12 November. 2013, ICES Geneva

Asian Monsoons in a changing climate

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Center for Ocean-Land-Atmosphere Studies (COLA)

Institute of Global Environment and Society (IGES)

"Revolution in Climate Prediction is Both Necessary and Possible"

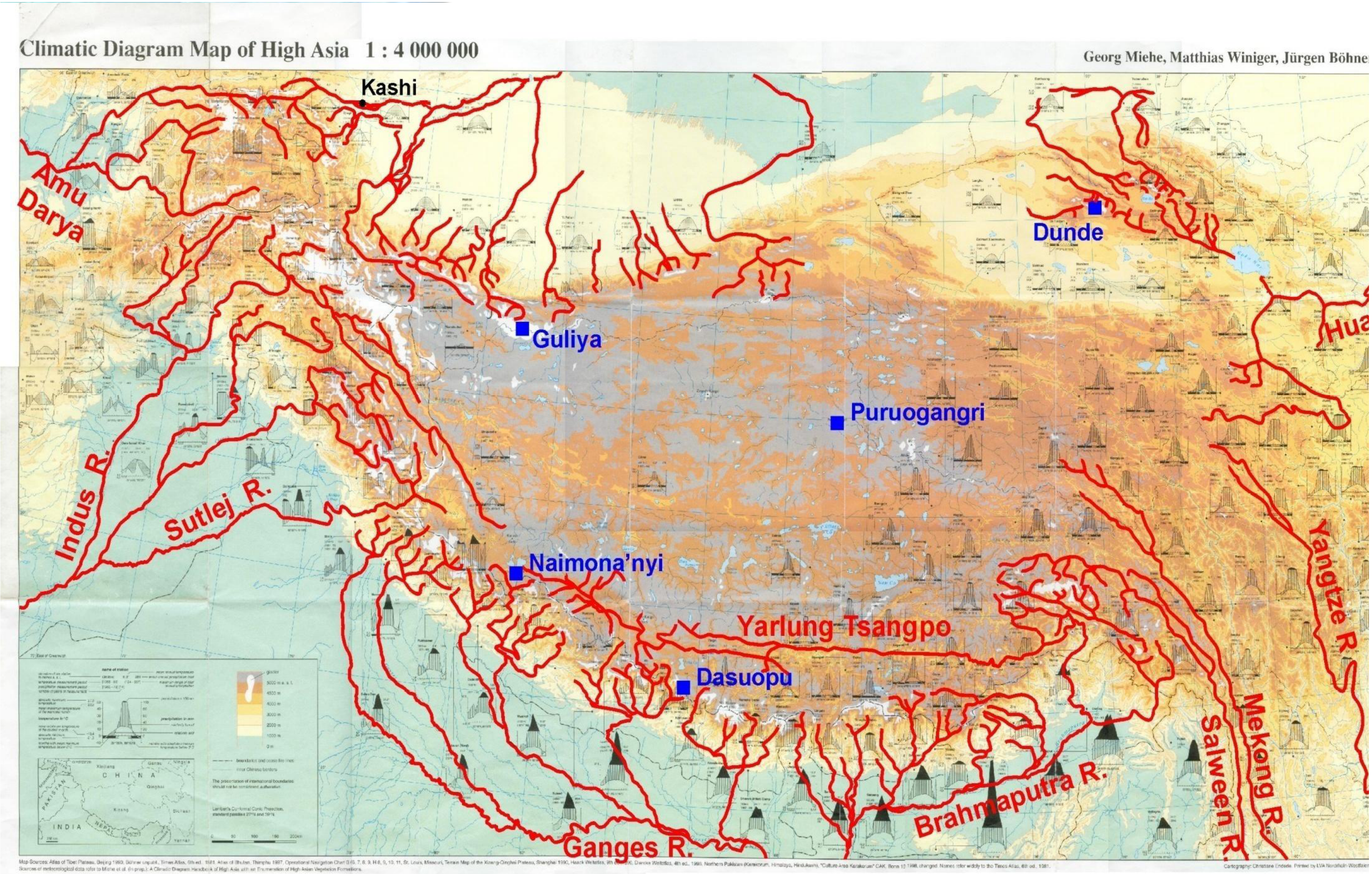
Shukla, Hagedorn, Hoskins, Kinter, Marotzke, Miller, Palmer, and Slingo, BAMS, Feb. 2009, pp 175-178

IGES

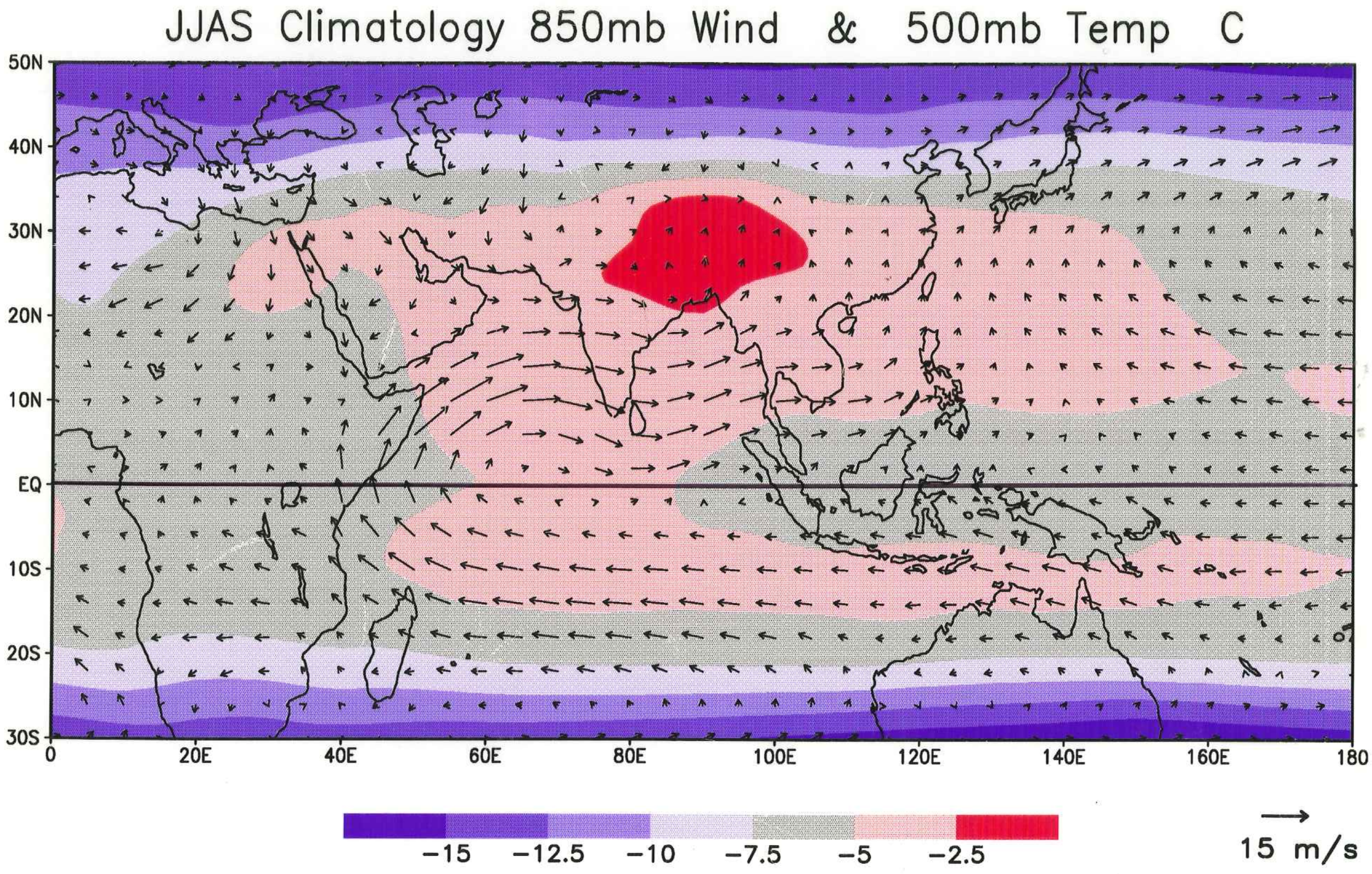
Center of Ocean-Land-Atmosphere studies COLA

George Mason University

Tibetan Plateau



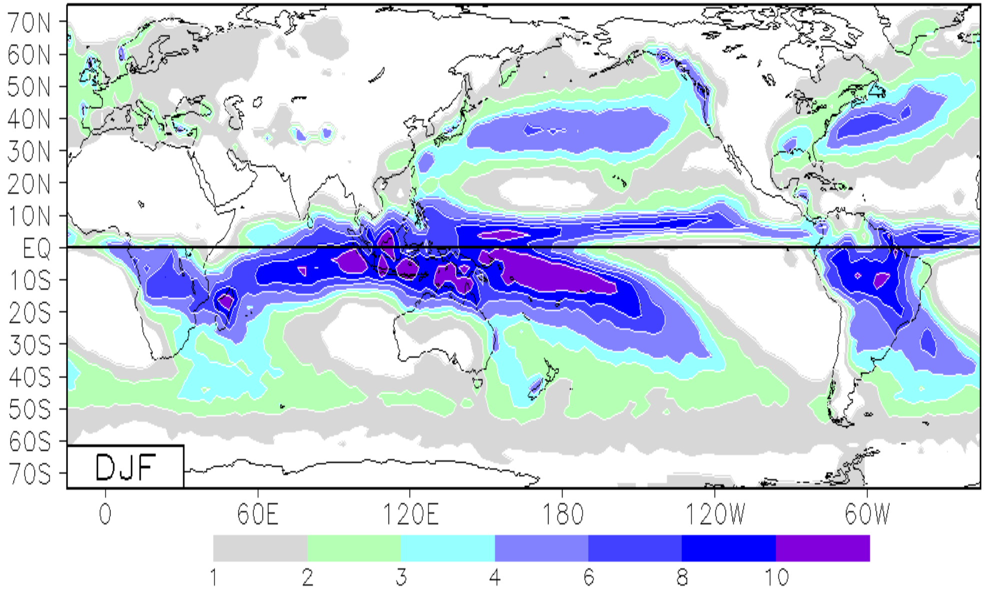
Himalayan glaciers store about 12,000 cubic kilometers of freshwater in ~15,000 glaciers and are the lifeline for millions of people (IPCC, 2007)


JJAS Climatology 850mb Wind & 500mb Temp C
50N
40N
30N
20N
10N
EQ
10S
20S
30S
0
20E
40E
60E
80E
100E
120E
140E
160E
180
−15
−12.5
−10
−7.5
−5
−2.5
15 m/s

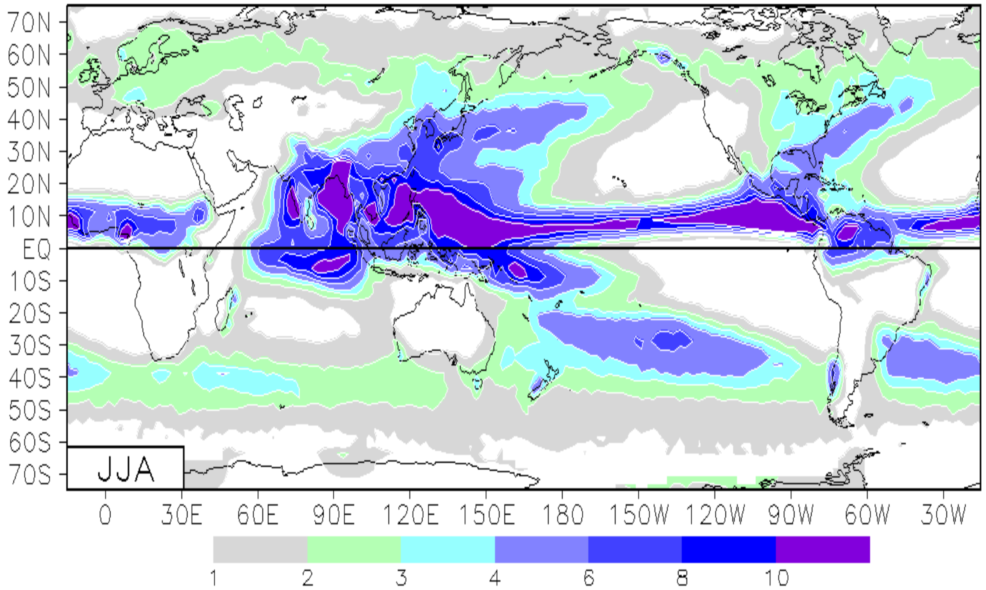
Climatological Precipitation

CMAP Precipitation for 1979-2007 (mm/day)

