The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1956-7

Targeted Training Activity: Seasonal Predictability in Tropical Regions to be followed by Workshop on Multi-scale Predictions of the Asian and African Summer Monsoon

4 - 15 August 2008

Revolution in Climate Prediction is Both Necessary and Possible.

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Revolution in Climate Prediction is Both Necessary and Possible*

A Declaration at the World Modelling Summit for Climate Prediction

Jagadish Shukla

University Professor, George Mason University (GMU)

President, Institute of Global Environment and Society (IGES)

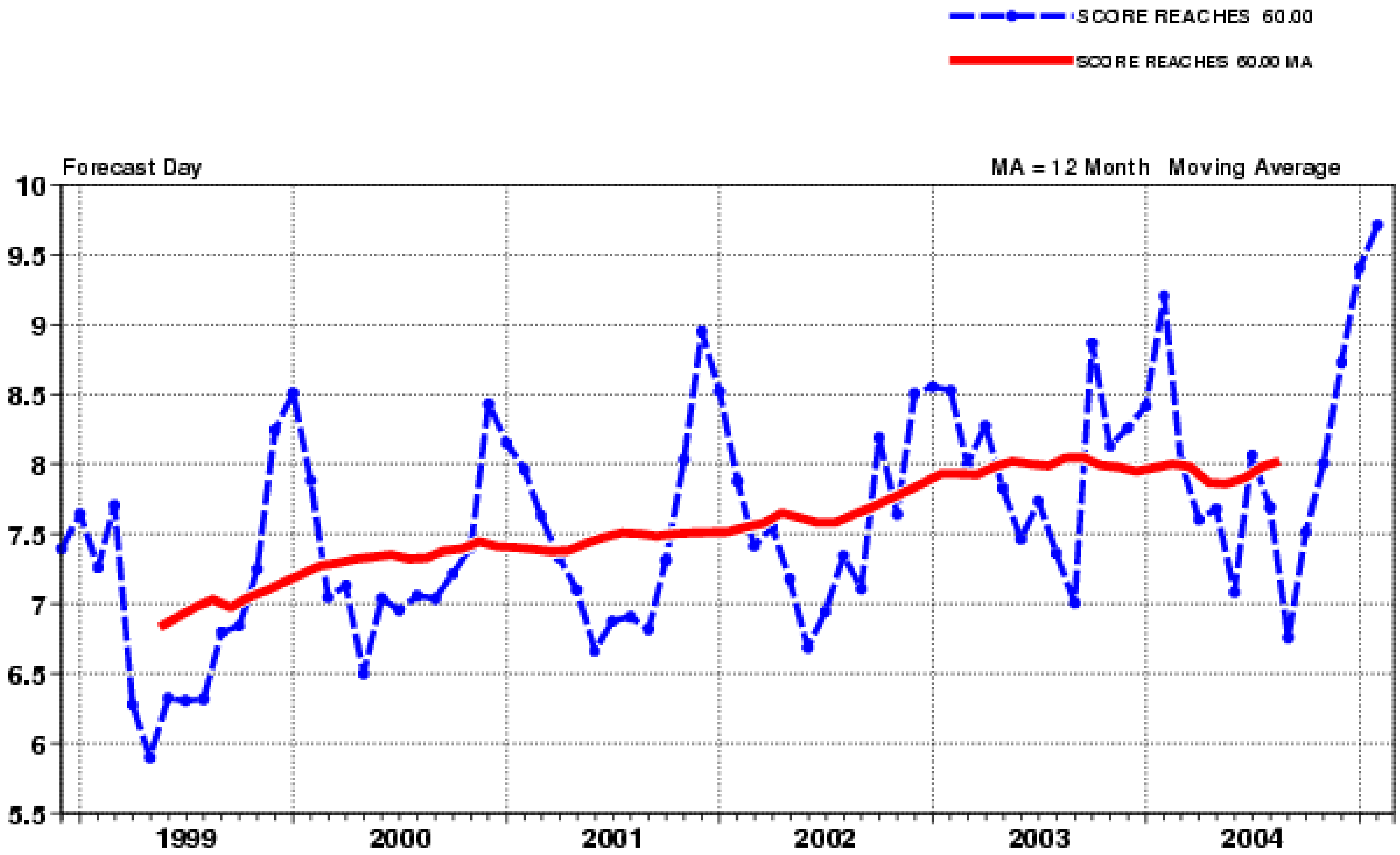
** Paper by Shukla, Hagedorn, Hoskins, Kinter, Marotzke, Miller, Palmer, and Slingo submitted in BAMS*

Outline

- Historical Overview
- Success of NWP during the past 30 years
- From Weather Prediction to Dynamical Seasonal Prediction
- Current Status of Dynamical Seasonal Prediction
- Model Deficiencies in Simulating the Present Climate
- Tropical Heating and ENSO Forced Response
- Model Fidelity and Prediction Skill
- Model Fidelity and Climate Sensitivity
- Factors Limiting Predictability: Future Challenges
  - ✓ Data Assimilation and Initialization
  - ✓ Biosphere, Cryosphere, Stratosphere Effects
  - ✓ Seasonal Prediction in a Changing Climate
  - ✓ Seamless Prediction of Weather and Climate
  - ✓ Computational Power
- Suggestions for the Future

ERA Forecast Verification

Anomaly Correlation of 500 hPa GPH, 20-90N



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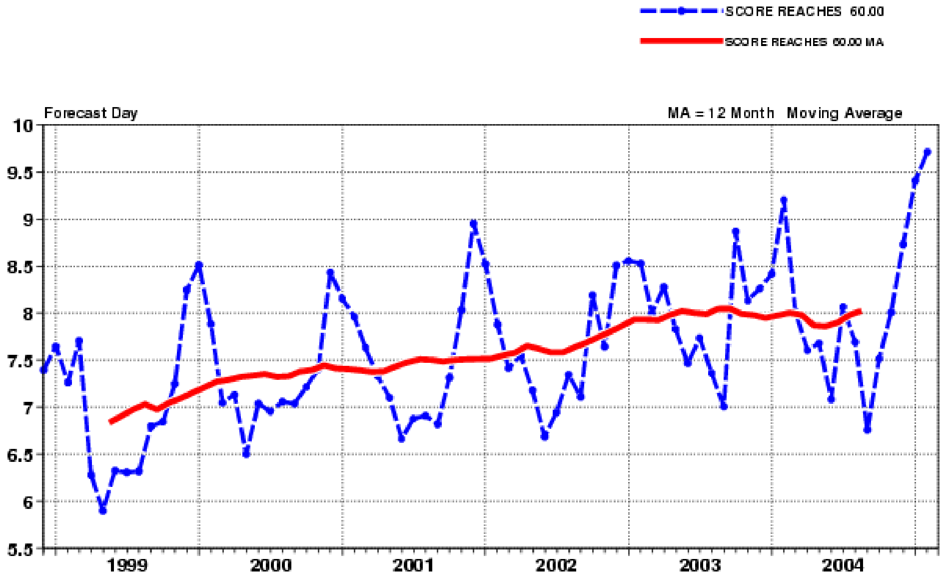


Growth of Random Errors in the simple model of Tropics and midlatitudes

Model 1: $X_{n+1} = X_n^2 - a$ (Tropics) $a = 1.98$

Model 2: $Y_{n+1} = 0.1Y_n^2 - 10b$ (Mid-latitude) $b = 1.60$

An ensemble of 10000 initial random errors was allowed to evolve for each model.

Empirical fit for Error growth

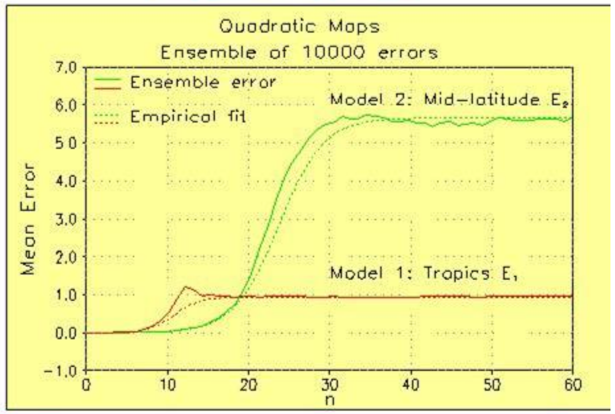
$$\frac{dE_1}{dt} = \lambda_1 E_1 - s_1 E_1^2$$

$$\frac{dE_2}{dt} = \lambda_2 E_2 - s_2 E_2^2$$

$$\lambda_1 > \lambda_2$$

$$\lambda_1 = 0.63$$

$$\lambda_2 = 0.37$$



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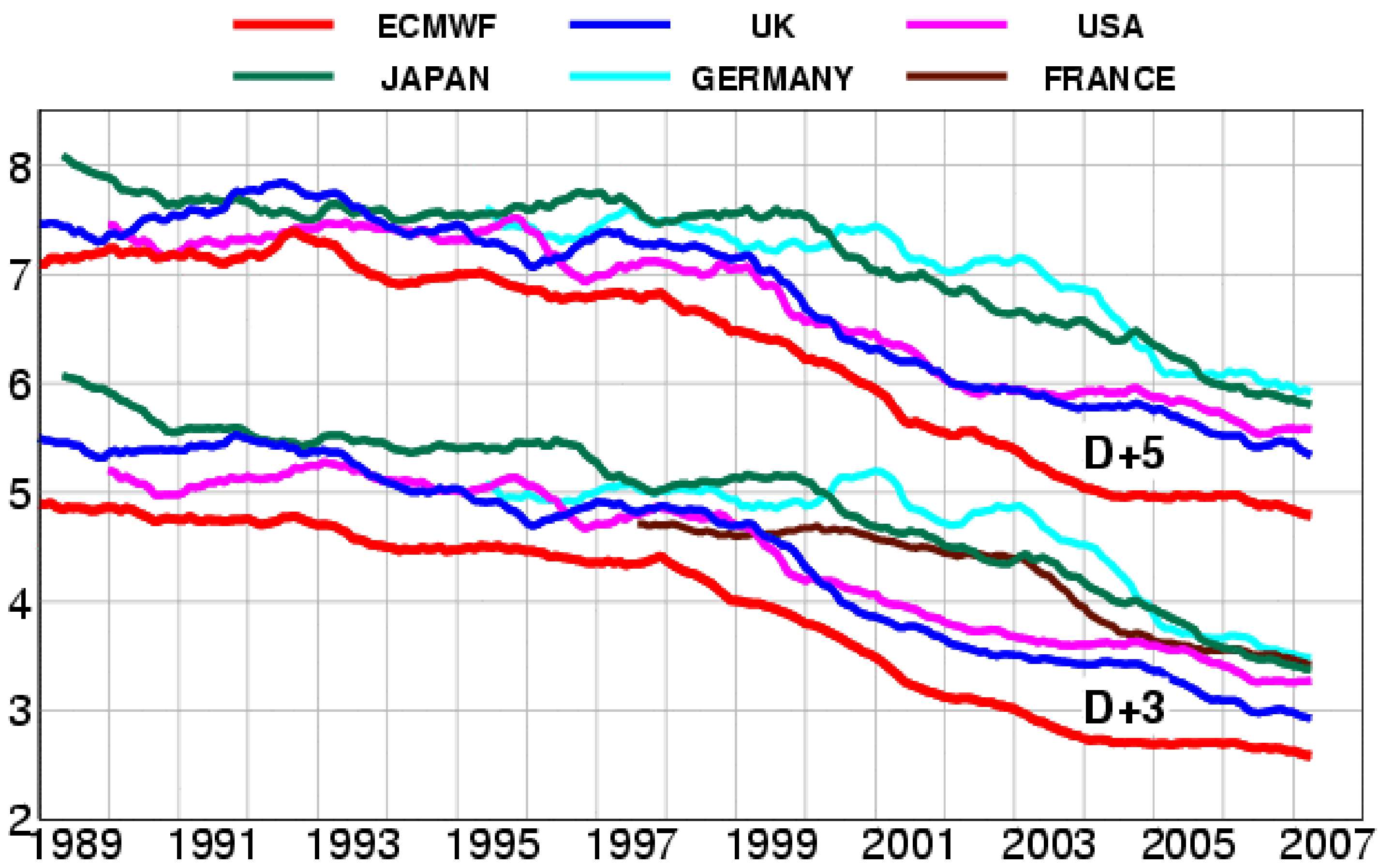
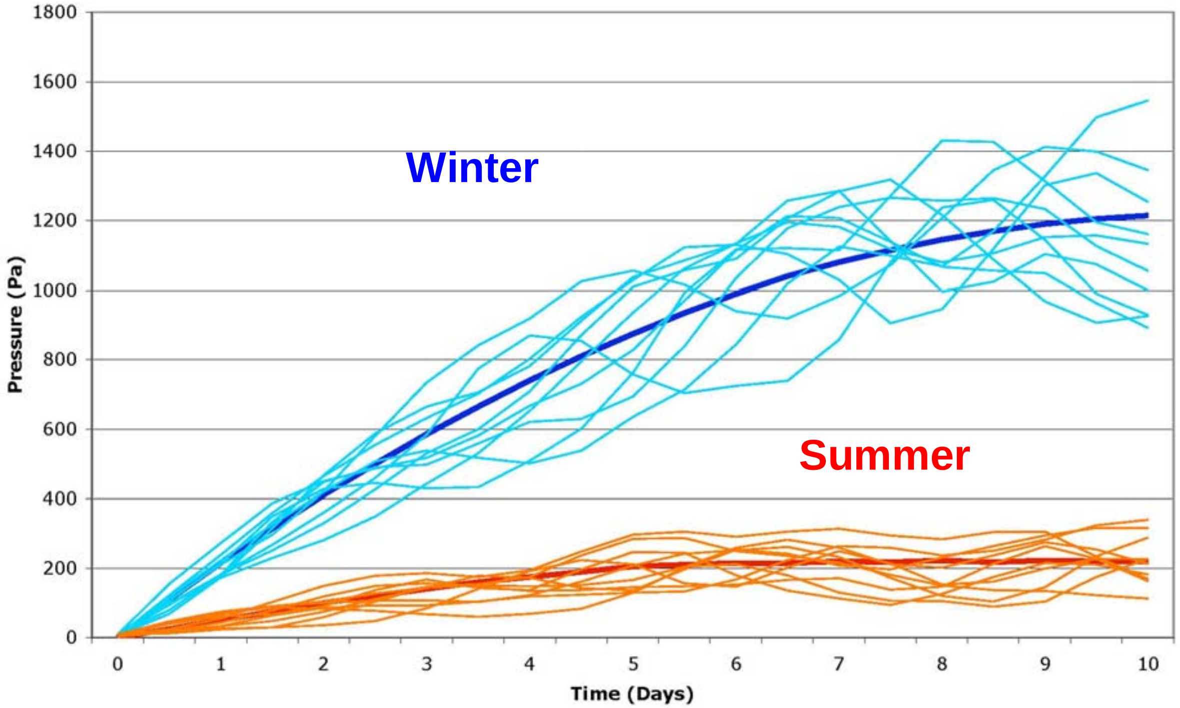
RMS Error (hPa) of Extratropical PMSL Forecasts for 3 and 5 days shade



(Thanks to ECMWF!)

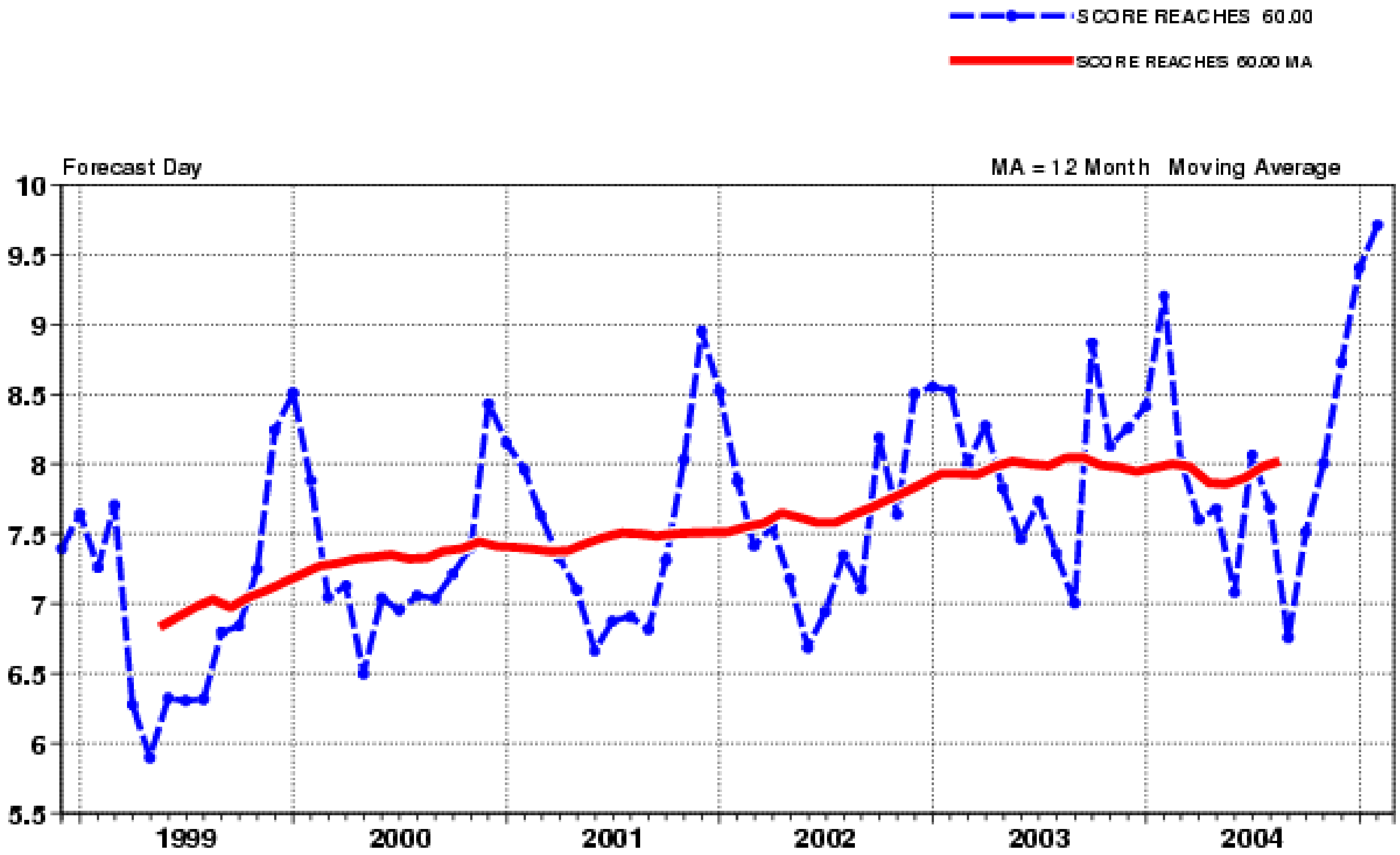
Schematic Error Growth for the Winter (Red) & Summer (Blue)



Schematic diagram illustrating the error growth in summer (red) and winter (blue). The thick lines in both panels depict the rates at which initially different states reach the boundary-forced state. The thin lines show typical spread of forecasts initialized with slightly perturbed initial conditions on day 0.

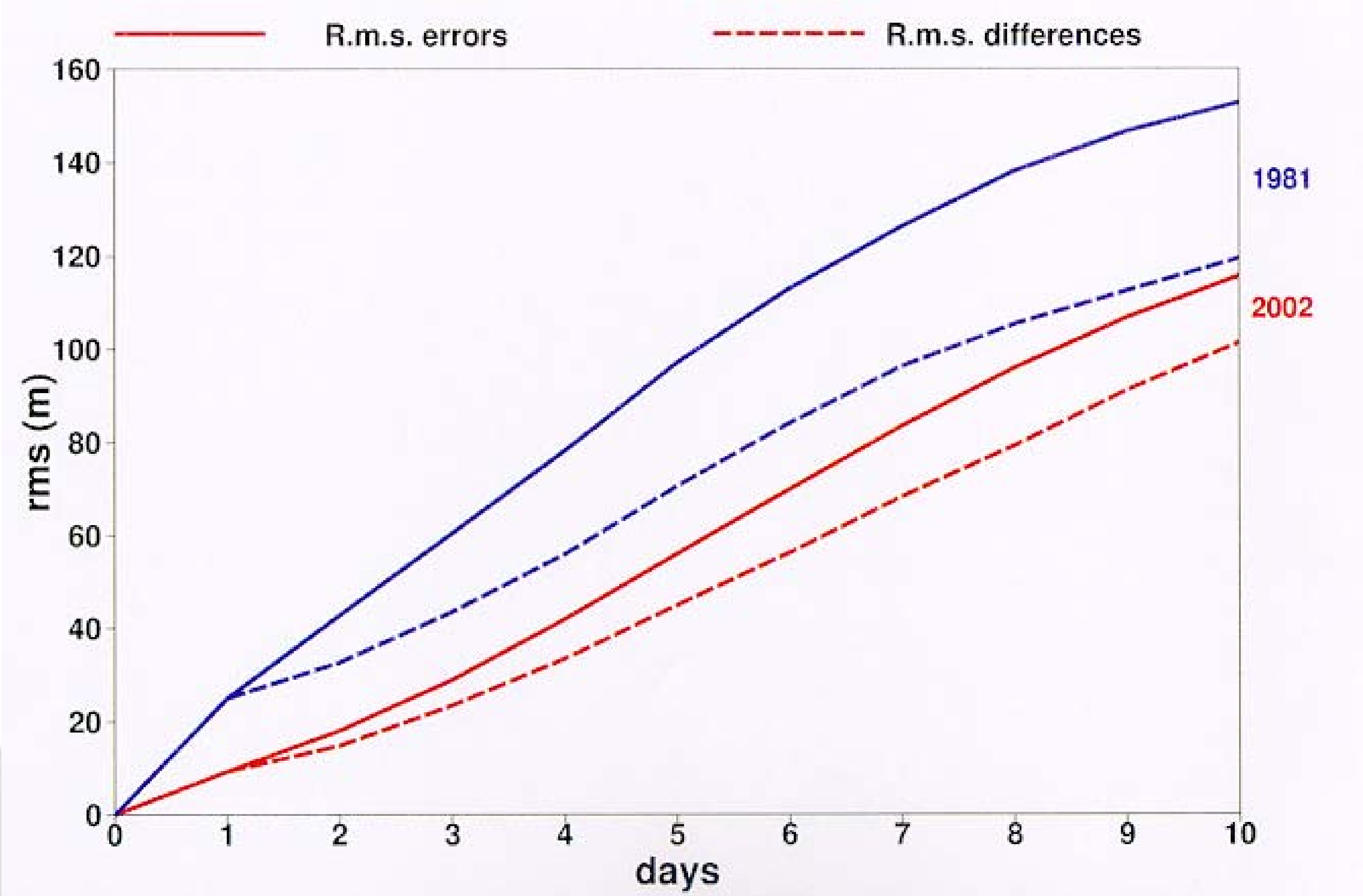
ERA Forecast Verification

Anomaly Correlation of 500 hPa GPH, 20-90N



RMS Error and Differences between Successive Forecasts

Northern Hemisphere 500 hPa Height in Winter



Current Limits of Predictability, A. Hollingsworth, Savannah, Feb 2003

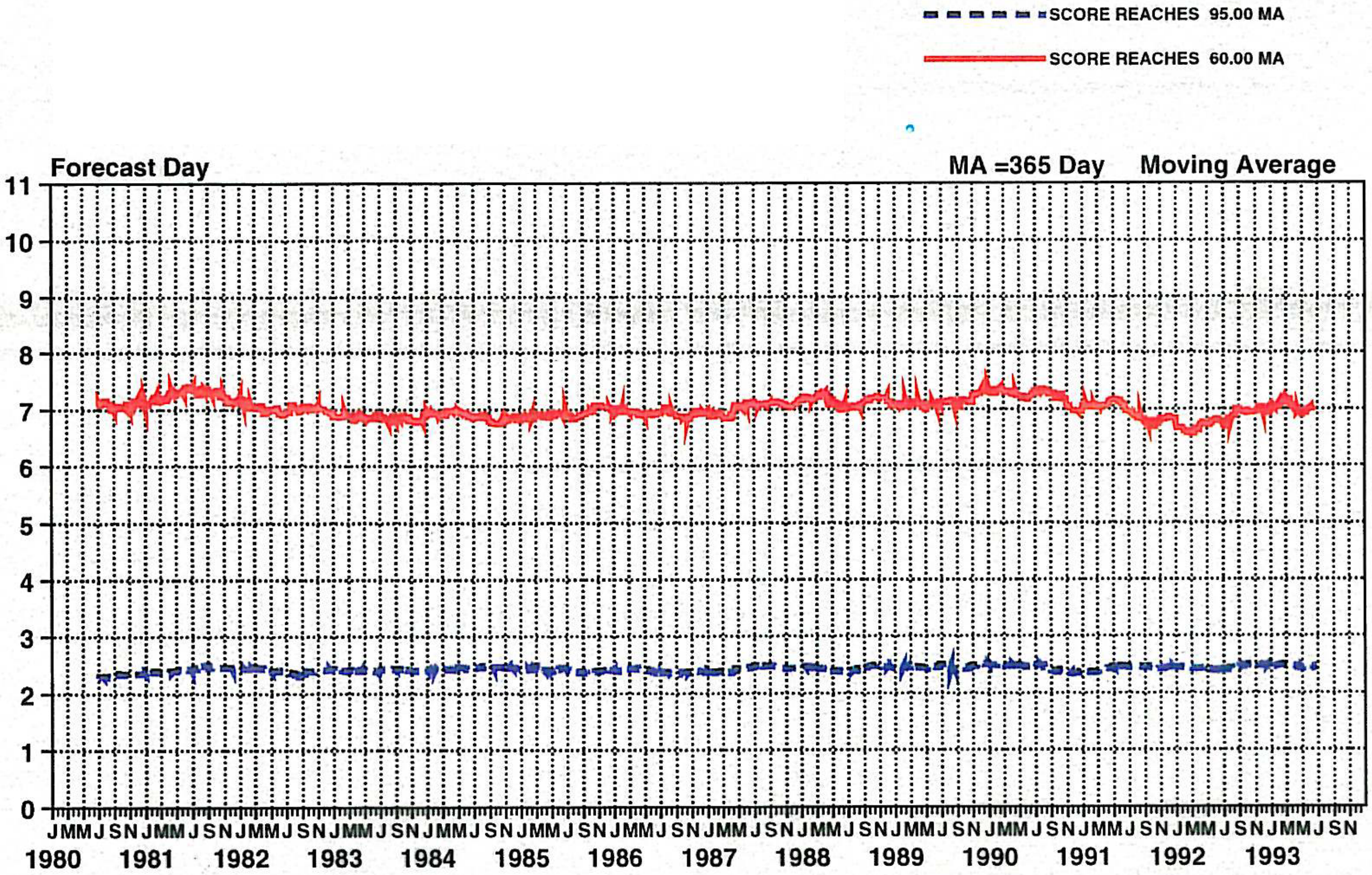
Evolution of 1-Day Forecast Error, Lorenz Error Growth, and Forecast Skill for ECMWF Model

