Oak Ridge National Laboratory, 16 March 2009

It is Necessary to Revolutionize Climate Prediction in the U.S. and the World: Is it Possible?

Jagadish Shukla

George Mason University (GMU), USA

Institute of Global Environment and Society (IGES)

"Revolution in Climate Prediction is Both Necessary and Possible"

Shukla, Hagedorn, Hoskins, Kinter, Marotzke, Miller, Palmer, and Slingo, ***BAMS***, Feb 2009, pp 175-178

Center of Ocean-Land-Atmosphere studies

Outline

1. WCRP - COPES - World Modeling Summit for Climate Prediction
2. Climate Models Have Serious Deficiencies
3. Model Fidelity versus Predictability
4. Resolution, Complexity, Computational Requirements
5. Summit Recommendation: Scientific and Computing Capacity
6. U.S. Climate Modeling
7. How to Implement Summit Recommendation? (US; World)
8. Recommendations/Suggestions

GEWEX 1988 →

WGNE
WGCM
WGSF

SPARC 1992→

WCRP Observation & Assmilation Panel

WCRP

Coordinated Observation and Prediction of the Earth System

WCRP Modelling Panel

CLIVAR 1995 →

SOLAS 2001 ->

CliC 2000 →

The WCRP Strategic Framework 2005-15

Coordinated Observation and Prediction of the Earth System

(WCRP-COPES)

AIM

To facilitate analysis & prediction of Earth system variability & change for use in an increasing range of practical applications of direct relevance, benefit & value to society

Seamless Prediction (COPES/WCRP)

1. Decadal and century-long climate projection will become an initial-value problem.
   - Requirement: initialize ocean, atmosphere, cryosphere, biosphere

2. The shorter-time-scale weather variations are important in influencing the longer-time-scale behavior.
   - Requirement: Make climate prediction with weather prediction resolution models

3. Although the prediction problem itself is seamless, the best practical approach may be to utilize unified prediction systems.
   - Seamless does NOT mean that the same model is used for everything!

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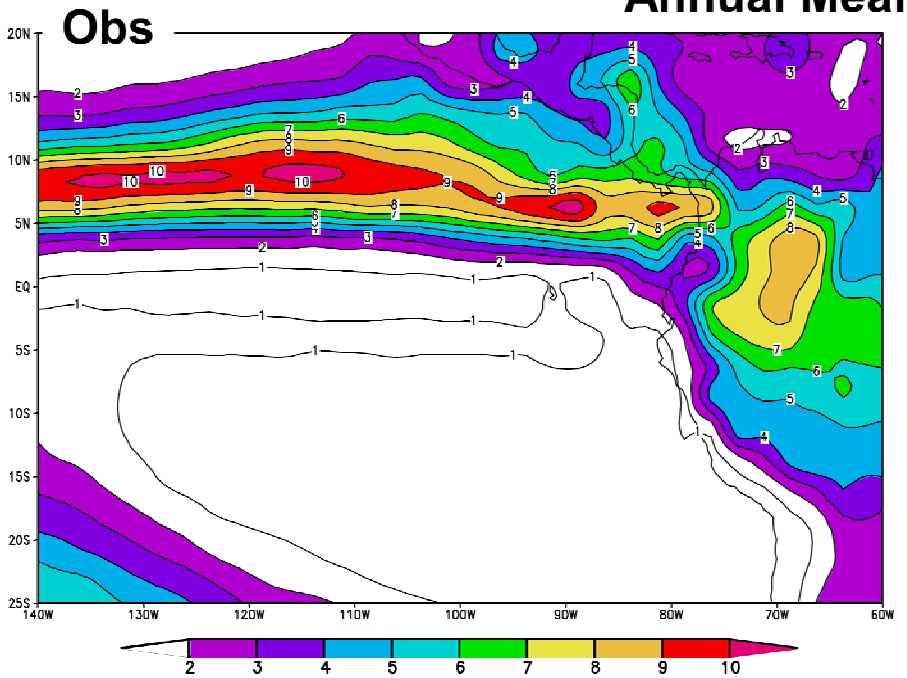
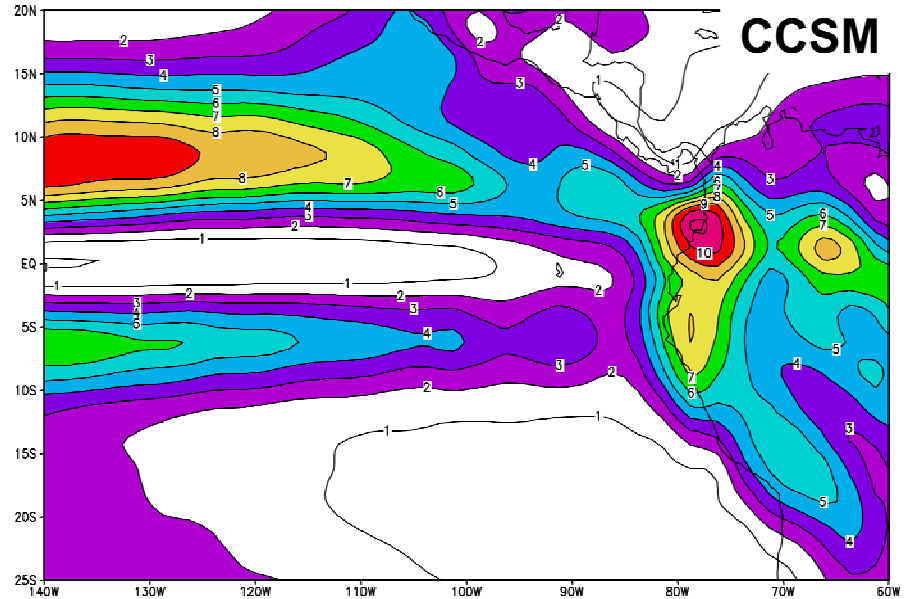
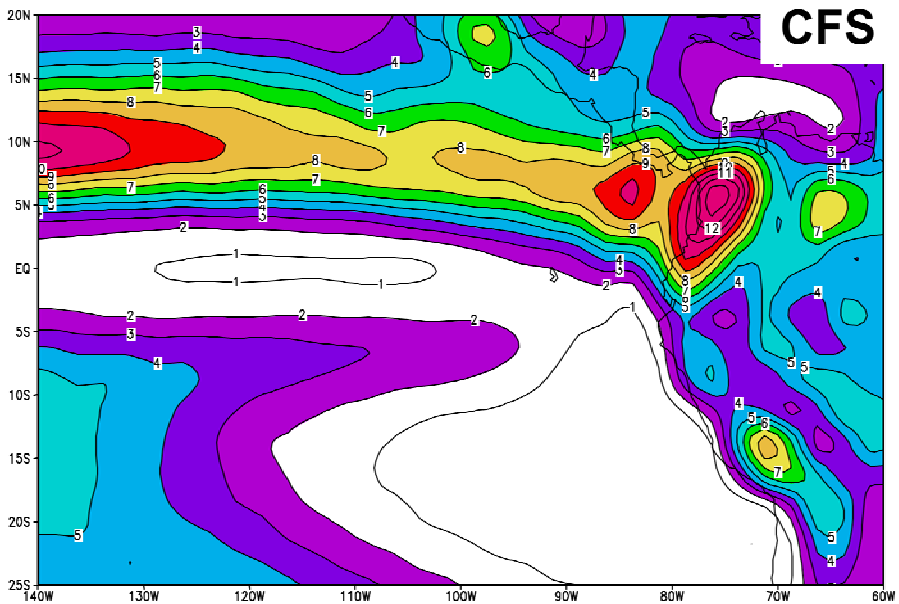
Annual Mean Precipitation