DJF



JJA

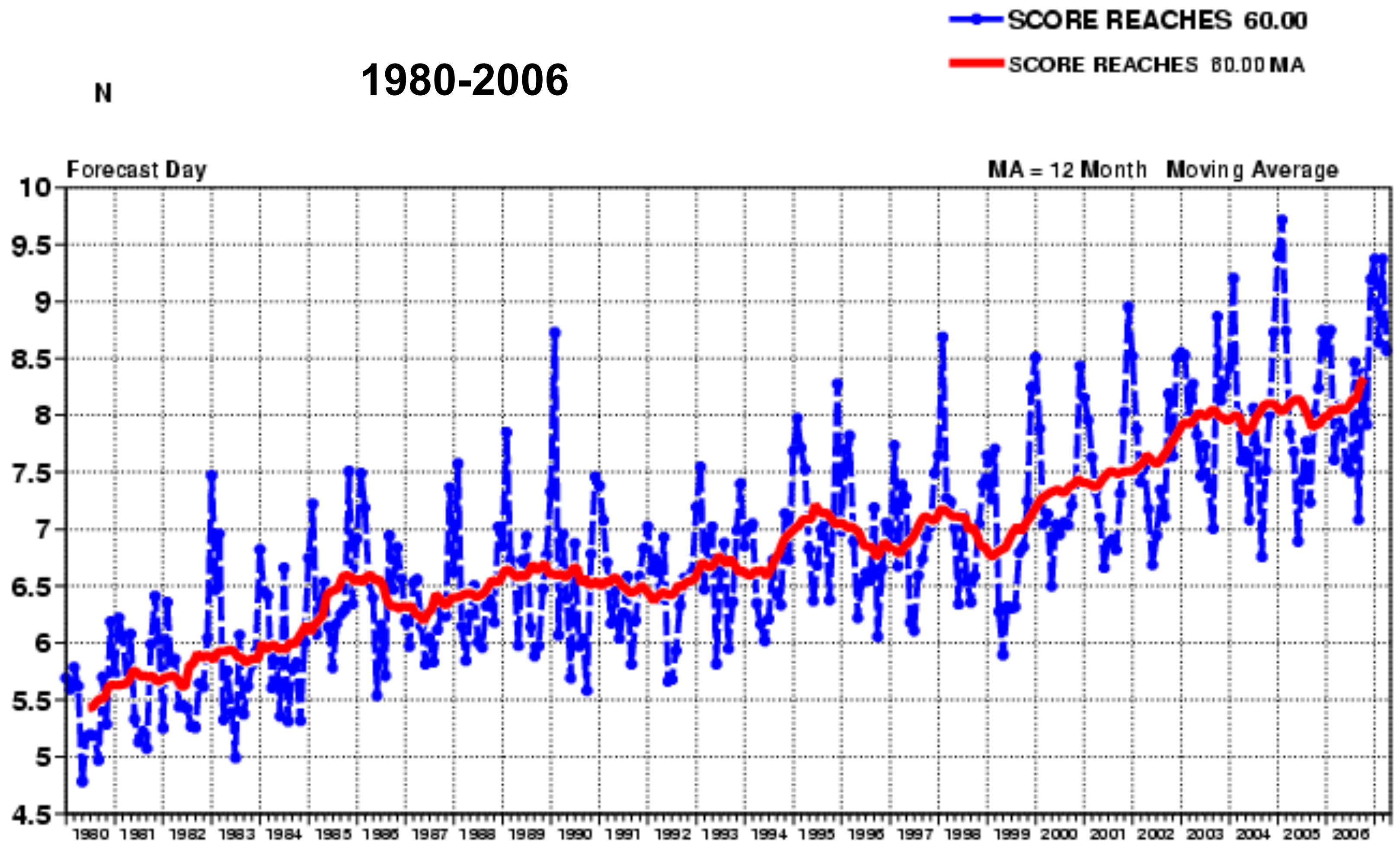


Outline

- Introduction
- Model Fidelity and Predictability
- Prediction of Asian Monsoons in a Changing Climate
- Climate CERN

ERA Forecast Verification

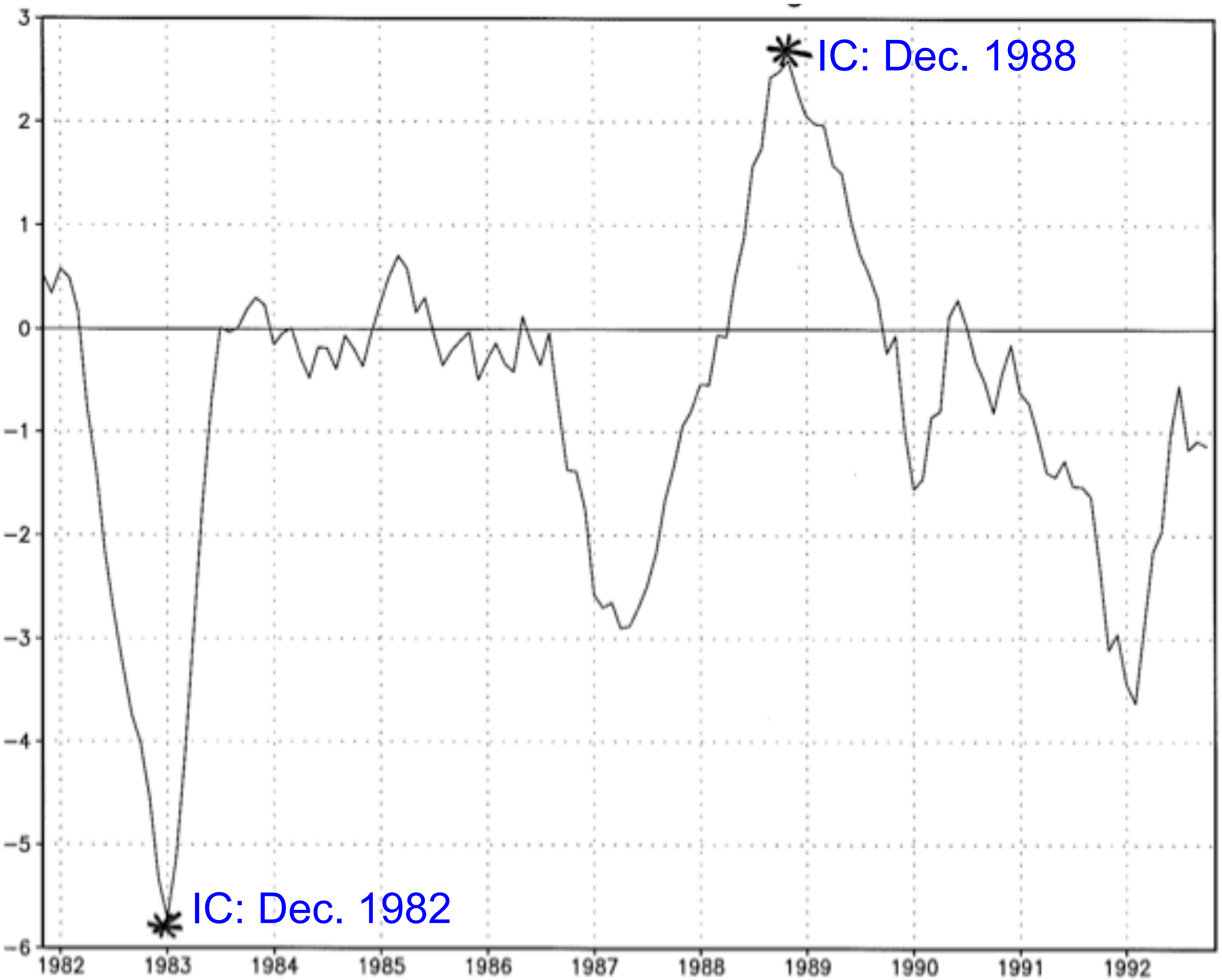
Anomaly Correlation of 500 hPa GPH, 20-90N



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

"Predictability in the midst of chaos"

Observed 5-month running mean SOI

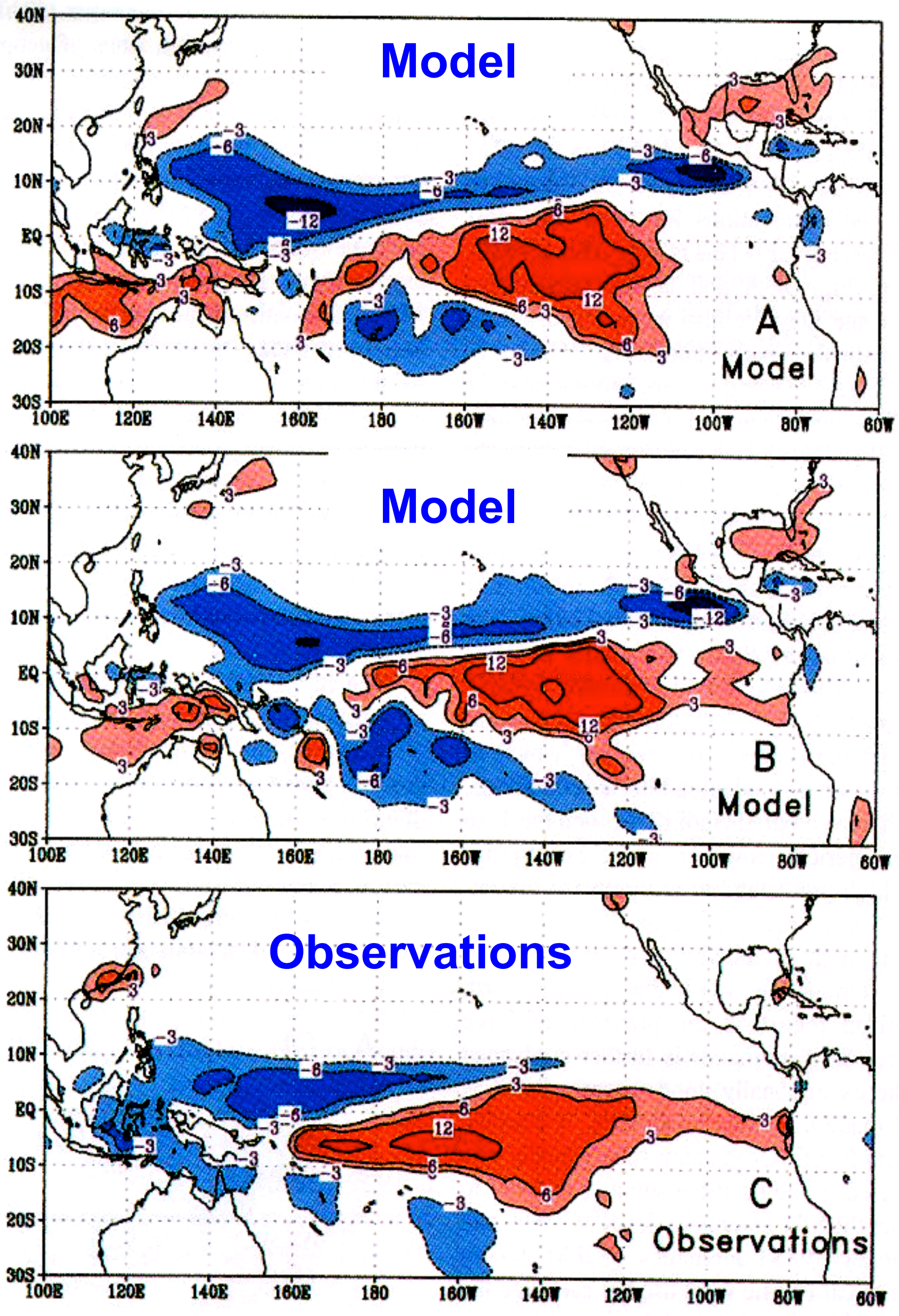


JFM Mean Rainfall Anomalies

"Predictability in the Midst Of Chaos"

IC: Dec. 1988

IC: Dec. 1982



B.C.(SST): 1982 -83

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Hypothesis

Models that simulate climatology "better" make better predictions.

Definition: Fidelity refers to the degree to which the climatology of the forecasts (including the mean and variance) matches the observed climatology

Testing the Hypothesis: Data

DEMETER Data

- 7 global coupled atmosphere-ocean models
- 9 ensemble members
- 1980-2001 (22 years)
- Initial conditions: 1 February, 1 May, 1 August, 1 November
- Integration length: 6 months

Climate Model Fidelity and Predictability

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

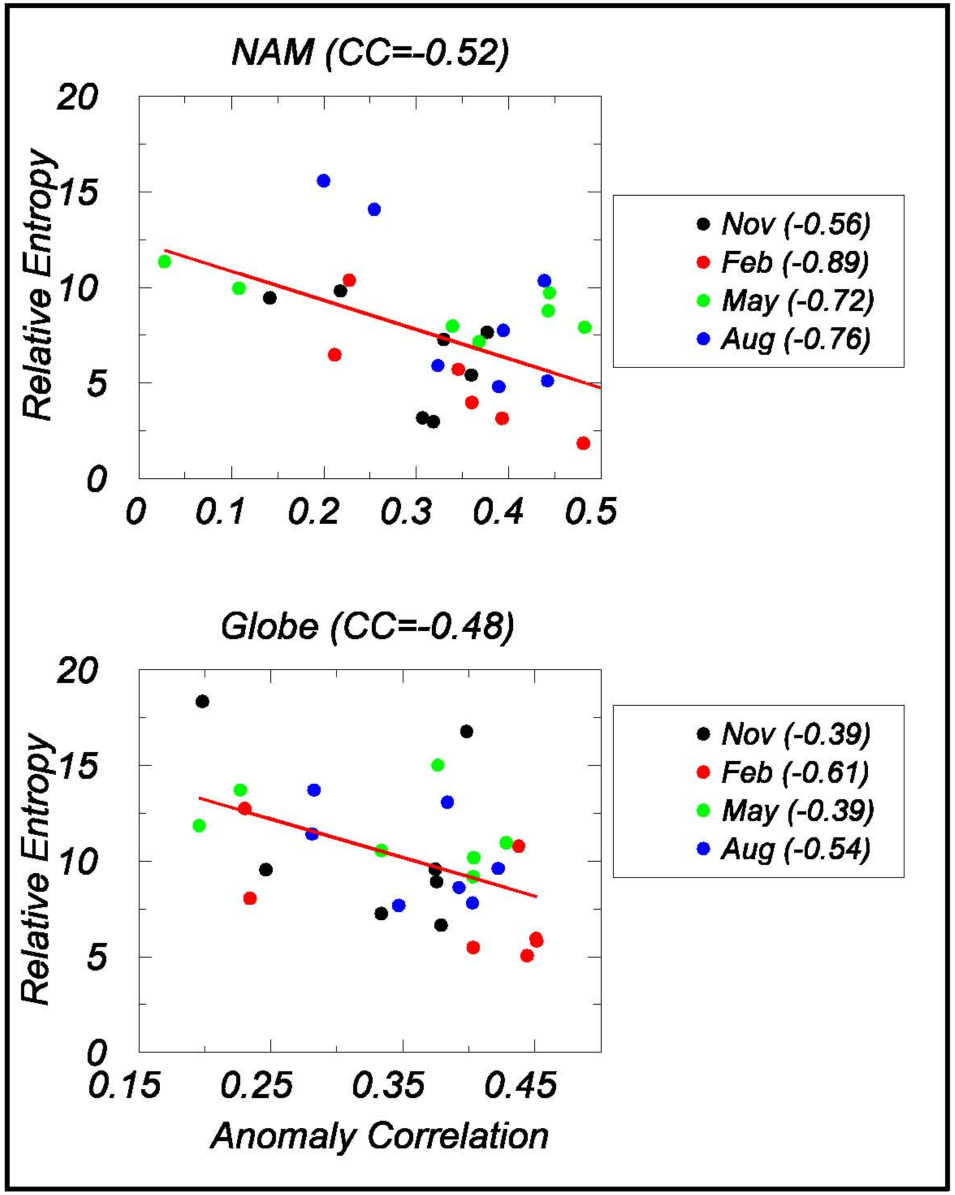
$$R(p_1, p_2) = \int_{R^M} p_1 \log\left(\frac{p_1}{p_2}\right) dx \qquad (1)$$

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.