(500 hPa NH Winter)

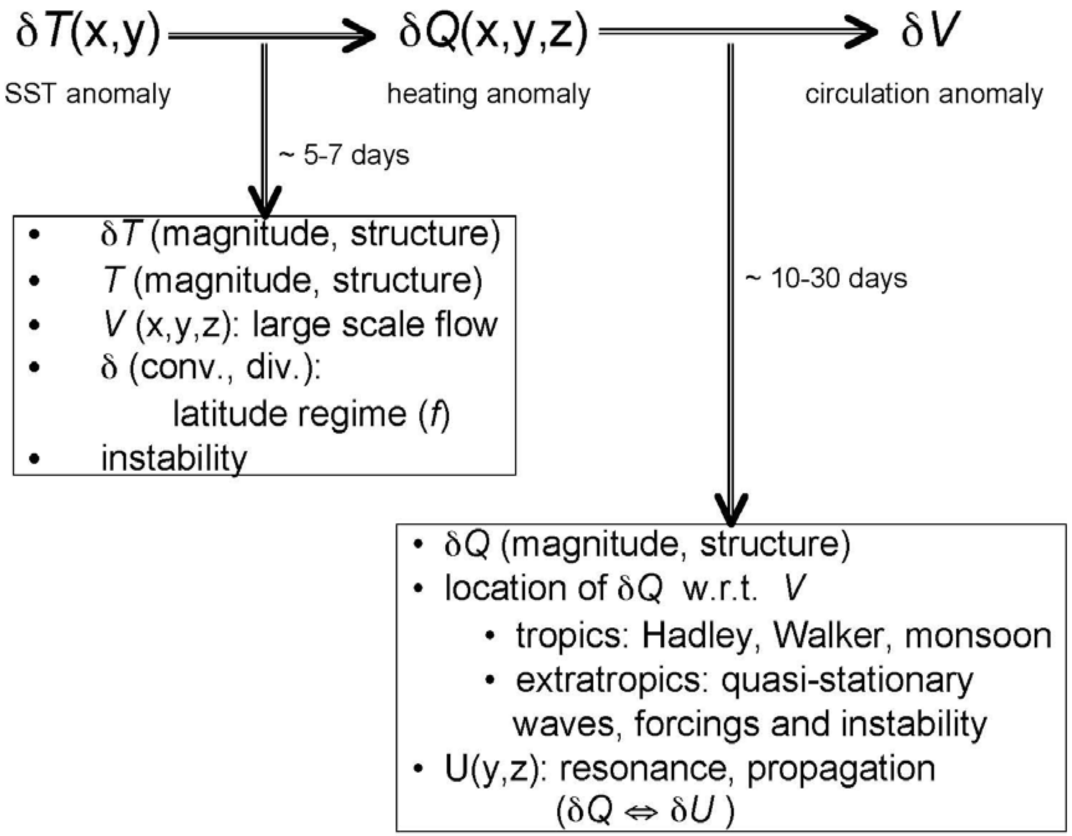
	1982	1987	1992	1997	2002
"Initial error" (1-day forecast error) [m]	20	15	14	14	8
Doubling time [days]	1.9	1.6	1.5	1.5	1.2
Forecast skill [day 5 ACC]	0.65	0.72	0.75	0.78	0.84

ERA Forecast Verification

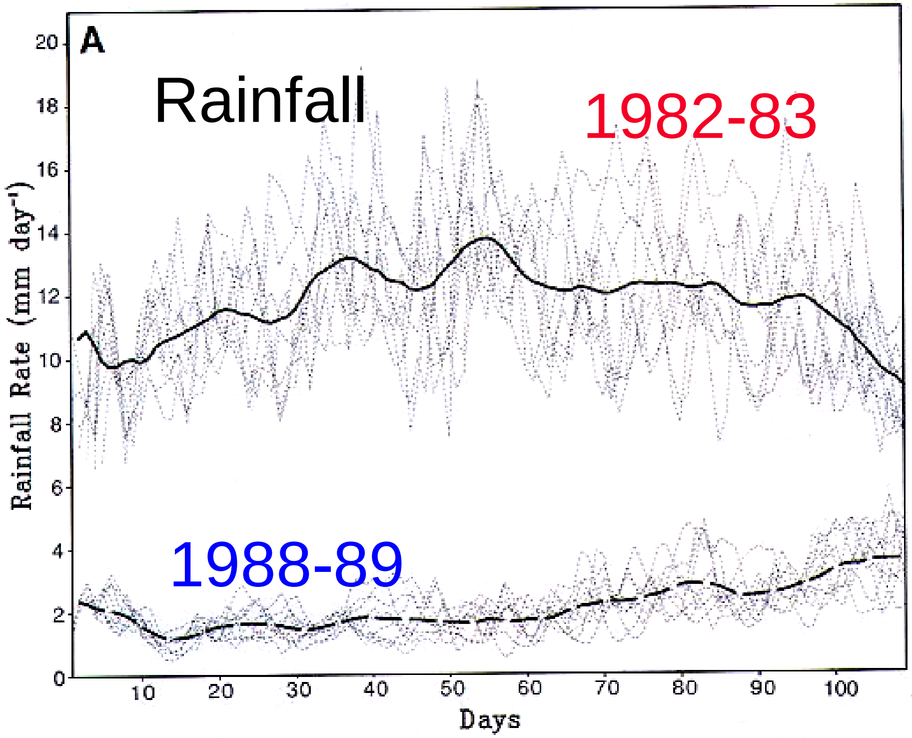
Anomaly Correlation of 500 hPa GPH, 20-90N

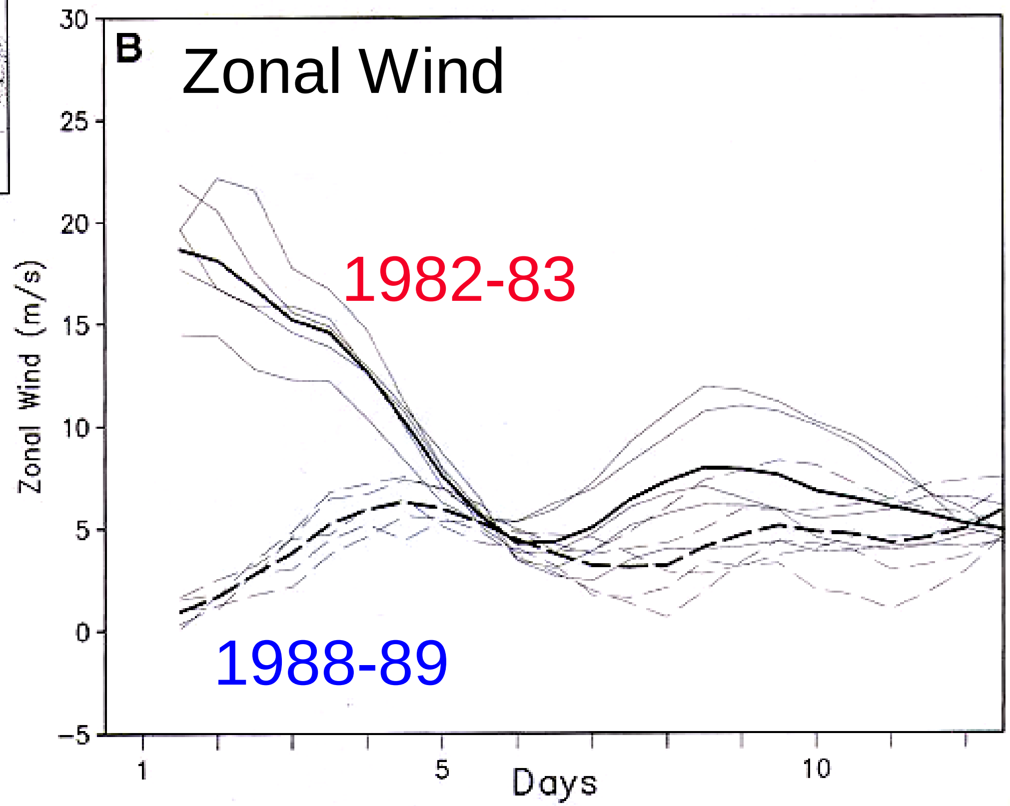


Effects of SST Anomaly



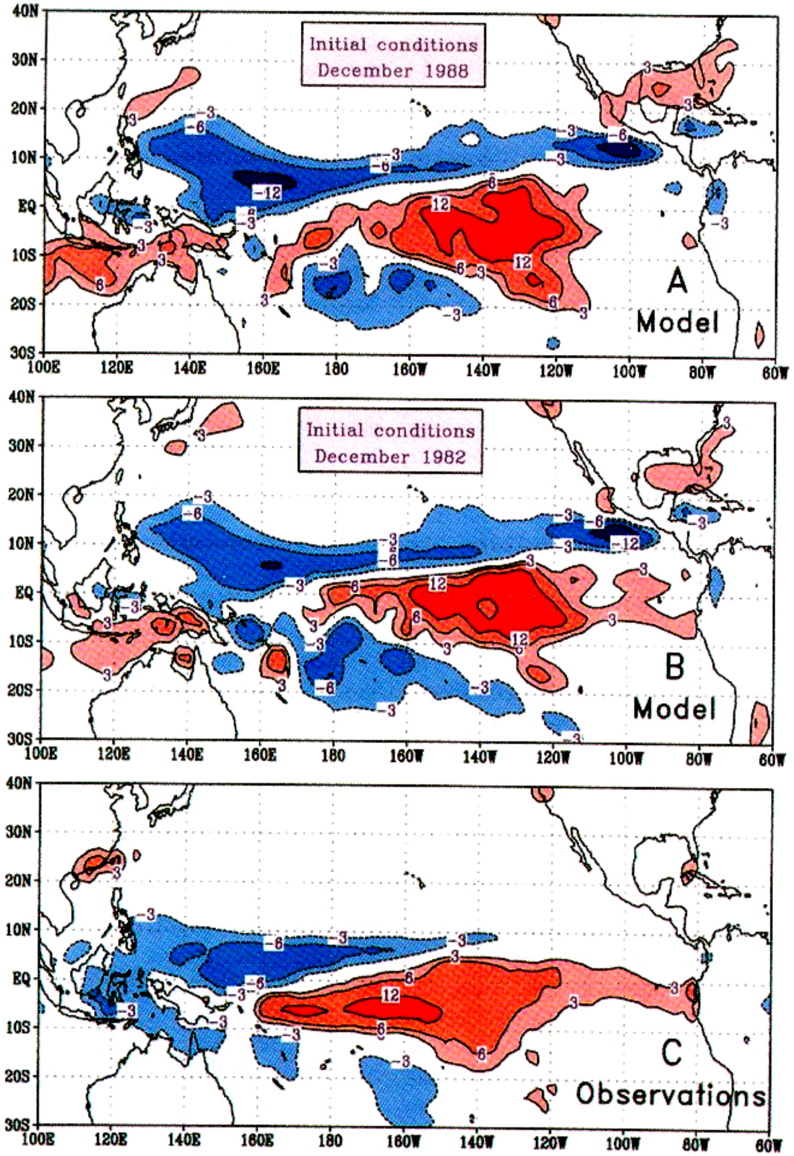
1. $\delta Q \Rightarrow \delta(\text{Hadley}) \Rightarrow \delta U \Rightarrow \delta$ (extratrop. stat. waves)
2. Forced Rossby waves
3. Normal modes





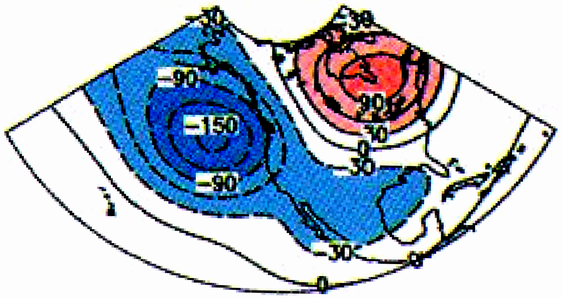
The atmosphere is so strongly forced by the underlying ocean that integrations with fairly large differences in the atmospheric initial conditions converge, when forced by the same SST (Shukla, 1982).

Rainfall Anomalies

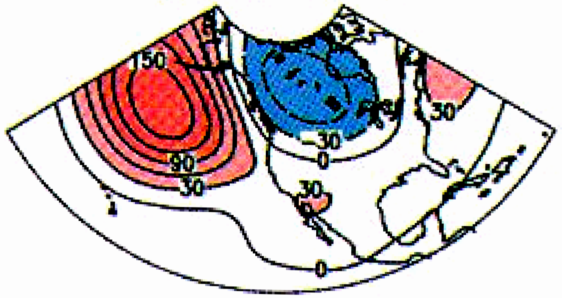


IC: 12/89

Observed SST JFM83



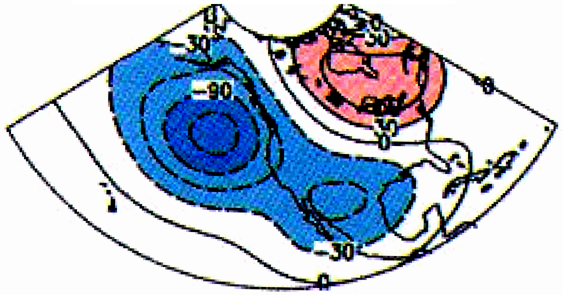
Observed SST JFM89



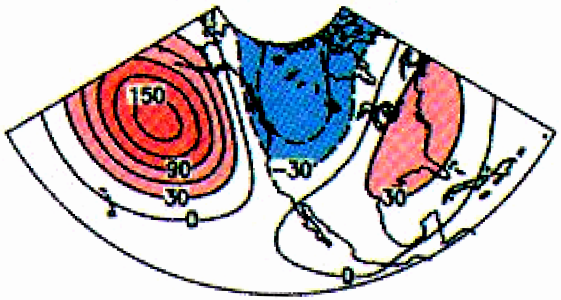
IC: 12/89

IC: 12/83

Observed SST JFM83

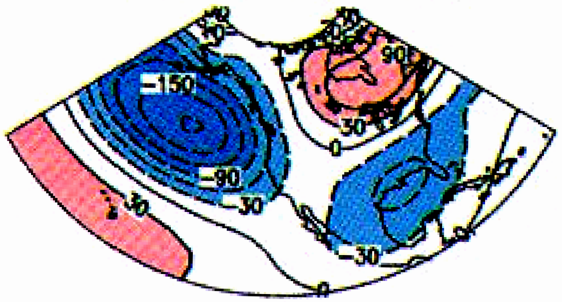


Observed SST JFM89

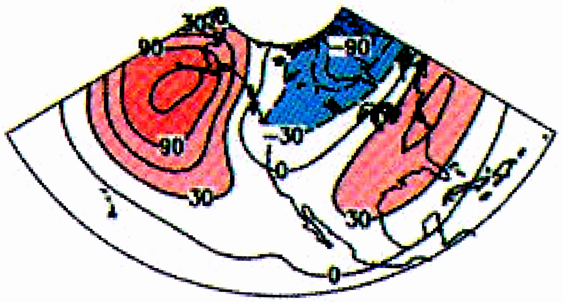


IC: 12/83

C. Observed JFM 1983



F. Observed JFM 1989



When tropical forcing is very strong, it can enhance even the predictability of extratropical seasonal mean circulation, which, in the absence of anomalous SST, has no predictability beyond weather.

Commentary

- Several NWP Models have comparable skill.
- Initial error growth has steadily increased, yet skill of five day forecast has also increased.
- NWP progress in past 30 years: Improved one day forecast.
- No scientific breakthrough (except ensemble forecasting).
- No enhancement of observations.
- Hard work, improve models, improved assimilation and initialization.
- Possible lesson for Dynamical Seasonal Prediction.

From Numerical Weather Prediction (NWP) To Dynamical Seasonal Prediction (DSP) (1975-2004)

- **Operational Short-Range NWP: was already in place**
- **15-day & 30-day Mean Forecasts: demonstrated by Miyakoda (basis for creating ECMWF-10 days)**
- **Dynamical Predictability of Monthly Means: demonstrated by analysis of variance**
- **Boundary Forcing: predictability of monthly & seasonal means (Charney & Shukla)**
- **AGCM Experiments: prescribed SST, soil wetness, & snow to explain observed atmospheric circulation anomalies**
- **OGCM Experiments: prescribed observed surface wind to simulate tropical Pacific sea level & SST (Busalacchi & O'Brien; Philander & Seigel)**
- **Prediction of ENSO: simple coupled ocean-atmosphere model (Cane, Zebiak)**
- **Coupled Ocean-Land-Atmosphere Models: predict short-term climate fluctuations**

Simulation of (Uncoupled) Boundary-Forced Response: Ocean, Land and Atmosphere

INFLUENCE OF OCEAN ON ATMOSPHERE

- Tropical Pacific SST
- Arabian Sea SST
- North Pacific SST
- Tropical Atlantic SST
- North Atlantic SST
- Sea Ice
- Global SST (MIPs)

INFLUENCE OF LAND ON ATMOSPHERE

- Mountain / No-Mountain
- Forest / No-Forest (Deforestation)
- Surface Albedo (Desertification)
- Soil Wetness
- Surface Roughness
- Vegetation
- Snow Cover

(Thanks to COLA!)

Questions:

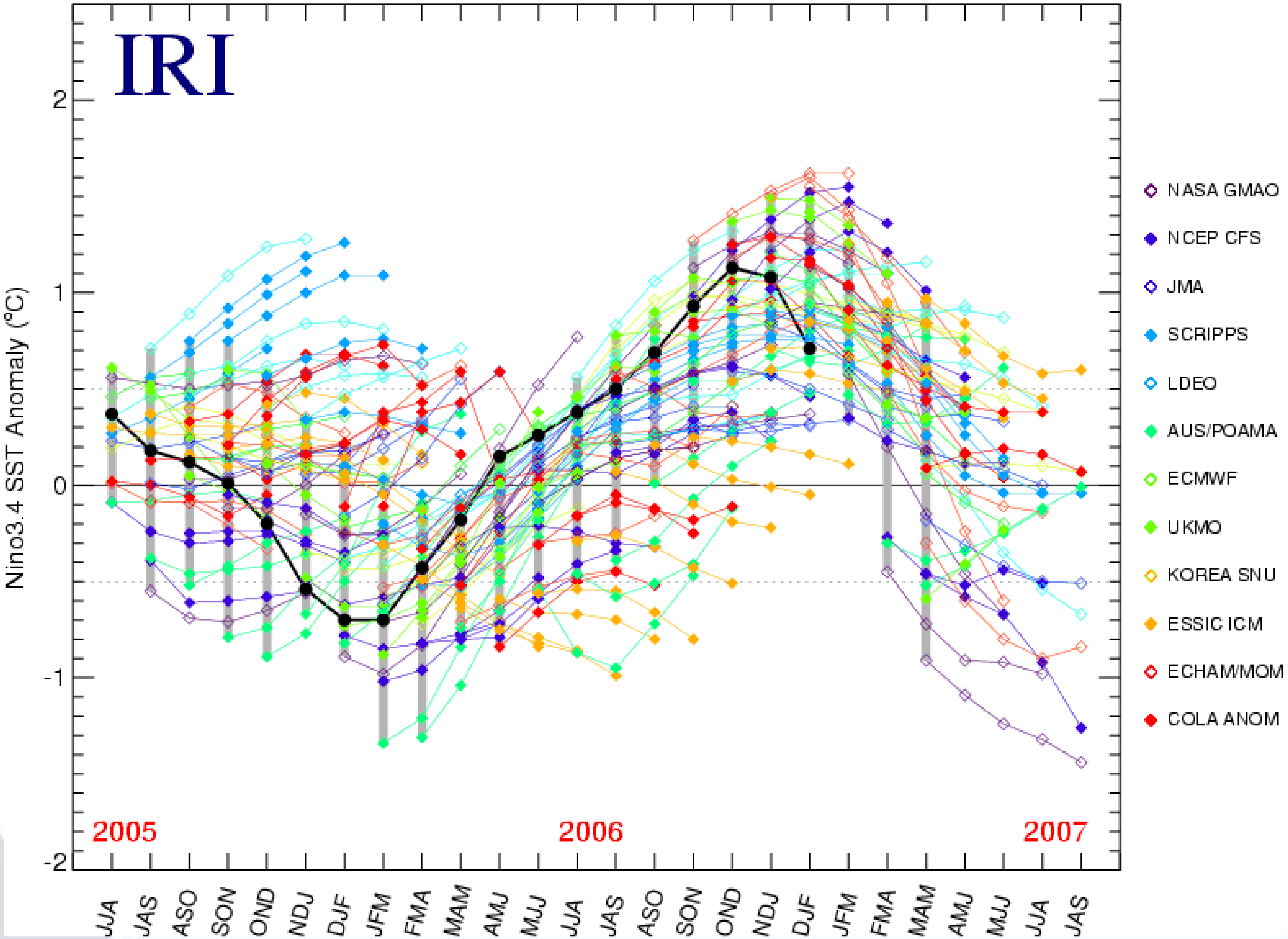
Have "We" Kept the Promises We Made?