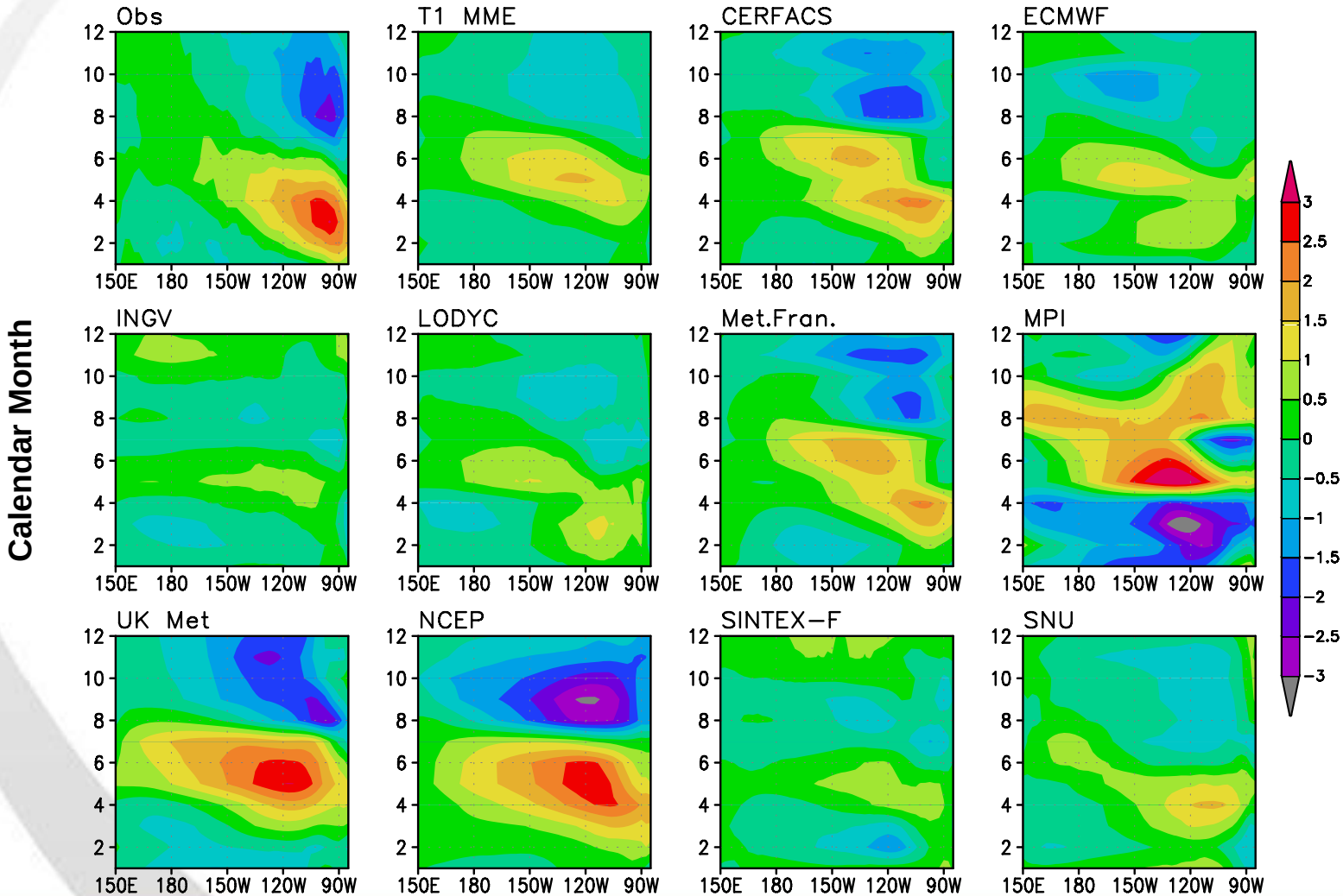




Infamous Double ITCZ Problem

Annual Cycle of SST Climatology

4-6 month forecast, APCC/CliPAS & DEMETER CGCMs

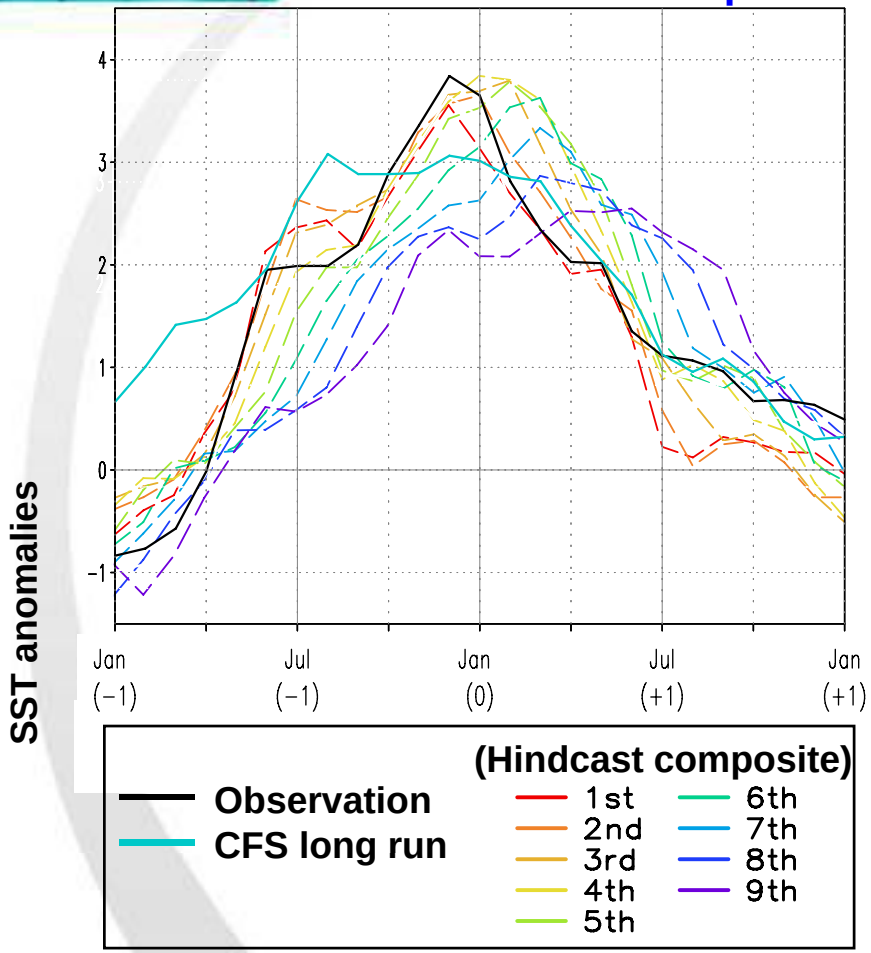


Center of Ocean-Land-Atmosphere studies

Jin et al. 2008
Climate Dynamics

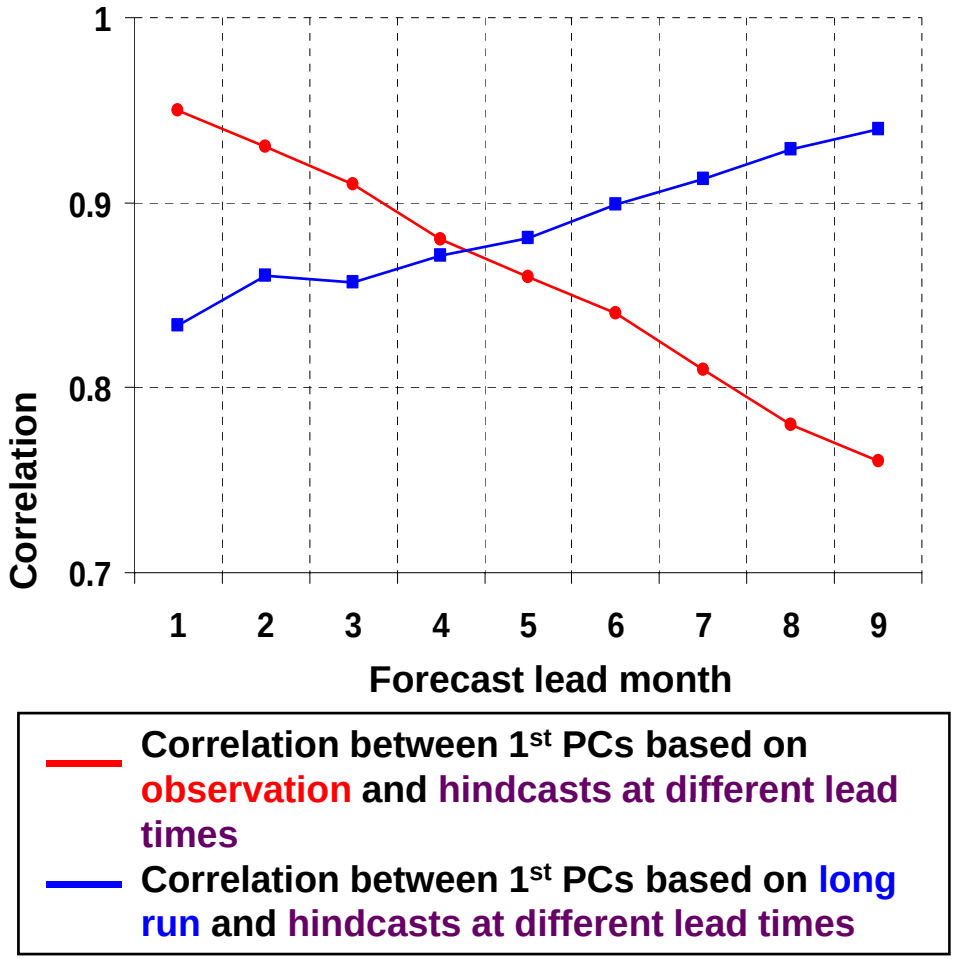
Influence of Systematic Error on CFS Forecast Skill

NINO3: Warm minus Cold composite



- Warm composite (82/83, 86/87, 91/92, 97/98) - Cold composite (84/85, 88/89, 98/99, 99/00)
- Dashed lines denote composite for Hindcasts at different lead times

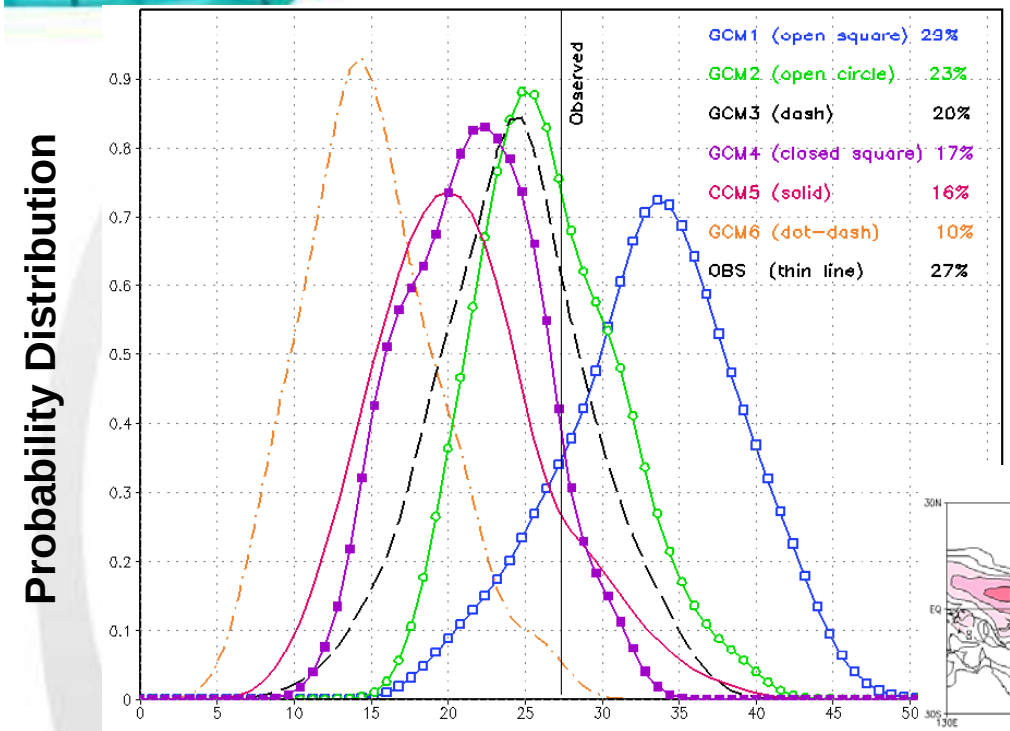
CORR. with respect to lead month based on 1st SEOF mode of SST



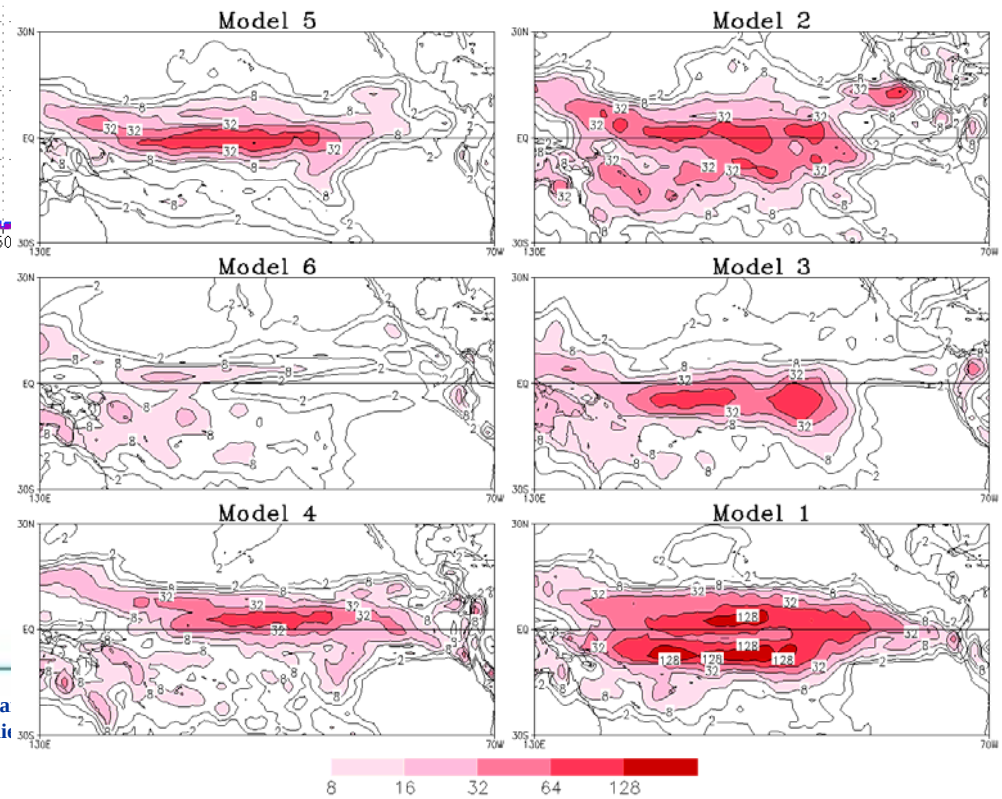
Jin and Kinter 2009, Climate Dynamics

→ **Model Flaw: Slow coupled dynamics of CGCM**

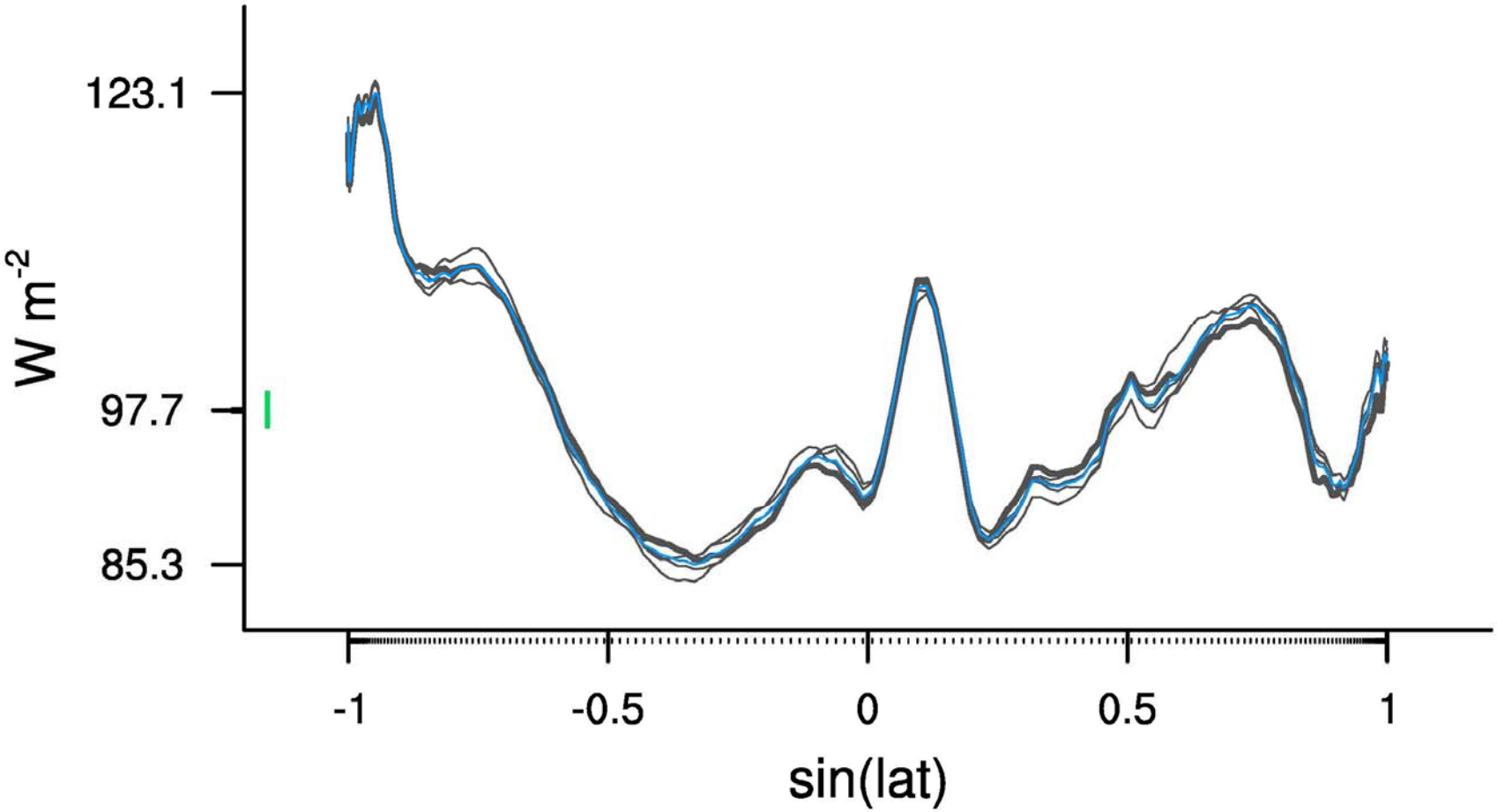
Percent Variance of PNA region explained by Tropical SST



Boreal Winter (DJF) Rainfall Variance in AGCMs



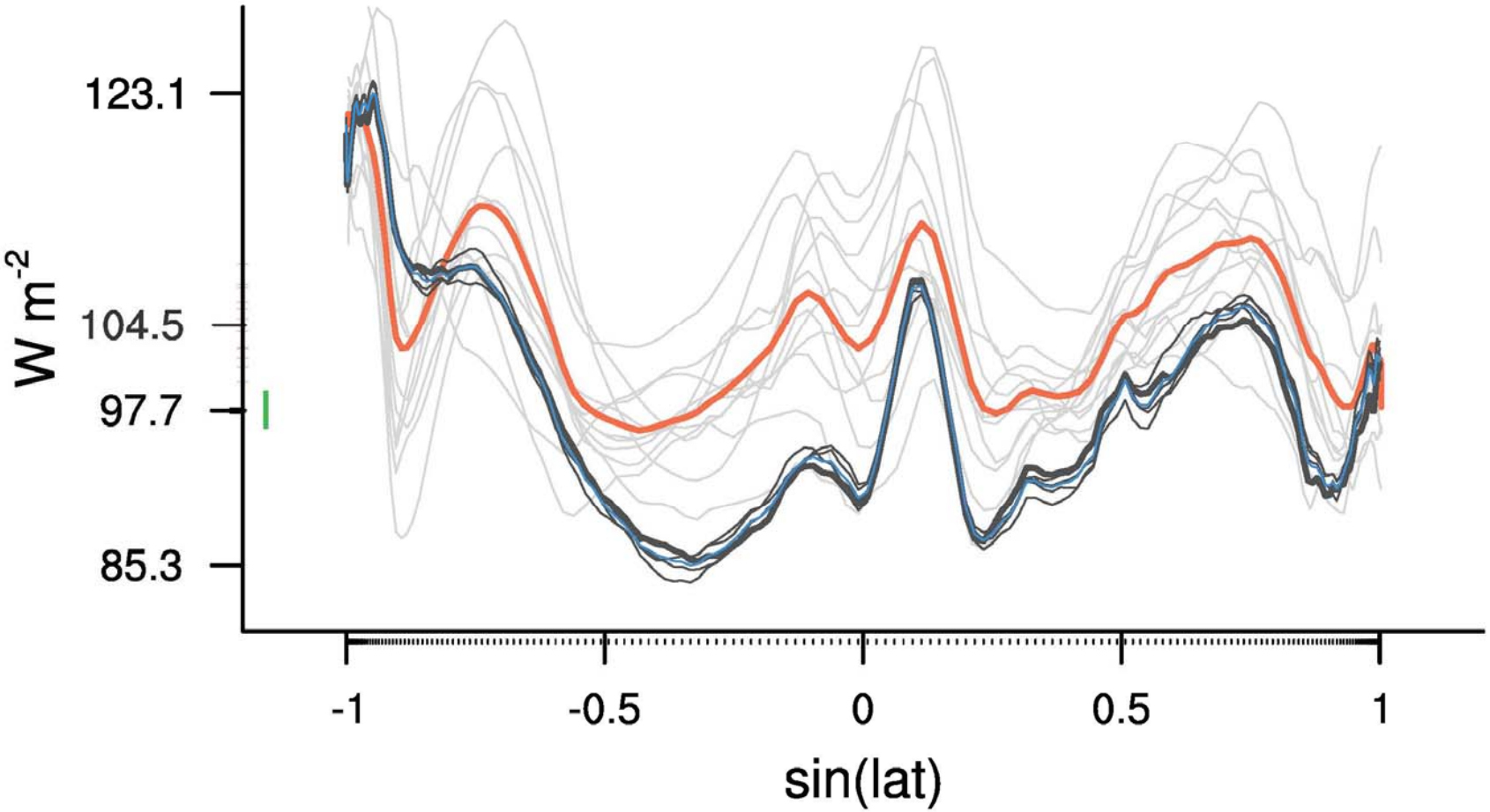
Annually & Zonally Averaged Reflected SW Radiation