Fidelity vs. Skill



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.

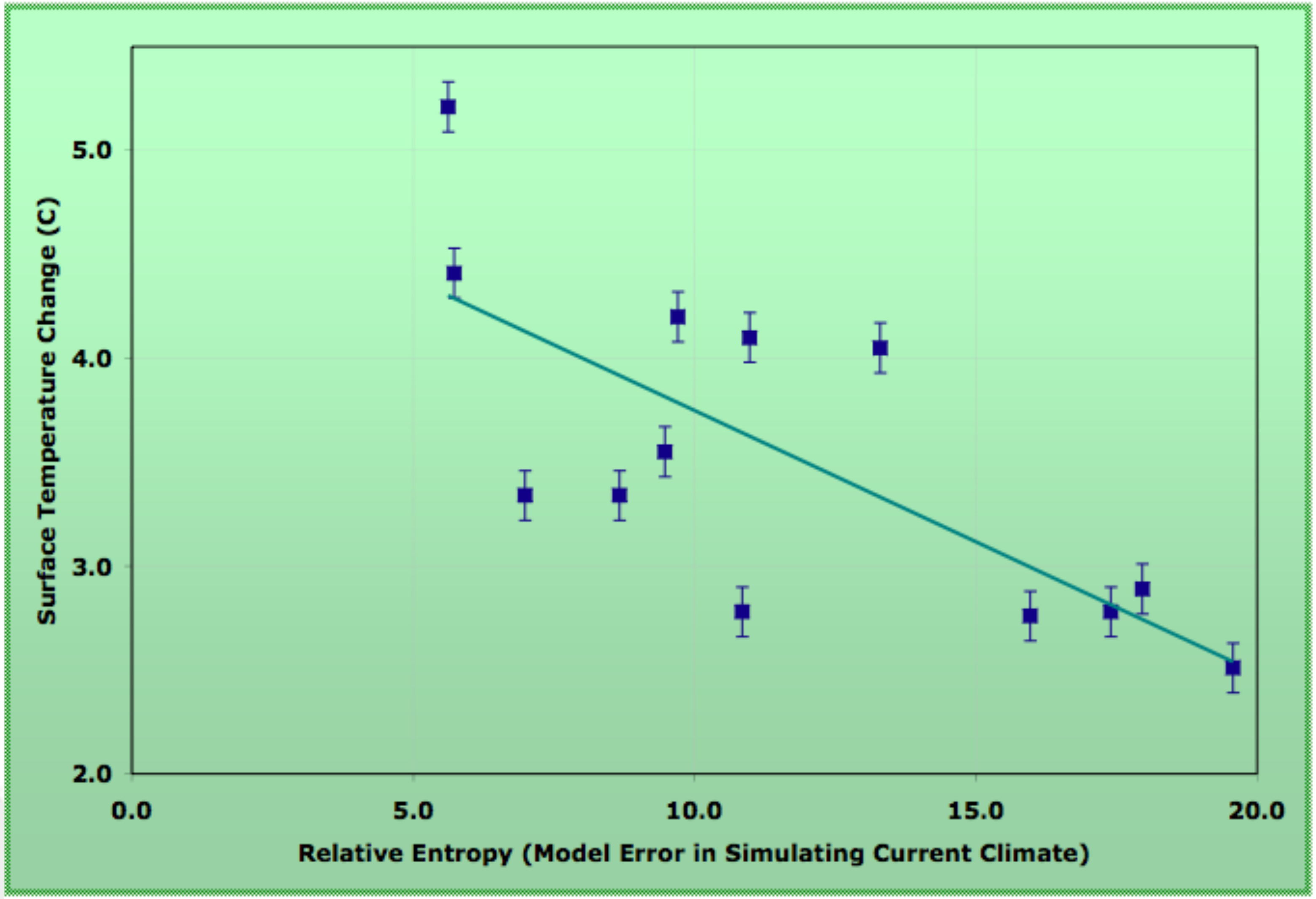
Models with better climatology tend to have better skill.

Courtesy of Tim DelSole

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

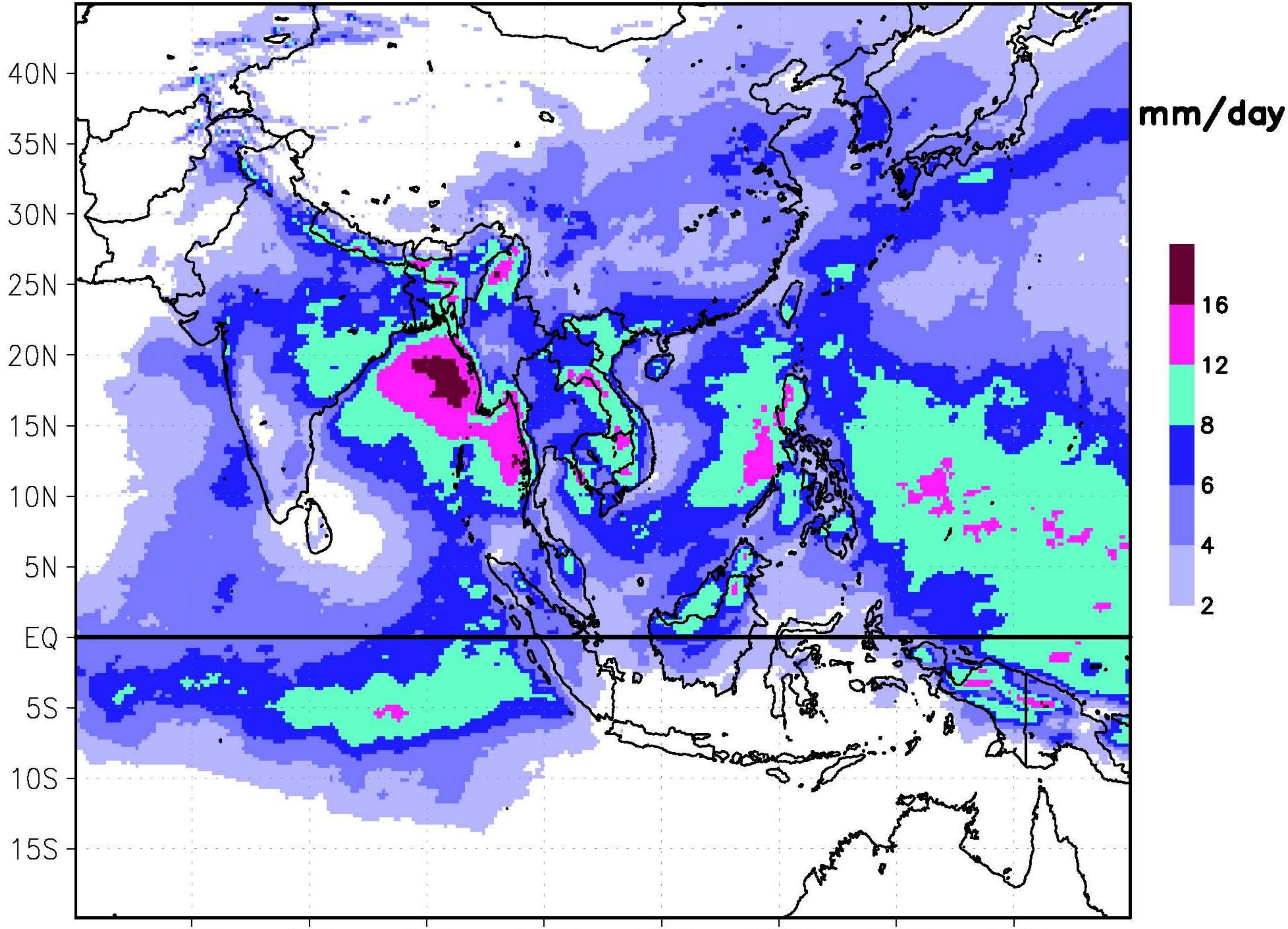


Model sensitivity versus model relative entropy for 13 IPCC AR4 models. Sensitivity is defined as the surface air temperature change over land at the time of doubling of CO_2. Relative entropy is proportional to the model error in simulating current climate. Estimates of the uncertainty in the sensitivity (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.

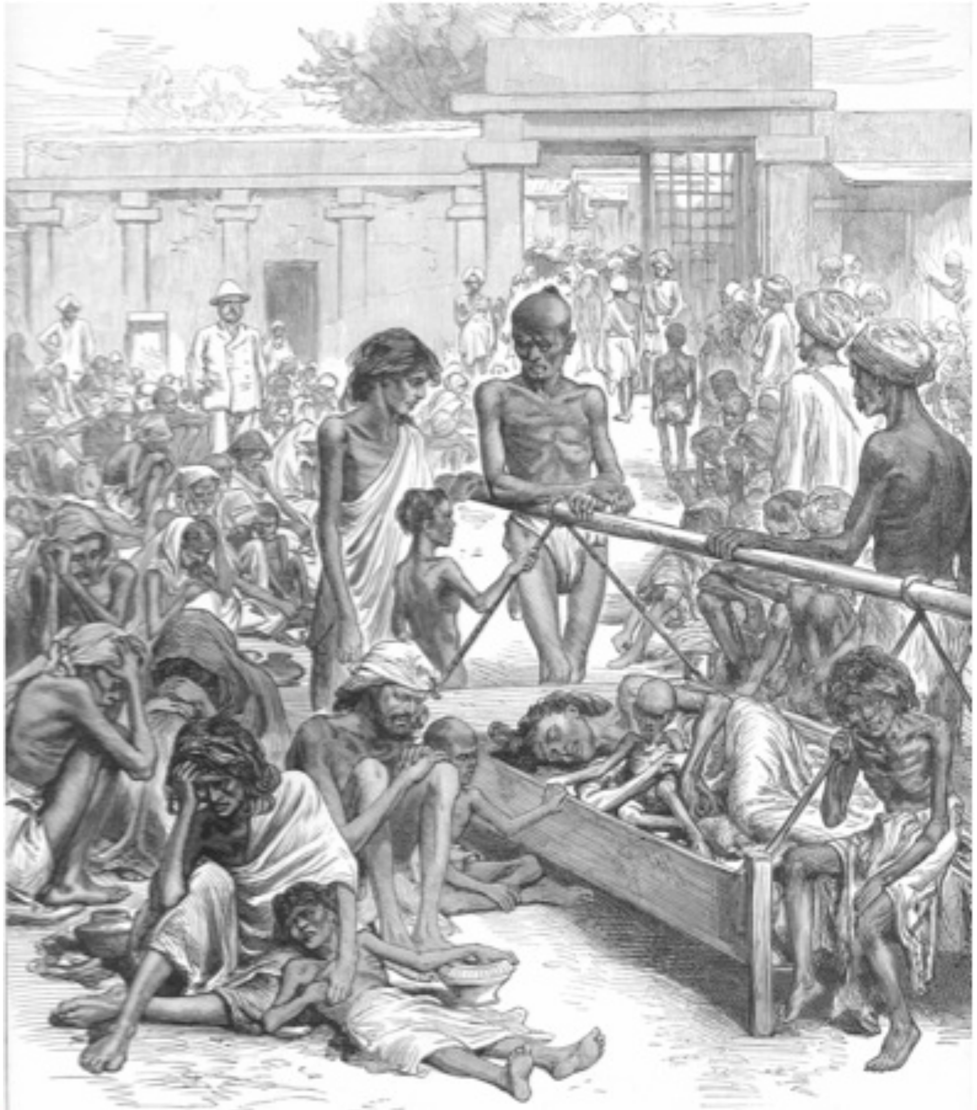
Dynamical Seasonal Prediction of Summer Monsoon Rainfall

After 50 years of climate modeling,
the current climate models can now produce
skillful prediction
of summer monsoon rainfall.