What are the Stumbling Blocks?

What are the Prospects for the Future?

ENSO Forecasts for Dynamic Models

Jun 2005 – March 2007



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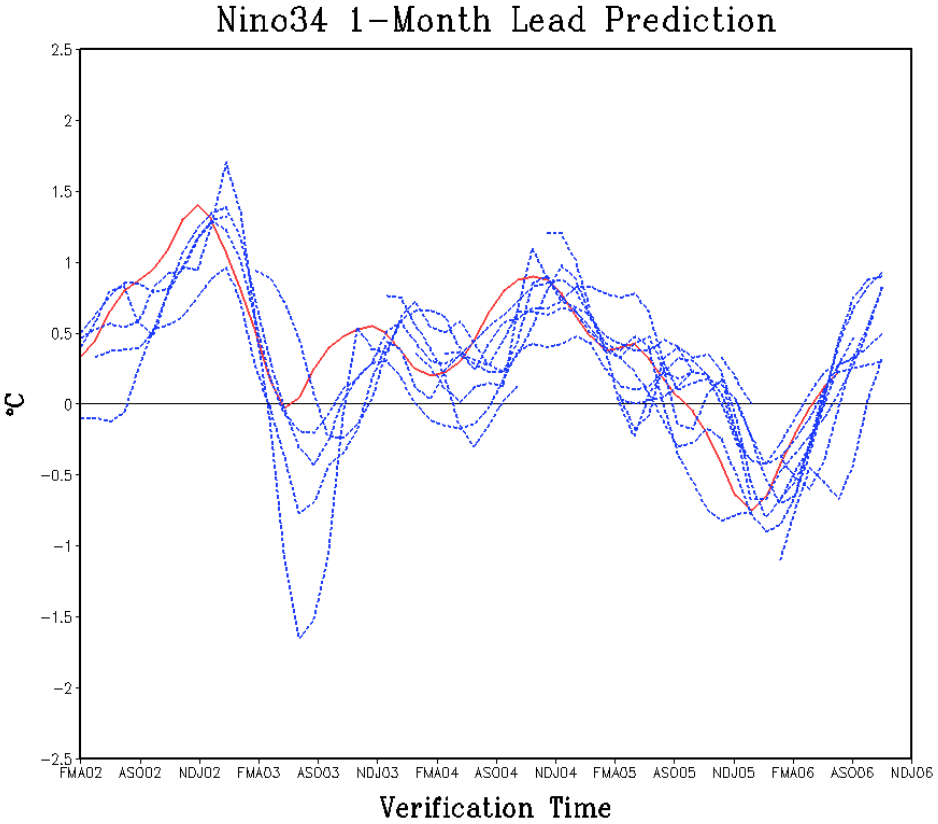
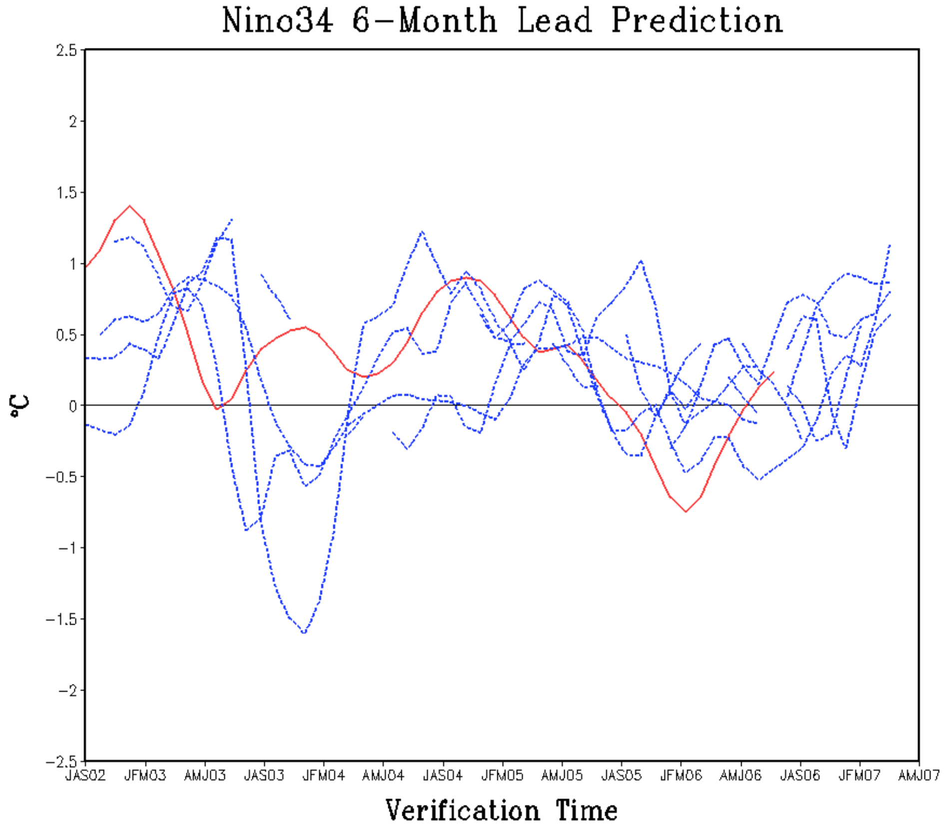


Dynamic CGCMs Only



IRI Nino34 Forecast Archive
February 2002-September 2006

Running Seasonal Means

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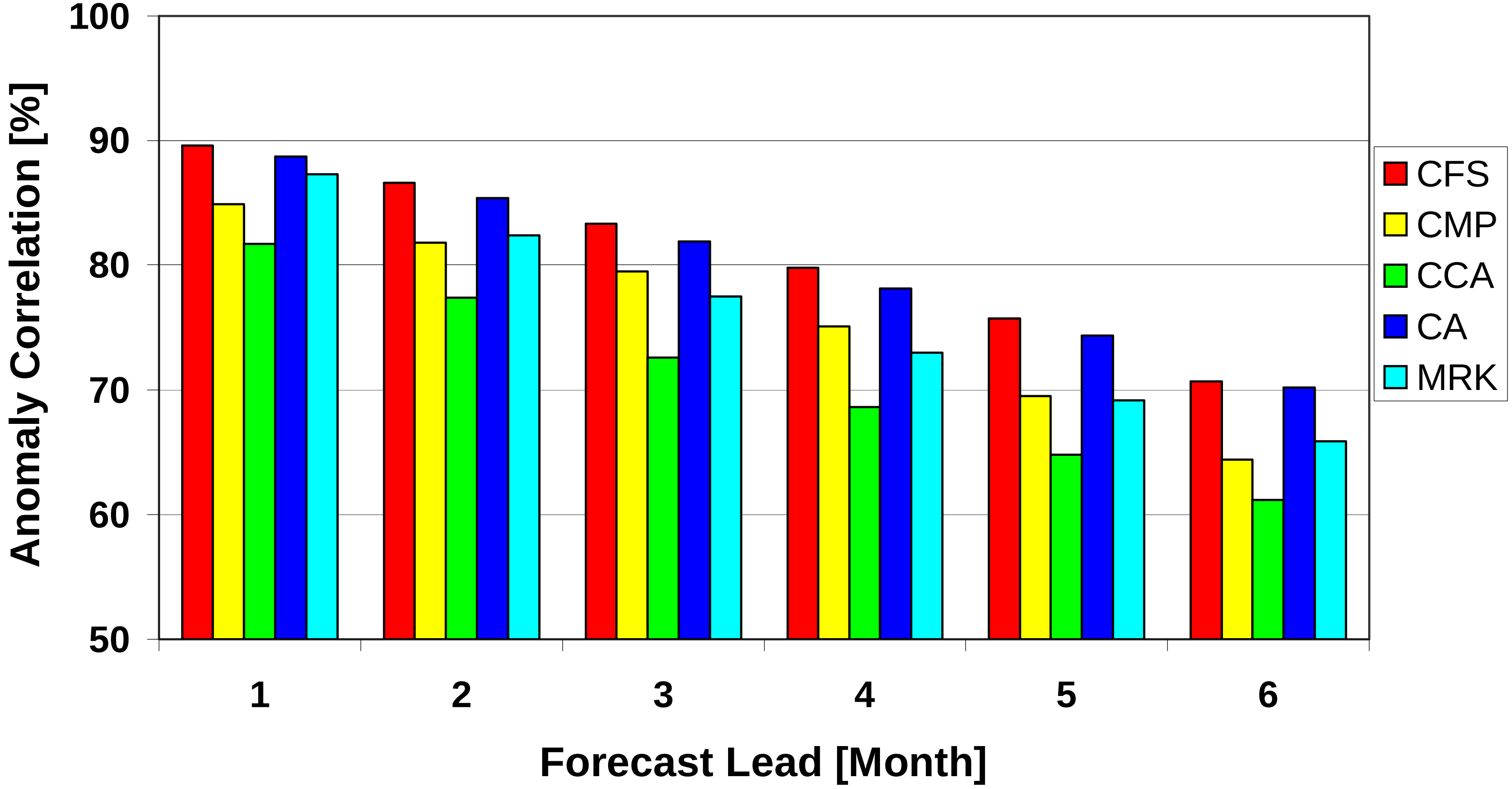
Skill in SST Anomaly Prediction for Nino3.4

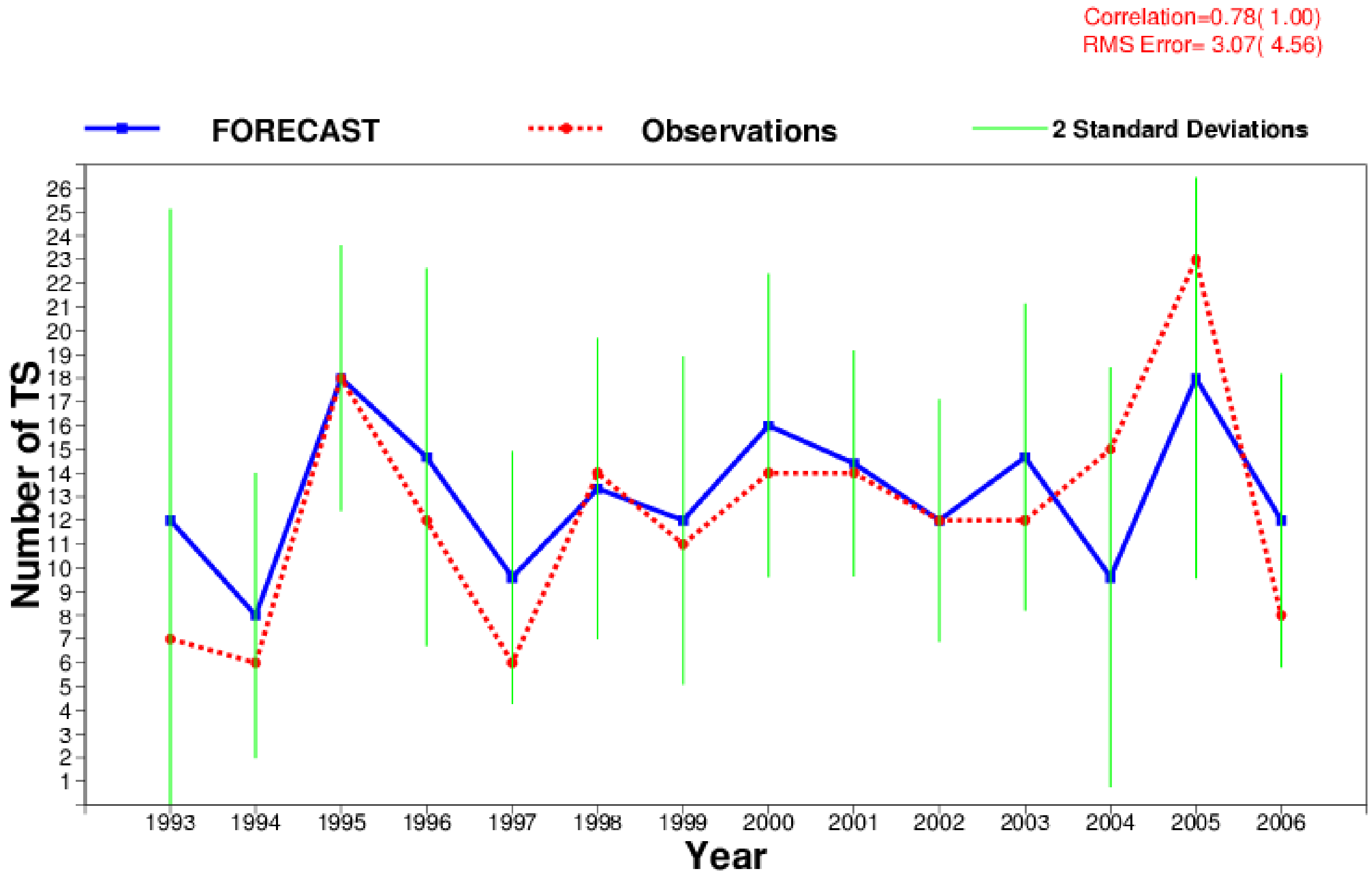
DJF 1981/82 to AMJ 2004

15-member CFS reforecasts



EUROSIP Atlantic Seasonal Forecasts

July to Nov



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Commentary

- **25 years ago, a dynamical seasonal climate prediction was not conceivable.**
- **In the past 20 years, dynamical seasonal climate prediction has achieved a level of skill that is considered useful for some societal applications. However, such successes are limited to periods of large, persistent anomalies at the Earth's surface. Dynamical seasonal predictions for one month lead are not yet superior to statistical forecasts.**
- **There is significant unrealized seasonal predictability. Progress in dynamical seasonal prediction in the future depends critically on improvement of coupled ocean-atmosphere-land models, improved observations, and the ability to assimilate those observations.**

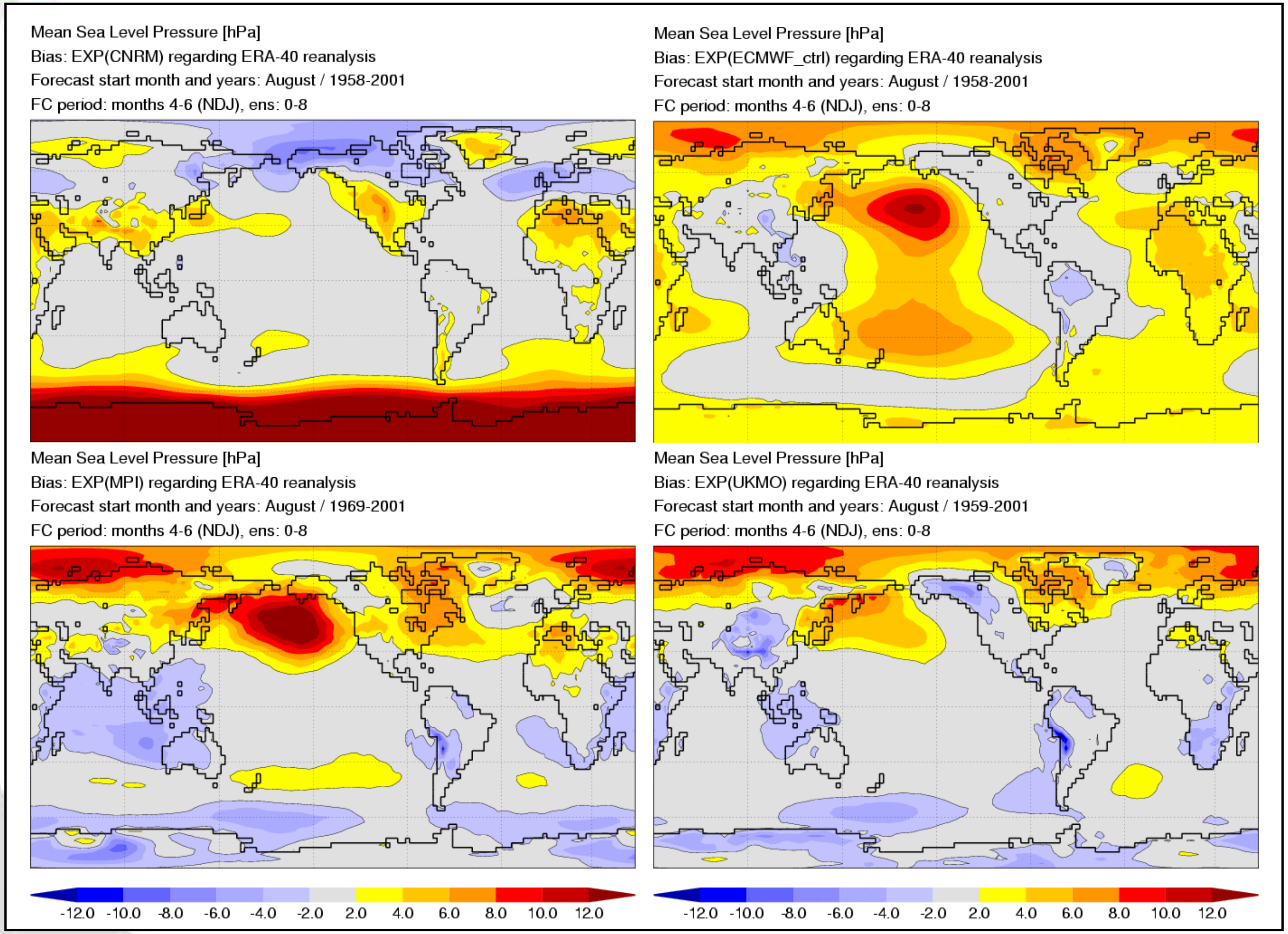
Current Status of Dynamical Seasonal Prediction

1. Coupled O-A models (both complex GCMs and intermediate complexity models) are frequently making skillful prediction of tropical Pacific SSTA (NINO 3, NINO 3.4, etc) and the corresponding tropical circulation up to six months. However, the skill is highly variable depending on IC, year (ENSO events), model, ensemble size etc. Multi Model ensembles are most skillful.
2. Even the prediction of ENSO is limited to a selective preconditioning of wind stress, SST, and subsurface temperature anomalies in the equatorial Pacific.
3. There is no robust evidence of skill in seasonal prediction of SSTA in the Indian Ocean, the tropical Atlantic, or the extratropical oceans; or any other planetary scale modes of atmospheric circulation (monsoons, NAO etc.)
4. There is no robust evidence that dynamical seasonal prediction of surface temperature and precipitation over North America is more skillful than statistical models.

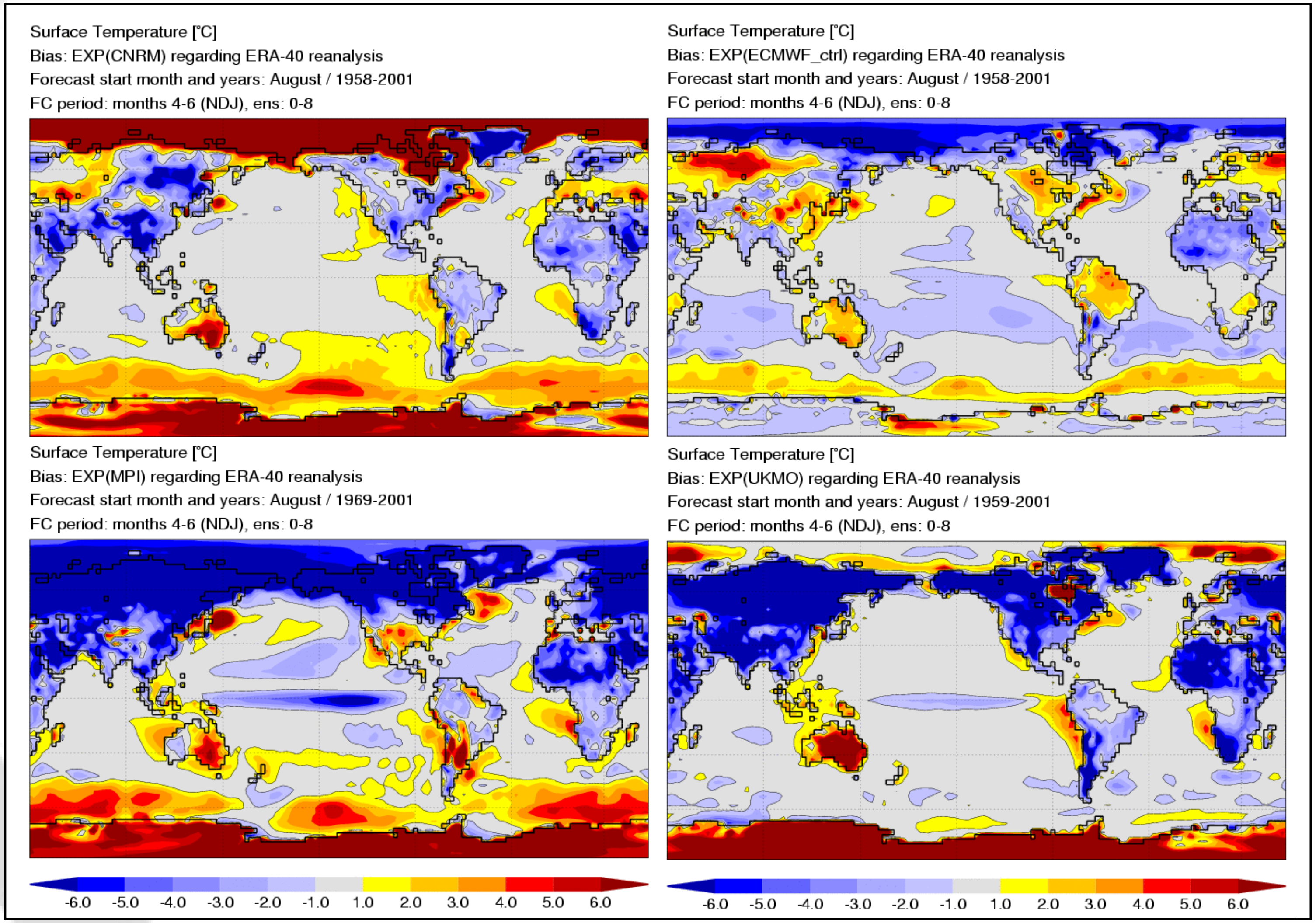
Commentary

- **The most dominant obstacle in realizing the potential predictability of intraseasonal and seasonal variations is inaccurate models, rather than an intrinsic limit of predictability.**