Bjorn Stevens, UCLA

World Modelling Summit, ECMWF, May 2008

Annually & Zonally Averaged SW Radiation (AR4)



- 101-106 W/m2 (Wild et al., survey)
- 107 W/m2 (Trenberth and Kiehl (ERBE)
- 101 W/m2 (CERES)

Bjorn Stevens, UCLA

World Modelling Summit, ECMWF, May 2008

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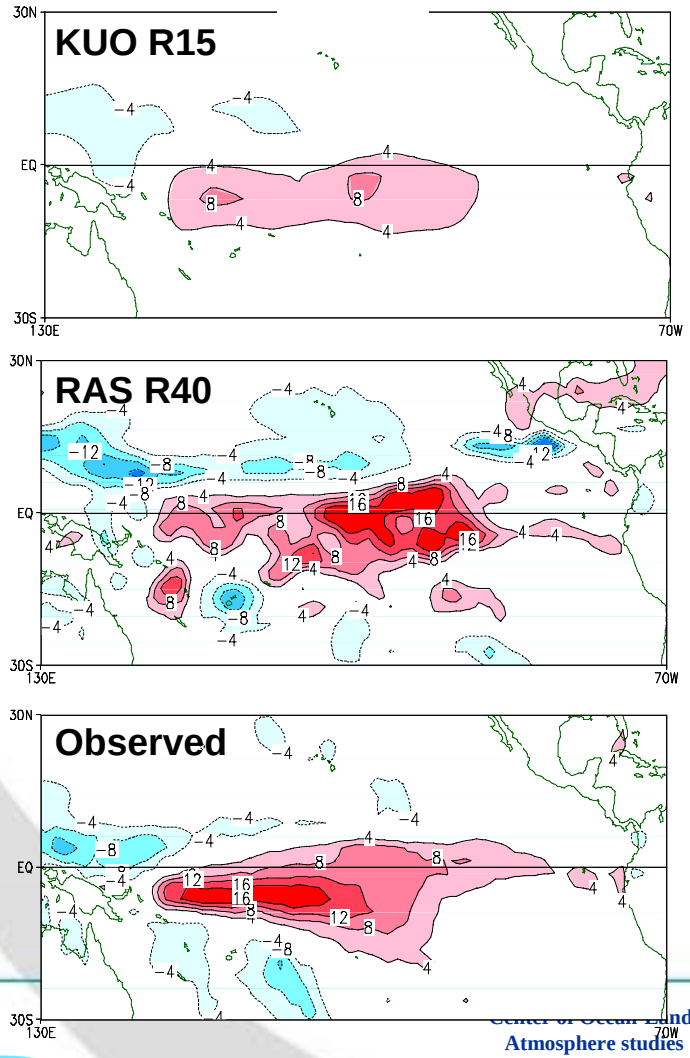
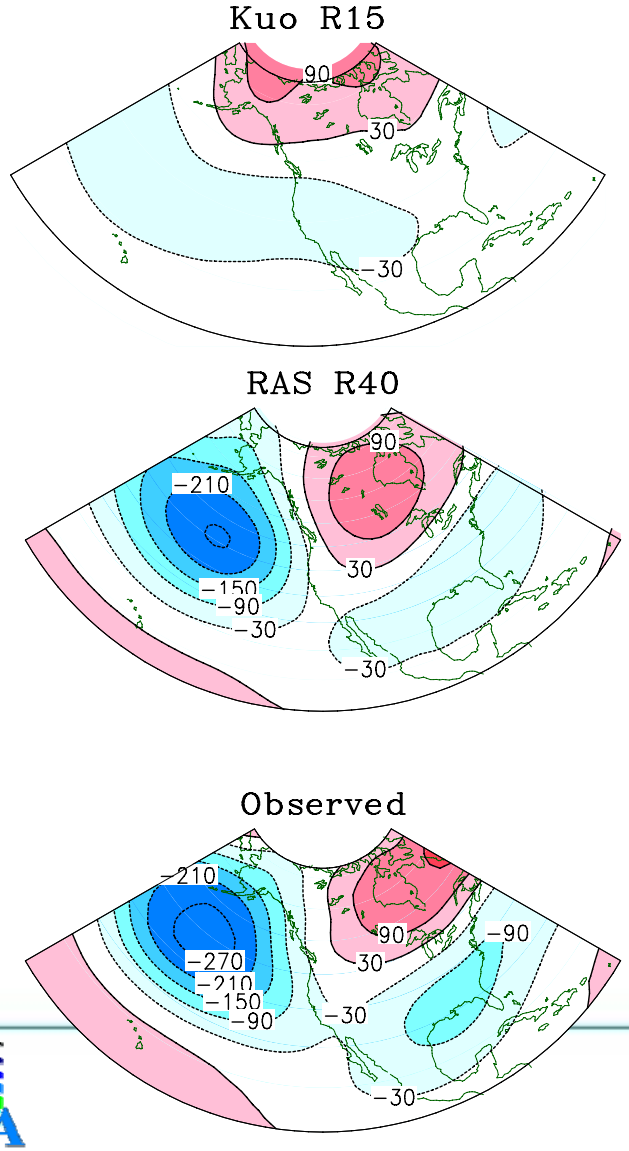
Evolution of Climate Models 1980-2000

Model-simulated and observed, 1983 minus 1989

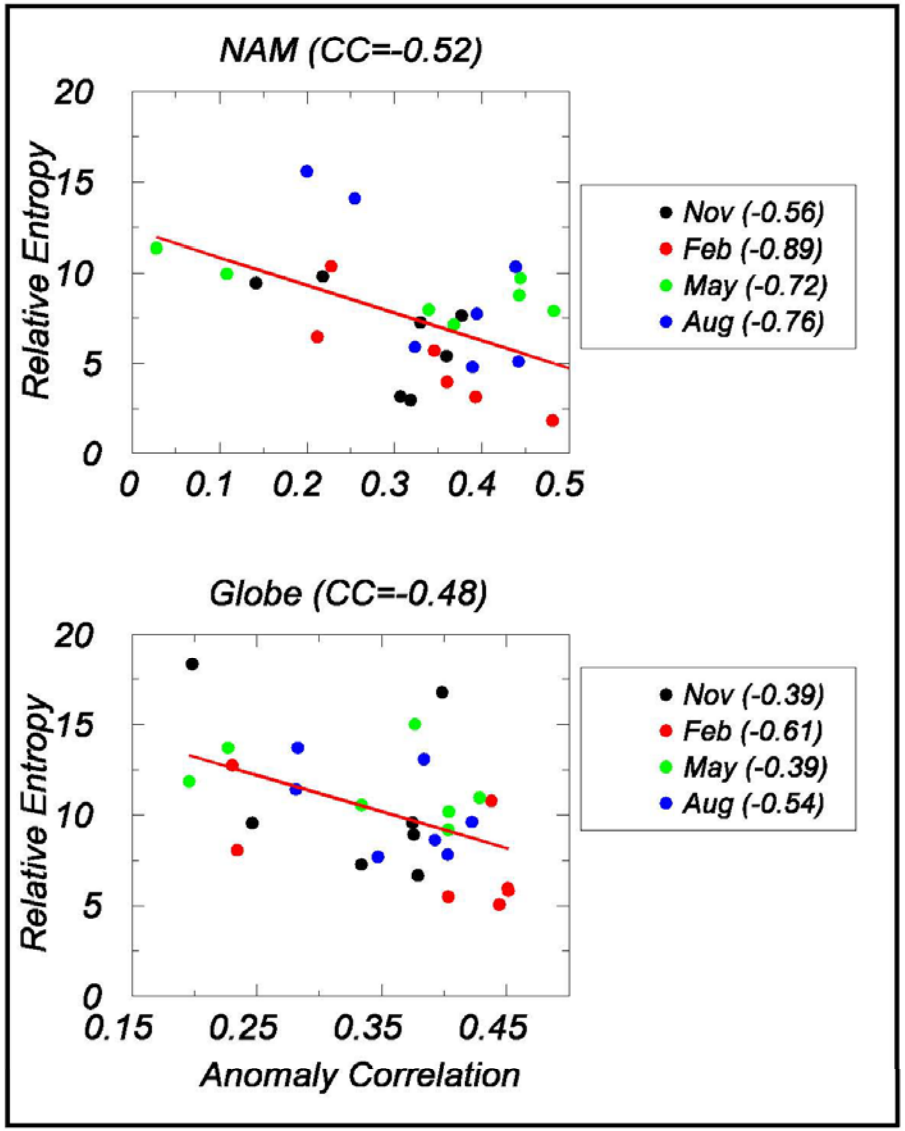
Rainfall (mm day-1)



500 hPa GPH anomaly (m)



Center of Ocean Land-Atmosphere studies



Fidelity vs. Skill
DEMETER 1980-2001
Seasonal Forecasts

7 models, 4 initial conditions

Lead Time = 0 months

Fidelity and Skill are related.

Models with poor climatology tend to have poor skill.

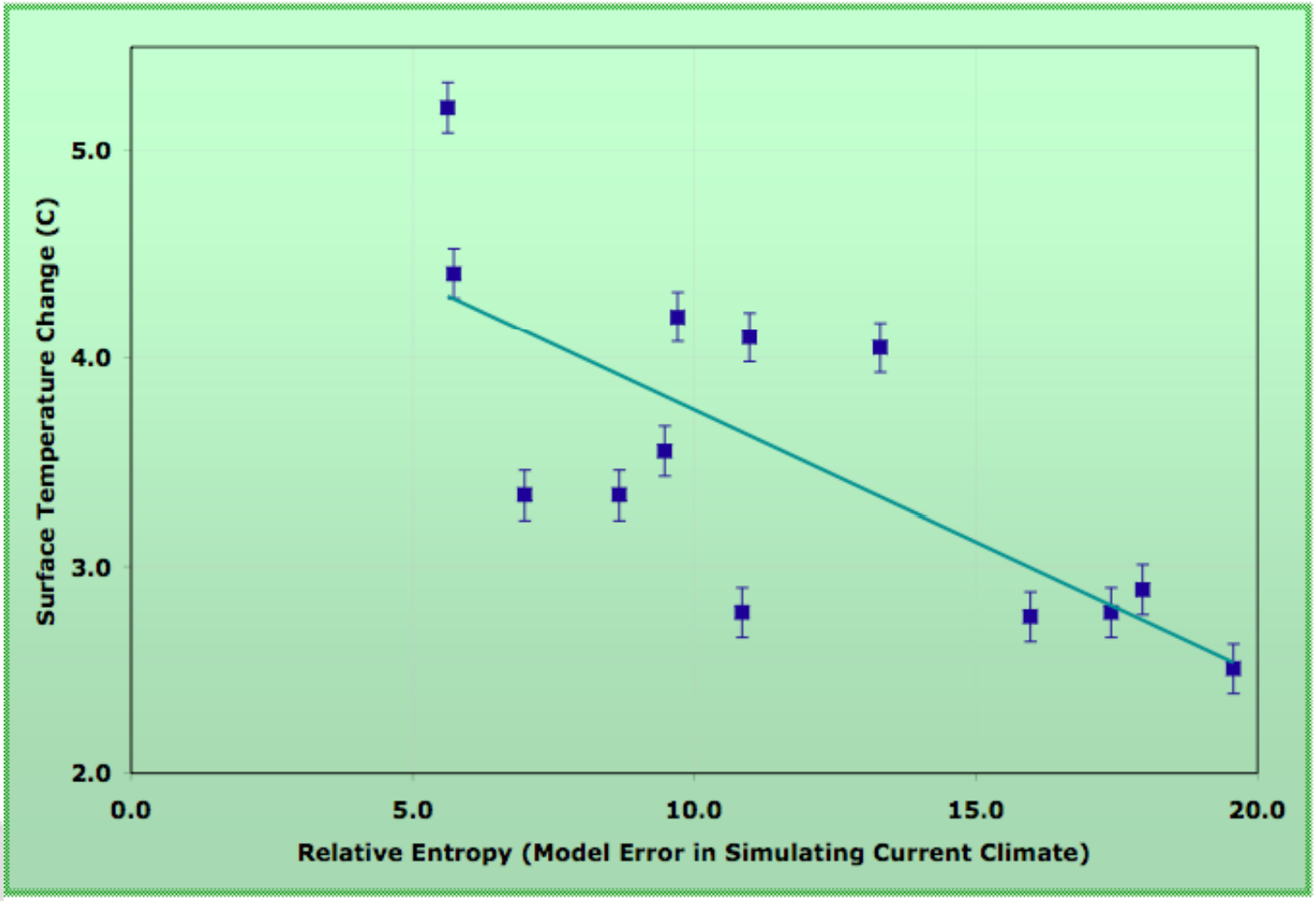
Models with better climatology tend to have better skill.

DelSole (research in progress)

Climate Model Fidelity and Projections of Climate Change

J. Shukla, T. DelSole, M. Fennessy, J. Kinter and D. Paolino

Geophys. Research Letters, 33, doi10.1029/2005GL025579, 2006



Model sensitivity versus model relative entropy for 13 IPCC AR4 models. Sensitivity is defined as the surface air temperature change over land at the time of doubling of CO_2. Relative entropy is proportional to the model error in simulating current climate. Estimates of the uncertainty in the sensitivity (based on the average standard deviation among ensemble members for those models for which multiple realizations are available) are shown as vertical error bars. The line is a least-squares fit to the values.

Climate Model Fidelity and Climate Prediction

Interim Conclusions:

- **If we conjecture that models that better simulate the present climate should be considered more credible in projecting the future climate change, then this relationship suggests that the actual changes in global warming will be closer to the highest projected estimates among the current generation of models used in IPCC AR4.**

- **Lack of understanding of causes of model differences – is source of uncertainty in predicting climate change.**

Question: Will AR5 be any different?