CMORPH OBS Precip Climo JJAS (2003–2006)



Great Famine of 1876-78 (India)



Great Famine of 1876-78 (India)

All India Monsoon Rainfall: -29%

Drought Area: 670,000 km²

Estimated Deaths (Wikipedia): 5.5 – 8.2 million

Governance:

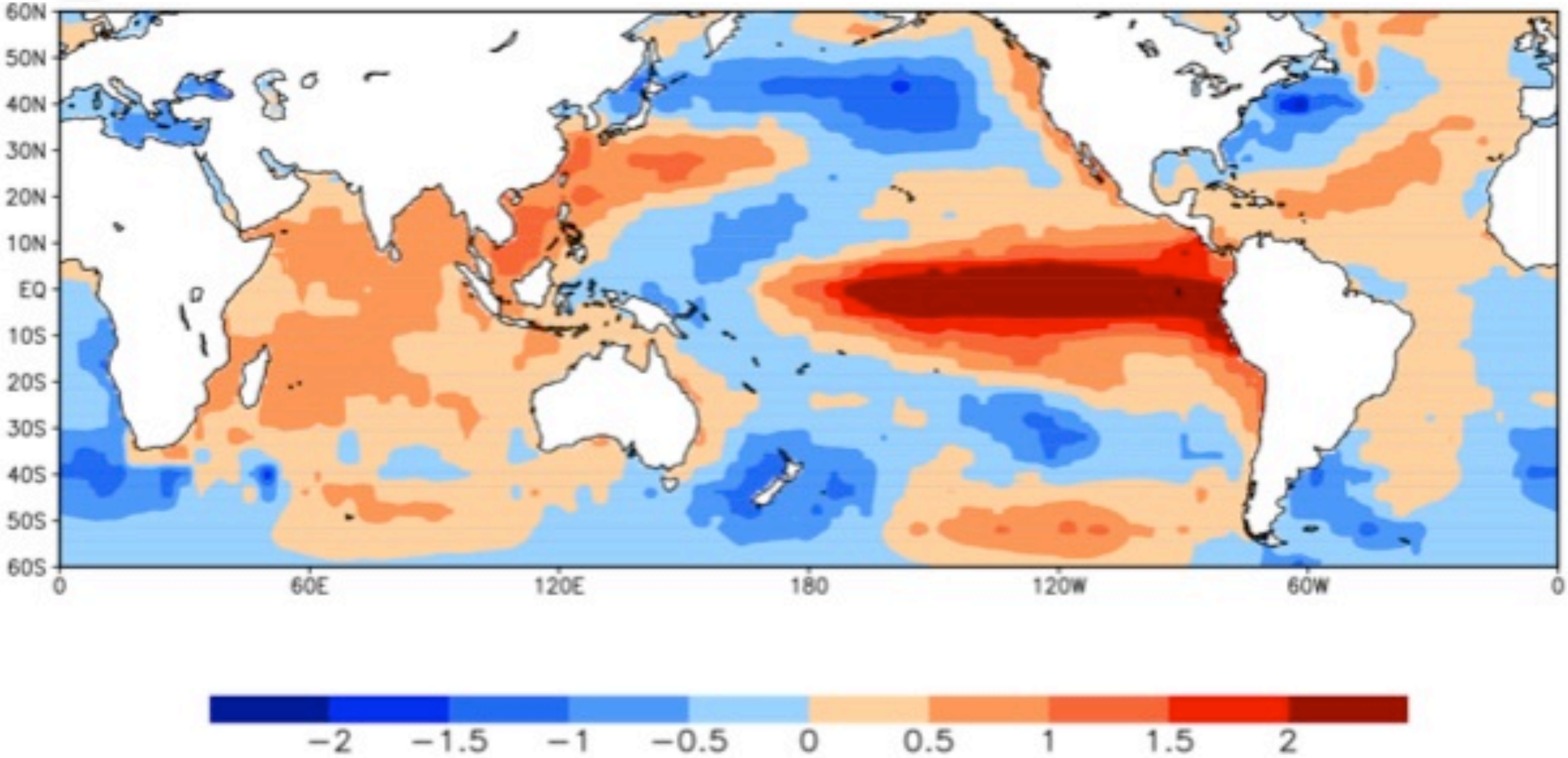
British Rule

(Lord Lytton exported food from India to England)

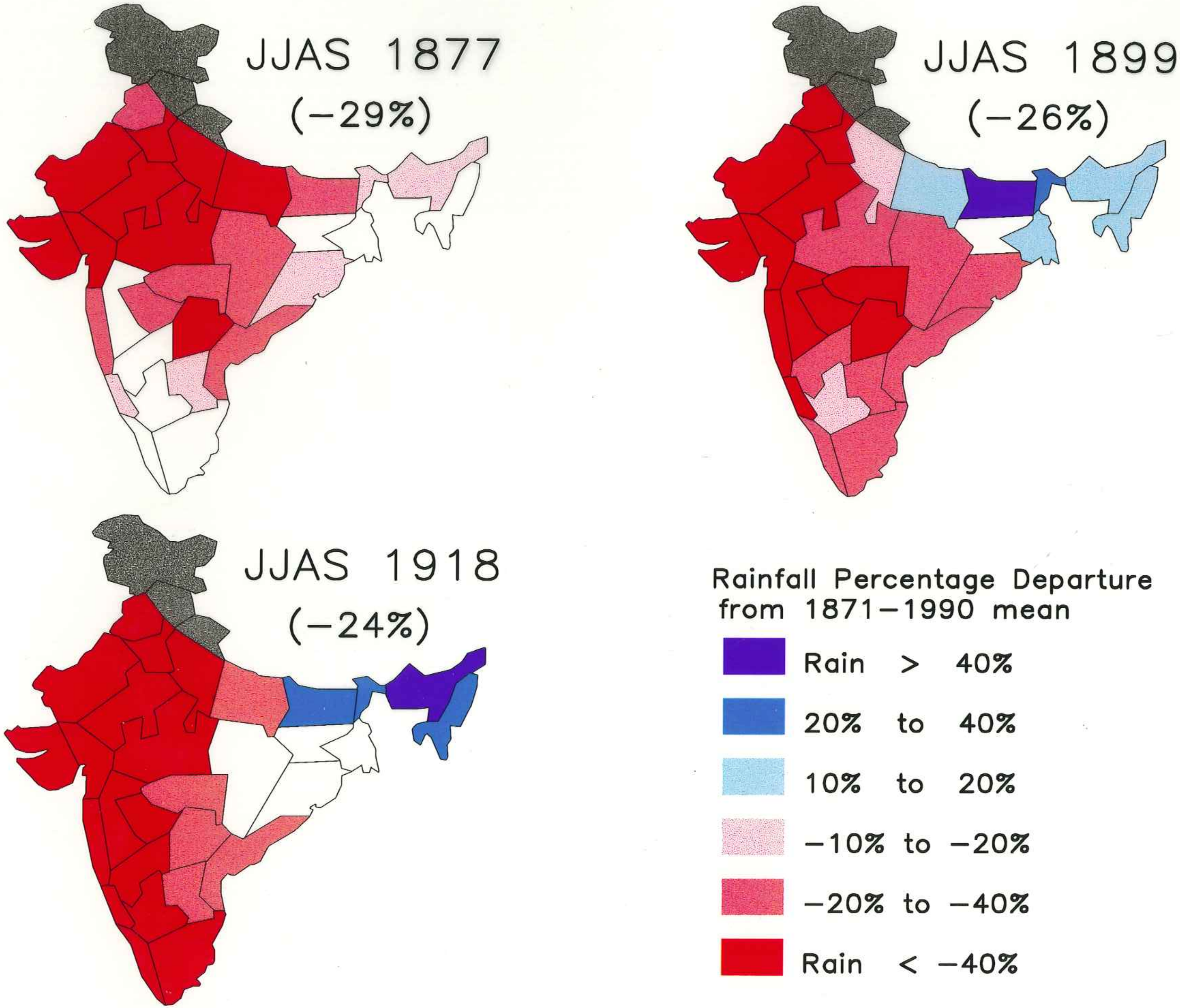
About 13 million people died in China

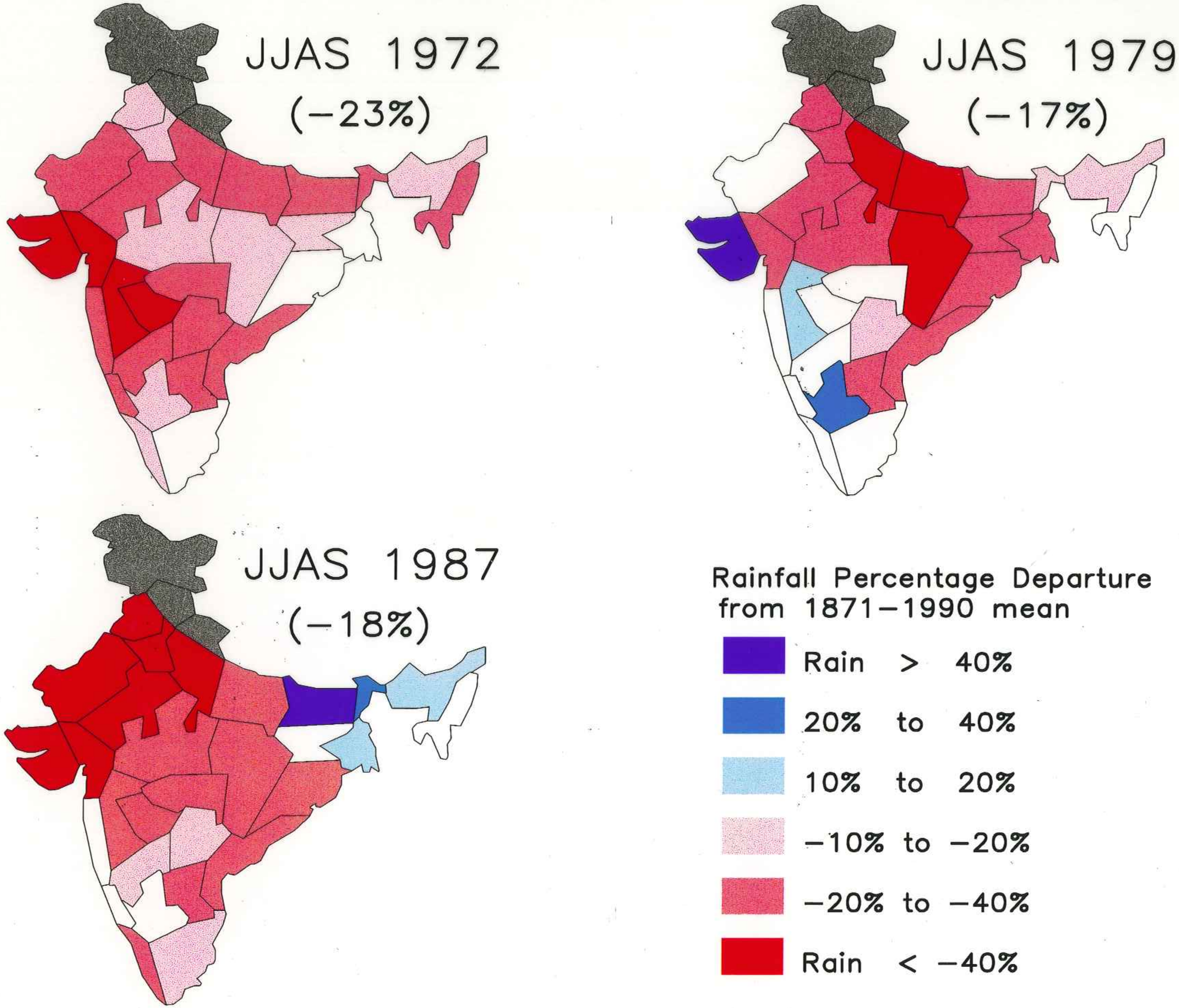
Late Victorian Holocausts **(2001)**
by Mike Davis
El Nino Famines and the Making of the Third World