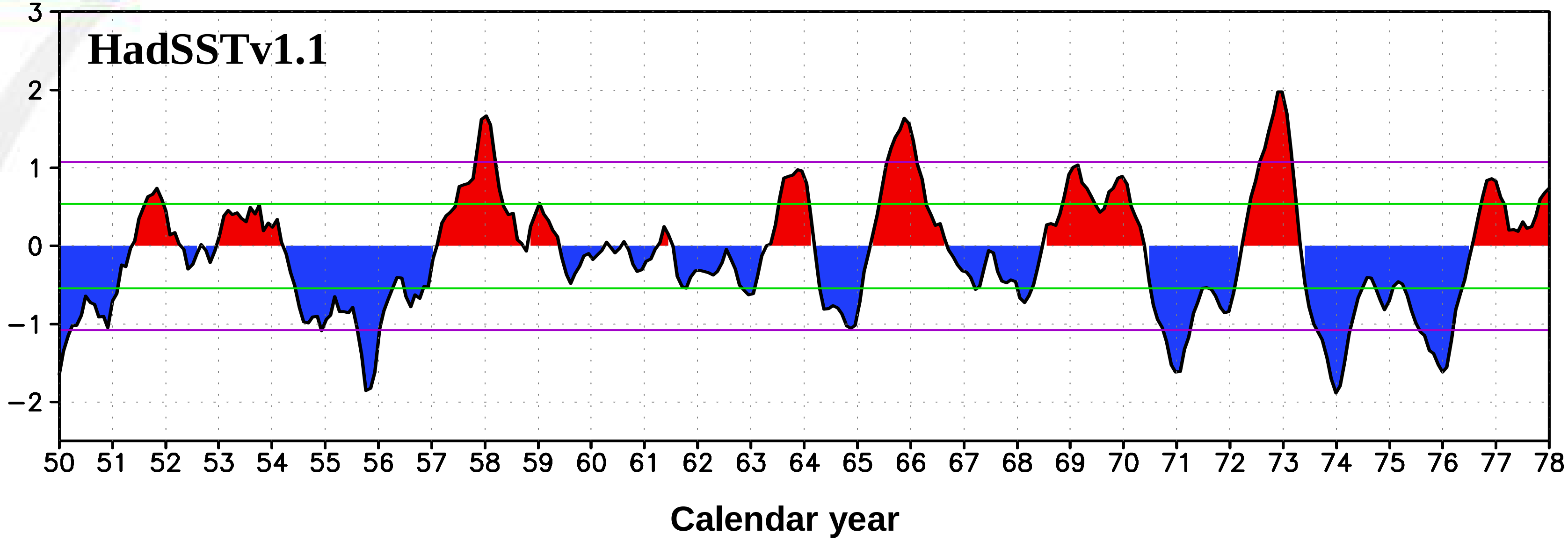
Systematic Error: MSLP (NDJ)

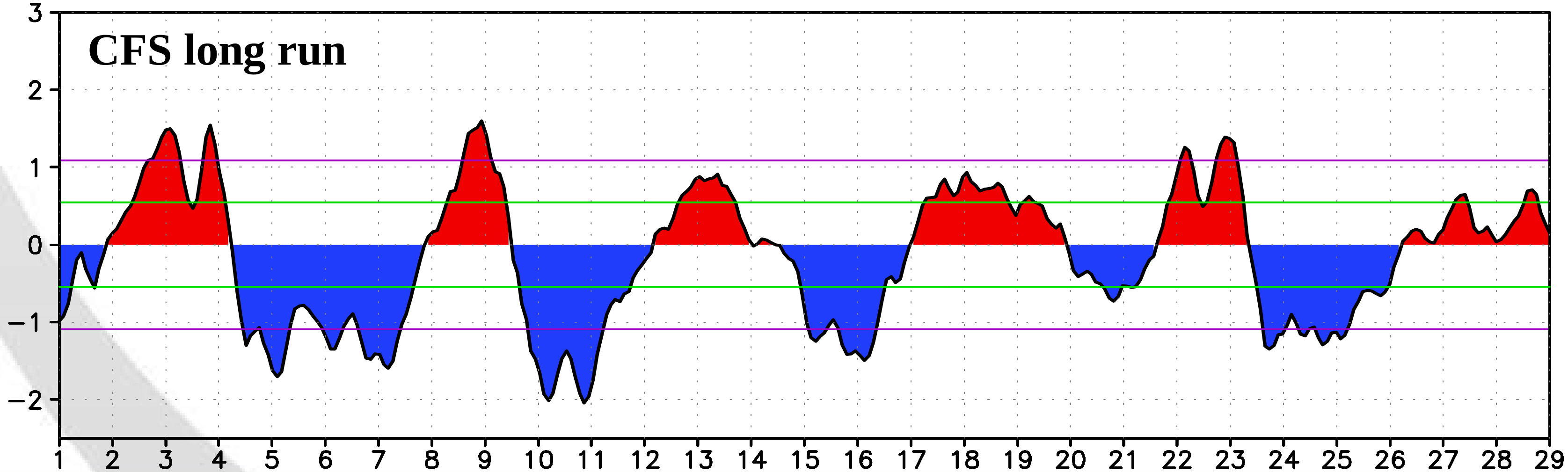


Systematic Error: Surface Temp. (NDJ)



NINO 3.4 Index (Observed and CFS)





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Commentary

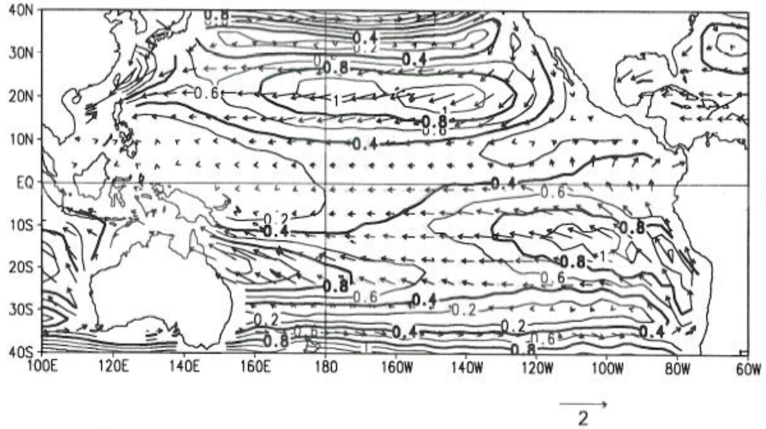
- **Models with high deficiencies in simulating tropical heating produce highly deficient extratropical response to ENSO**
- **Examples: ECMWF, NCEP, GFDL, COLA**

Thanks to Arun Kumar (CPC/NCEP)

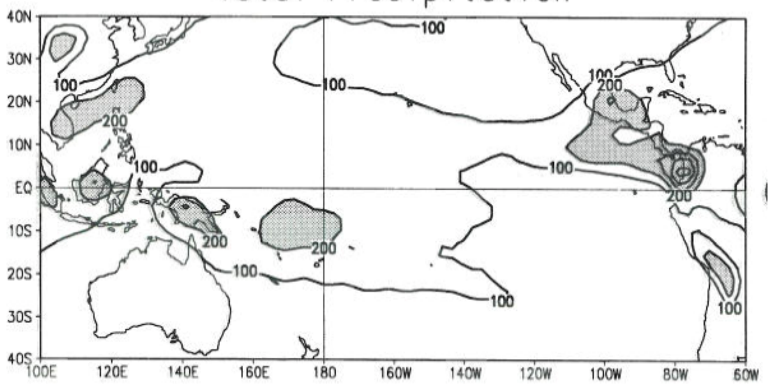
MRF8

SEP–NOV Climatology (AMIP)

Surface Stress



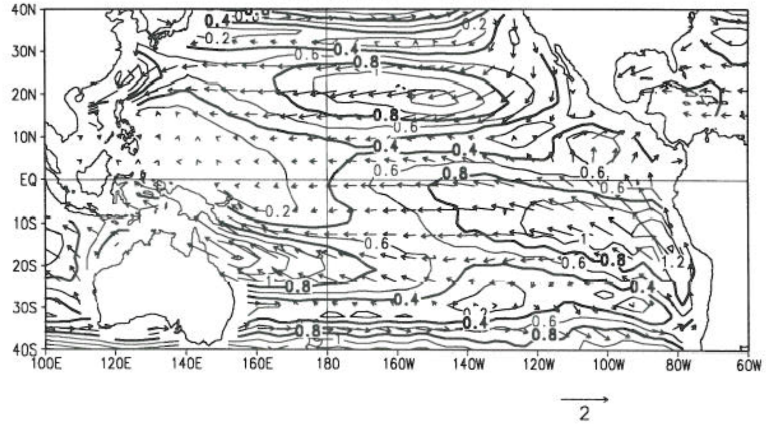
Total Precipitation



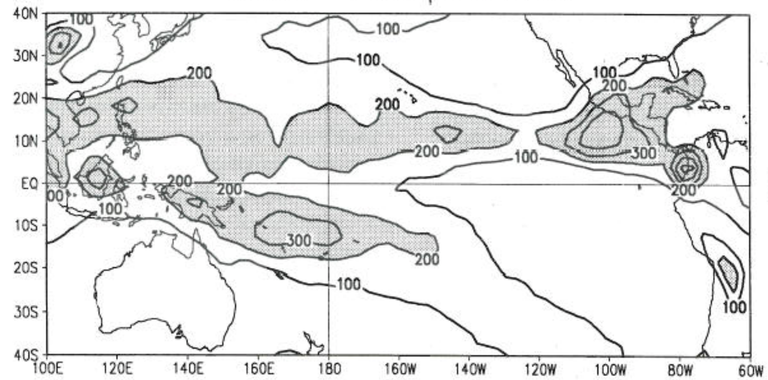
MRF9

SEP–NOV Climatology (CMP)

Surface Stress



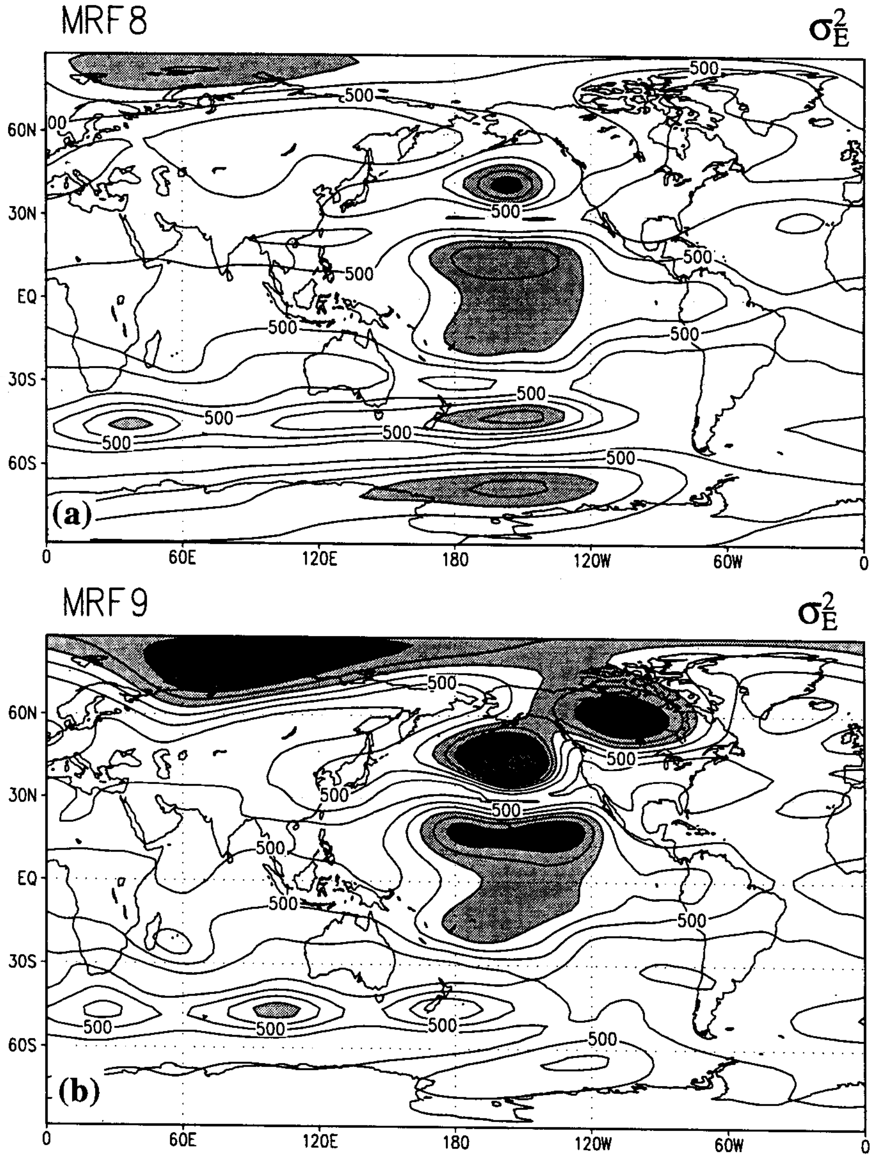
Total Precipitation

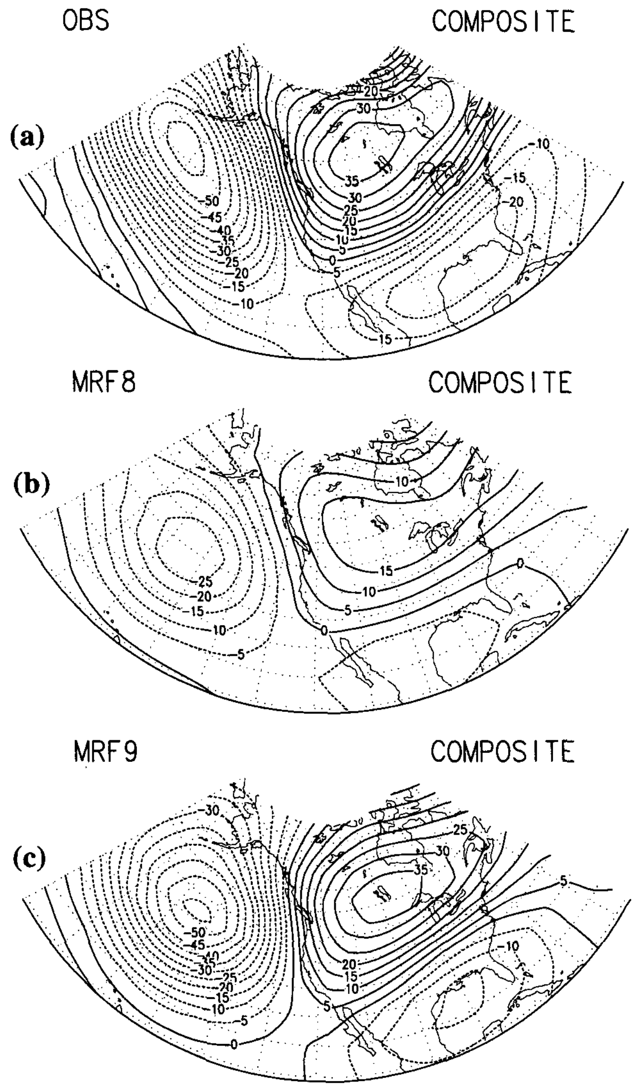


MRF8: high, middle, low clouds allowed to exist

MRF9: Only high cloud allowed to exist over regions of tropical deep convection

Thanks to Arun Kumar (CPC/NCEP)





MRF8: high, middle, low clouds allowed to exist

MRF9: Only high cloud allowed to exist over regions of tropical deep convection

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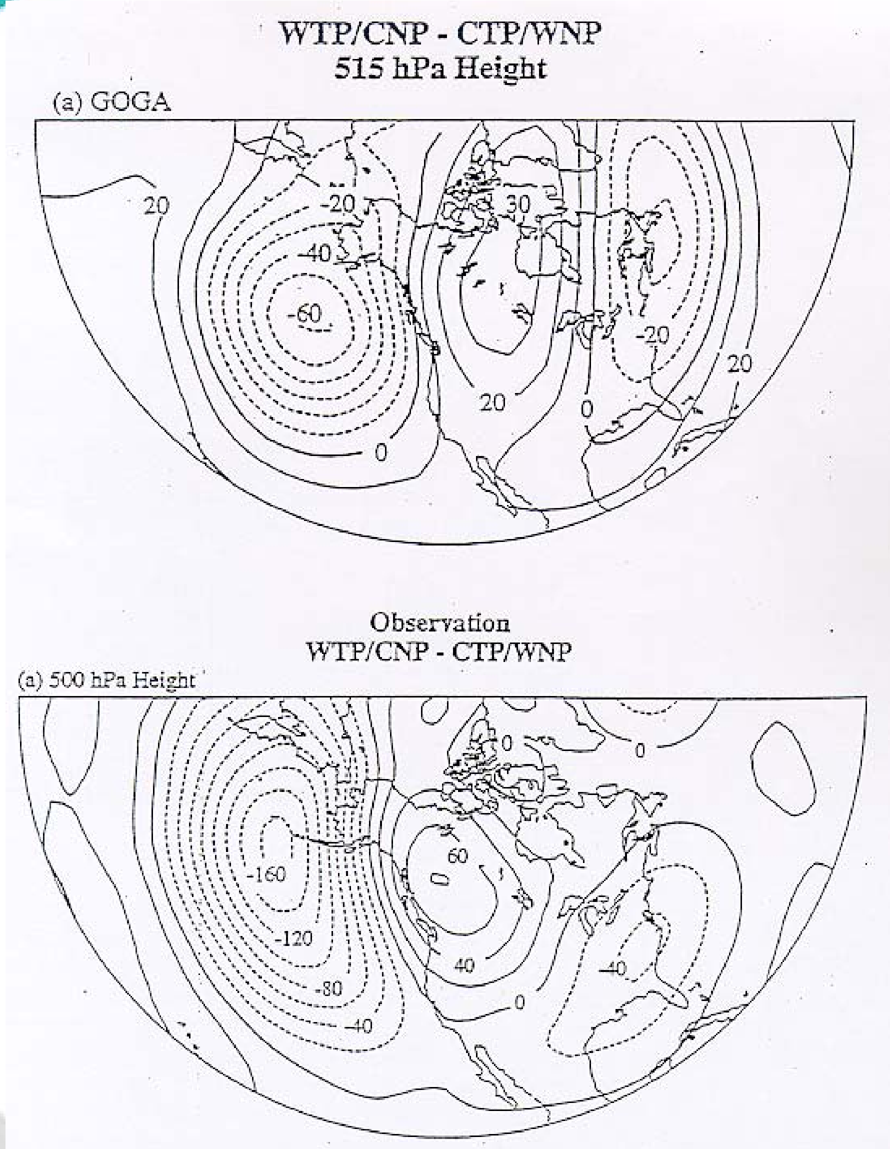


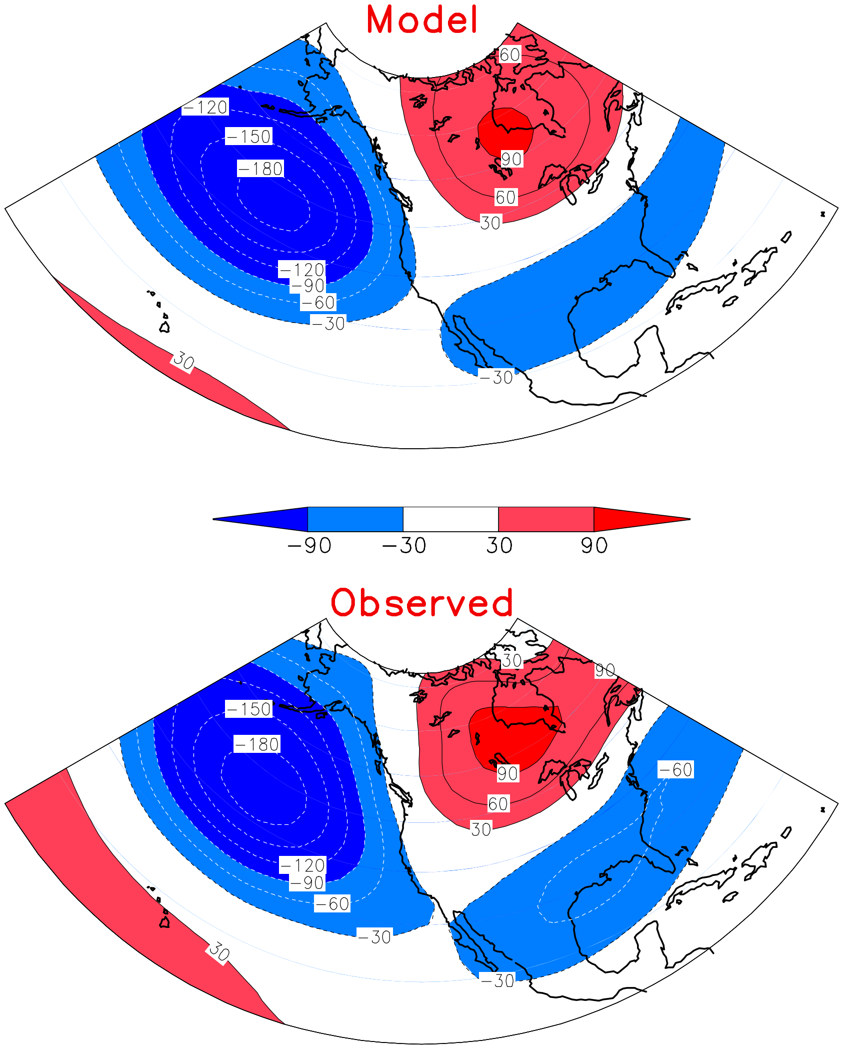
Note: amplitude of model response quite weak; structure is PNA rather than ENSO forced

Vintage 1980 AGCM (Lau, 1997, BAMS)

Model Simulation of ENSO Effects

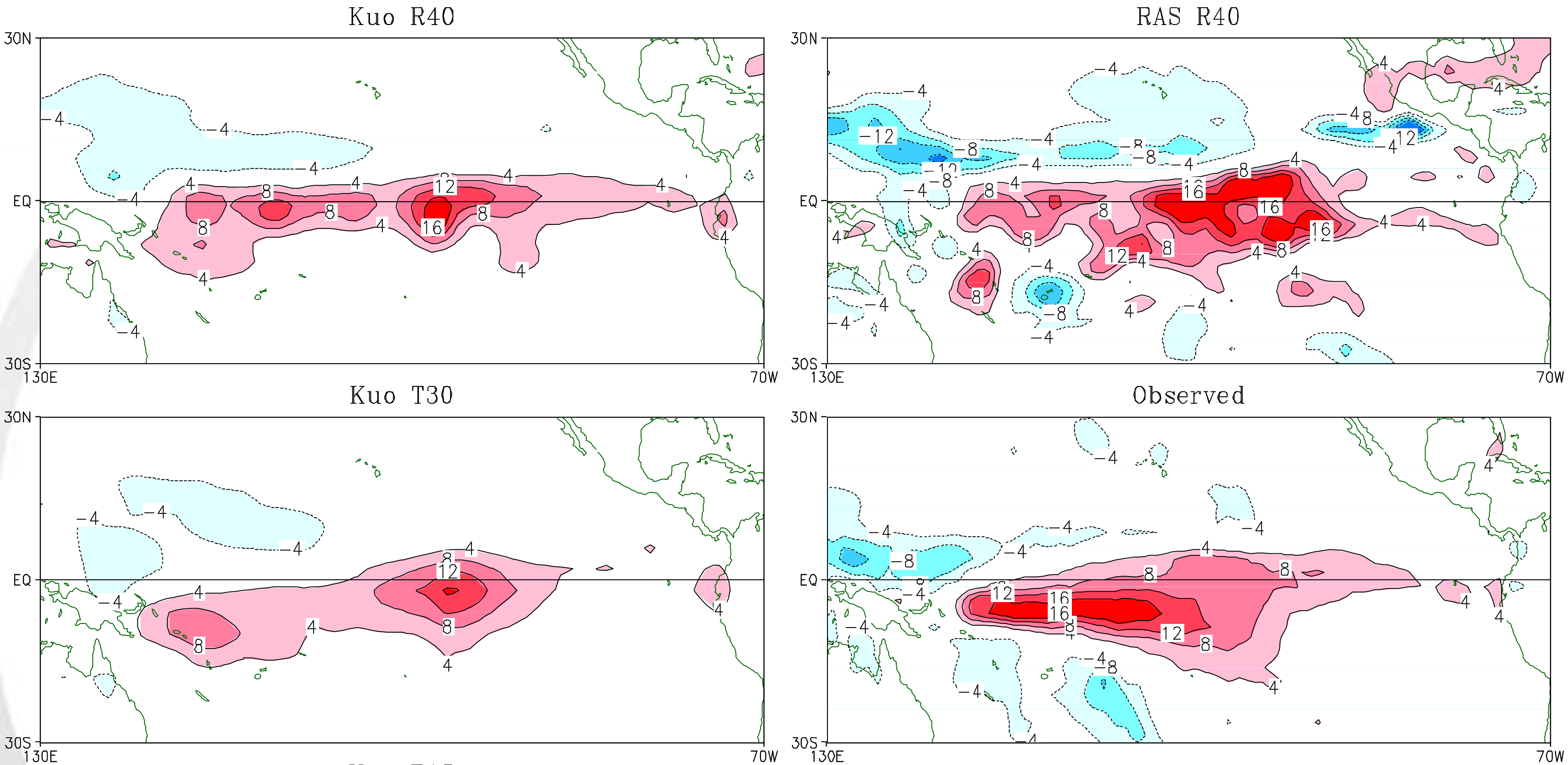
500 hPa height (meters) anomalies

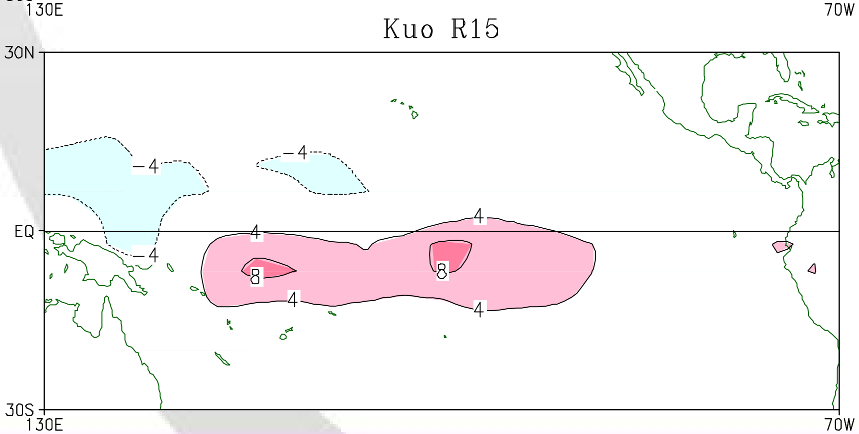
ACC = 0.98



NINO3 Warm(83,87,92) – Cold(85,89)