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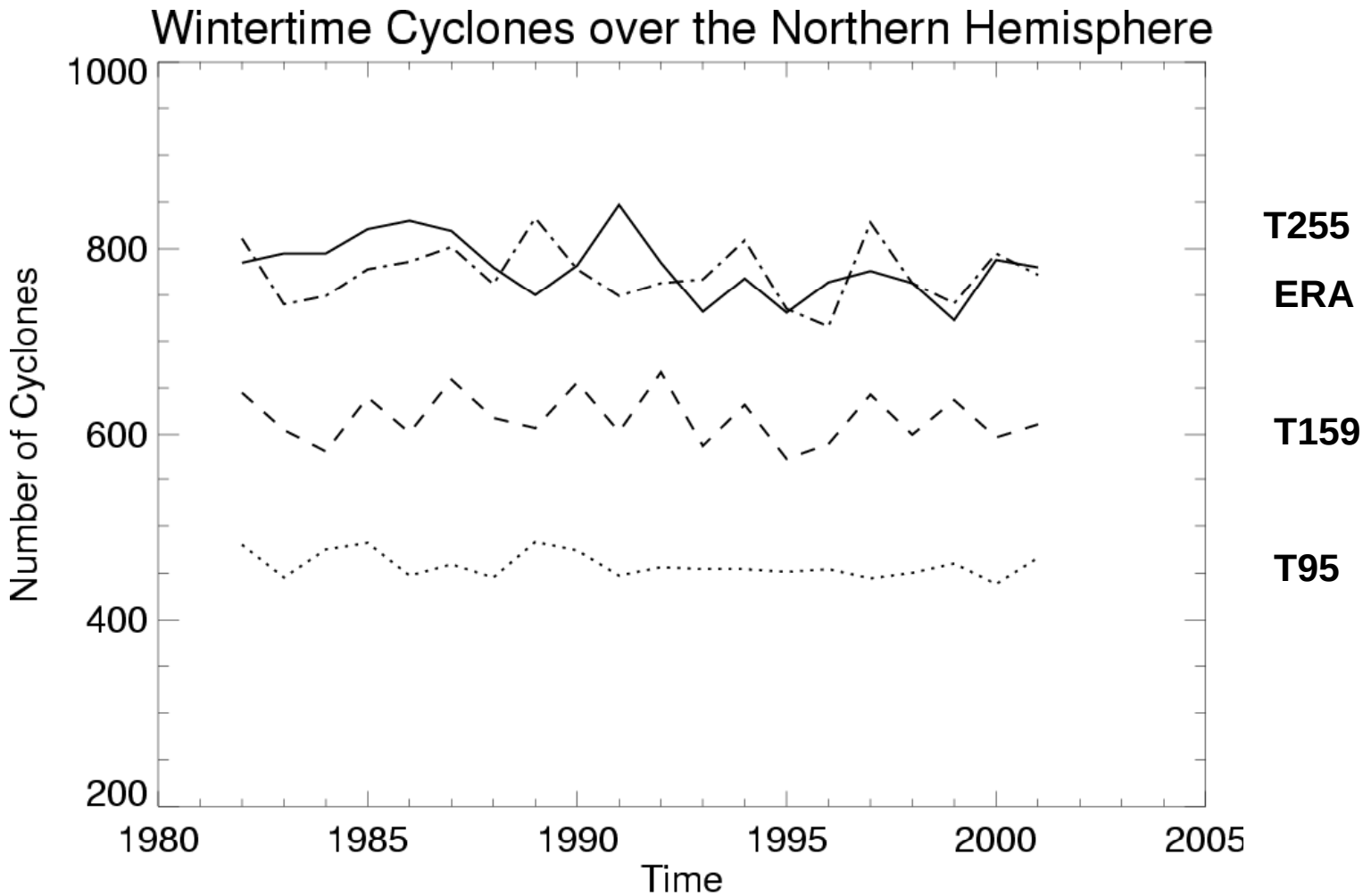
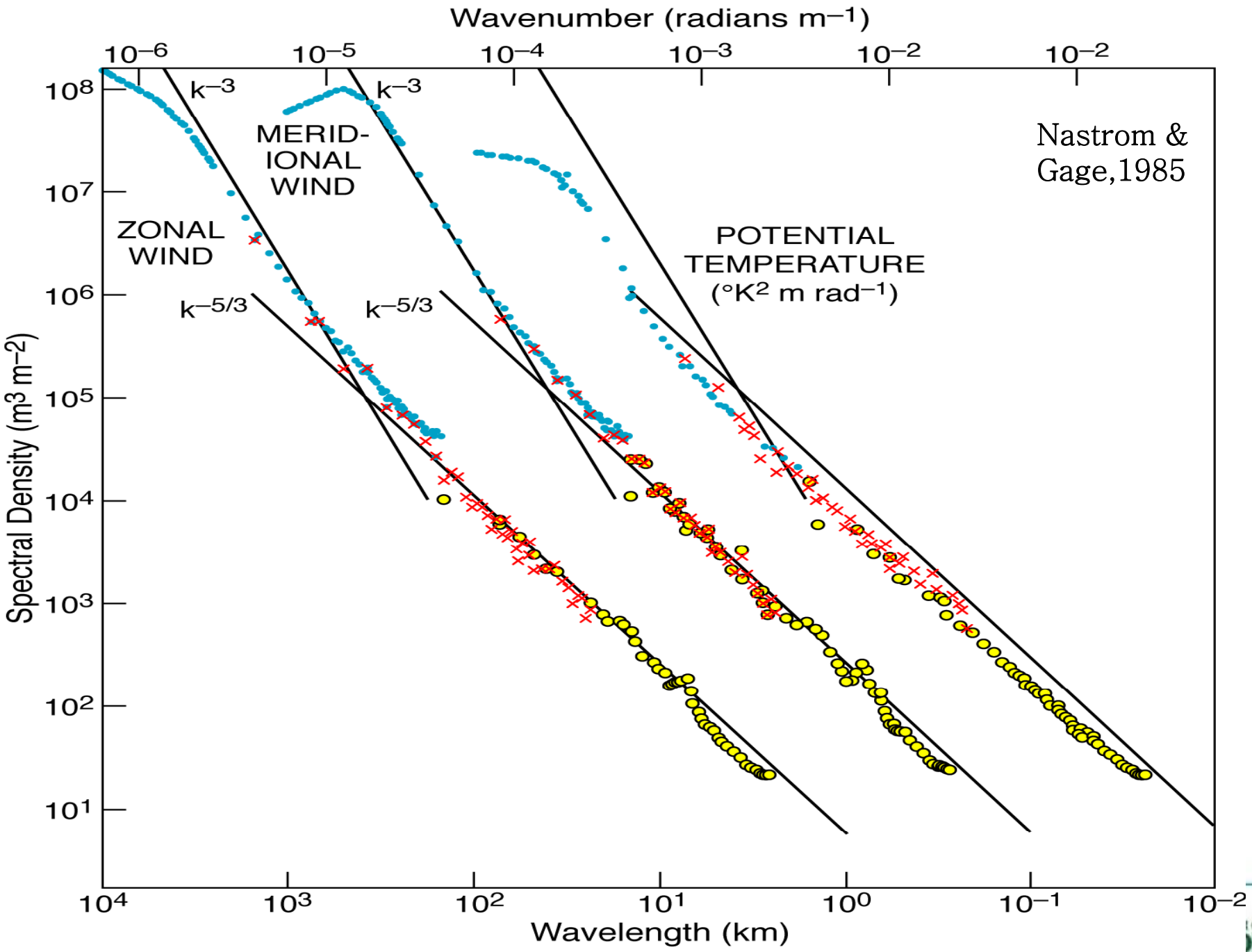
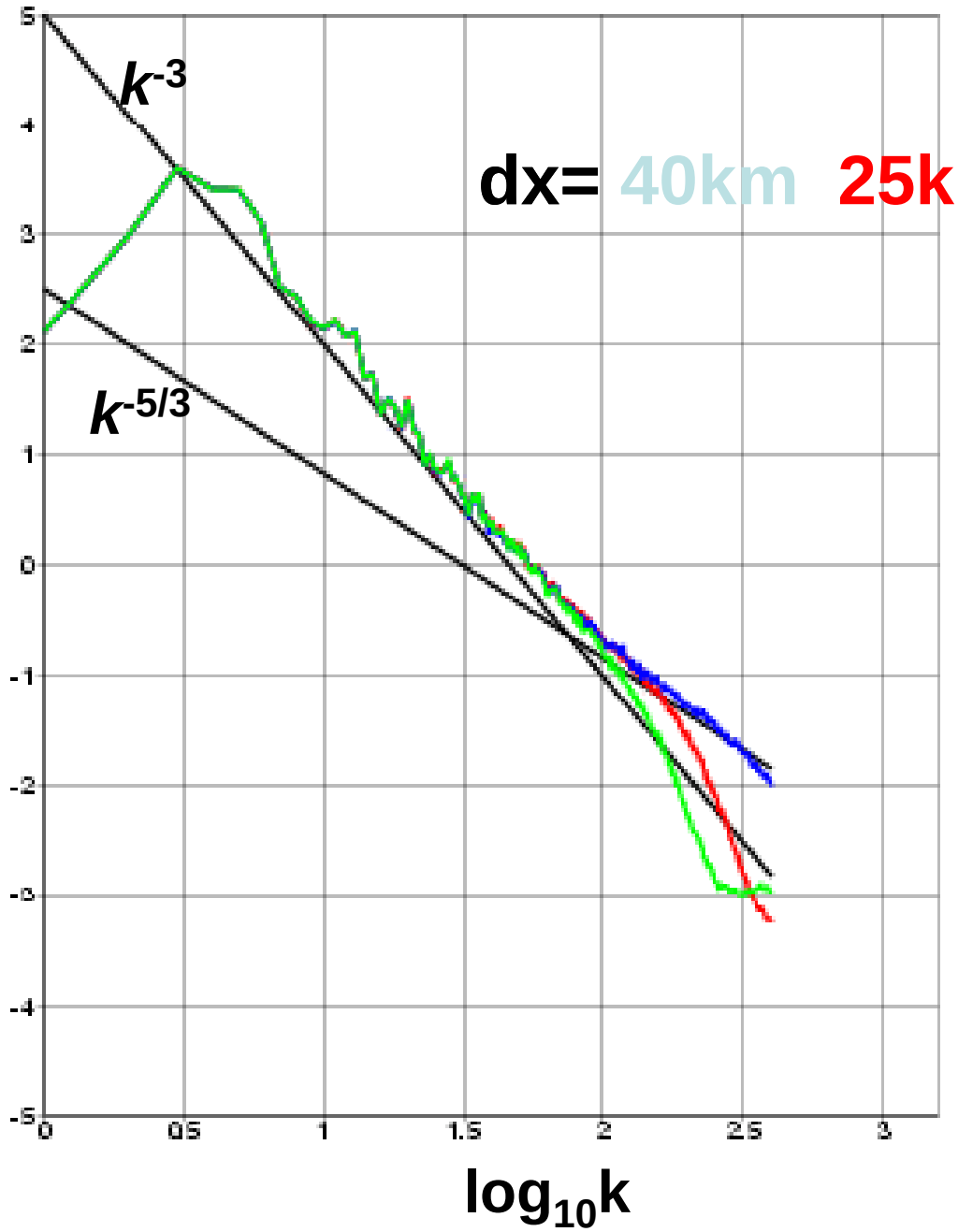
Number of Northern Hemisphere Cyclones



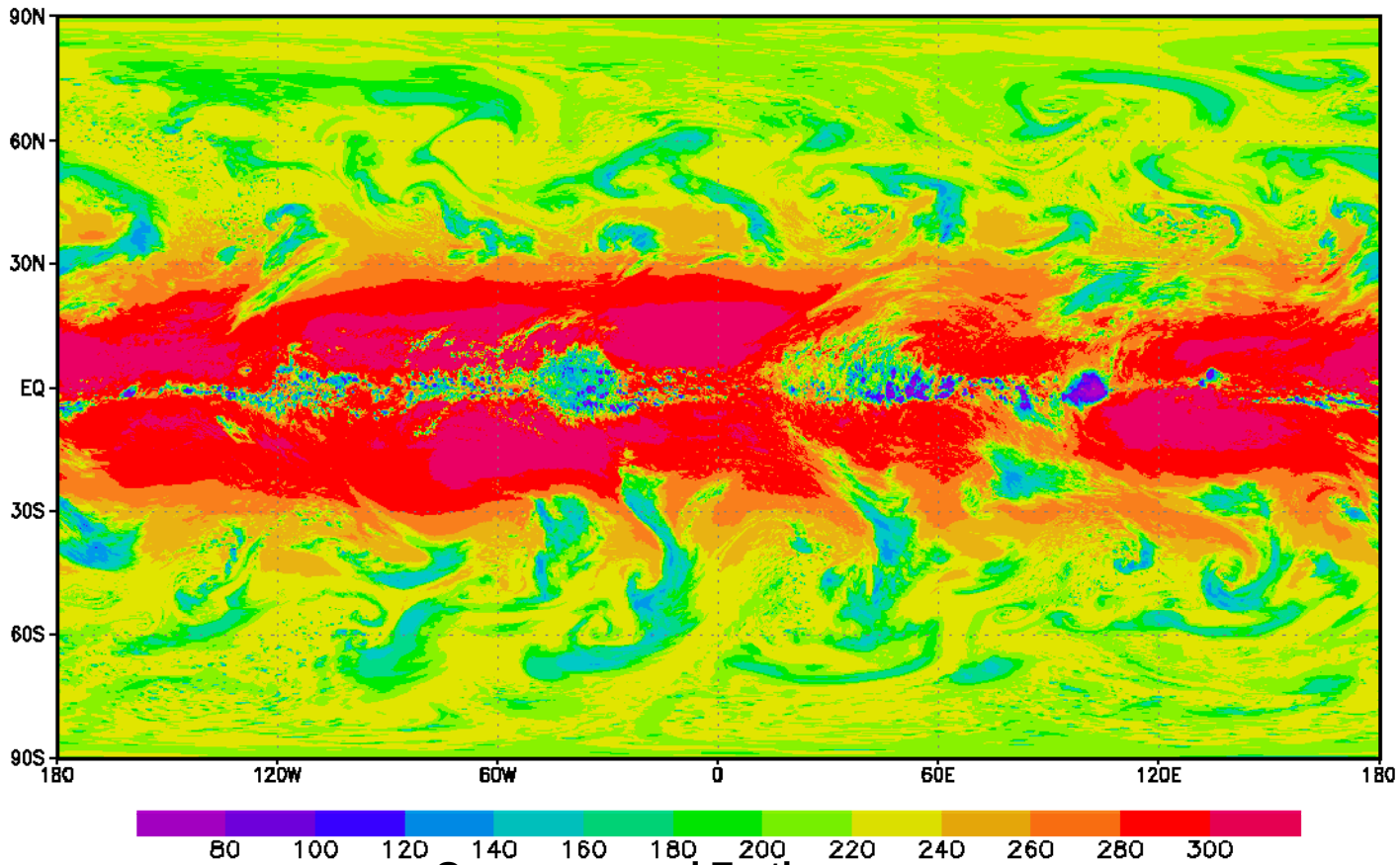
Jung 2006


Wavenumber (radians m⁻¹)
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻²
k⁻³
k⁻³
MERID-
IONAL
WIND
ZONAL
WIND
k⁻⁵/³
k⁻⁵/³
POTENTIAL
TEMPERATURE
(°K² m rad⁻¹)
Nastrom &
Gage,1985
Spectral Density (m³ m⁻²)
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
Wavelength (km)

