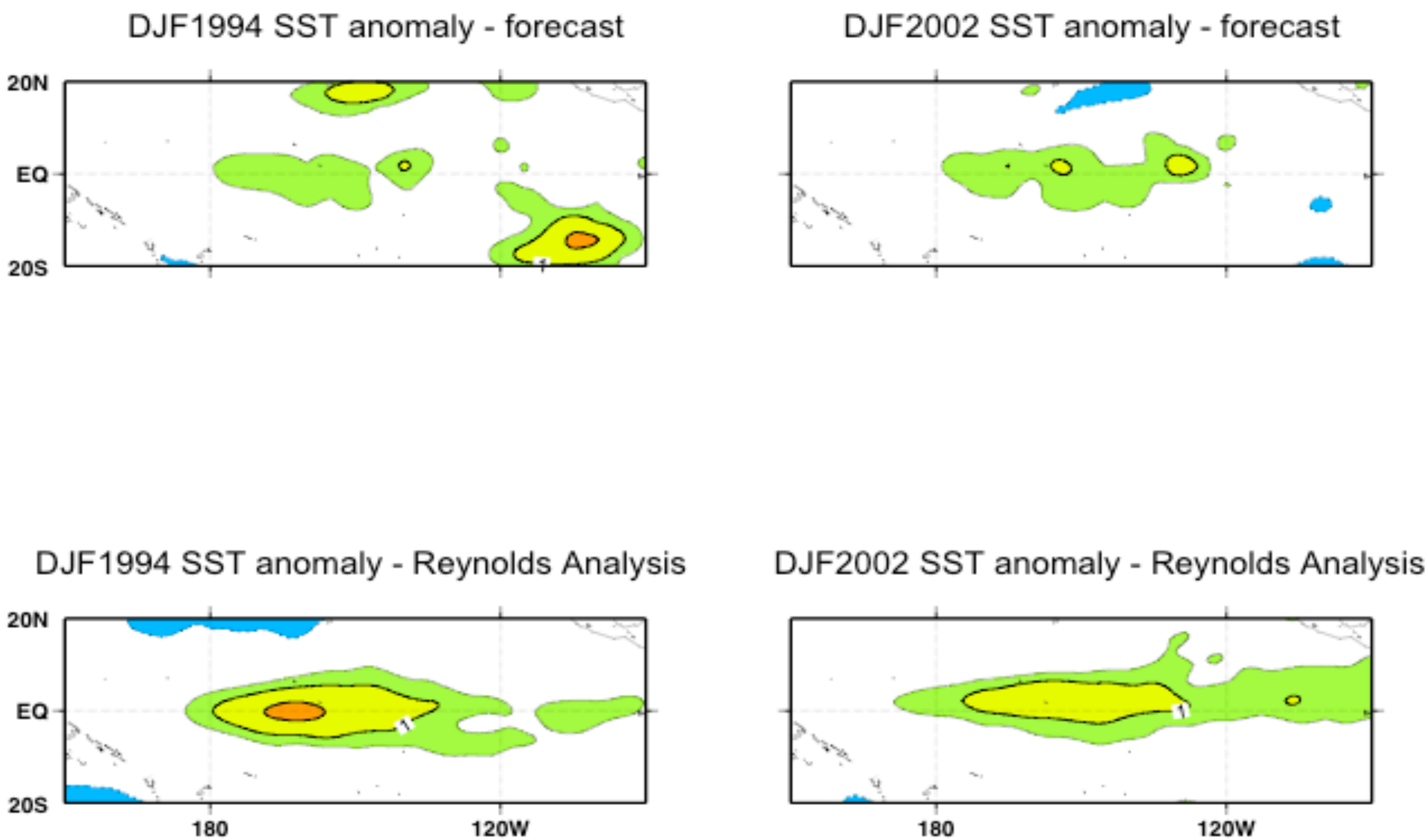
- Initial conditions: March 5th, June 5th
- 5 - member ensemble over 9 years (1993-2002)
- 15 - month long runs; 180 runs
- Initial atmospheric states: From long AGCM run with clim. SST.
- Two initial ocean states: 1) JPL's ECCO Project; 2) Long OGCM run with prescribed climatol. wind stress and SST.