SST Anomaly (°C) for DJF 1877

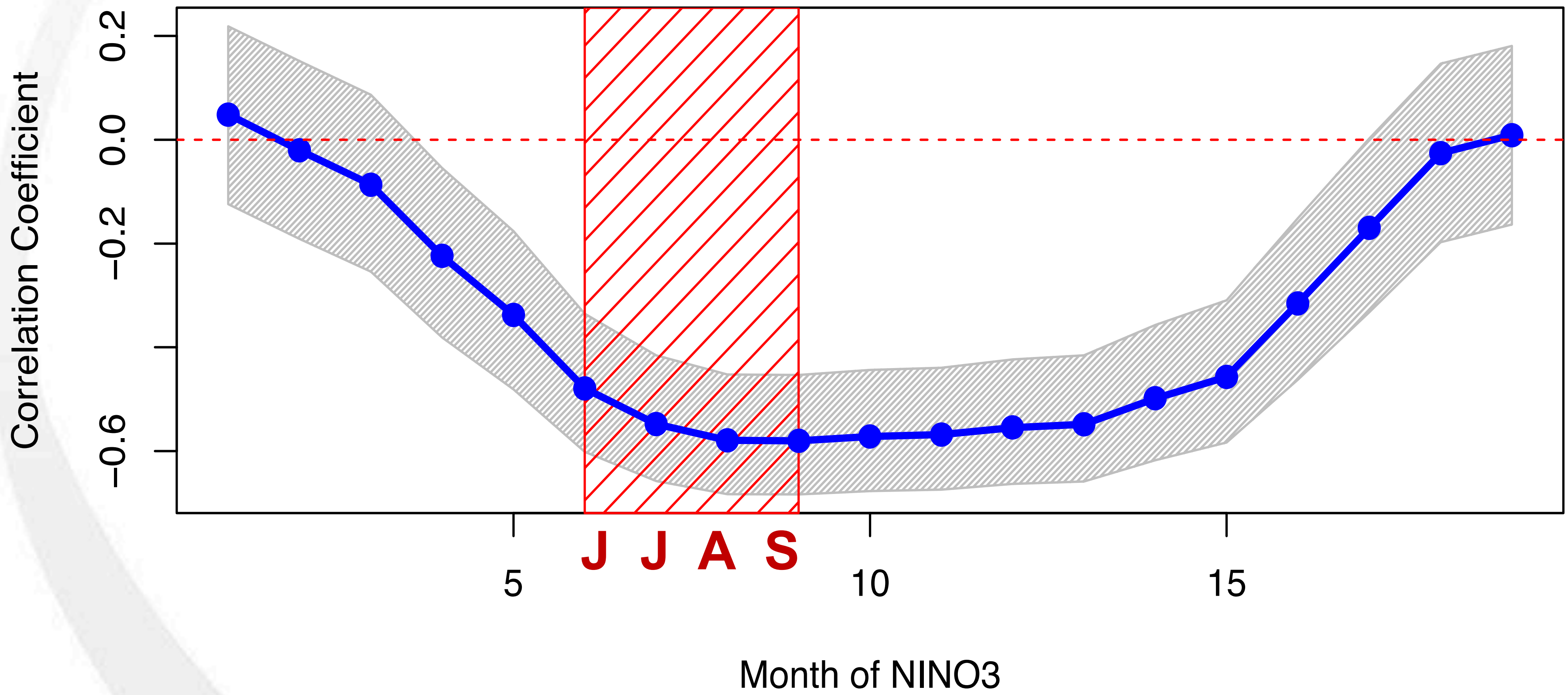


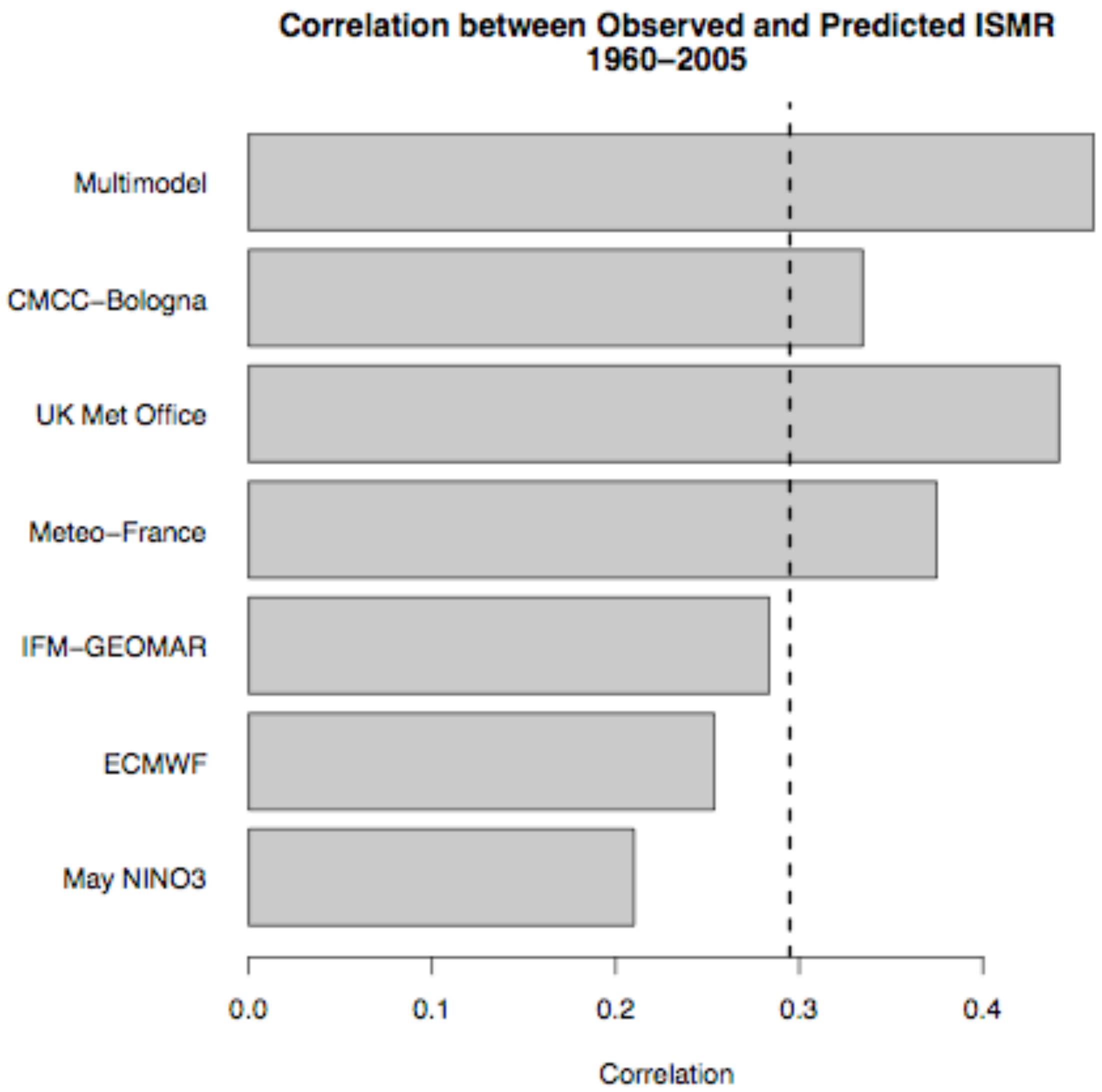
Courtesy of Lakshmi Krishnamurti


JJAS 1877
(−29%)
JJAS 1899
(−26%)
JJAS 1918
(−24%)
Rainfall Percentage Departure from 1871−1990 mean
Rain > 40%
20% to 40%
10% to 20%
−10% to −20%
−20% to −40%
Rain < −40%


JJAS 1972
(−23%)
JJAS 1979
(−17%)
JJAS 1987
(−18%)
Rainfall Percentage Departure
from 1871−1990 mean
Rain > 40%
20% to 40%
10% to 20%
−10% to −20%
−20% to −40%
Rain < −40%

Correlation between NINO3 and All–India JJAS Rainfall 1880–2010





(46 years (1960-2005); Ens.=9)

For 1960-2005 Obs,

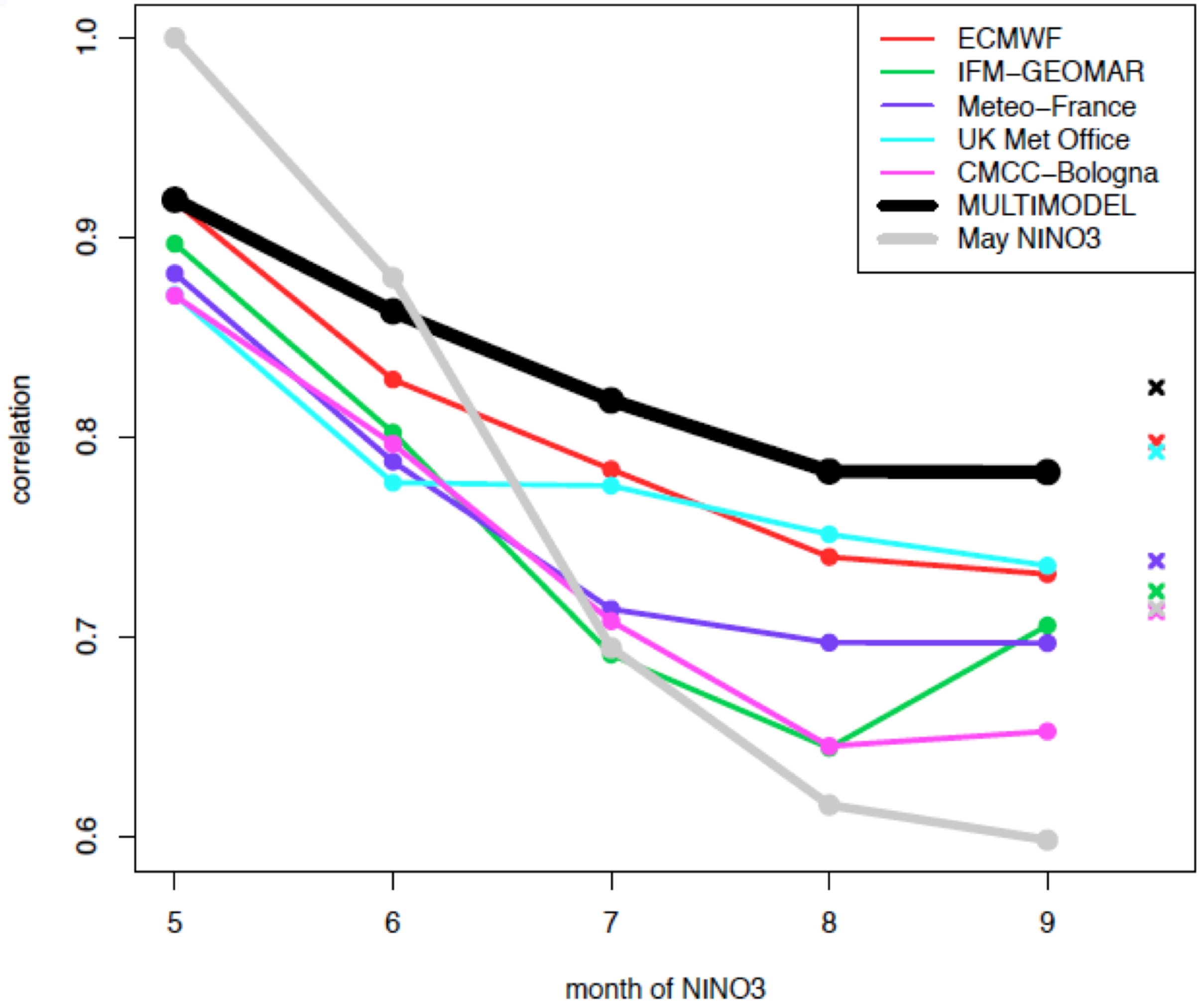
CC (April Nino3, ISMR): −0.18

CC (May Nino3, ISMR): −0.21

Correlation between observed and predicted JJAS all-India rainfall for hindcasts in the ENSEMBLES data set for the period 1960-2005. All-India rainfall in dynamical models is defined as the total land precipitation within 70E − 90E and 10N − 25N .

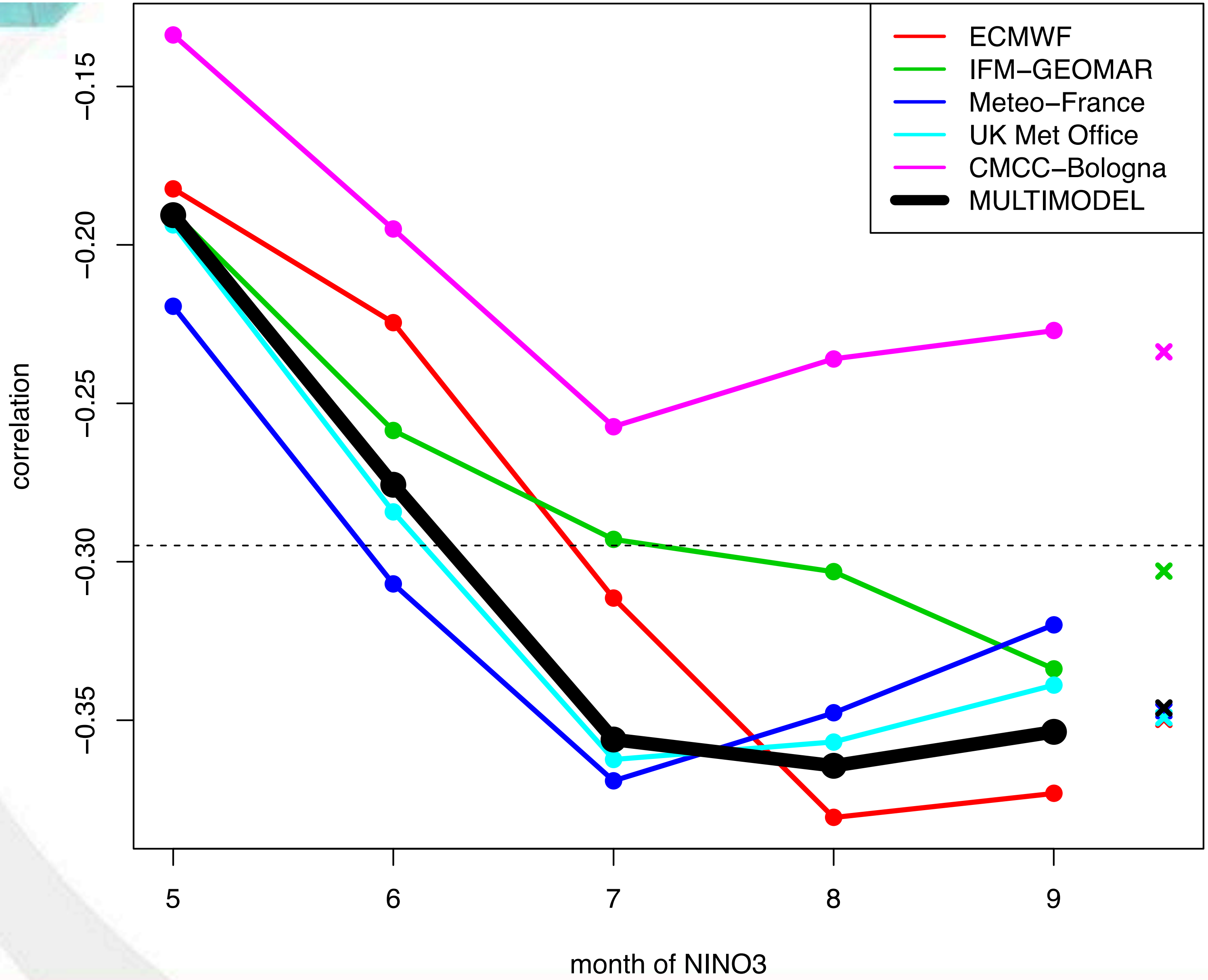
Last row shows empirical prediction using observed May NINO3.

Correlation between Observed and Predicted NINO3



Correlation between observed NINO3, and ensemble mean NINO3 predicted by the ENSEMBLES models, for hindcasts in the period 1960-2005, as a function of calendar month. Also shown is the correlation between observed NINO3 and the least squares prediction of NINO3 based on the observed May NINO3 value (thick grey). The ‘x‘-symbols on the far right give the correlations between the observed and predicted JJAS NINO3 index.

Correlation between Observed JJAS all India rainfall and Model NINO3



Summary (monsoon prediction)

- Model's ability to simulate SST and Q in West Pacific and Indian Ocean are critical for accurate monsoon prediction.

- Predictability (Analysis of Variance, F test) calculation for 5 coupled model ("ENSEMBLES" Project) seasonal predictions for 46 years, 9 member ensembles:

  (ISMR is predictable at 95% significance)

- Skill of coupled O-A models for predicting ISMR for 1960-2005 is significant at 95%.

  (Coupled O-A models for monsoon prediction is the future.)