Spectra of Total KE



Closest attempt to global cloud resolving model so far …

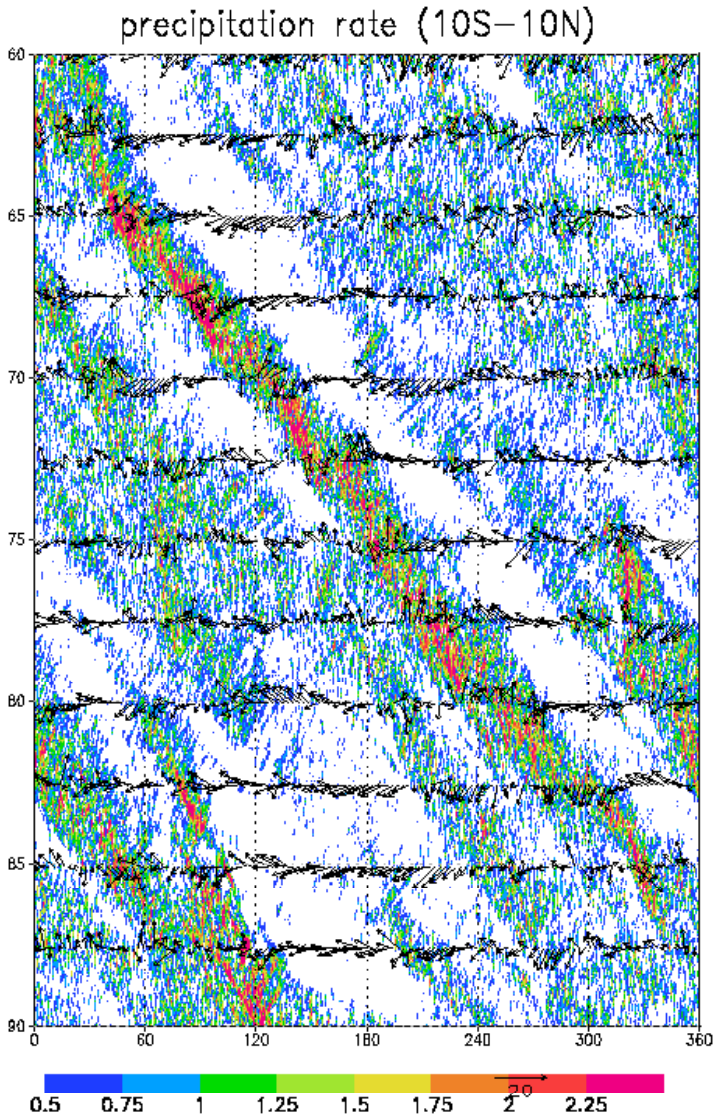


Running on Earth Simulator

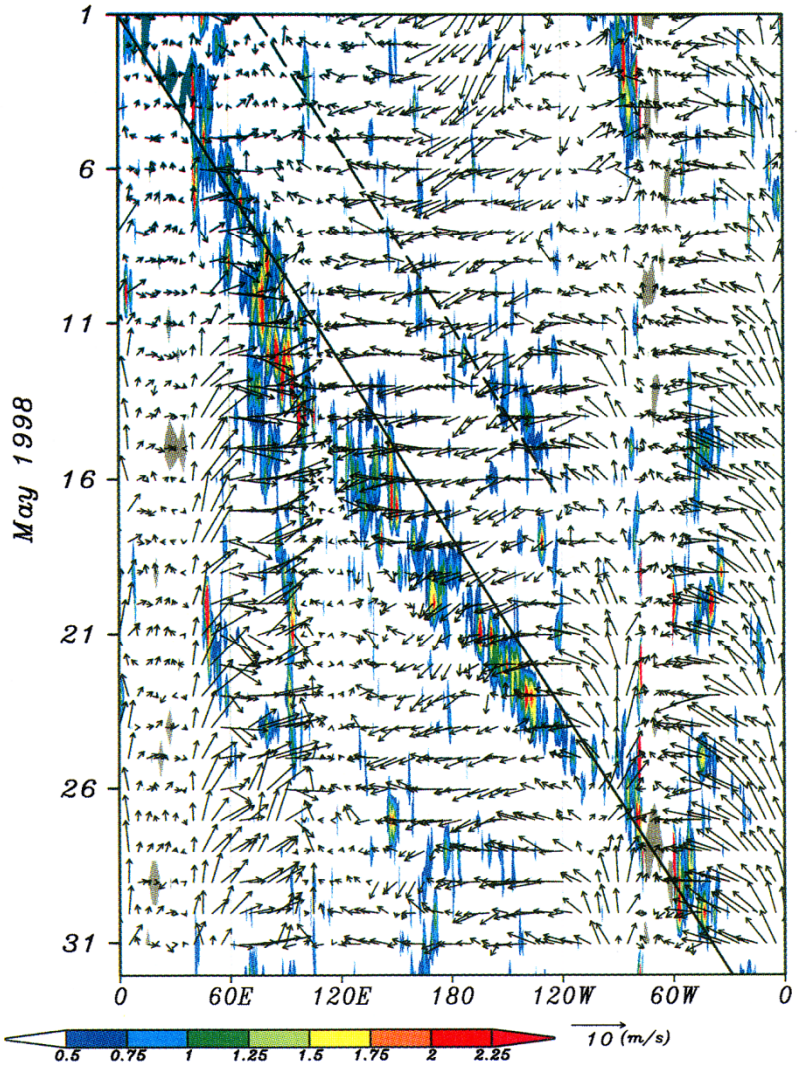
- **Ocean-covered Earth**
- **Geodesic grid**
- **3.5 km cell size, ~10^7 columns**
- **54 layers, top at 40 km**
- **15-second time step**
- **~ 1 TF-day per simulated day**

*Masaki Satoh, Hirofumi Tomita, Hiroaki Miura, Shinichi Iga and Tomoe Nasuno, 2005: J. Earth Simulator, **3**, 1-9.*

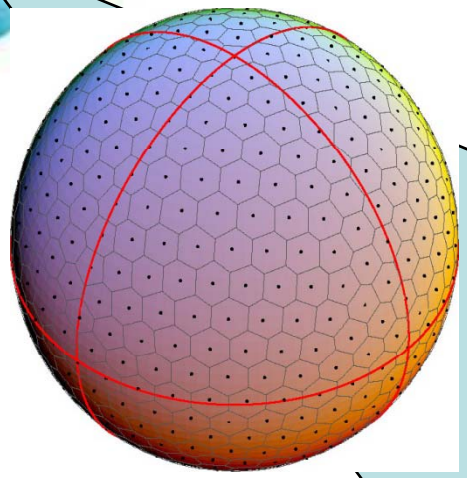
NICAM (7-km)

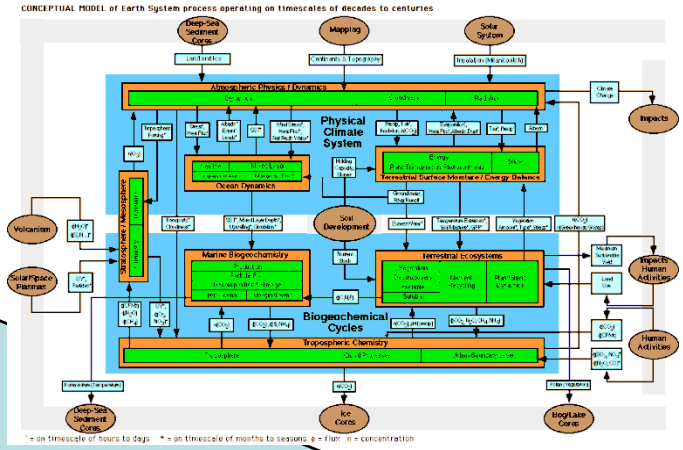


Obs. (Takayabu et al. 1999)



Matsuno (AMS, 2007)



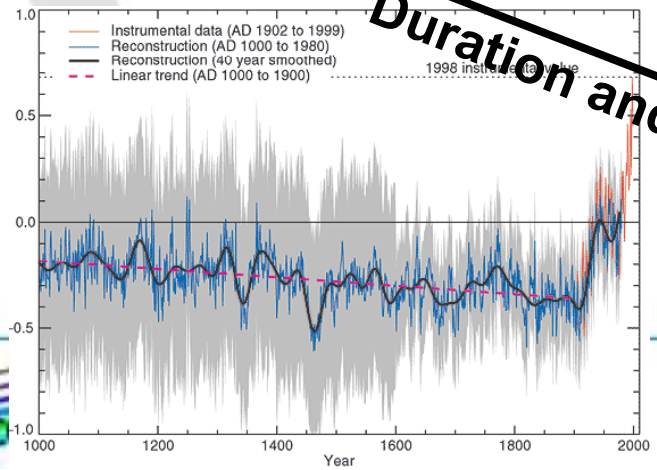


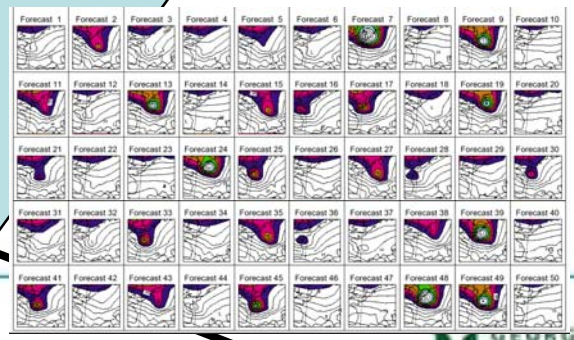
Computing Resources

Resolution

Complexity

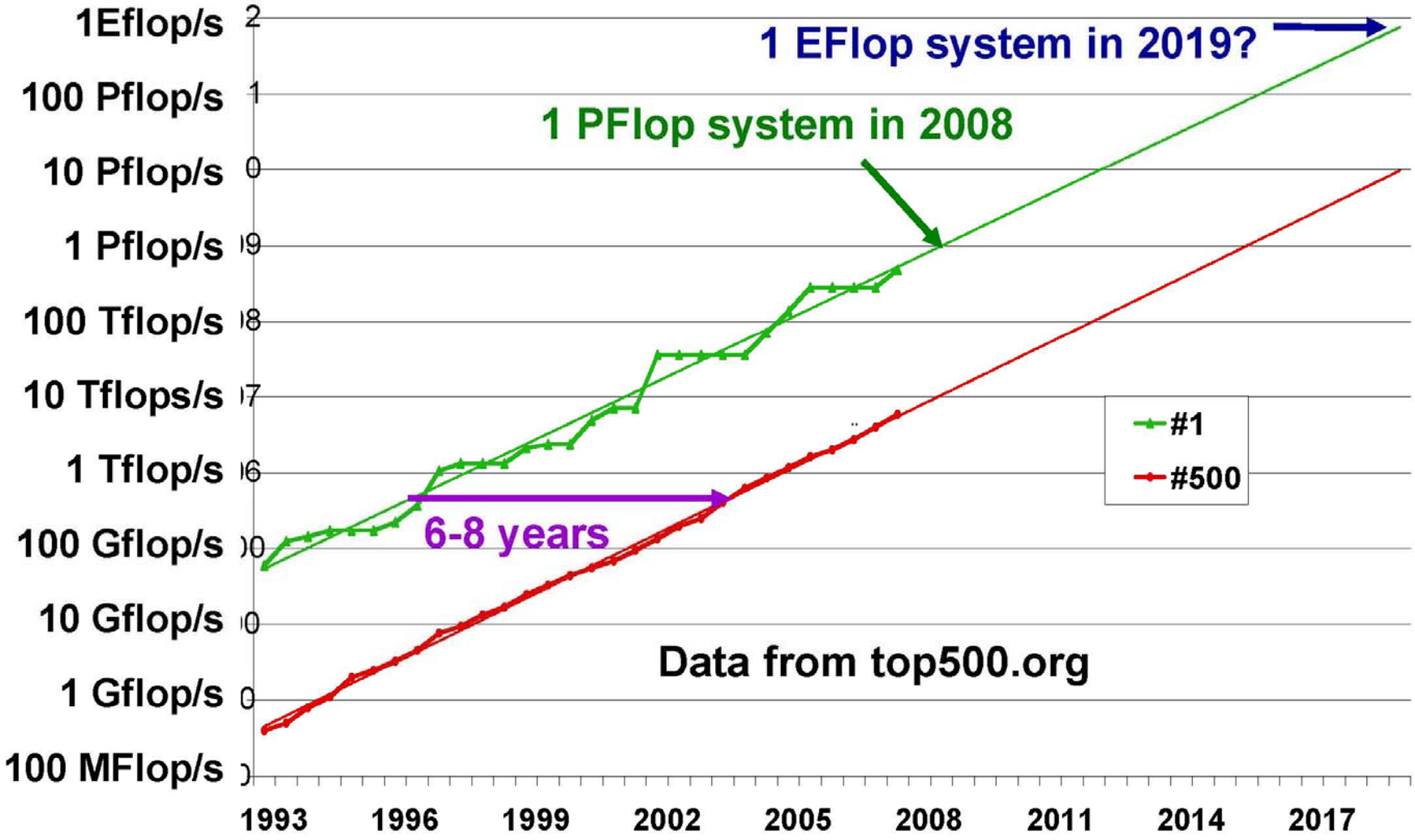
Duration and/or Ensemble size





GEORGE MASON UNIVERSITY

Petaflop with ~1M Cores by 2008



Slide source Horst Simon, LBNL

Computing Capability & Model Grid Size (~km)

Peak Rate:	10 TFLOPS	100 TFLOPS	1 PFLOPS	10 PFLOPS	100 PFLOPS
Cores	1,400 (2006)	12,000 (2008)	80-100,000 (2009)	300-800,000 (2011)	6,000,000? (20xx?)
Global NWP[0]: 5-10 days/hr	18 - 29	9 - 14	4 - 6	2 - 3	1 - 2
Seasonal[1]: 50-100 days/day	17 - 28	8 - 13	4 - 6	2 - 3	1 - 2
Decadal[1]: 5-10 yrs/day	57 - 91	27 - 42	12 - 20	6 - 9	3 - 4
Climate Change[2]: 20-50 yrs/day	120 - 200	57 - 91	27 - 42	12 - 20	6 - 9

Range: Assumed efficiency of 10-40%
0 - Atmospheric General Circulation Model (AGCM; 100 levels)
1 - Coupled Ocean-Atmosphere-Land Model (CGCM; ~ 2X AGCM computation with 100-level OGCM)
2 - Earth System Model (with biogeochemical cycles) (ESM; ~ 2X CGCM computation)

* Core counts above $O(10^4)$ are unprecedented for weather or climate codes, so the last 3 columns require getting 3 orders of magnitude in scalable parallelization (scalar processors assumed; vector processors would have lower processor counts)

Thanks to Jim Abeles (IBM)

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WMS takes place at ECMWF (6-9 May 2008). Nearly 150 participants from all modelling centers of the world.

They say they want a revolution

Climate scientists call for major new modelling facility.

Climatologists have called for massive investment in computer and research resources to help revolutionize modelling capabilities. The eventual aim is to provid predictions that are as weather forecasts.

At the end of a four-da at the European Centr Weather Forecasts in Rea made the case for a clim on the scale of the Hum key component of this cost something up to, lars, would be a world cl research facility with co

— to speeds in the hundreds of petaflops — would allow modellers to study simulations at the kilometre scale, enabling better predictions

Article in Nature, May 2008

Researchers from around the world gathered in Reading, UK, for the summit.