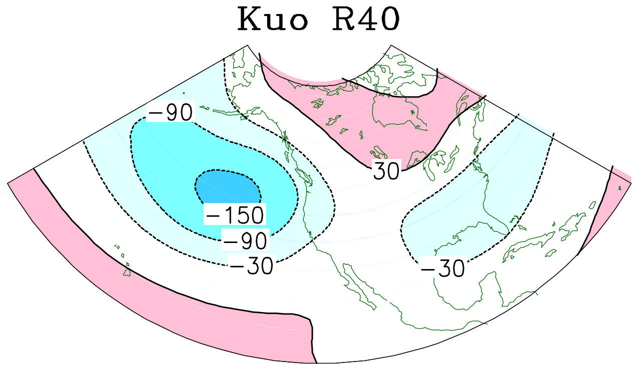
Vintage 2000 AGCM

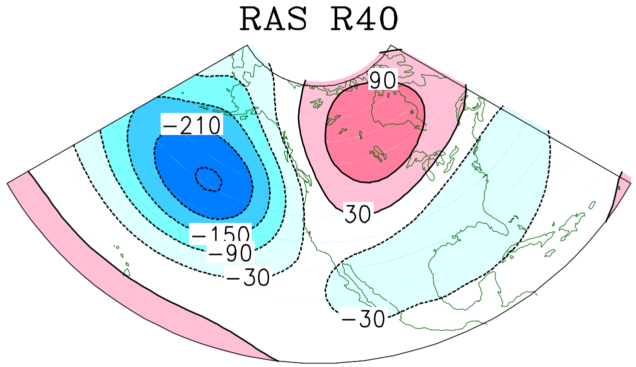


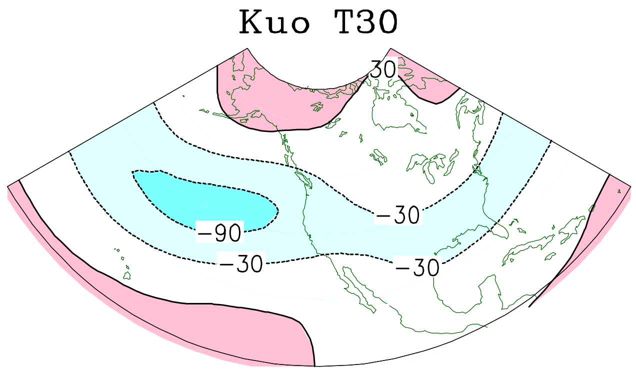


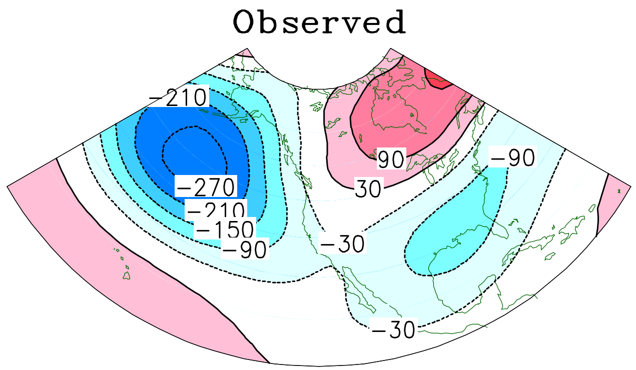
Evolution of Climate Models 1980-2000

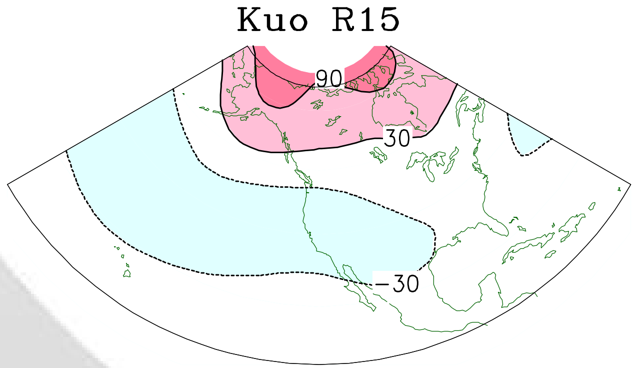
Model-simulated and observed rainfall anomaly (mm day^{-1})
1983 minus 1989







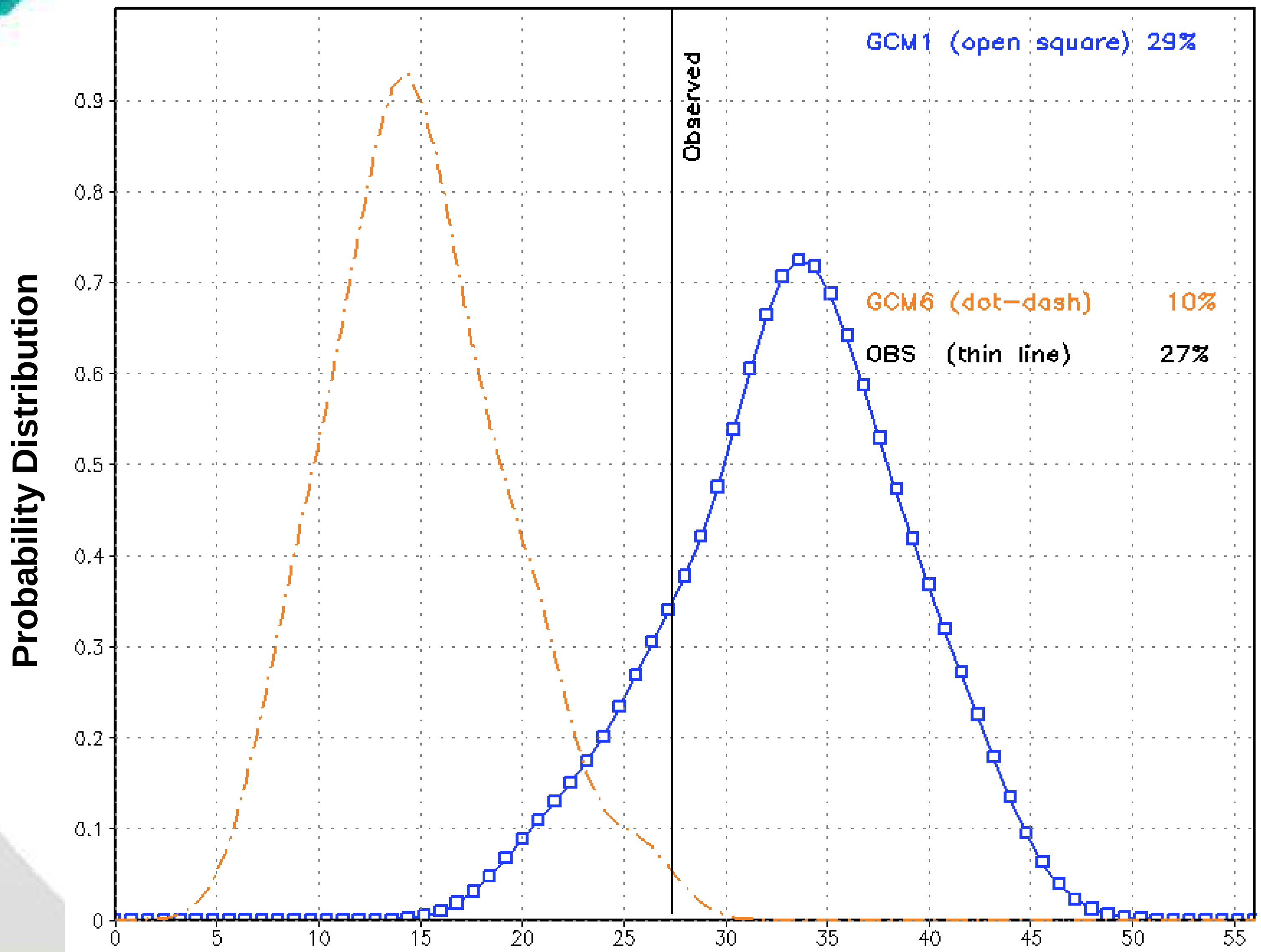




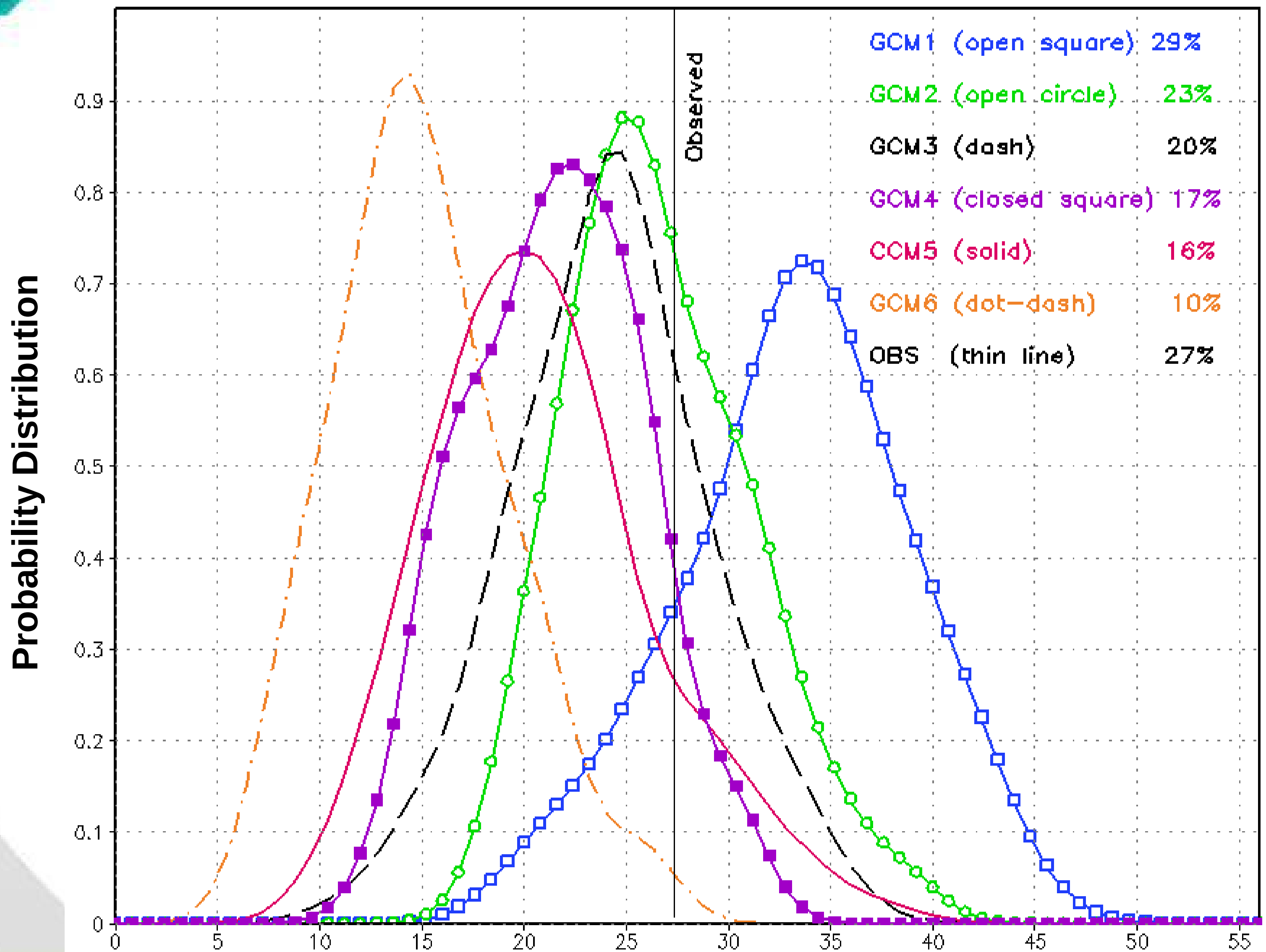
Evolution of Climate Models 1980-2000

Model-simulated and observed 500 hPa height anomaly (m) 1983 minus 1989

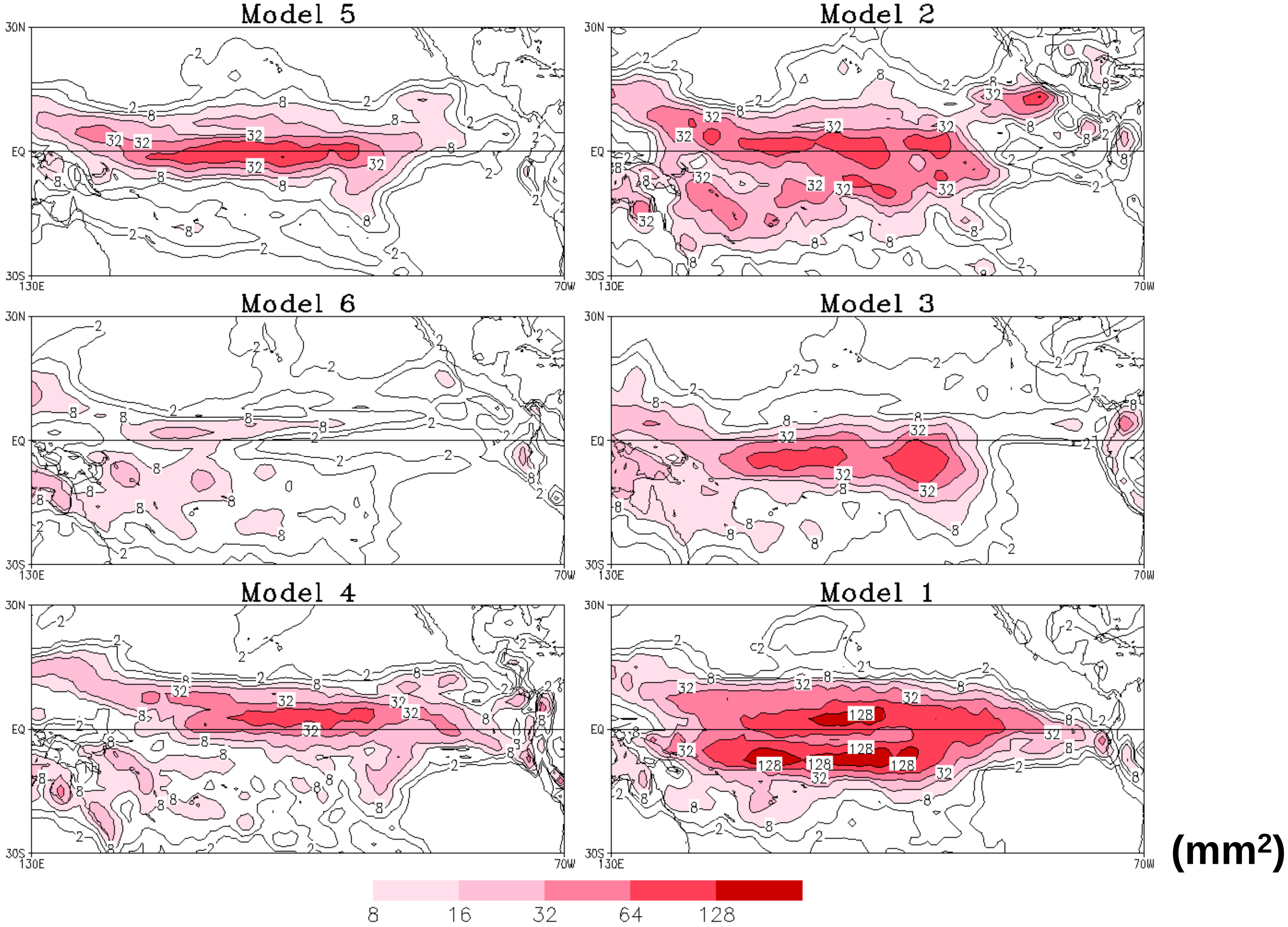
Percent Variance of PNA region explained by Tropical SST



Percent Variance of PNA region explained by Tropical SST



Boreal Winter (DJF) Rainfall Variance in AGCMs



Hypothesis

Models with low fidelity in simulating climate statistics have low skill in predicting climate anomalies.

DelSole 2007 (research in progress)

Measure of Fidelity: Relative Entropy

(Kleeman 2001; DelSole and Tippett, 2007)

- Measure of the "distance" between two pdfs

$$R = \int a(x) \log \frac{a(x)}{f(x)} dx$$

- f = climatology of model forecasts at fixed lead time, fixed initial time
-
- a = climatology of analyses ("observations") (distribution of variable in JFM, FMA, etc.)

- For 1D normal distributions with mean μ and variance σ^2

$$R = \log \frac{\sigma_a^2}{\sigma_f^2} + \frac{\sigma_f^2}{\sigma_a^2} - 1 + \frac{(\mu_f - \mu_a)^2}{\sigma_a^2}$$

Measure of Fidelity: Anomaly Correlation

ACC = correlation between forecast and verification at each grid point

$$ACC = \frac{cov(F, A)}{\sigma_f \, \sigma_a}$$

Notes:

- ACC is calculated from seasonal means for 1981-2001.
- ACC measures joint variability (i.e. skill), relative entropy does not. Relative entropy measures fidelity of climatological distribution.
- ACC is not a spatial correlation, but a temporal correlation at each grid point.

DEMETER

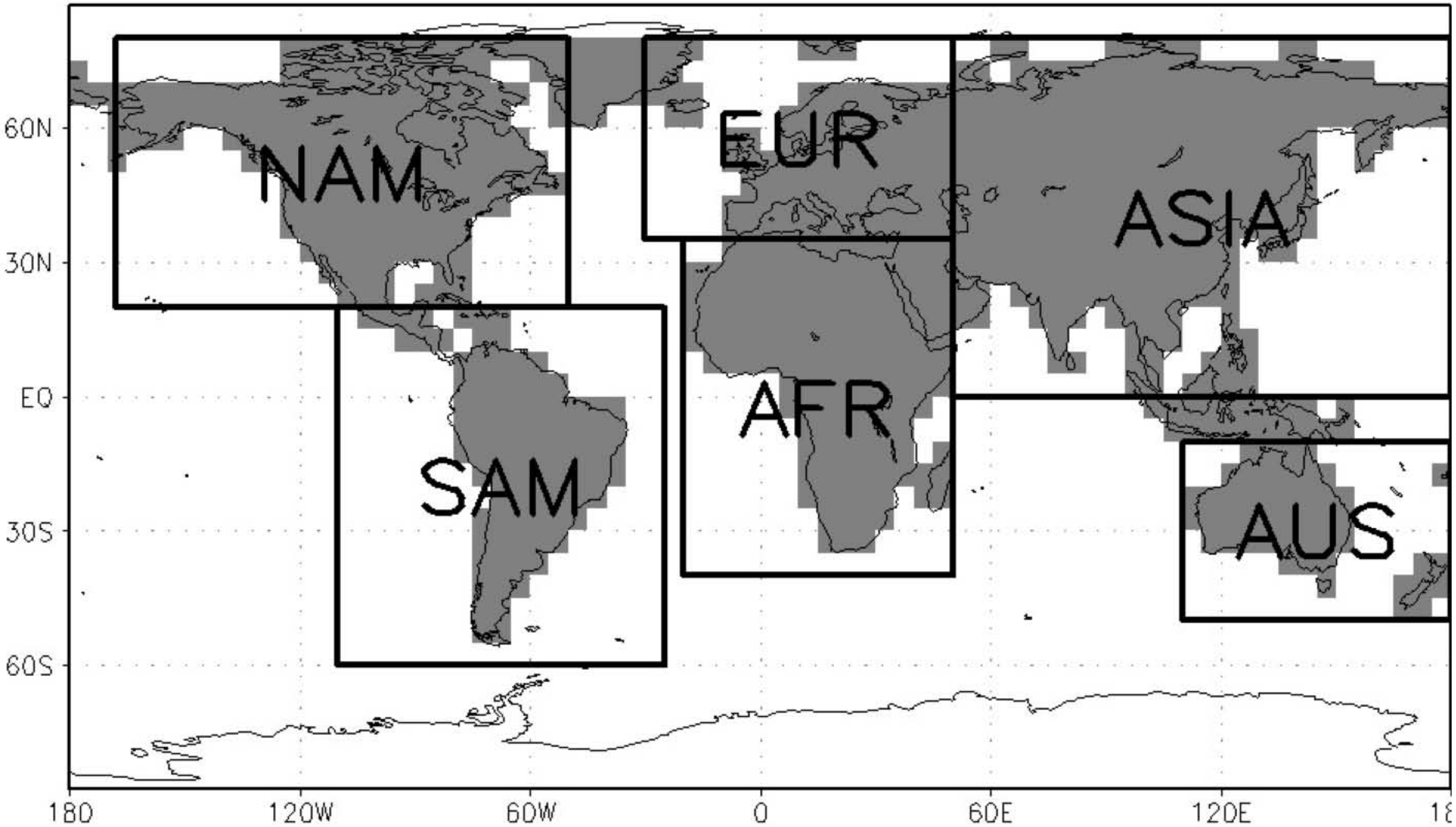
- Demeter hindcasts downloaded from ECMWF[1]
- 7 models (CER, ECM, ING, LOD, MET, MPI, UKM)
- 9 ensemble members
- Initial conditions: February 1, May 1, August 1, November 1
- 6-month lead time
- 22 Years: 1980-2001
- 2m temperature over land
- Consider only 3-month means (JFM, FMA, . . ., OND)

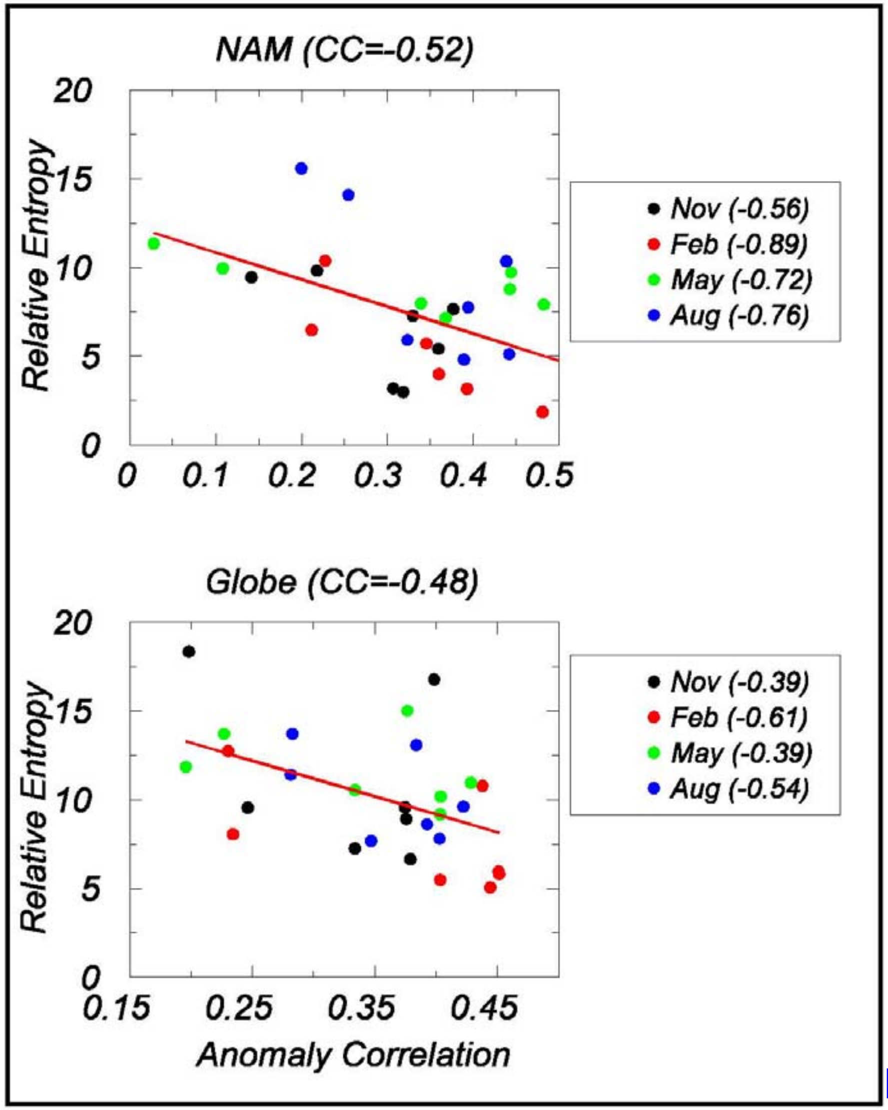
Thanks to Emilia Jin for providing the DEMETER data.