Monsoon in a Changing Climate

- There are many complex climate models in the world which have calculated the projected changes in the Indian monsoon rainfall in the 21st century.

- Most of the models are projecting that in the worst case scenario of very high emissions and high global warming (3-4 °C) long-term mean monsoon rainfall for the 21st century, over the entire Asian region, will be the same or more than that in the current climate.

- There will be much larger year to year variability (floods and droughts)

23 IPCC Global Climate Models

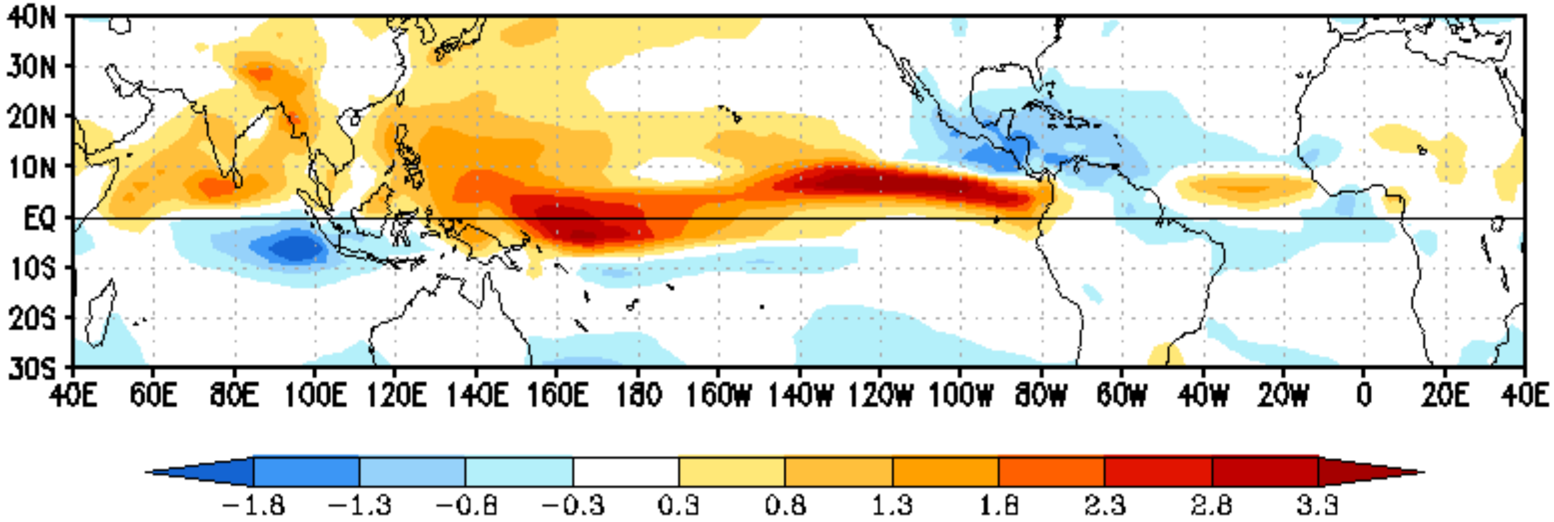
CMIP5 Models

	Model	Institution
1	CCCma-CanESM-2	Canadian Centre for Climate Modelling and Analysis, **Canada**
2	CERFACS-CNRM-CM5	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique, **France**
3	CMCC-CM	Centro Euro-Mediterraneo per I Cambiamenti Climatici. **Italy**
4	CSIRO-BOM- ACCESS1-0	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), and BOM (Bureau of Meteorology, Australia), **Australia**
5	CSIRO-QCCCE-MK3-6-0	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence , **Australia**
6	HadGEM2-CC	Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais), **UK**
7	HadGEM2-ES	
8	INM-CM4	Institute for Numerical Mathematics**, Russia**

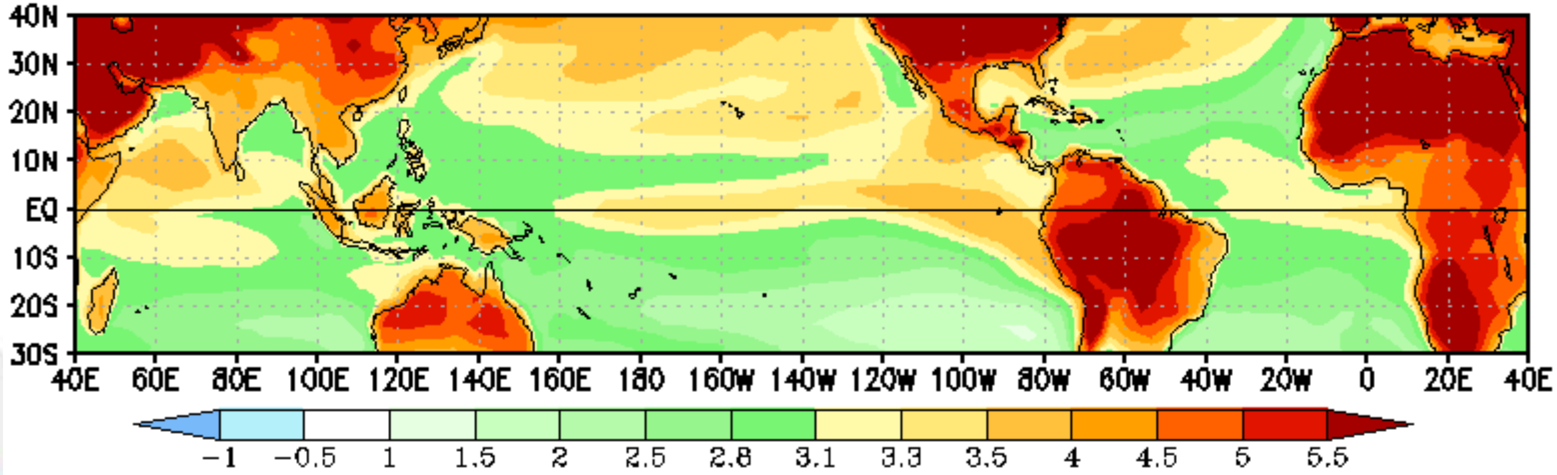
CMIP5 Models

	Model	Institution
9	IPSL-CM5A-LR	Institut Pierre-Simon Laplace, **France**
10	IPSL-CM5A-MR	
11	IPSL-CM5B-LR	
12	MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, **Japan**
13	MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, **Japan**
14	MIROC-ESM-CHEM	
15	MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M), **Germany**
16	MPI-ESM-MR	
17	MRI-CGCM3	Meteorological Research Institute, **Japan**
18	NASA-GISS-E2R	NASA Goddard Institute for Space Studies, **USA**
19	NCAR-CCSM4	National Center for Atmospheric Research, **USA**
20	NCC-NorESM1-M	Norwegian Climate Centre, **Norway**
21	NOAA-GFDL-CM3	Geophysical Fluid Dynamics Laboratory, **USA**
22	NOAA-GFDL-ESM-2G	
23	NOAA-GFDL-ESM-2M	

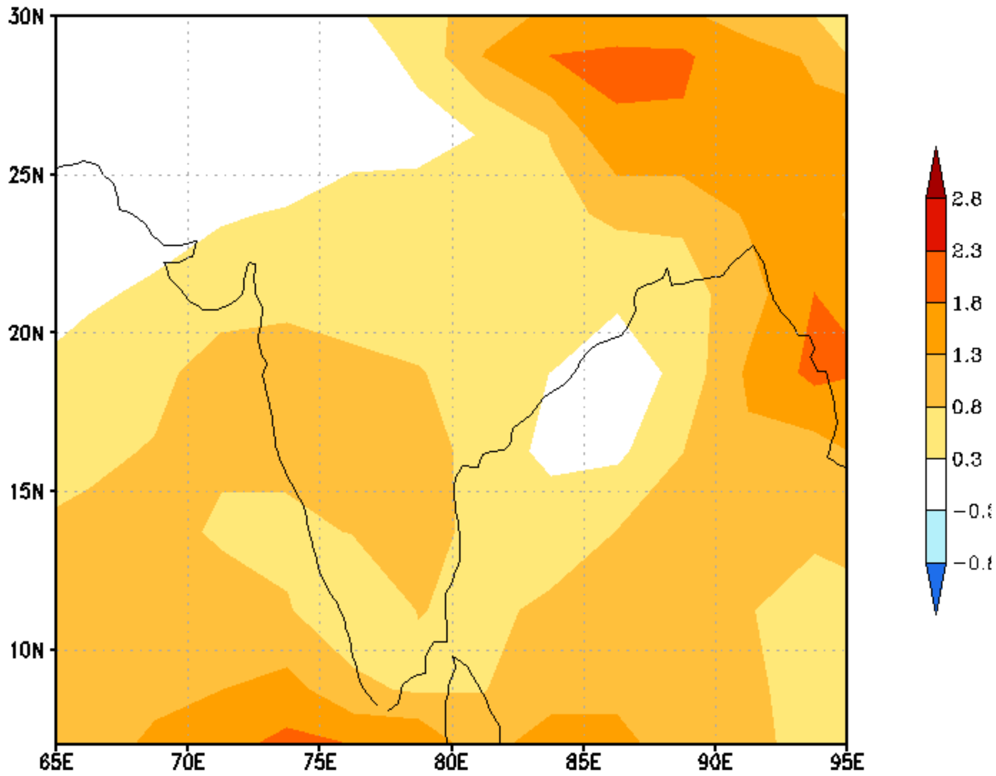
JJAS Rainfall Difference (mm/day) due to Climate Change (RCP8.5, 2071-2099)



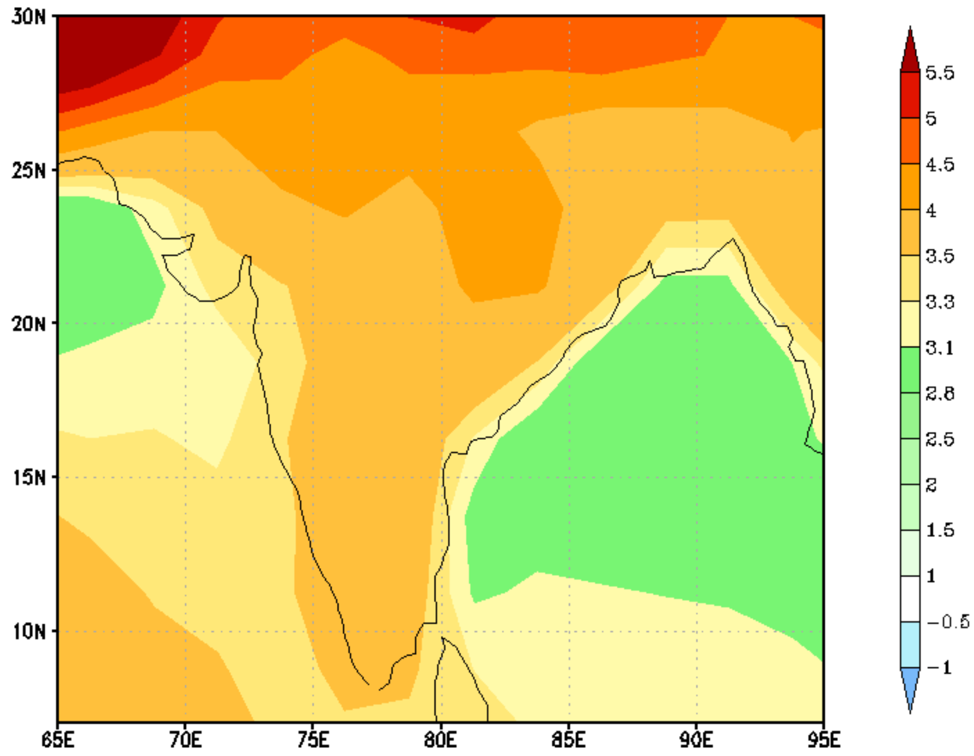
JJAS Surf Temp Difference (°C) due to Climate Change (RCP8.5, 2071-2099)



JJAS Difference due to Climate Change (RCP8.5, 2071-2099)



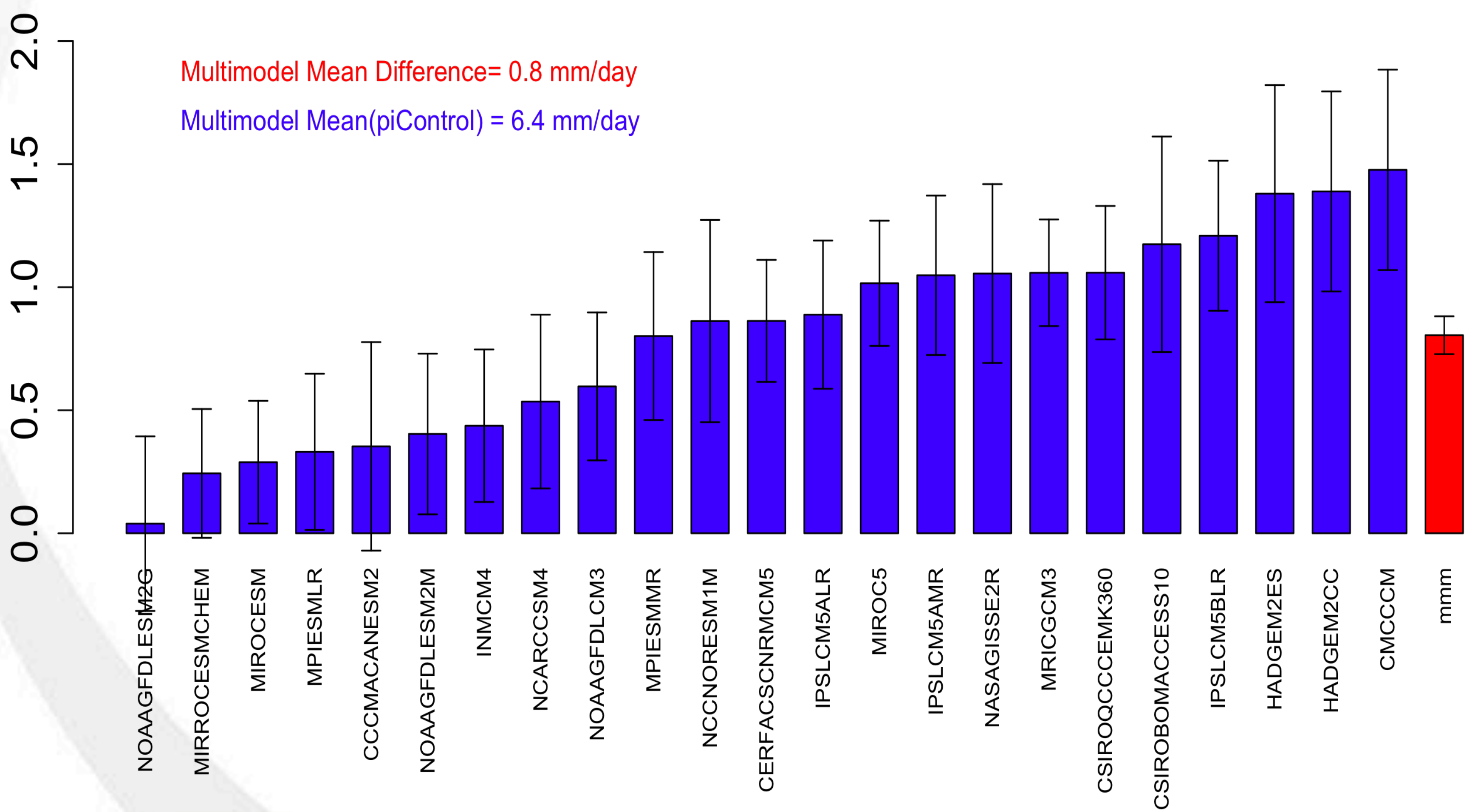
Rainfall (mm/day)