Summary of WMS
(summit declaration)

Summary of Summit Declaration

1. Most important requirement: Prediction of changes in the statistics of regional weather variations.

2. Models have serious problems and cannot provide information with accuracy required by society

3. "A revolution in climate prediction is necessary and possible." (one of the most important declarations of the summit)

4. Proposal to establish a Climate Prediction Project

5. Enhance national centers

6. Establish a small number of climate research facilities for decadal prediction.

Summary of Summit Declaration

7. Dedicated high-end computing facilities are required (at least a thousand times more powerful than the currently available computers)

8. More computing power will help to enhance resolution and include complexity (e.g. biogeochemical cycles).

9. Global observations and assimilations are needed for prediction project.

10. Better estimates of uncertainties in climate prediction.

11. Collaboration between weather and climate prediction research communities (Seamless prediction).

12. Encourage the participation of young generation of climate modelers

International Research and Computational Facility to Revolutionize Climate Prediction

- **There is a scientific basis for revolutionizing climate prediction**
- **The problem is beyond a person, a center, a nation …**
- **International collaboration is required**

International Research and Computational Facility to Revolutionize Climate Prediction

1. Computational Requirement:

- Sustained Capability of 2 Petaflops by 2011
- Sustained Capability of 10 Petaflops by 2015

Earth Simulator (sustained 7.5 Teraflops) takes 6 hours for 1 day forecast using 3.5 km global atmosphere model; ECMWF (sustained 2 Teraflops) takes 20 minutes for 10 day forecast using 24 km global model

2. Scientific Staff Requirement:

- Team of 200 scientists to develop next generation climate model
- Distributed team of 500 scientists (diagnostics, experiments)

A computing capability of sustained 2 Petaflops will enable 100 years of integration of coupled ocean-atmosphere model of 5 km resolution in 1 month of real time

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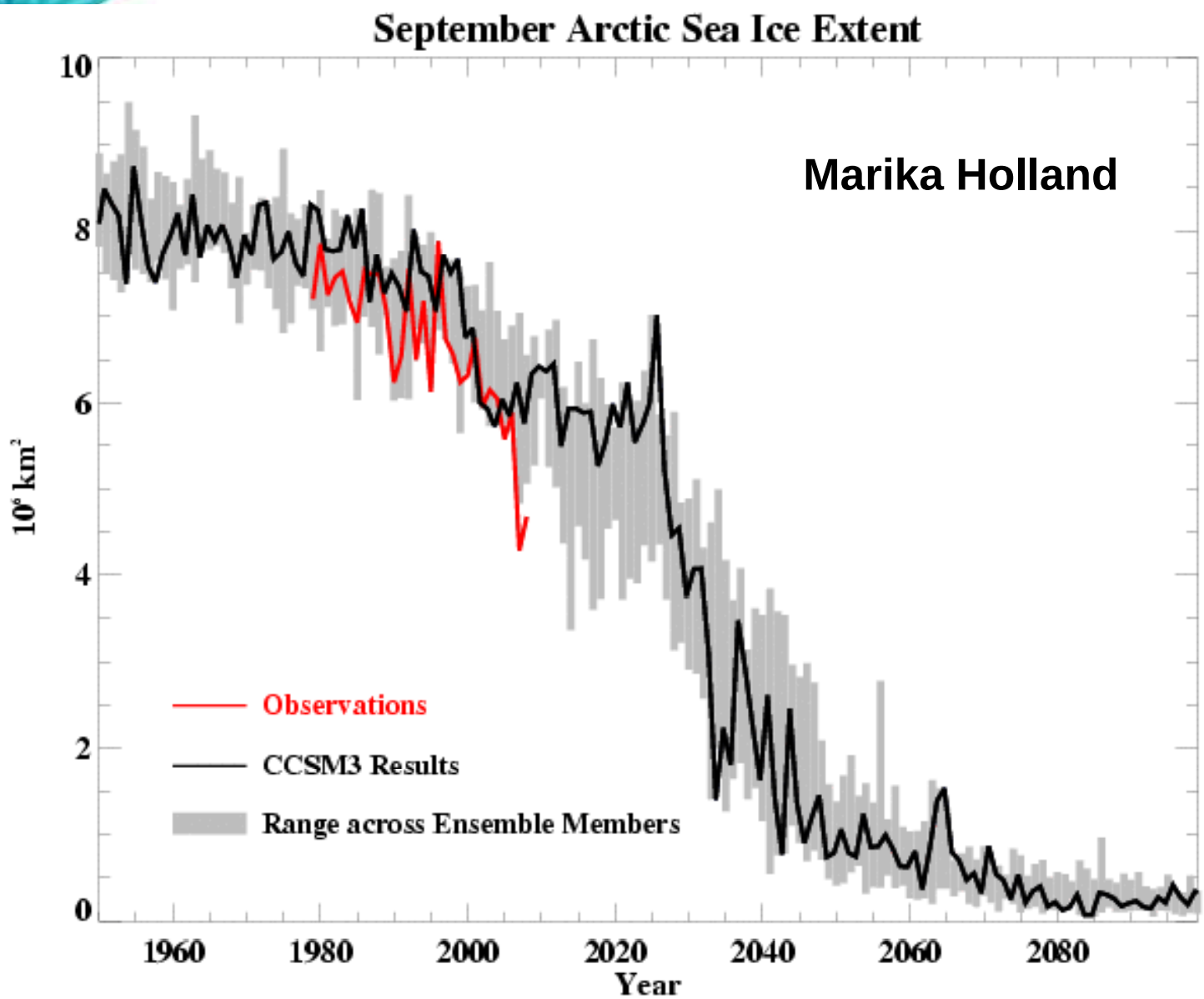
NSF/NCAR CCSM Project
Major Contributions

- **CSM1 1996 – first ever climate model to give a non-drifting control simulation without flux corrections.**

- **CCSM3 results published in special issue of J. Climate, June 2006, and in the Journal of High Performance Computing Applications in November 2005.**

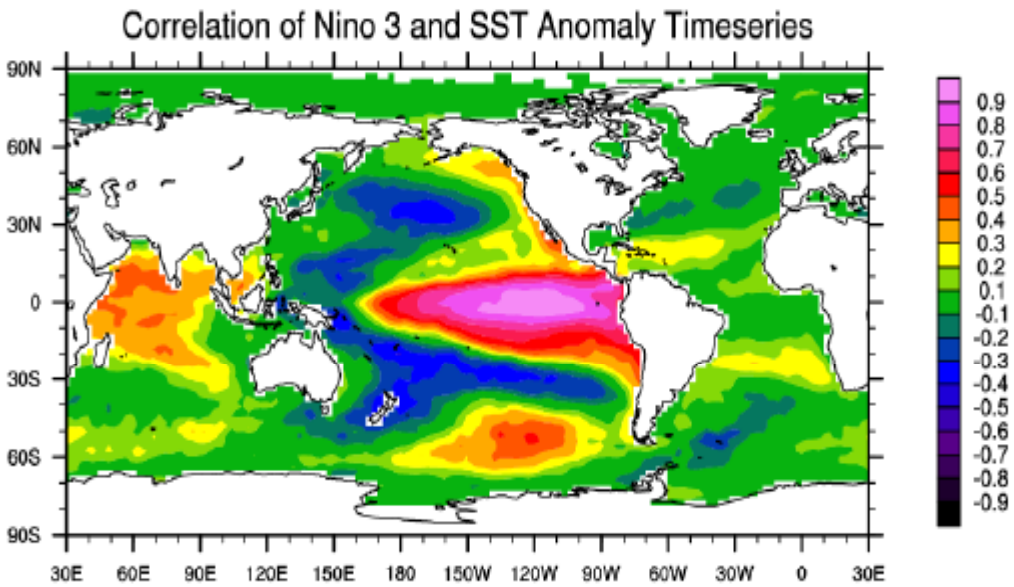
- **Arctic sea ice reductions from CCSM3 used to justify listing of the Polar Bear as 'Threatened' in May 2008.**

- **CCSM4 – much improved ENSO and much else. Expanded to earth system model by inclusion of carbon cycle, chemistry, whole atmosphere and land ice.**

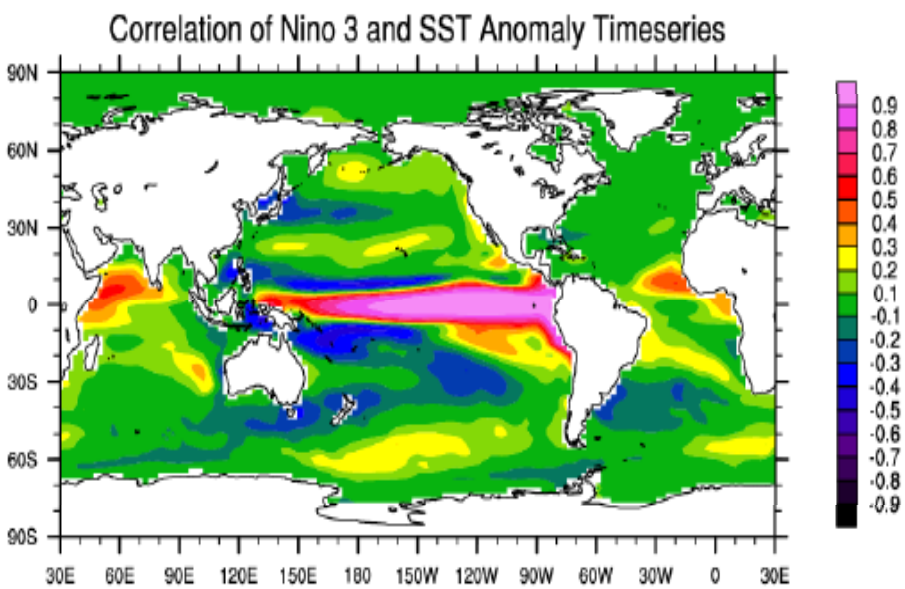


Center of Ocean-Land-Atmosphere studies

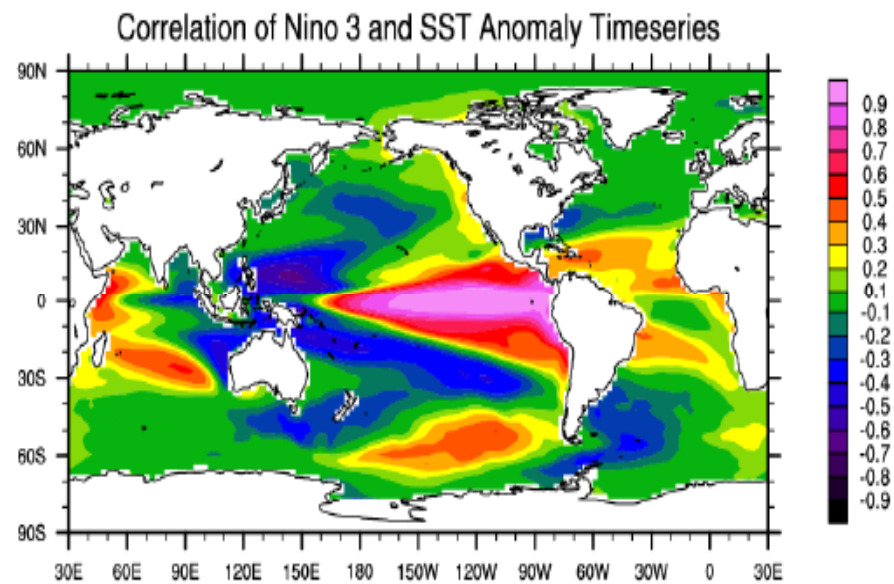
HadiSST Obs



Control



Neale+Richter



CCSM Project– Major Impediments

- CCSM budget has decreased from FY 03 to FY 09.
- Scientist and Programmer positions lost in that time.
- IPCC AR5 wants both new carbon cycle runs and decadal projections/predictions – not enough time to really thoroughly explore the new science in both.
- CCSM allocation on NCAR computer has increased by factor of nearly 20 from 2003 to 2009. Need expanded computer resources, but budget problem more severe.