UCLA

DJF 1997 Forecast from March 5, 1996

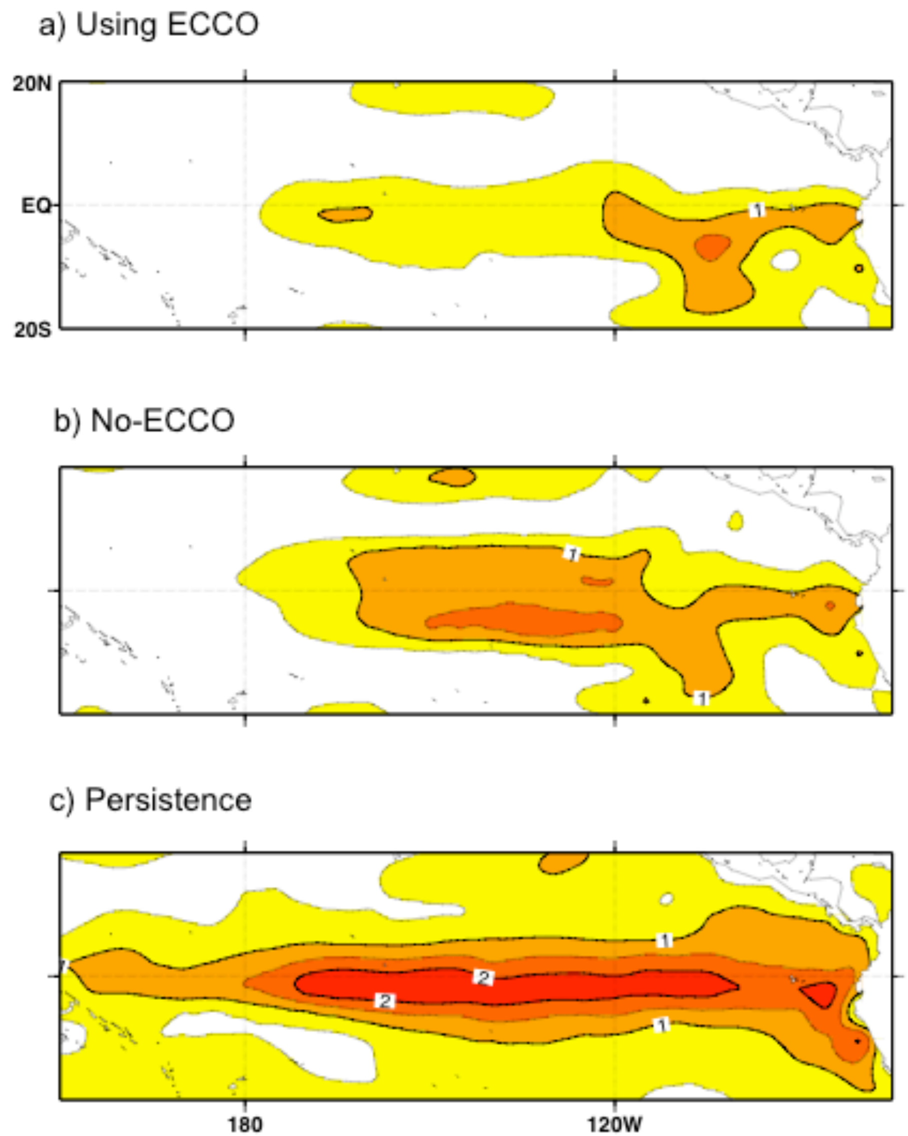


Two DJF Forecasts with Different Success
From Early March Initial Conditions



UCLA AGCM 7.3 HighRes
MIT Global OGCM

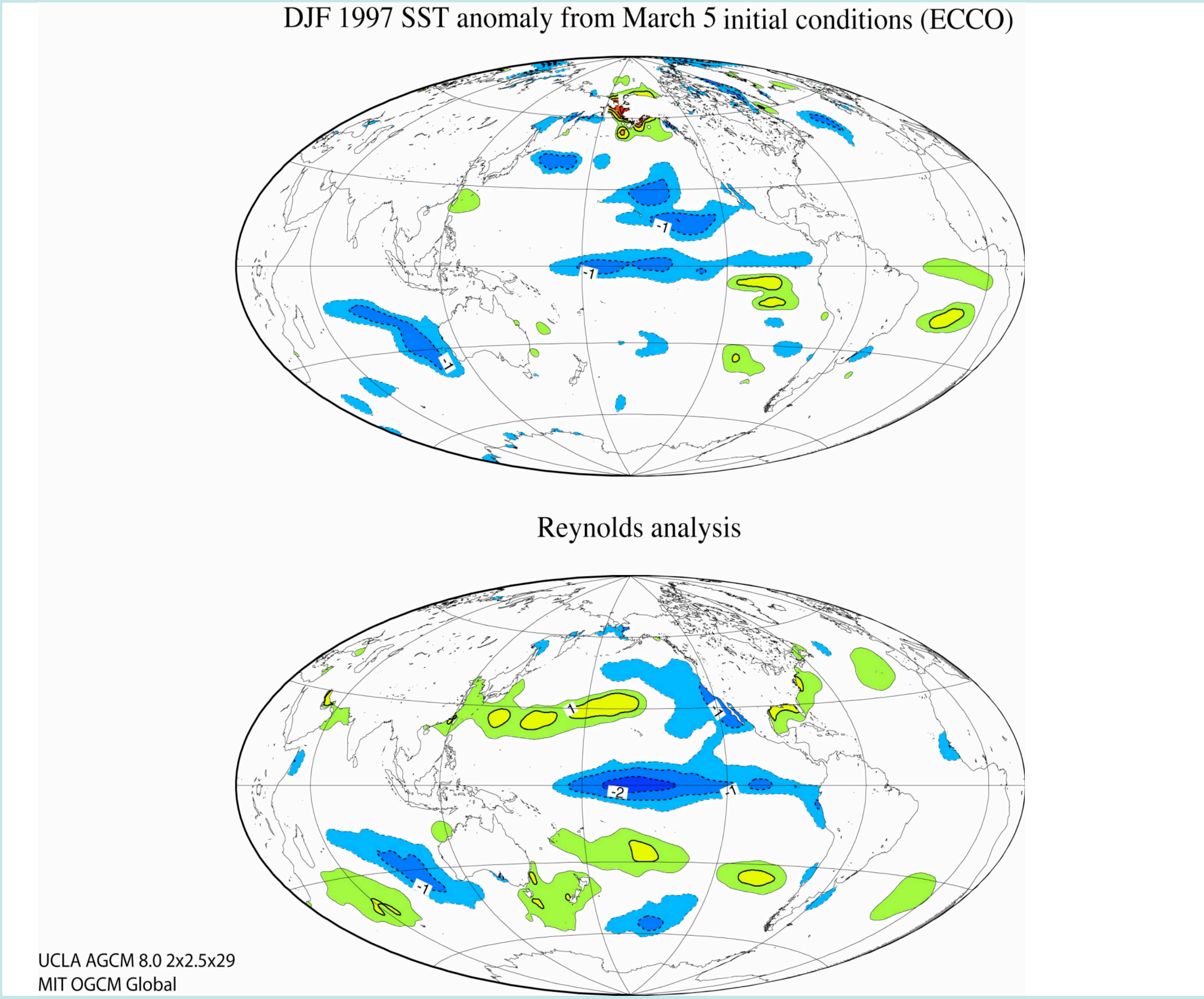
Standard Deviation of DJF Forecast Error
From Early March Initial Conditions



UCLA AGCM 7.3 HighRes
MIT Global OGCM

contour interval, 0.5°C

DJF 1998 Forecast from March 5, 1996



EPIC Contributions

- Much was learned on ITCZ variability and the cross-equatorial flow in the eastern Pacific
- A new parameterization of oceanic solar absorption based on satellite color and chlorophyl concentration was developed by using radiative flux profiles from EPIC (Ohlman, *J. Clim.,* 2003). This is used derive surface fluxes from the TAO buoy network (Wick et al., *JPO* 2006)
- The simulation of PBL height over the eastern Pacific by NCAR CCSM2 was evaluated by using EPIC data (Zeng et al, *J. Clim.* 2004)
- The methodology to obtain ship-based liquid water path estimates in marine stratus was improved (Zuidema et al., *JGR* 2005)
- A new probabilistic approach for the relationship between cloud LWP and cloud fraction (CF) was developed (Zhou et al., *JAM* 2006)

Ohlmann, J. C., 2003: Radiant heating in climate models. *J. Clim.*, **16**, 1337-1351.

Wick, Gary A., J. Carter Ohlmann, Christopher W. Fairall, and Andrew T. Jessup, 2006: Improved oceanic cool-skin corrections using a refined solar penetration model. *J. Phys. Oceanogr.*, to appear.

Zeng, X., M. A. Brunke, M. Zhou, C. W. Fairall, N. A. Bond, and D. H. Lenschow, 2004: Marine atmospheric boundary layer height over the Eastern Pacific: Data analysis and model evaluation. *J. Clim.*, 17, **21**, 4159-4170.

Zhou, Mingyu, Xubin Zeng, Michael Brunke, Zhanhai Zhang, and C. W. Fairall, 2006: Study on macro- and microphysical properties of stratus and stratocumulus over the Eastern Pacific. *J Appl. Meteorol.*, to appear.

Zuidema, P., C. W. Fairall, E. Westwater, and D. Hazen, 2005: Ship-based liquid water path estimates in marine stratus. *J. Geophys. Res.*, 110 (D20): Art. No. D20206 OCT 26.