Temperature (°C)

Precipitation difference (mm/day) between RCP8.5 and piControl Runs of CMIP5

INDIA [65E-95E,7N-30N]



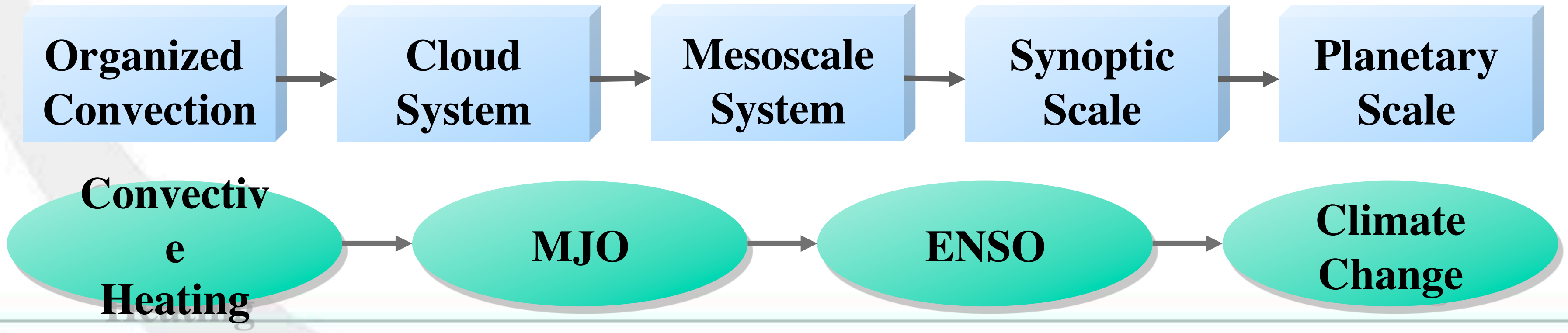
Towards a Hypothetical "Perfect" Model

- 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 → Better prediction (??)

Seamless Prediction of Weather and Climate

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♪

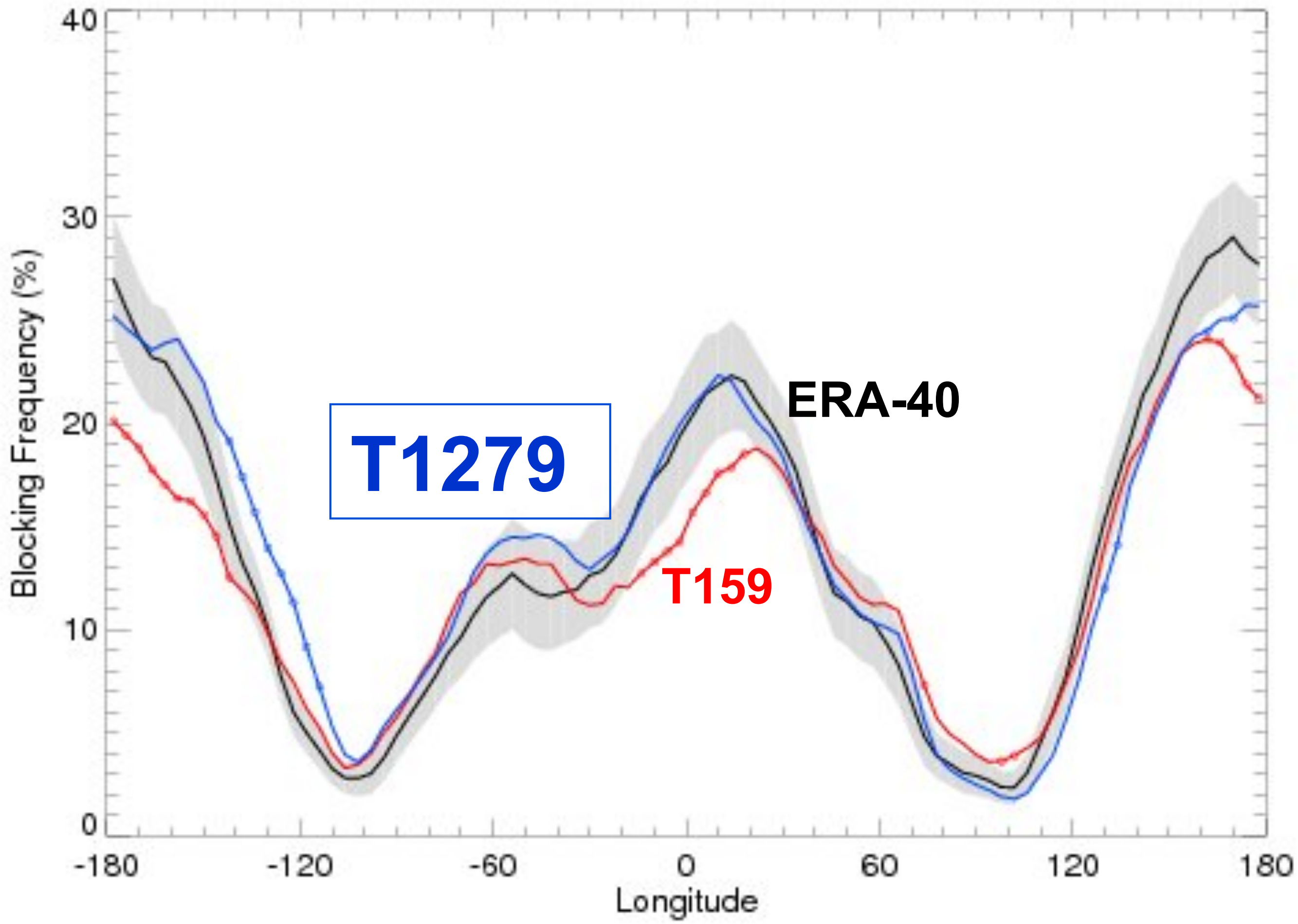


Examples of improved climate simulation by global climate models with higher numerical accuracy (high resolution) and improved physics

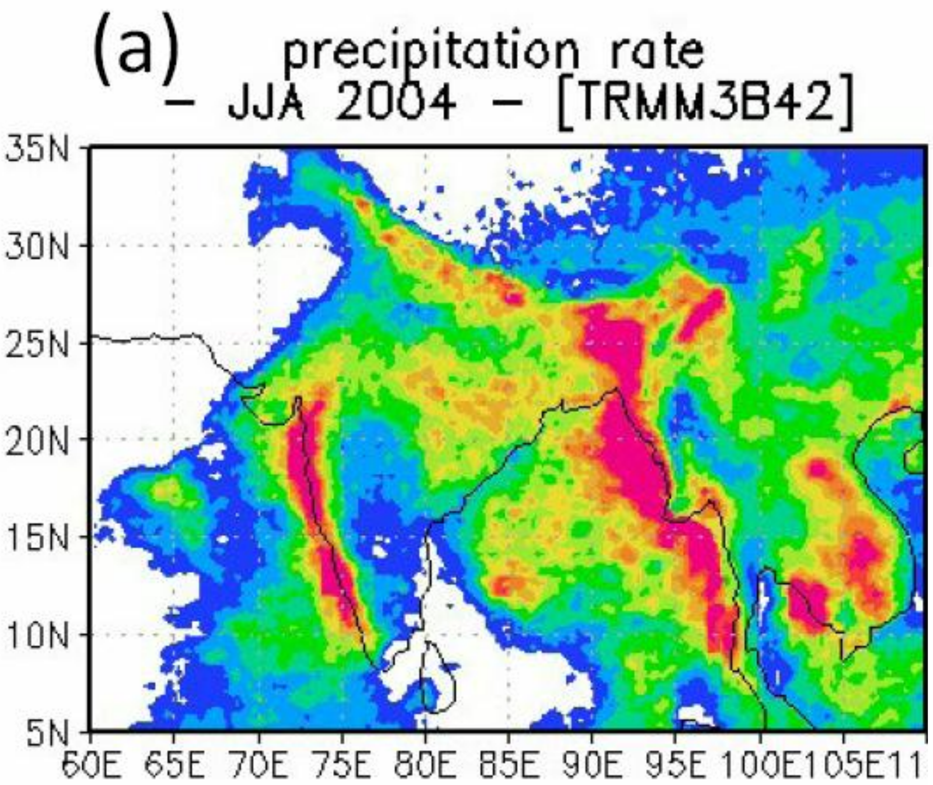
Blocking Frequency

Black: Reanalysis (ERA); Red: T 159; Blue: T 1279 (ECMWF)

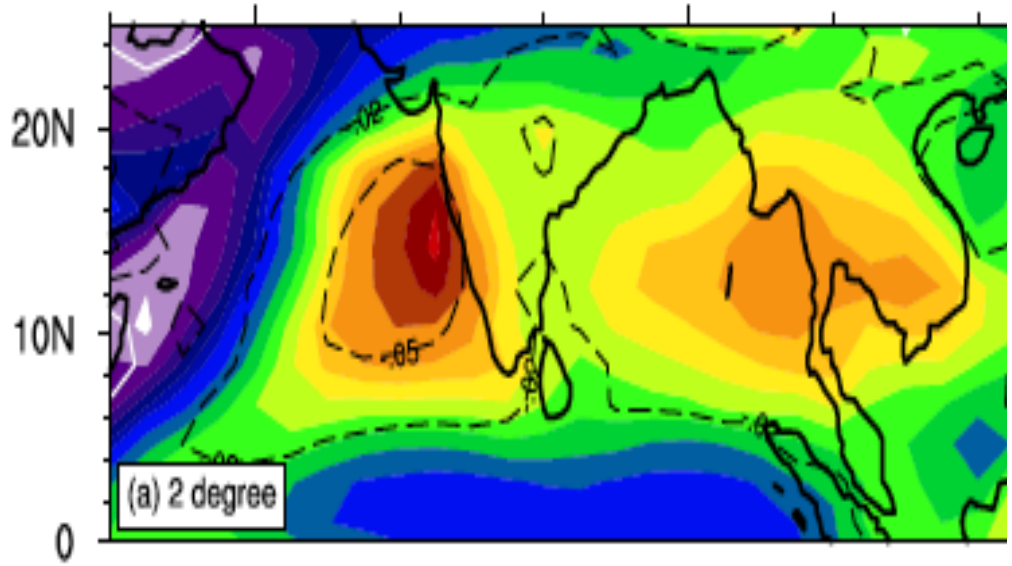
(Higher Resolution Model Improves Simulation of Blocking Frequency)