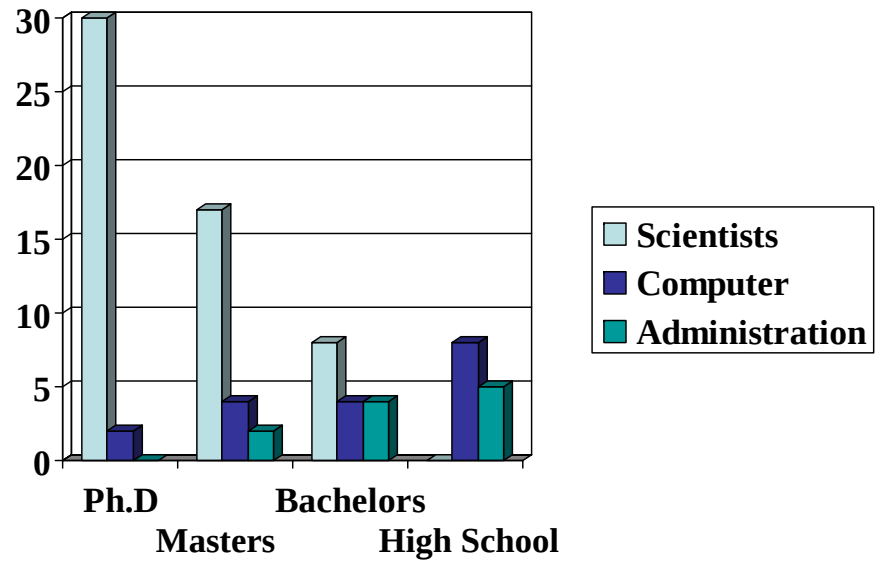
An Introduction to NOAA/ GFDL

Princeton University

Princeton, NJ

Staffing

Education by Functional Area for GFDL's 84 Permanent Govt. Staff

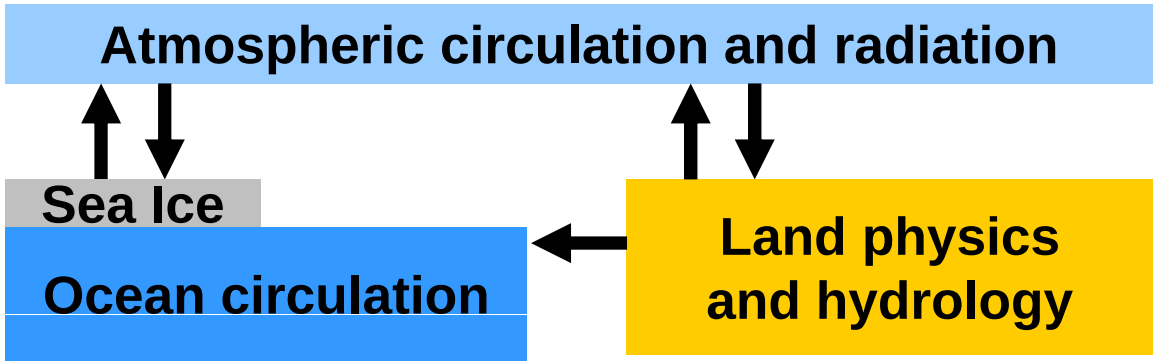


GFDL / Princeton University / UCAR / Contractors

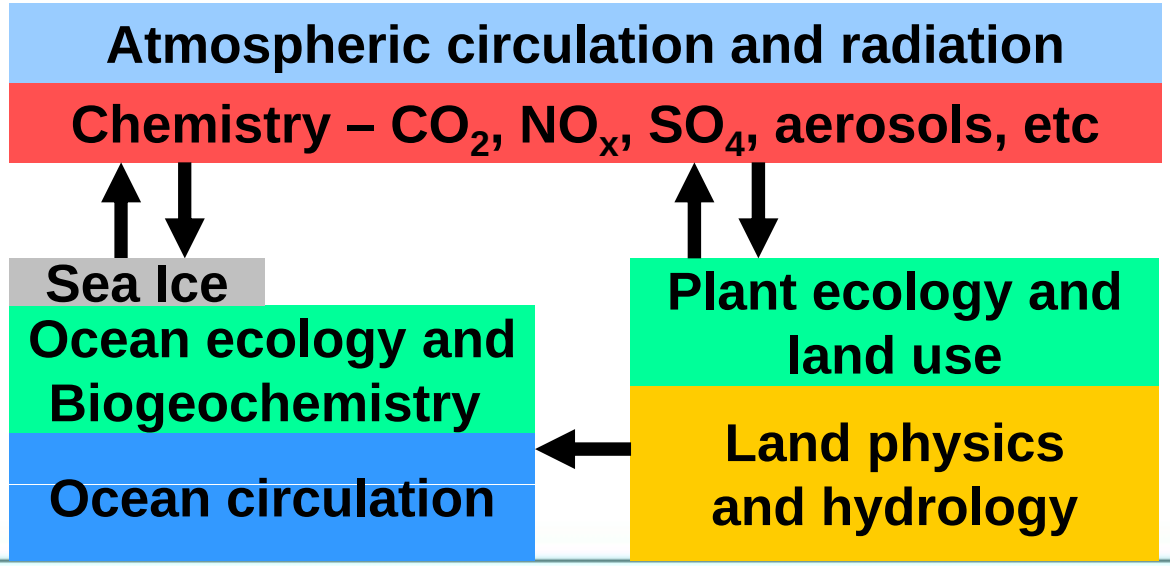
•Professors / Senior Staff	8
•Visiting Scientists / Postdocs	31
•Research Staff	54
•Graduate Students / Interns	14
•Administrative / Computer Staff	58
Total People Funded at GFDL	**165**

GFDL's models

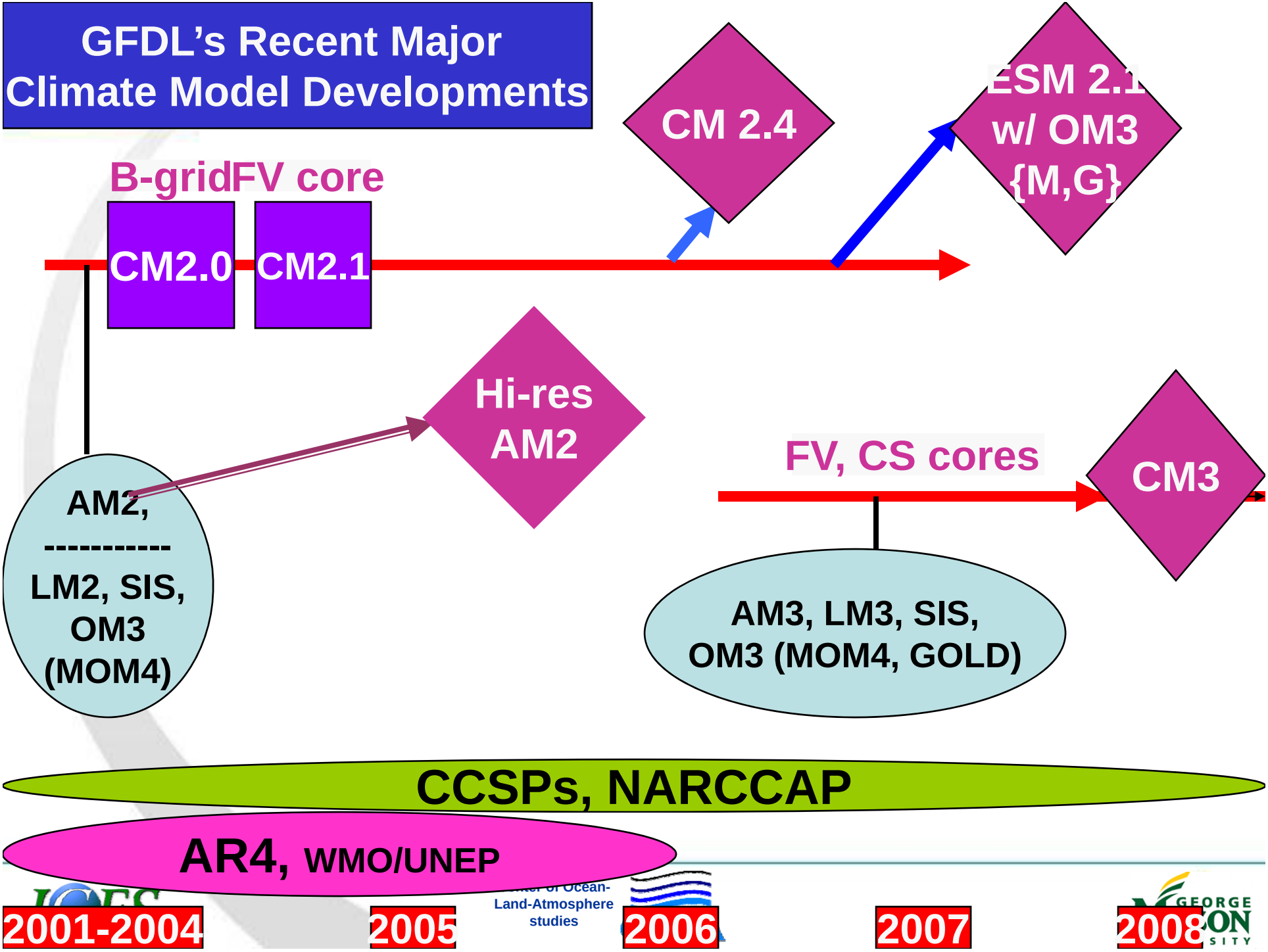
Climate Model



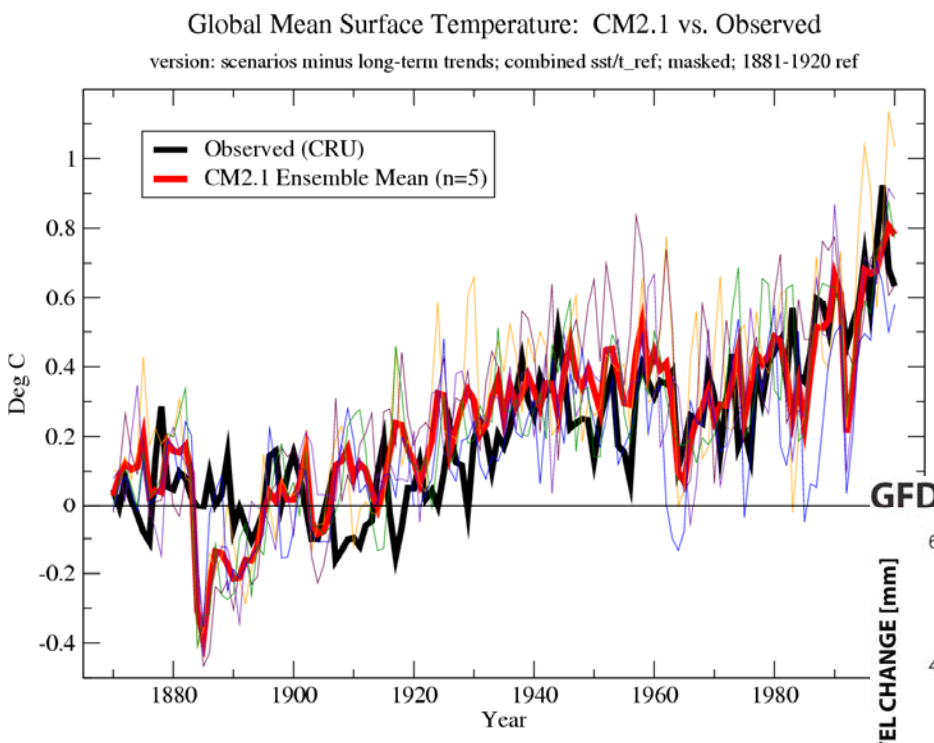
Earth System Model



GFDL's Recent Major Climate Model Developments



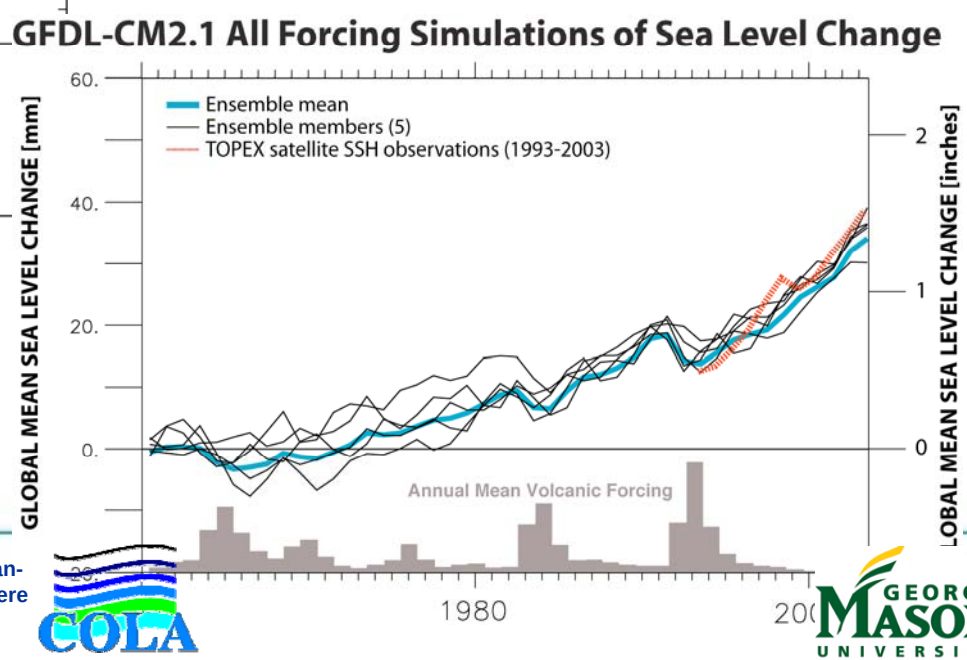
Modeling Metrics



<u>Performance in the ARCTIC</u>

"Based on the aggregate of the two sets of rankings, the top-performing models for Alaska are Geophysical Fluid Dynamics Laboratory Climate Model, version 2.1 (GFDL CM2.1) …. The top-performing models for Greenland are GFDL CM2.1 …."

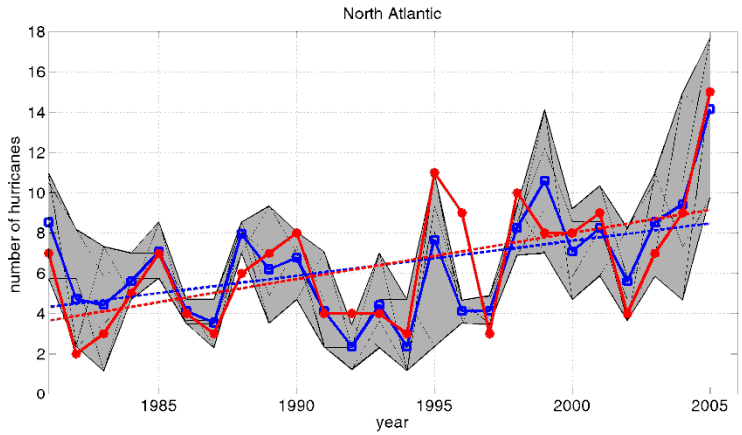
Walsh, J.E., et al., 2008: Global Climate Model Performance over Alaska and Greenland. *J. Climate*, 21, 6156–6174.

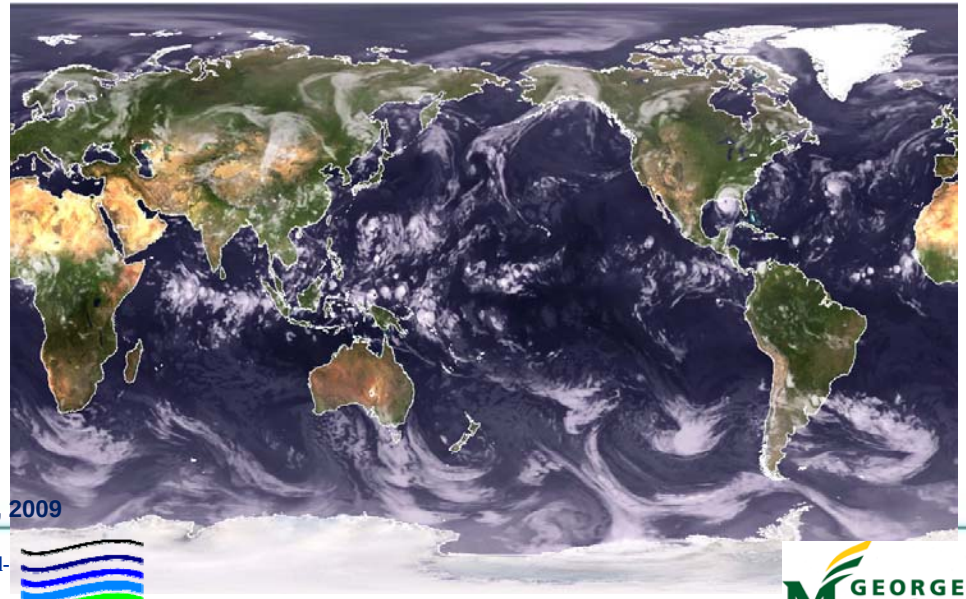


Center of Ocean-Land-Atmosphere studies

UNDERSTANDING AND PREDICTING SEASONAL HURRICANE ACTIVITY

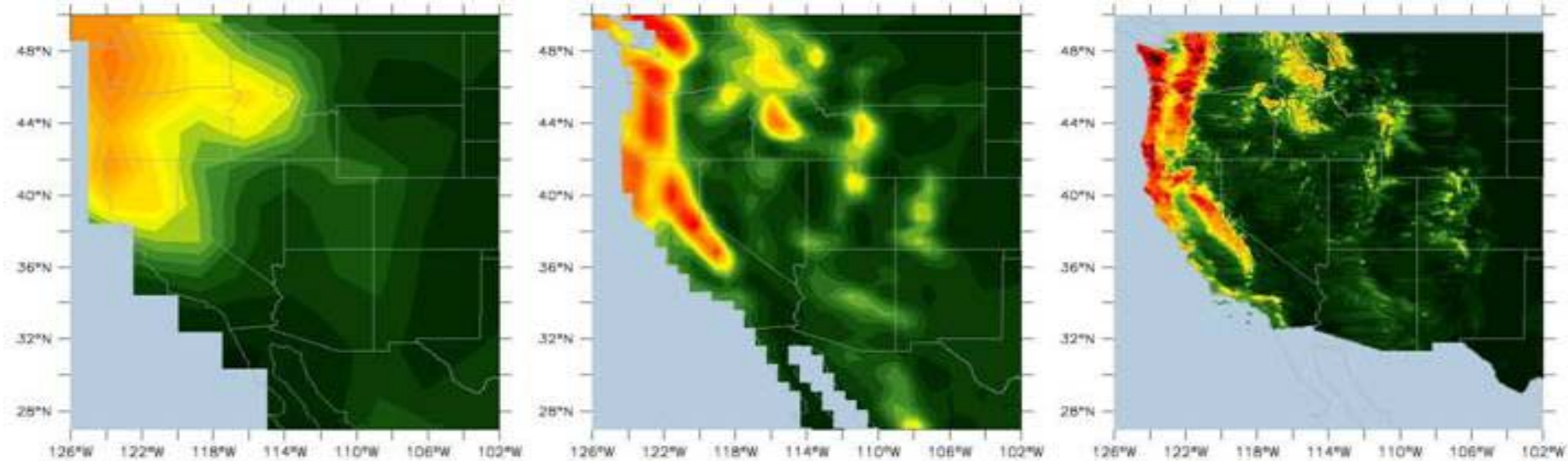
- NOAA/GFDL global atmospheric models are capable of simulating observed trends in tropical storms very well with only observed ocean temperatures as input
- These models can provide an estimate of the predictability of Atlantic storms
- The quality of the simulations suggest that these models are valuable for studying the effect of global warming on hurricane frequency