Calculation Details

- Verification data: HADCRUT2 from CRU (Jones & Moberg)
- All data interpolated onto HADCRUT2 observation grid
- Relative entropy and anomaly correlation computed at each grid point separately for 1980-2001.
- Grid point values of R and ACC averaged over selected regions.

Regions Investigated





Fidelity vs. Skill
DEMETER 1980-2001
Seasonal Forecasts

7 models, 4 initial conditions

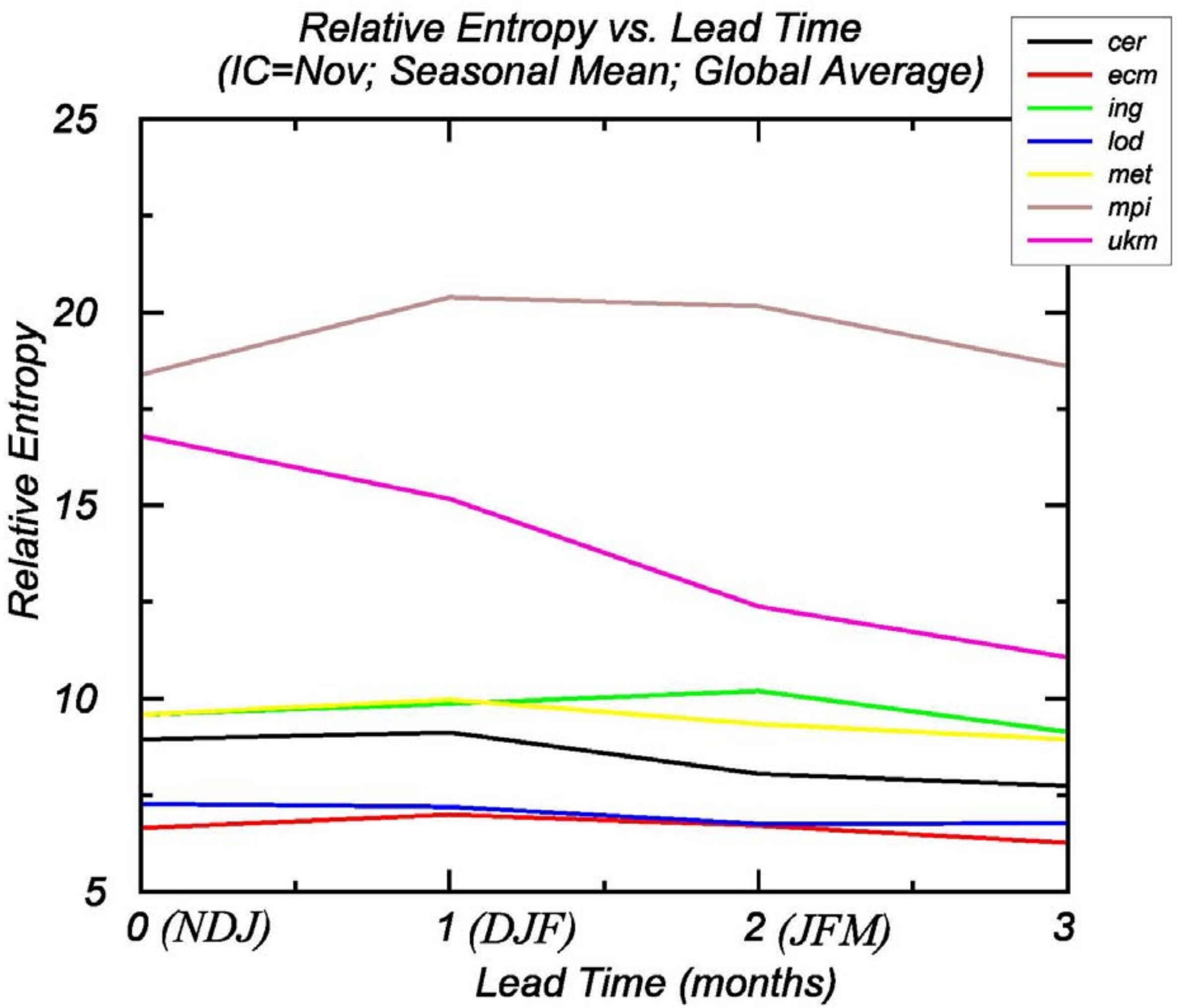
Lead Time = 0 months

Fidelity and Skill are related.

Models with poor climatology tend to have poor skill.

Models with better climatology tend to have better skill.

DelSole 2007 (research in progress)



Note: Model errors saturate within the first season

DelSole 2007 (research in progress)

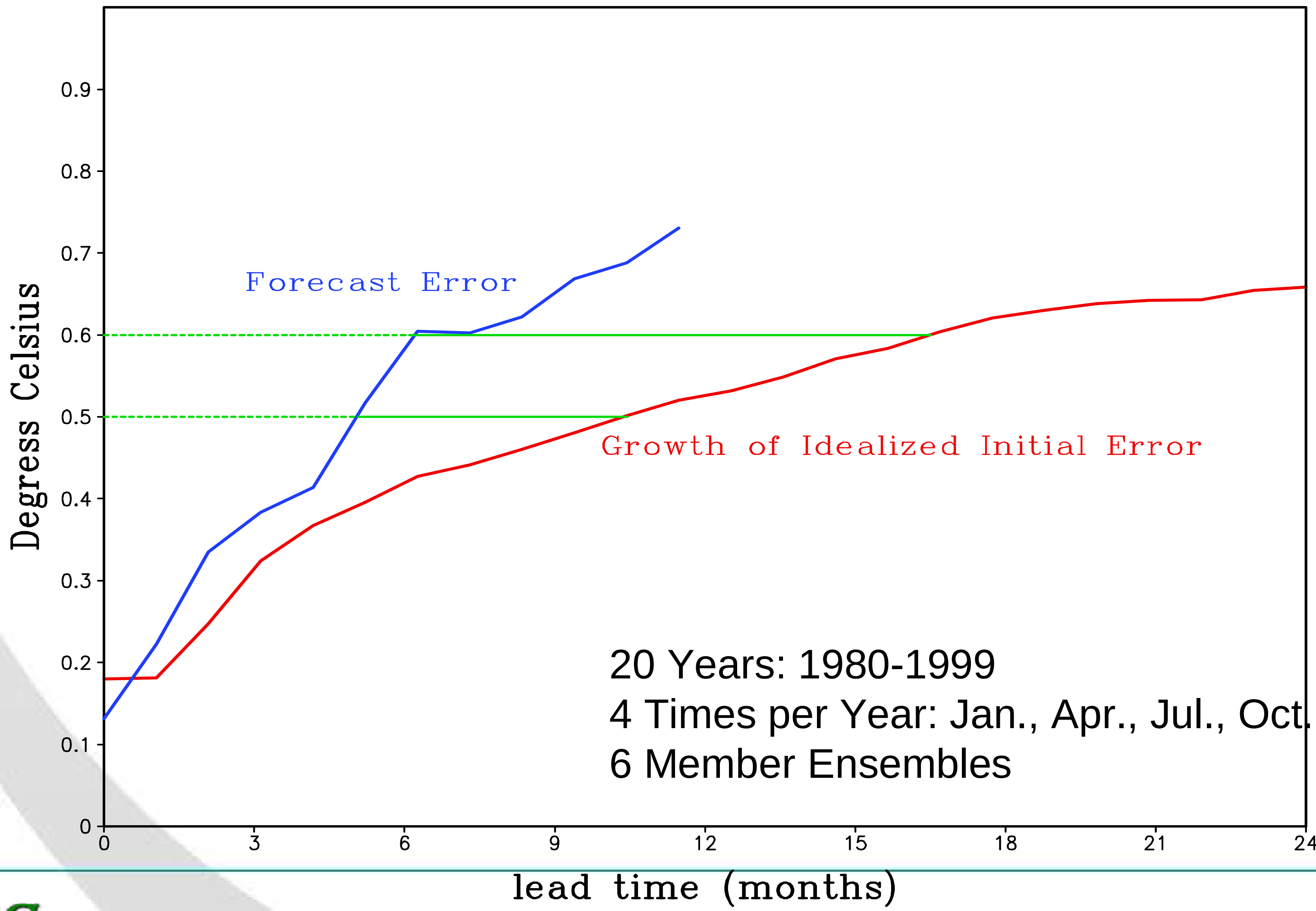
Systematic errors of climate models can be substantially reduced by empirical corrections (e.g. flux correction, anomaly coupling, nudging based on tendency error, etc.)

However, empirical corrections do not consistently improve forecast skill.

Understanding Variations in Forecast Skill

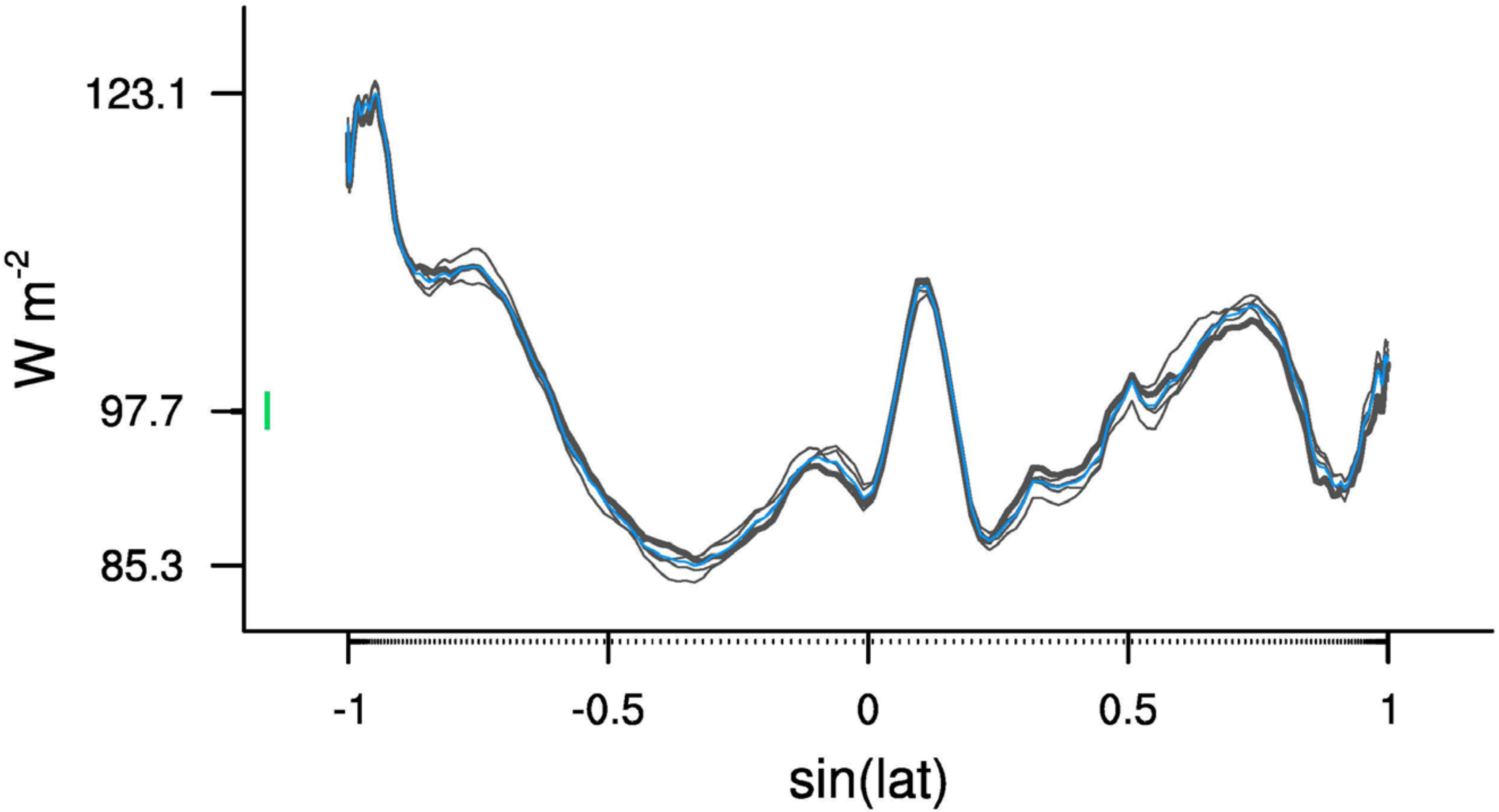
- **What is the Overall Limit of Predictability?**
- **What Limits Predictability?**
  - **<u>Uncertainty in Initial Conditions:</u> Chaos within Non-Linear Dynamics of the Coupled System**
  - **<u>Uncertainty as the System Evolves:</u> External Stochastic Effects**
- **Model Dependence?**
  - **Model Error**

Current Limit of Predictability of ENSO (Nino3.4)
Potential Limit of Predictability of ENSO

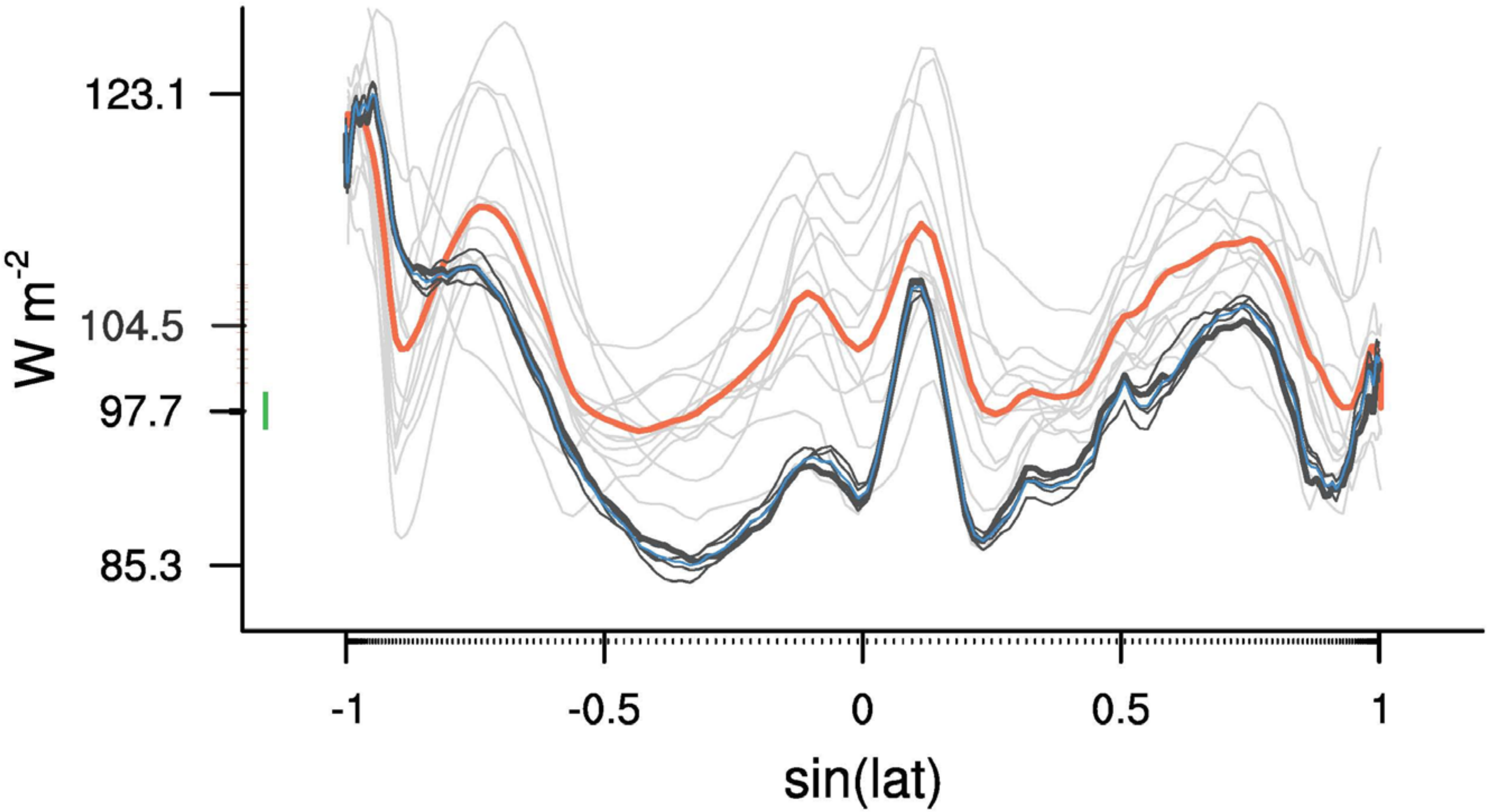


Kirtman, 2003

annually & zonally averaged reflected sw radiation

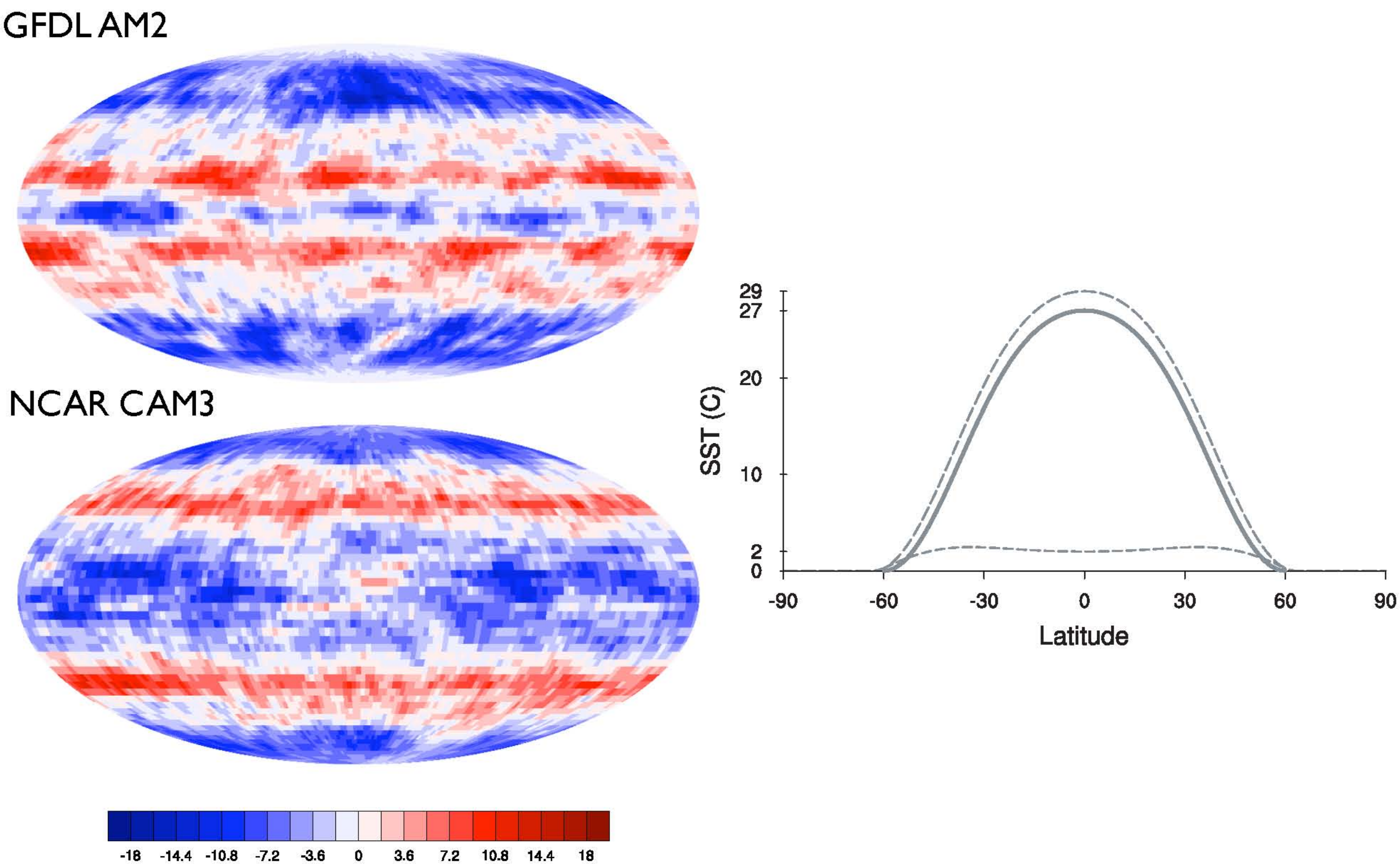


annually & zonally averaged sw radiation (AR4)



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

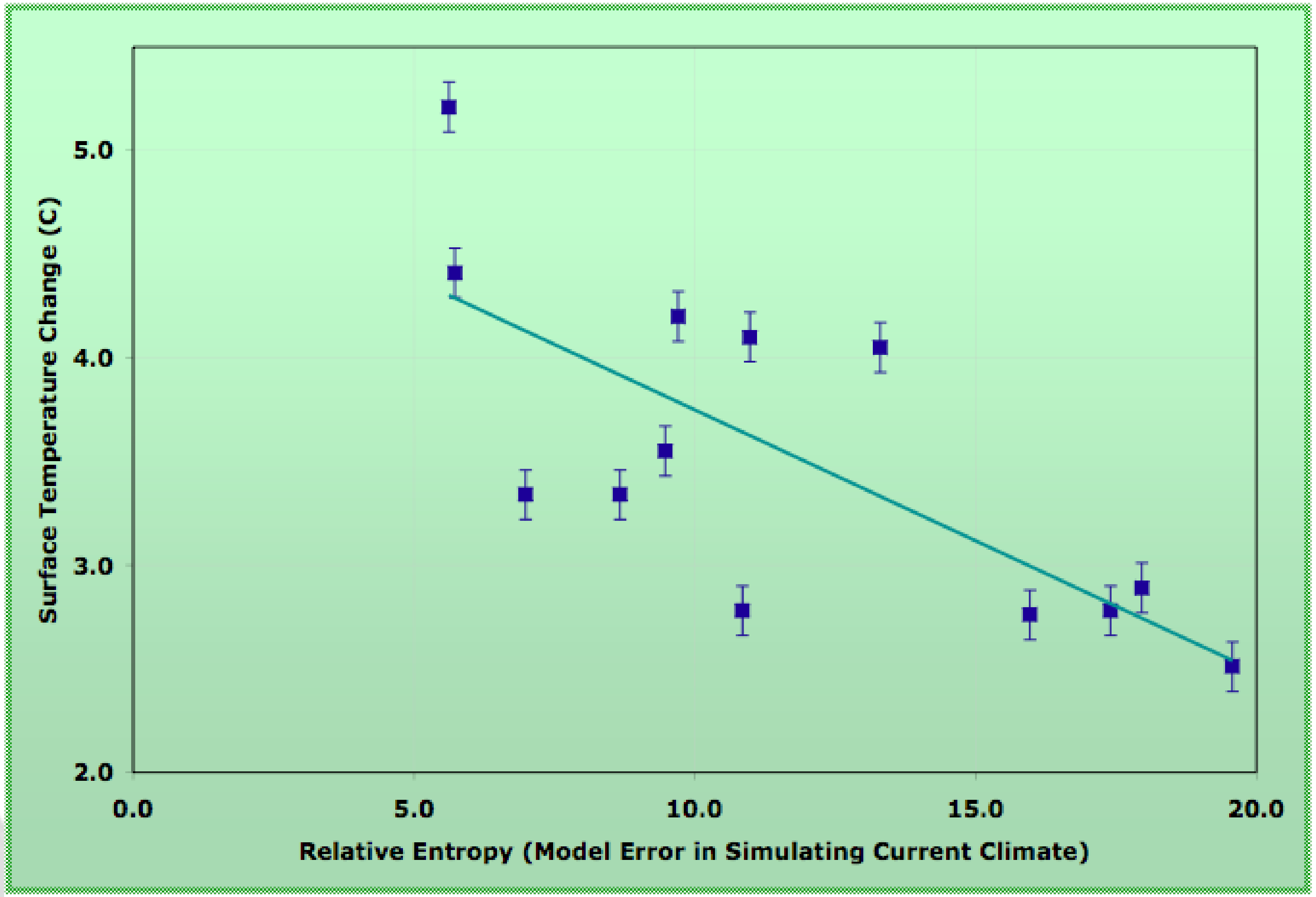
Clouds as ultimate, rather than proximate, sources of bias



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 Projections of Climate Change

Relative Entropy: The relative entropy between two distributions, $p_1(x)$ and $p_2(x)$, is defined as

$$R(p_1, p_2) = \int_{R^M} p_1 \log\left(\frac{p_1}{p_2}\right) dx \qquad (1)$$

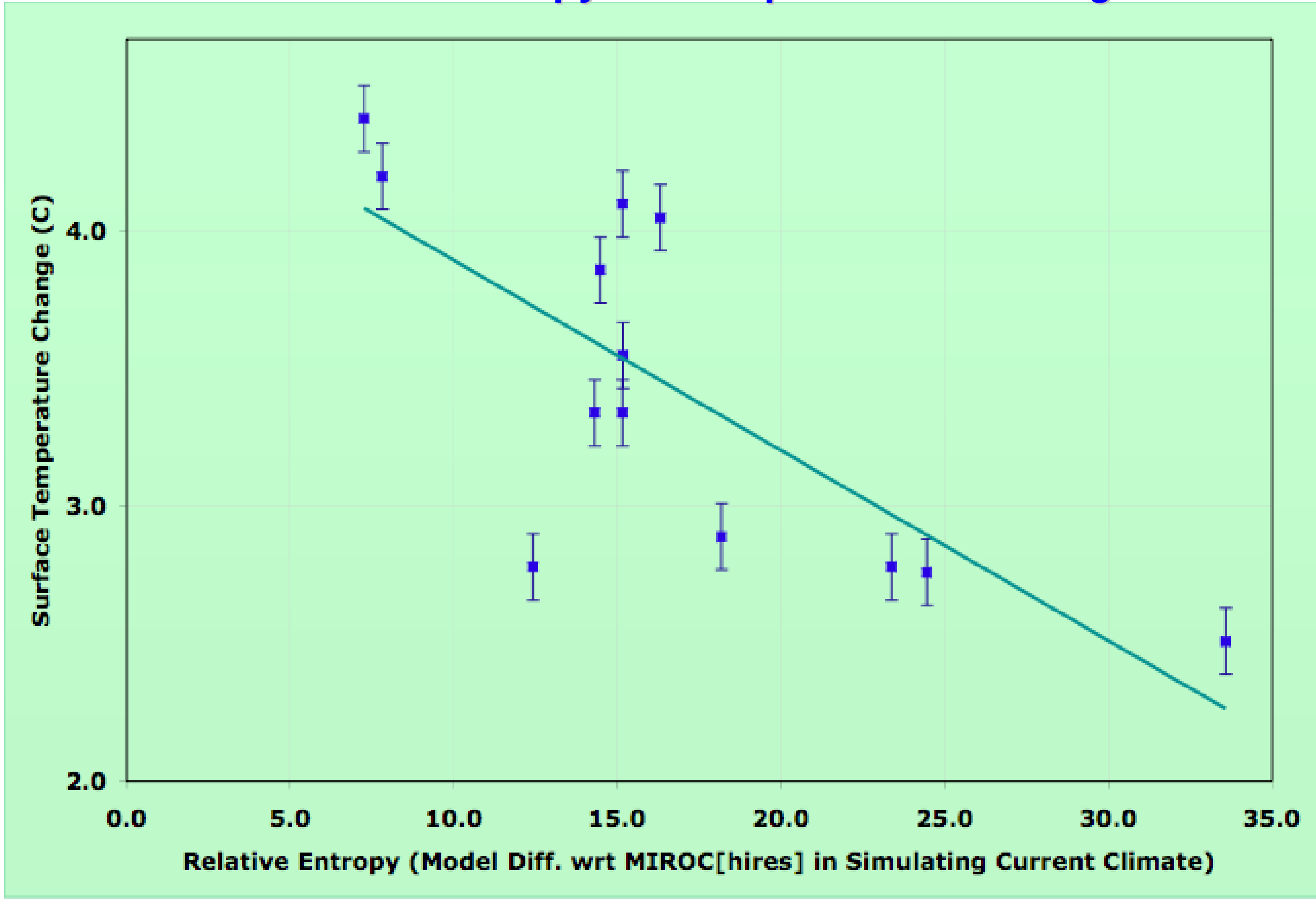
where the integral is a multiple integral over the range of the *M*-dimensional vector *x*.

$$R(p_1, p_2) = \frac{1}{2}\log\left(\frac{|\Sigma_2|}{|\Sigma_1|}\right) + \frac{1}{2} Tr\left\{\Sigma_1\left(\Sigma_2^{-1} - \Sigma_1^{-1}\right)\right\} + \sum_{k=1}^{4}\frac{1}{2}\left(\mu_1^k - \mu_2^k\right)^T \Sigma_1^{-1}\left(\mu_1^k - \mu_2^k\right) \qquad (2)$$

where μ_j^k is the mean of $p_j(x)$ in the *k*th season, representing the annual cycle, Σj is the covariance matrix of $p_j(x)$, assumed independent of season and based on seasonal anomalies. The distribution of observed temperature is appropriately identified with p_1, and the distribution of model simulated temperature with p_2.

Climate Model Fidelity and Projections of Climate Change

Model vs. Model Relative Entropy with respect to MIROC high-resolution



Interim Conclusion:

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.

Factors Limiting Predictability: Future Challenges

Fundamental barriers to advancing weather and climate diagnosis and prediction on timescales from days to years are (partly) (almost entirely?) attributable to gaps in knowledge and the limited capability of contemporary operational and research numerical prediction systems to represent precipitating convection and its multi-scale organization, particularly in the tropics.

(Moncrieff, Shapiro, Slingo, Molteni, 2007)

Seamless Prediction

Since climate in a region is an ensemble of weather events, understanding and prediction of regional climate variability and climate change, including changes in extreme events, will require a unified initial value approach that encompasses weather, blocking, intraseasonal oscillations, MJO, PNA, NAO, ENSO, PDO, THC, etc. and climate change, in a seamless framework.

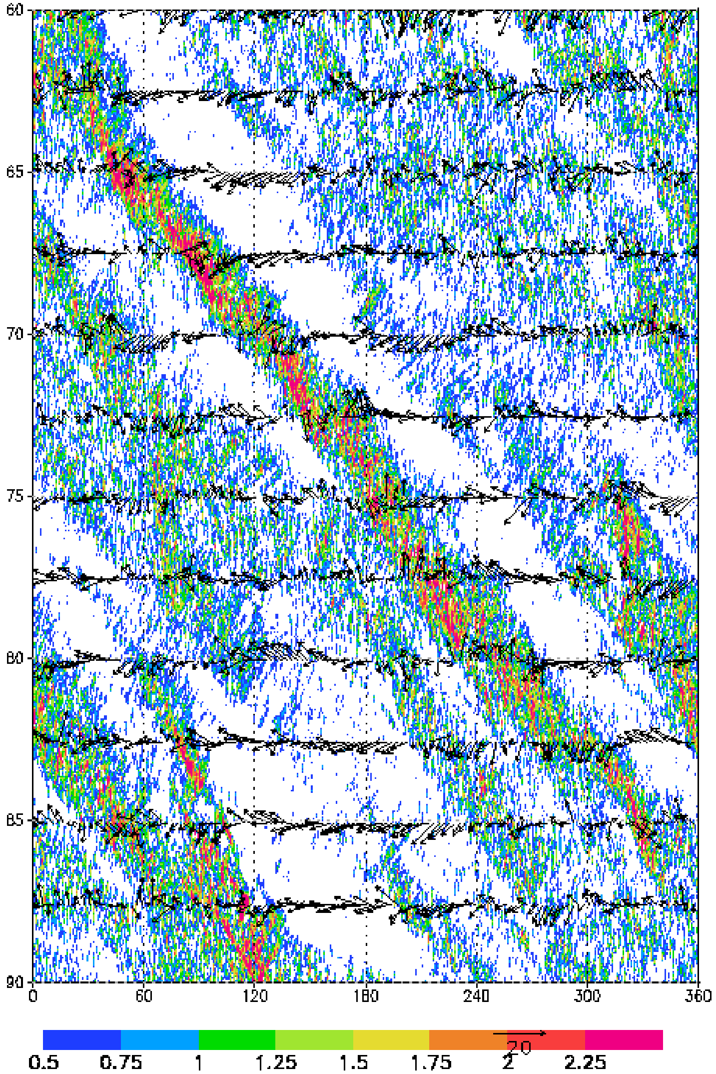
From Cyclone Resolving Global Models
to
Cloud System Resolving Global Models

1. Planetary Scale Resolving Models (1970~): *Δx*~500Km
2. Cyclone Resolving Models (1980~): *Δx*~100-300Km
3. Mesoscale Resolving Models (1990~): *Δx*~10-30Km
4. Cloud System Resolving Models (2000 ~): *Δx*~3-5Km

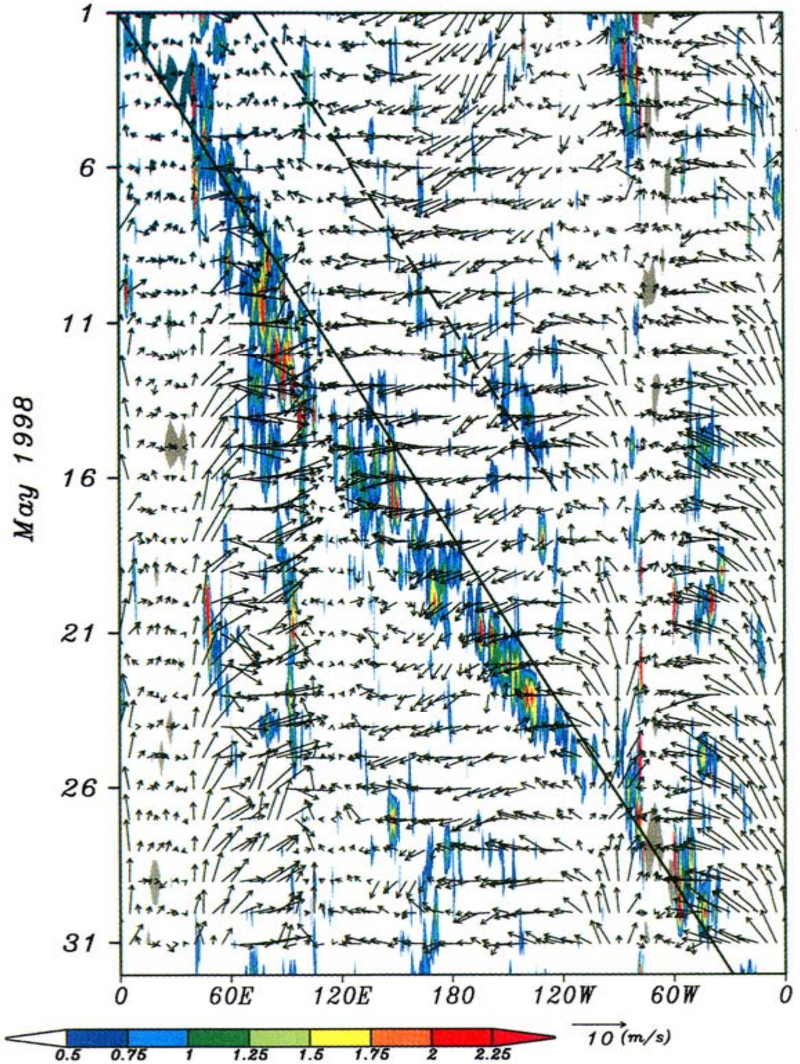
Organized Convection → Cloud System → Mesoscale System → Synoptic Scale → Planetary Scale

Convective Heating → MJO → ENSO → Climate Change

NICAM (7-km)

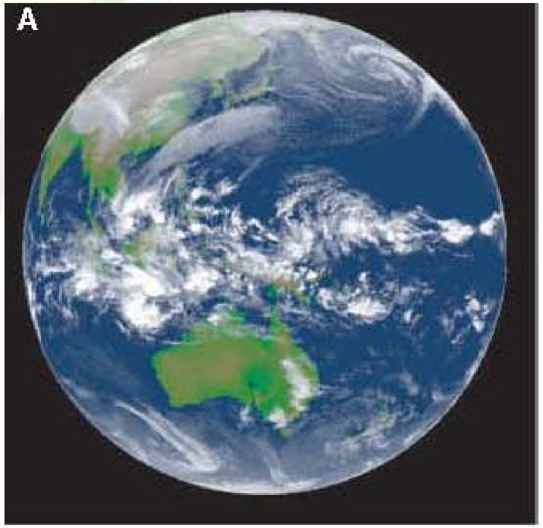


Obs. (Takayabu et al. 1999)

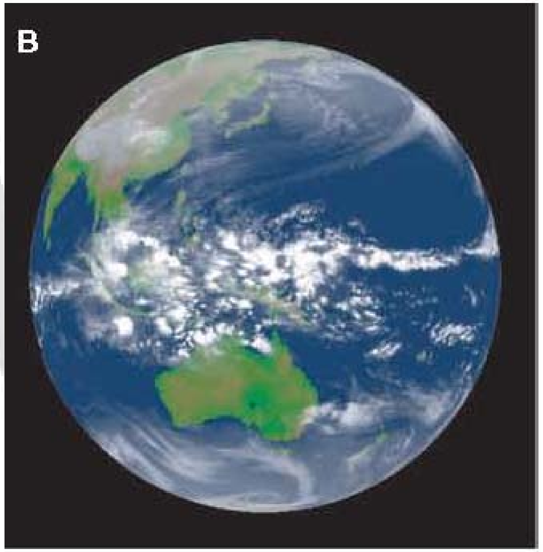


Matsuno (AMS, 2007)

MJO in High Resolution Model



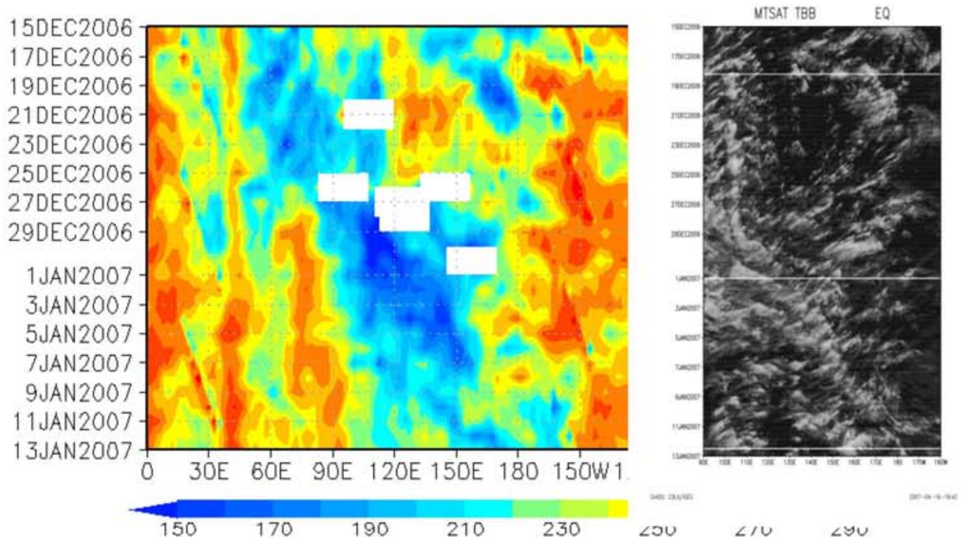
(A) Infrared image from the Multi Functional Transport Satellite (MTSAT-1R) at 00:30 UTC on 31 Dec 2006.



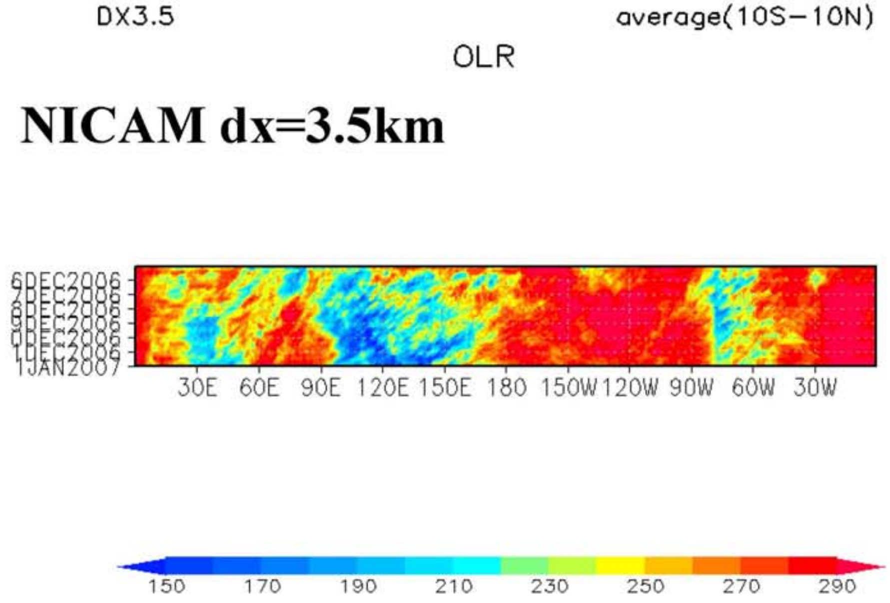
(B) outgoing longwave radiation from the 3.5km-run averaged from 00:00 UTC to 01:30 UTC on 31 Dec 2006.

A Madden-Julian Oscillation Event Realistically Simulated by a Global Cloud-Resolving Model.
H. Miura, M. Satoh, T. Nasuno, A. T. Noda, and K. Oouchi
Science, 1763 (2007); **318,** DOI: 10.1126/science.1148443

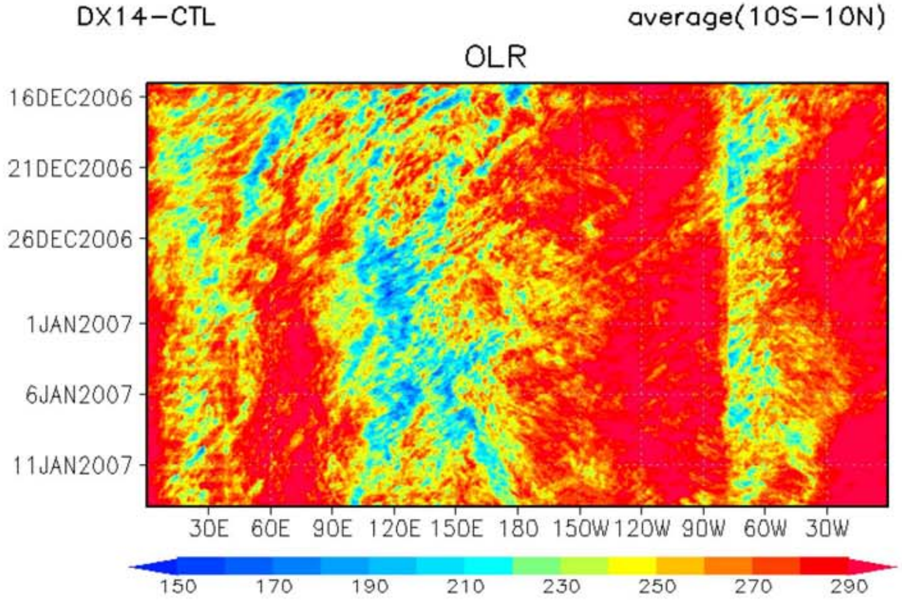
NOAA OLR, MTSAT TBB



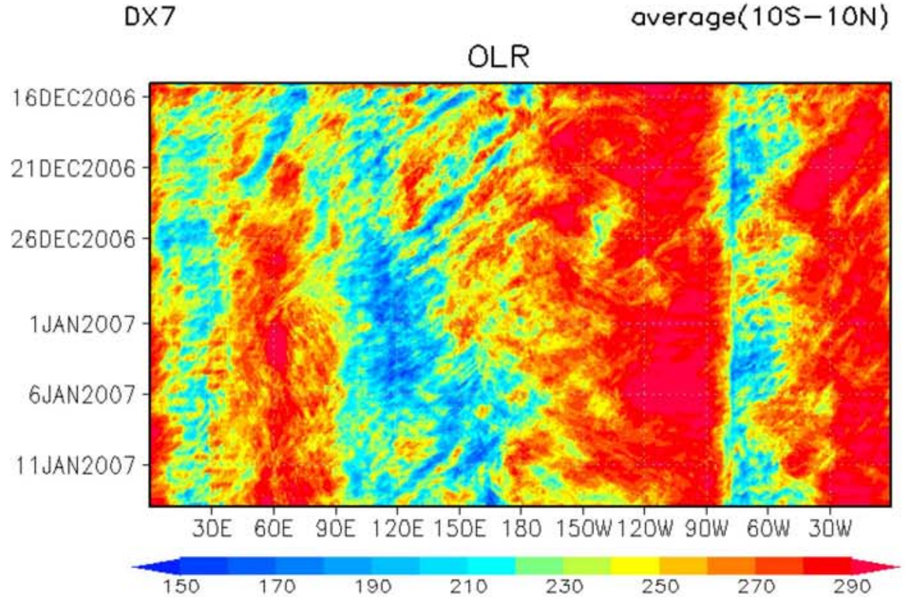
NICAM dx=3.5km



NICAM dx=14km



NICAM dx=7km



Masaki Satoh, JAMSTEC

World Modelling Summit, ECMWF, May 2008

Towards a Hypothetical "Perfect" Model

- Replicate the statistical properties of the past observed climate
  - Means, variances, covariances, and patterns of covariability
- Utilize this model to estimate the limits of predicting the sequential evolution of climate variability
- Better model $\rightarrow$ Better prediction (??)