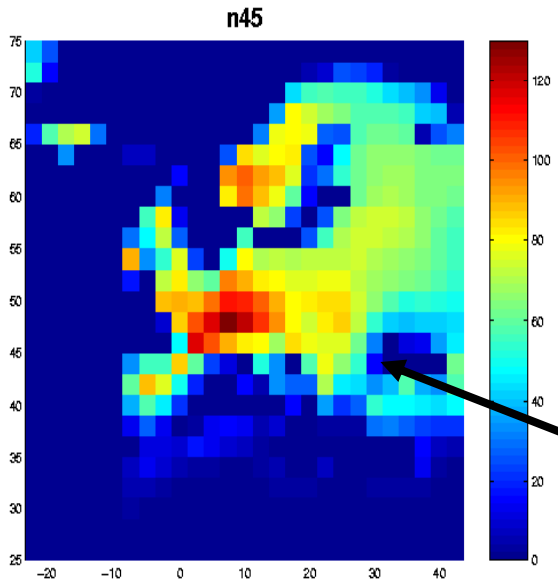
Center of Ocean-Land-Atmosphere studies

Winter mean precipitation in Western U.S. in 50km model

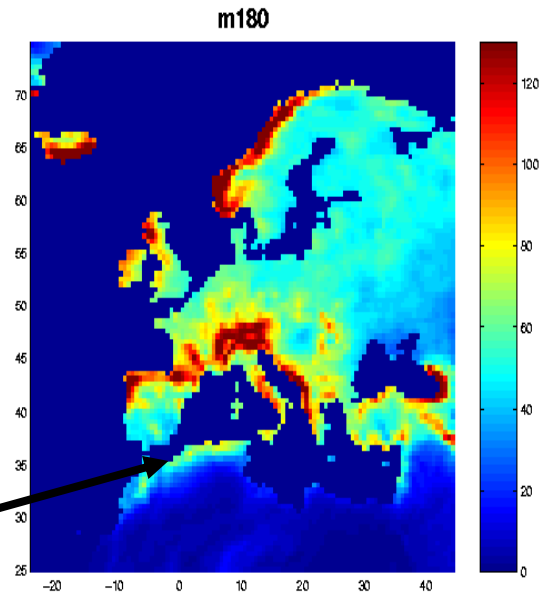


200 km res. **50 km res.** **Observations**

2 deg.



Annual mean precipitation in Europe
200km
50km



1/2 deg.

IGES

Center of Ocean-Land-Atmosphere studies

COLA

GEORGE MASON UNIVERSITY

- **Technical resources (Modeling Services and Technical Services): Staff ~15.**

- **Responsibilities:**
  - Model development and performance optimization
  - Runtime environment: configuration, running, post-processing and analysis on multiple sites
  - Data transfer, archival and publication
  - Hardware and software maintenance on NOAA-owned system.

Outline

1. WCRP - COPES - World Modeling Summit for Climate Prediction
2. Climate Models Have Serious Deficiencies
3. Model Fidelity versus Predictability
4. Resolution, Complexity, Computational Requirements
5. Summit Recommendation: Scientific and Computing Capacity
6. U.S. Climate Modeling
7. **How to Implement Summit Recommendation? (US; World)**
8. Recommendations/Suggestions

How to Implement a Seamless Prediction System in the midst of Several Pre-existing Separate, Independent National Centers for Weather, Climate, and Earth System Science?

US Climate Modeling Infrastructure and World Climate Computing Facility

- **The US has 4 major climate modeling groups**
  - GFDL, GISS, GSFC, NCAR (Three contribute to IPCC)
- **The US has 2 major data assimilations/reanalysis groups**
  - GSFC, NCEP (both in Washington, DC area)
- **The US has multiple small groups that utilize climate models**
  - COLA, CSU, FSU, IRI, MIT, UCLA, UH, UMCP….
- **The US has a large number of individual researchers (with students, post-doc's, etc.) utilizing climate models and/or model outputs for research- too many to list.**

→ How will the US participate in a World Climate Facility?

How to Implement a Seamless Prediction System in USA

1. Establish a multi-agency computational facility (10-100 Petaflops, 2011-2015) dedicated to climate research for running models with complexity/ resolution/ensemble size unaffordable at individual centers.

2. Create one new national (govt.; academia) "model development entity" consisting of current and new staff that builds a new generation of weather-climate-earth system models for assimilation and prediction. (NWP, DSP, IPCC, etc.)

How to Implement a Seamless Prediction System in the midst of Several Pre-existing Separate, Independent National Centers for Weather, Climate, and Earth System Science?

Outline

1. WCRP - COPES - World Modeling Summit for Climate Prediction
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8. **Recommendations/Suggestions**

International Research and Computational Facility to Revolutionize Climate Prediction

1. Computational Requirement:

- Sustained Capability of 2 Petaflops by 2011
- Sustained Capability of 10 Petaflops by 2015

Earth Simulator (sustained 7.5 Teraflops) takes 6 hours for 1 day forecast using 3.5 km global atmosphere model; ECMWF (sustained 2 Teraflops) takes 20 minutes for 10 day forecast using 24 km global model

2. Scientific Staff Requirement:

- Team of 200 scientists to develop next generation climate model
- Distributed team of 500 scientists (diagnostics, experiments)

A computing capability of sustained 2 Petaflops will enable 100 years of integration of coupled ocean-atmosphere model of 5 km resolution in 1 month of real time

International Research and Computational Facility to Revolutionize Climate Prediction

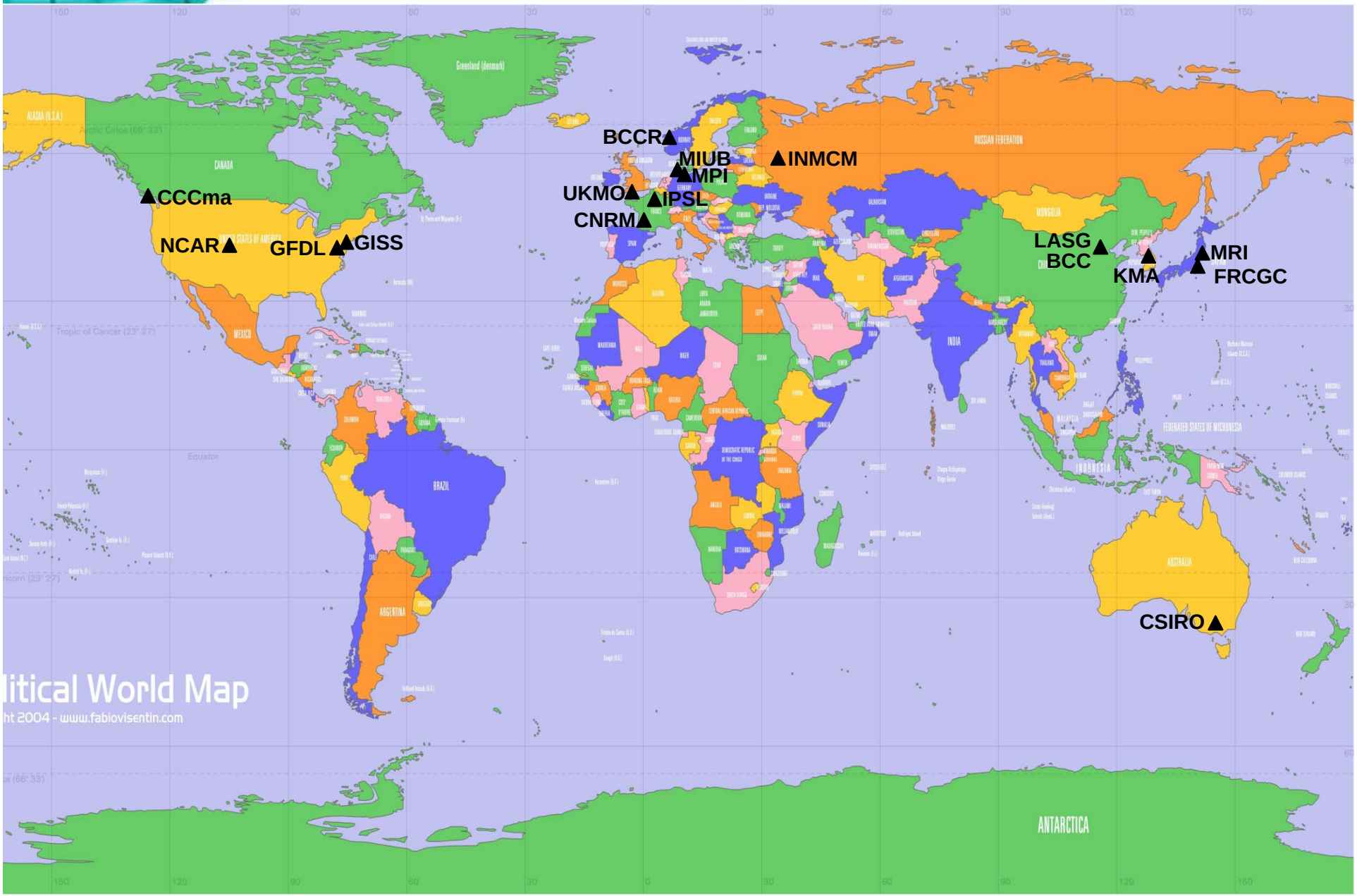
Examples of International Collaboration

- **CERN: European Organization for Nuclear Research**
  (Geneva, Switzerland)

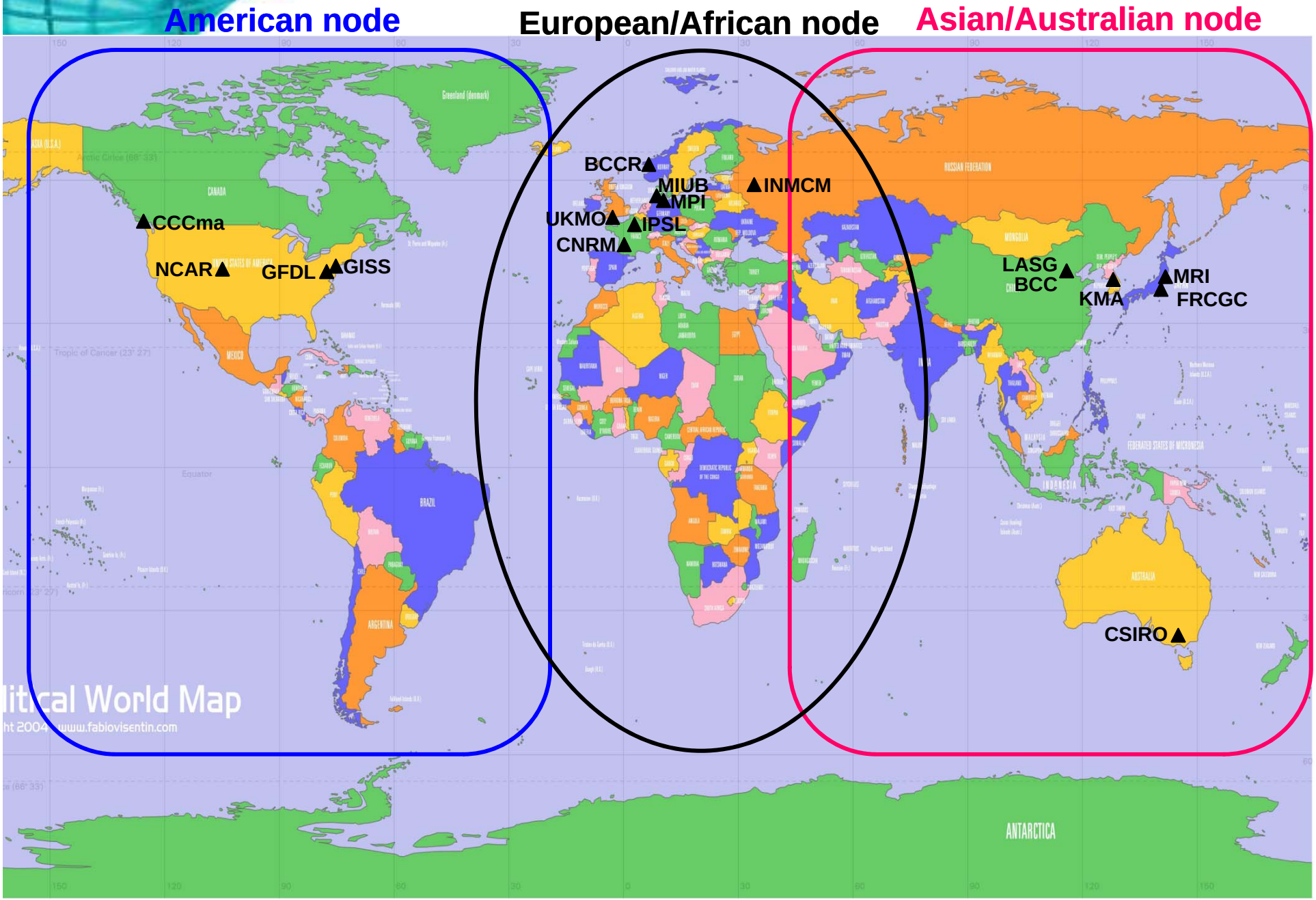
- **ITER: International Thermonuclear Experimental Reactor**
  (Gadarache, France)

- **ISS: International Space Station**
  (somewhere in sky..)

IPCC AR4 Climate Modeling Centers



Scientific/Political Domains of Climate Modeling Facilities



THANK YOU!