Societal Needs

- Regional climate prediction from days to decades
  - Global cloud system resolving models are required
- Science based adaptation and mitigation strategies
  - Billion to trillion dollar decisions to be made by policymakers
- Optimum utilization of space and in-situ observation

Revolution in Climate Prediction is Possible and Necessary

Coupled Ocean-Land-Atmosphere Model ~2015

Assumption: Computing power enhancement by a factor of 10^6

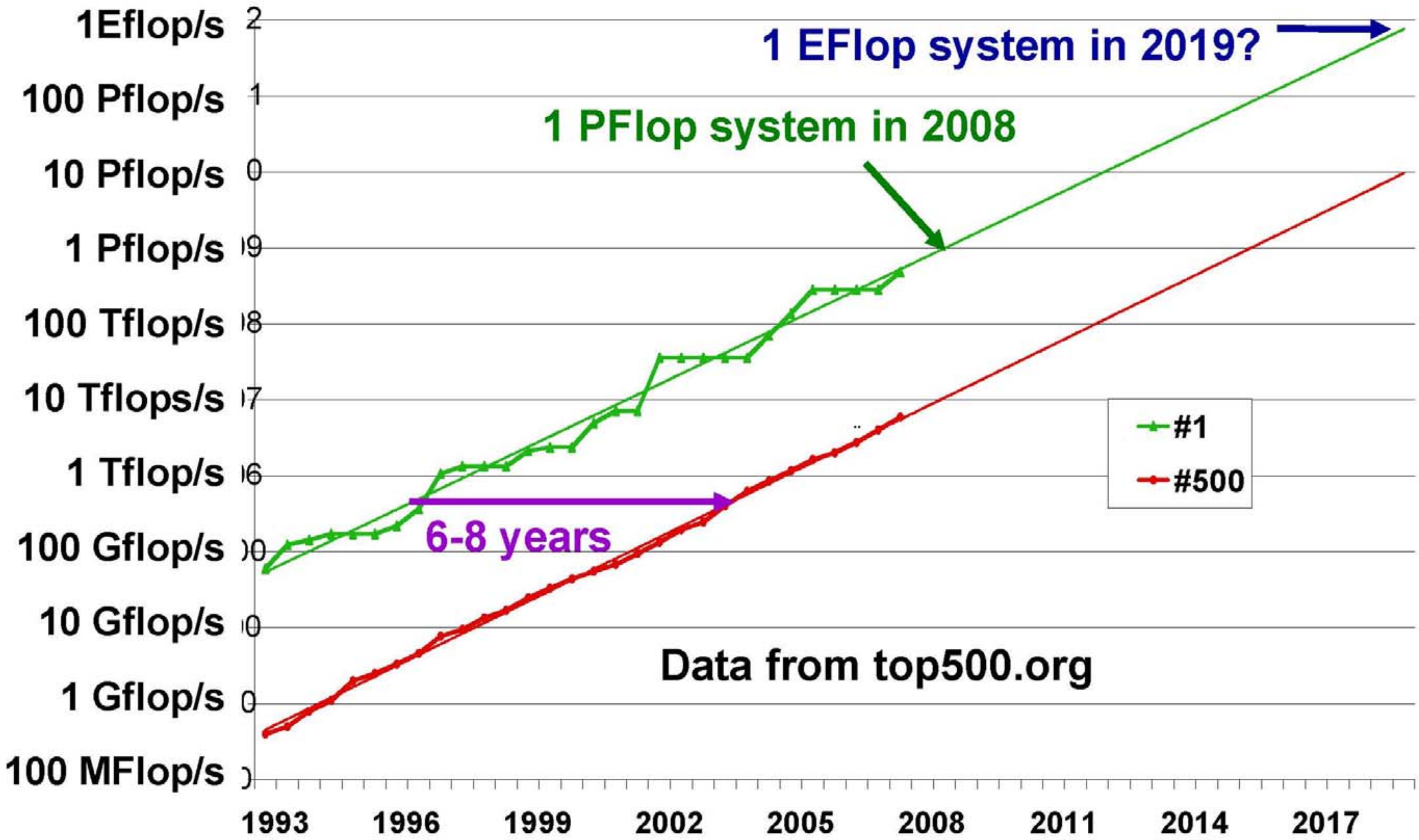
~1 km x ~1 km (cloud-resolving)
100 levels
(Unstructured, adaptive grids)

~100 m
10 levels
Landscape-resolving

~10 km x ~10 km (eddy-resolving)
100 levels
(Unstructured, adaptive grids)

- **Improved understanding of the coupled O-A-B-C-S interactions**
- **Data assimilation & initialization of coupled O-A-B-C-S system**

Petaflop with ~1M Cores By 2008



Slide source Horst Simon, LBNL

Yelick, U.C. Berkeley

World Modelling Summit, ECMWF, May 2008

Challenges

Conceptual/Theoretical

Modeling

Observational

Computational

Institutional

Applications for Benefit to Society

Challenges

Conceptual/Theoretical

ENSO: unstable oscillator?

ENSO: stochastically forced, damped linear system?

(The past 50 years of observations support both theories)

- **Role of weather noise?**

Modeling

- **Systematic errors of coupled models - too large**
- **Uncoupled models not appropriate to simulate Nature in some regions/seasons: CLIMATE IS A COUPLED PROCESS**
- **Atmospheric response to warm and cold ENSO events is nonlinear (SST, rainfall and circulation)**
- **Distinction between ENSO-forced and internal dynamics variability**

Challenges

Observational

- Observations of ocean variability
- Initialization of coupled models

Computational

- Very high resolution models of climate system need million fold increases in computing
- Storage, retrieval and analysis of huge model outputs
- Power (cooling) and space requirements-too large

Challenges

Institutional

- Development of accurate climate (O-L-A) models, assimilation and initialization techniques, require a dedicated team with a critical mass of scientists (~200) and resources (~$100 million per year: $50M computing; $30M research; $20M experiments)

- Climate modeling and prediction efforts should be 10 times NWP but is currently only ~10% of NWP

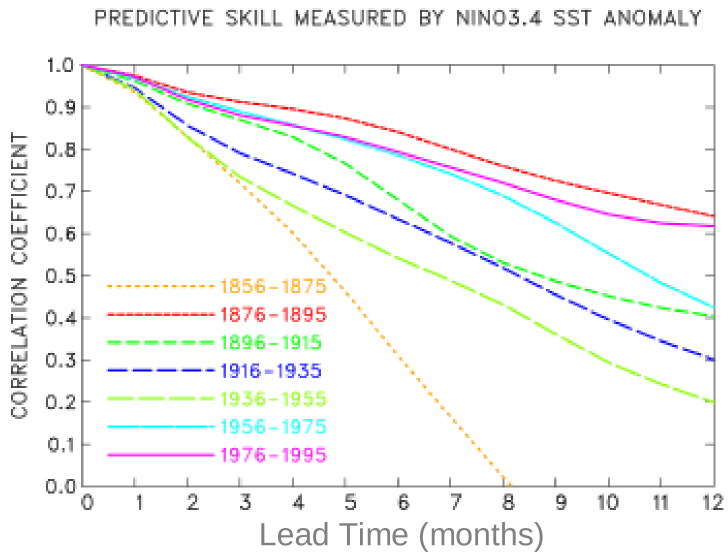
Applications for Benefit to Society

- Educate the consumers about the limits of predictability (uncertainty and unreliability)

- Decision making and risk management using probabilistic predictions

Factors limiting the current skill of forecasts:

- **Model flaws**
- **Flaws in the way the data is used**
  (data assimilation and initialization)
- **Gaps in the observing system**
- **Inherent limits to predictability**
  forecast skill is different in different decades: some times are more predictable than others



Chen, et al 2004 *Nature*

Courtesy of Mark Cane (TTA/ICTP, 2008)

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..)**

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 200 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

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

Summary

1. Models that better simulate the present climate produce the highest values of global warming for the 21st century.

2. Models with low fidelity in simulating climate statistics have low skill in predicting climate anomalies.

3. Revolution in climate prediction is necessary and possible.

4. Seamless Prediction: From cyclone resolving global models to cloud system resolving global models

Nature News

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 provide probabilistic climate predictions that are as useful, and usable, as weather forecasts.

At the end of a four-day summit held last week at the European Centre for Medium-Range Weather Forecasts in Reading, UK, the scientists made the case for a climate-prediction project on the scale of the Human Genome Project. A key component of this scheme, which would cost something [illegible] lars, would be [illegible] research facili[illegible] ter power far b[illegible] rently used in [illegible]

Questions [illegible] the effects of gl[illegible] regions will b[illegible] the capabiliti[illegible] least in part be[illegible] Today's climate models are run on computers in the 10-teraflop range, meaning they are capable of 10 trillion operations a second. Despite this speed, models on these computers are still coarse-grained, cutting the world into cells more than 100 kilometres across.

Increasing computing power 10,000 times — to speeds in the hundreds of petaflops — would allow modellers to study simulations at the kilometre scale, enabling better predictions on the activity of hurricanes and, eventually, the local deep convection that transfers much energy into the upper atmosphere (see 'A real solution?'). This research could then be fed into operational models.

The scientists think they could answer at least some of the 'big' questions on the effects of global warming if the technology was available. But national climate-modelling efforts, [illegible] UK, or [illegible] Atmos[illegible] AR) in [illegible] attract[illegible] unding. [illegible] Simula[illegible] fastest [illegible] with the [illegible] y. [illegible] frankly, in terms of some of the calculations that we're going to do in order to push the climate-prediction effort forward," says Leo Donner, a physical scientist at the Geophysical Fluid Dynamics Laboratory of Princeton University, New Jersey. Antonio Navarra, a climate modeller at the National Institute of Geophysics and Volcanology in Bologna, Italy, spells out the implication: "We're reaching the point where national resources are insufficient to answer the scientific questions."

"We need to be breathtakingly bold" - Leo Donner

More money and cutting-edge challenges would also provide some hope of retaining highly trained programmers with expertise in climate modelling. Conference chair Jagadish Shukla of the Institute of Global Environment and Society in Calverton, Maryland, says this resource is "decreasing faster than the sea ice" as staff are lured from research by the financial rewards and job security provided by companies such as Google.

Addressing the summit on its opening day, economist Jeffrey Sachs, the director of the Earth Institute at Columbia University, New York, said that there would be "a lot of interest among politicians in investing the hundreds of millions of dollars necessary, if scientists can provide answers to key questions... such as future food supply". Although governments are the obvious source of funding, Lawrence Gates, a now-retired climate scientist from the Lawrence Livermore National Laboratory in California, urged the attendees to explore philanthropic options.

How increased investment is divided between new facilities and existing ones is likely to be controversial. Some fear that a single global institute could threaten national centres, potentially taking the onus off governments to fund the institutions that are closest to stakeholders and could be expected to provide the predictions that have most real-world use. "Everyone is agreed that there needs to be a substantial investment in climate modelling, but whether a single centre is the solution is another question. There may be other ways," says John Mitchell, the chief scientist at the Met Office. Donner says that a sketch, presented on the conference's last day, of how the global facility might fit into the research world "seems to relegate national centres to little more than distributors of data".

However, Shukla was adamant that "every science breakthrough leads to the formation of an a darwinian change in the way we are working and we shouldn't be afraid of that," says Navarra. The meeting could have come to grief on such differences, according to Julia Slingo, the director of the Centre for Global Atmospheric Modelling at the University of Reading, but in the end the level of consensus, she says, was "fantastic".

Various attendees expressed frustration at the fact that the new facility could not be funded purely on the basis of the world-class science it would do — and indeed the fact that it would produce great research might count against it, making it seem more like a "toy for the boys" than a policy-informing instrument.

"If we just ask for enhanced understanding, then we have very little chance of getting the necessary funding," warned Shukla. But as Mitch Moncrieff from NCAR put it "we need a quantum leap in research to provide better predictions, even if the politicians don't get that". And there was widespread agreement that they need to get it fast. "We need a revolution as it has got to be done extremely quickly", said Brian Hoskins, director of the Grantham Institute for Climate Change at Imperial College London, UK.

Olive Heffernan

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

State of the art: a model (left) from the UK National Centre for Atmospheric Science and the Met Office running on Japan's Earth Simulator.

A real solution?

Is the answer to climate prediction sitting in your pocket? Lenny Oliker, John Shalf and Michael Wehner of the Lawrence Berkeley National Laboratory in California think it could be. In a proposal discussed at the Reading climate-modelling summit (see main story) they suggest that the very small processors in mobile phones might be ideal components for very large climate computers — if 20 million of them could be wired together in the right way.

To run at the sort of kilometre-scale resolution that could accurately model cloud processes, they argue, a computer has to be able to run at a sustained speed of around 10 petaflops, and a peak speed of perhaps 20 times that or more. If built with traditional high-performance chips such as AMD's Opteron or Intel's Xeon, such a machine would be extremely expensive and power-hungry — perhaps requiring as much as 100 megawatts. Processors developed for cell phones are small — less than a square millimetre in area — and frugal in their power requirements, needing less than a tenth of a watt each. These advantages, the researchers argue, far outweigh the slower speed at which such processors work and would permit construction of a multi-petaflop computer that was much cheaper both to build and to run.

In some ways this is an extrapolation of the approach that IBM has taken to its successful Blue Gene line of supercomputers, which also rely on many relatively small and slow processors. But it goes further in the sheer number of processors and in an architecture designed specifically for the demands of climate calculations, rather than general-purpose computing.

Per Nyberg of Seattle-based supercomputer makers Cray — which, like rivals IBM and NEC, sent speakers to the summit with an eye to business opportunities — was understandably sceptical. "You can come up with back-of-an-envelope calculations about how cheaply you can build a computer but you have to be very, very careful." He argues that radical approaches can founder on software and on efficiency of usage, with a useful rate of number crunching far below the peak speed. And if the machine doesn't work as advertised, the expense of developing programs for it could be wasted. Wehner acknowledges the risks, but thinks careful prototyping and code development could minimize them. "We should build it and see," he says. **Oliver Morton**

THANK YOU!

ANY QUESTIONS?

nature

www.nature.com/nature

Vol 453 | Issue no. 7193 | 15 March 2008

The next big climate challenge

Governments should work together to build the supercomputers needed for future predictions that can capture the detail required to inform policy.

Few scientific creations have had greater impact on public opinion and policy than computer models of Earth's climate. These models, which unanimously show a rising tide of red as temperatures climb worldwide, have been key over the past decade in forging the scientific and political consensus that global warming is a grave danger.

Now that that consensus is all but universal, climate modellers are looking to take the next step, and to convert their creations from harbingers of doom to tools of practical policy. That means making their simulations good enough to guide hard decisions, from targets for carbon dioxide emissions on a global scale to the adaptations required to meet changing rainfall and extreme weather events on regional and local scales.

Today's modelling efforts, though, are not up to that job. They all agree on the general direction in which the climate will move as greenhouse gases build up, but they do not reliably capture all the nuances of today's climate, let alone tomorrow's. Moreover, each model differs from reality in different ways.

It was in recognition of this that a cross section of climate modellers gathered for a 'summit' at the European Centre for Medium-Range Weather Forecasts in Reading, UK, last week (see page 268). The meeting called for an ongoing project aimed at understanding and modelling the climate system well enough to provide the sorts of prediction that policy-makers and other stakeholders need — or, at the very least, to show why such prediction might not, in fact, be achievable. Key to this project would be one or more dedicated facilities offering world-class computational resources to the climate-modelling community.

A clear resolution

Those resources are notably lacking at the moment. The world's very fastest computers run at hundreds of teraflops (which is to say, hundreds of trillions of mathematical operations a second), and the first forays into the petaflop range are expected by the end of the year. But today's climate models rarely run on machines that can manage more than a few tens of teraflops. This translates into spatial resolutions of a hundred kilometres or so. There was a general agreement at the summit that more realistic models will require resolutions in the tens of kilometres, at least. And even higher resolutions — a kilometre or less, say — may well be needed to handle such critical issues as cloud formation realistically. Hence the need for computers a couple of generations beyond the current state of the art.

Meeting this need is not just a matter of buying a supercomputer. It means moving climate modelling up the petaflop pecking order for a sustained period of time. One plausible goal might be to assure that the most powerful supercomputer in the public realm should be devoted to climate work by 2012, and that the field's lead should be regularly renewed for several computer generations after that. After all, the fastest computers are nearly always paid for out of the world's public purses, often for use in areas of national security such as communications intelligence or nuclear weapons design. And climate prediction is a national security issue if ever there was one.

If funding agencies were to embrace such a goal, the implications would go well beyond money. Profound changes would be required of the community itself. Because the cost over a decade or more might easily top a billion dollars, such an investment in cutting-edge climate modelling would all but certainly have to be done multinationally, or even globally. This would pull climate modelling into the world of 'big science' alongside space telescopes and particle accelerators — a transformation that would require new, and possibly disruptive, institutional arrangements.

> "Climate prediction is a national security issue if ever there was one."

Living large

Aware of budgetary realities and the history of scientific centralizations, national centres of climate modelling and expertise such as Britain's Hadley Centre or the US National Center for Atmospheric Research might reasonably see the development as a threat. International collaborations such as CERN — the European particle-physics laboratory — and the European Southern Observatory have served the scientific communities of their member states well, yet have undoubtedly taken their toll on national facilities. With the upcoming inauguration of the Large Hadron Collider (LHC) at CERN, Europe will have the world's best particle-physics facility — but it will have very few of its other particle-physics facilities.

This analogy is not, however, fully convincing. Building an LHC does not make it significantly easier to build lesser accelerators. But advances in supercomputing do make it easier to build computers formerly known as super: a petaflop will seem slow in less than a decade. A world facility where teams of researchers try out very high resolutions and new techniques, and where software engineers and programmers learn how to get the most out of bleeding-edge hardware, will require a network of more modest centres around the world from which to draw its problem-list and into which to feed its insights. A range of operational climate-prediction capabilities could help keep modelling close to stakeholders' needs, and lessen the all-eggs-in-one-basket group-think risk of a global facility.

An ambitious climate-modelling facility dedicated to solving problems beyond the capability of today's national programmes carries risks, but they are risks worth taking. The world's governments — and even, conceivably, its high-tech philanthropists — should listen to the modellers. Big science is often, and gloriously, justified on the basis of pure intellectual excitement. This field offers that — and a chance to improve the world as well. ■

"Climate prediction is a national security issue if ever there was one"

Challenge

The world recognizes that the consequences of global climate change constitute one of the most important threats facing humanity. The peoples, governments, and economies of the world must develop mitigation and adaptation strategies, which will require investments of trillions of dollars, to avoid the dire consequences of climate change. The development of reliable, science-based adaptation and mitigation strategies will only be possible through a revolution in regional climate predictions, supported by appropriate climate observations and assessment, and the delivery of this information to society.

Summit Declaration

1.Considerably improved prediction of the changes in the statistics of regional climate, especially of extreme events and high-impact weather, are required to assess the impacts of climate change and variations, and to develop adaptive strategies to ameliorate their effects on water resources, food security, energy, transport, coastal integrity, environment and health. Investing today in climate science will lead to significantly reduced costs of coping with the consequences of climate change tomorrow.

Summit Declaration

2. Despite tremendous progress in climate modeling and the capability of high-end computers in the past 30 years, our ability to provide robust estimates of the risk to society, particularly from possible catastrophic changes in regional climate, is constrained by limitations in computer power and scientific understanding. There is also an urgent need to build a global scientific workforce that can provide the intellectual power required to address the scientific challenges of predicting climate change and assessing its impacts with the level of confidence required by society.

Summit Declaration

3. Climate prediction is among the most computationally demanding problems in science. It is both necessary and possible to revolutionize regional climate prediction: *necessary* because of the challenges posed by the changing climate, and *possible* by building on the past accomplishments of prediction of weather and climate. However, neither the necessary scientific expertise nor the computational capability is available in any single nation. A comprehensive international effort is essential.

Summit Declaration

4. The Summit strongly endorsed the initiation of a Climate Prediction Project coordinated by the World Climate Research Program (WCRP), in collaboration with the World Weather Research Program (WWRP) and the International Geosphere-Biosphere Program (IGBP), and involving the national weather and climate centers, as well as the wider research community. The goal of the project is to provide improved global climate information to underpin global mitigation negotiations and for regional adaptation and decision-making in the 21st century.

WCRP World Climate Research Programme

WWRP World Weather Research Programme

GLOBAL IGBP CHANGE

Summit Declaration

5. The success of the Climate Prediction Project will critically depend on significantly enhancing the capacity of the world's existing weather and climate research centers for prediction of weather and climate variations including the prediction of changes in the probability of occurrence of regional high-impact weather. This is particularly true for the developing countries whose national capabilities need to be increased substantially.

Summit Declaration

6. An important and urgent initiative of the Climate Prediction Project will be a world climate research facility for climate prediction that will enable the national centers to accelerate progress in improving operational climate prediction at all time scales, especially at decadal to multi-decadal lead times. This will be achieved by increasing understanding of the climate system, building global capacity, developing a trained scientific workforce, and engaging the global user community.

Summit Declaration

7. The central component of this world facility will be one or more dedicated high-end computing facilities that will enable climate prediction at the model resolutions and levels of complexity considered essential for the most advanced and reliable representations of the climate system that technology and our scientific understanding of the problem can deliver. This computing capability acceleration, leading to systems at least a thousand times more powerful than the currently available computers, will permit scientists to strive towards kilometer-scale modeling of the global climate system which is crucial to more reliable prediction of the change of convective precipitation especially in the tropics.

Summit Declaration

8. Access to significantly increased computing capacity will enable scientists across the world to advance understanding and representation of the physical processes responsible for climate variability and predictability, and provide a quantum leap in the exploration of the limits in our ability to reliably predict climate with a level of detail and complexity that is not possible now. It will also facilitate exploration of biogeochemical processes and feedbacks that currently represent a major impediment to our ability to make reliable climate projections for the 21st century.

Summit Declaration

9. Sustained, long-term, global observations are essential to initialize, constrain and evaluate the models. Well documented and sustained model data archives are also essential for enabling a comprehensive assessment of climate predictions. An important component of the Climate Prediction Project will therefore be an accessible archive of observations and model data with appropriate user interface and knowledge-discovery tools.

Summit Declaration

10. To estimate the quality of a climate prediction requires an assessment of how accurately we know and understand the current state of natural climate variability, with which anthropogenic climate change interacts. All aspects of estimating the uncertainty in climate predictions pose an extreme burden on computing resources, on the availability of observational data, and on the need for attribution studies. The Climate Prediction Project will enable the climate research community to make better estimates of model uncertain[illegible] assess how they limit the skill of climate predictions.

Summit Declaration

11. Advances in climate prediction will require close collaboration between the weather and climate prediction research communities. It is essential that decadal and multi-decadal climate prediction models accurately simulate the key modes of natural variability on the seasonal and sub-seasonal time scales. Climate models will need to be tested in sub-seasonal and multi-seasonal prediction mode also including use of the existing and improved data assimilation and ensemble prediction systems. This synergy between the weather and climate prediction efforts will motivate further the development of seamless prediction systems.

Summit Declaration

12. The Climate Prediction Project will help humanity's efforts to cope with the consequences of climate change. Because the intellectual challenge is so large, there is great excitement within the scientific community, especially among the young who want to contribute to make the world a better place. It is imperative that the world's corporations, foundations, and governments embrace the Climate Prediction Project. This project will help sustain the excitement of the young generation, to build global capacity, especially in developing countries, and to better prepare humanity to adapt to and mitigate the consequences of climate change.

Summary

1. Models that better simulate the present climate produce the highest values of global warming for the 21st century.

2. Models with low fidelity in simulating climate statistics have low skill in predicting climate anomalies.

3. Revolution in climate prediction is necessary and possible.

4. Seamless Prediction: From cyclone resolving global models to cloud system resolving global models

THANK YOU!

ANY QUESTIONS?