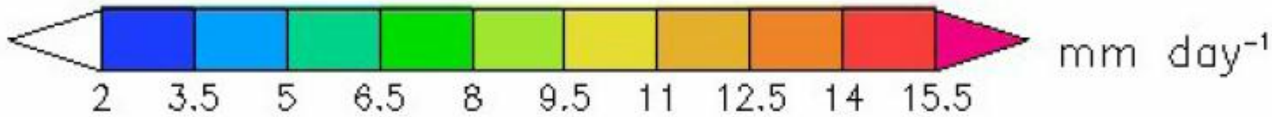


Monsoon Rainfall in Low Resolution Model

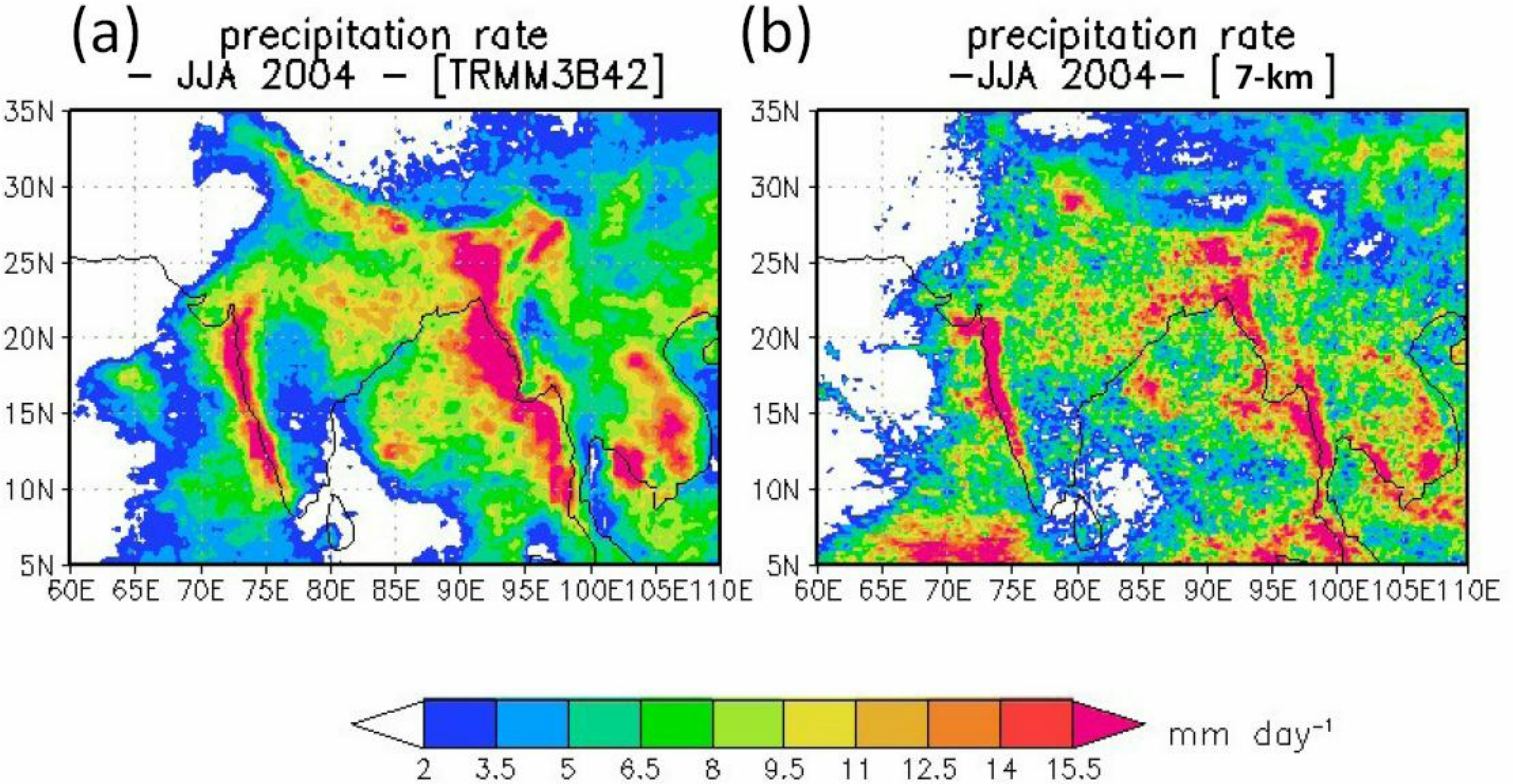


(b) Coupled model (2 degree)
- Climatology -





Monsoon Rainfall in High Resolution Model



***Oouchi et al. 2009*: (a) Observed and (b) simulated precipitation rate over the Indo-China monsoon region as June-July-August average (in units of mm day -1). The observed precipitation is from TRMM_3B42, and the simulation is for 7km-mesh run.**

Center of Ocean-Land-Atmosphere studies

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)

A Challenge!

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?

Examples of Internationally Funded Infrastructures for Advancement of Science

- **CERN: European Organization for Nuclear Research**
  (Geneva, Switzerland)
- **ITER: International Thermonuclear Experimental Reactor**
  (Gadarache, France)
- **ISS: International Space Station**
  (somewhere in sky..)

WHAT ABOUT CLIMATE PREDICTION?


CERN Policies
for Collaboration
John Ellis,
CERN

Particle Accelerators for High Energy Physics Research

CERN
Geneva, Switzerland
LHC, 7 TeV

FermiLab
Batavia, IL, USA
Tevatron 980 GeV

SLAC
Menlo Park, CA, USA
50 GeV

DESY
Hamburg, Germany
HERA, 920 GeV

Brookhaven
Upton, NY USA
RHIC, 100-250 GeV

Supercomputers for Weather, Climate and Earth-System Research

ECMWF
Europe
IBM 236 TFlops

Hadley Center and Met Office
United Kingdom
IBM 104 TFlops

GFDL/NOAA
USA
Cray 260 TFlops

NCAR
USA
IBM 77 TFlops

NCEP
USA
IBM 146 TFlops

MRI
Japan
Hitachi 51 TFlops

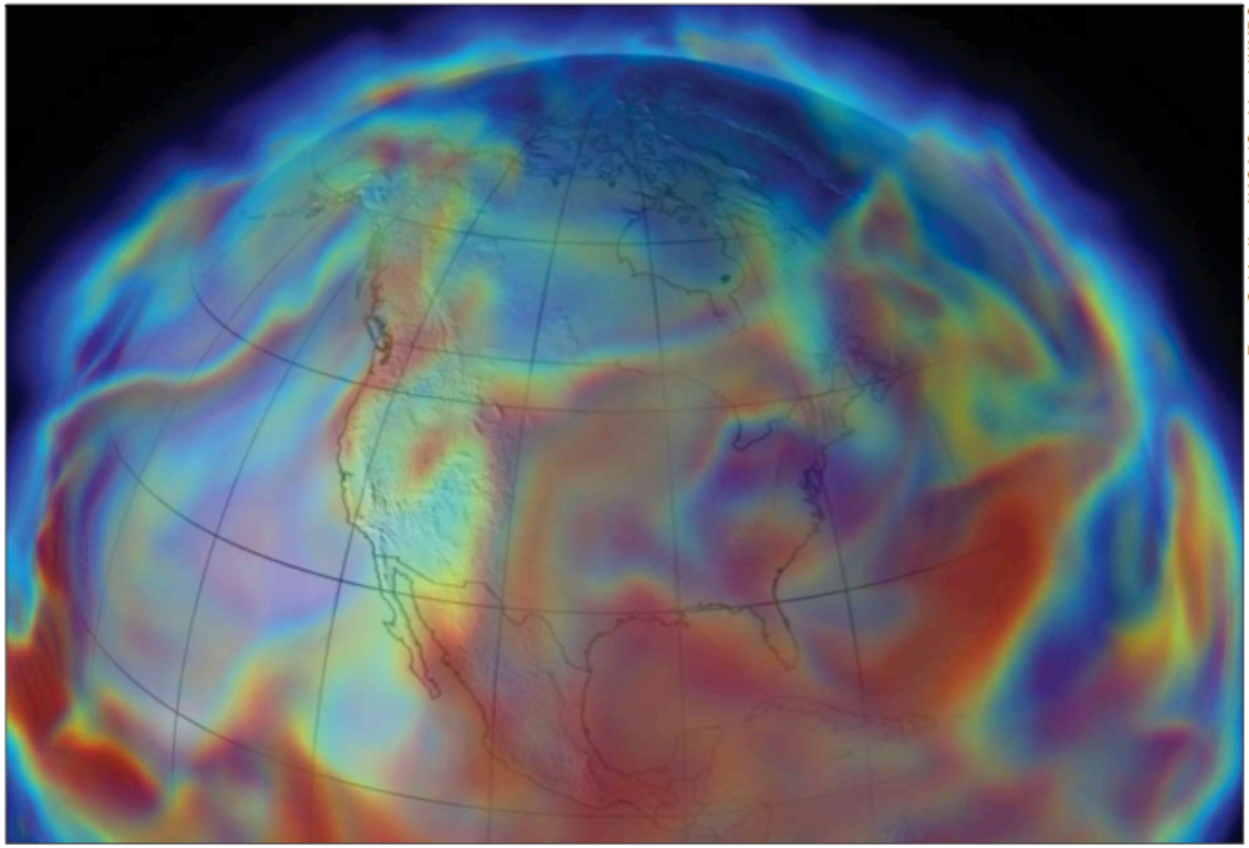
KMA
Korea
Cray 632 TFlops

Max Planck
Germany
IBM 152 TFlops

A CERN for climate change?

Providing reliable predictions of the climate requires substantial increases in computing power. **Tim Palmer** argues that it is time for a multinational facility fit for studying climate change

This winter has seen unprecedented levels of travel chaos across Europe and the US. In particular, the UK experienced the coldest December temperatures on record, with snow and ice causing many airports to close. Indeed, George Osbourne, the UK's Chancellor of the Exchequer, attributed the country's declining economy in the last quarter of 2010 to this bad weather. A perfectly sensible question to ask is whether this type of weather will become more likely under climate change? Good question, but the trouble is we do not know the answer with any great confidence.

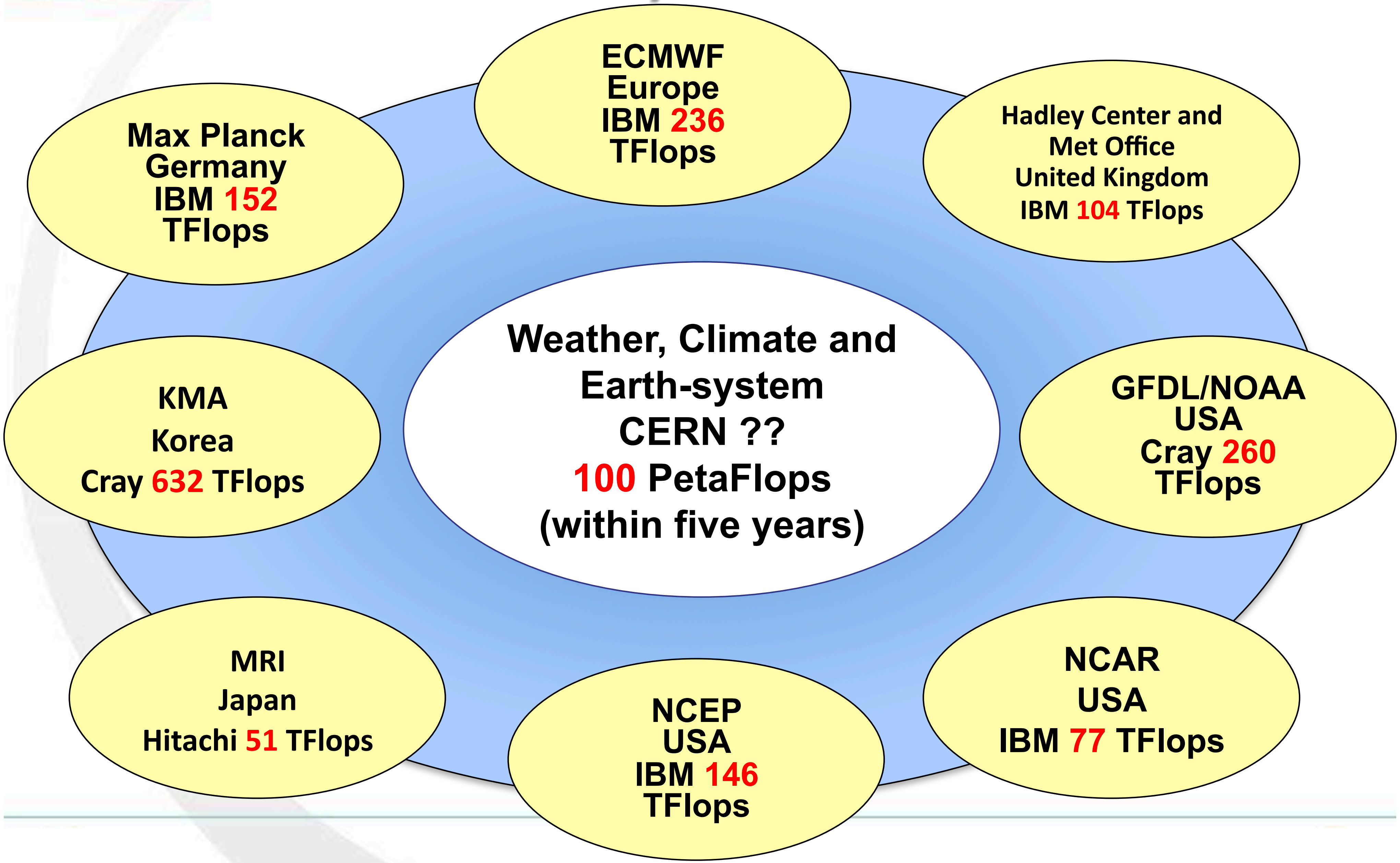


Trent Schindler, NASA/Goddard/UMBC

A global approach to a global problem Modelling the climate may require a unified strategy for computing.

In **Physics World** by Tim Palmer

Supercomputers for Weather, Climate and Earth-System Research



Summary

• 1 .While maintaining and enhancing the existing research on climate science, the world should establish a few (~3)100 petaflops multi-national computing facilities dedicated to climate, and accessible to world centers and universities.

• Sustained Capability of 10 Petaflops by 2015
• Core team of 200 scientists and distributed team of 500 scientists to develop next generation climate model.

• 2. Support sustained research on modeling of physical, chemical, and biological processes for kilometer scale global models, data assimilation, unstructured adaptive grids, numerical methods, and, hardware and software for about a million cores and about a billion threads.

THANK YOU!

ANY QUESTIONS?

Particle Accelerators for High Energy Physics Research

1939: Ernest Lawrence (Radiation lab at Berkeley) received the Nobel Prize in Physics for building Cyclotron.

1940s – 1950s: (Competitive) construction of high energy particle accelerators in USA and Europe.

It was recognized that no single institution could afford to construct or staff the new machines, consortiums were formed to build them.

A group of universities in the eastern US joined forces in 1947 to construct an accelerator on Long Island – Brookhaven National Laboratory's Cosmotron.

Europe's major nations banded together in 1954 to found CERN, the European Organization for Nuclear Research (in French: *Conseil Européenne pour la Recherche Nucléaire*).

Summary

• 1 .While maintaining and enhancing the existing research on climate science, the US should establish a 10 - 100 petaflops national multi-agency computing facility dedicated to climate, and accessible to national centers and universities.

• Sustained Capability of 10 Petaflops by 2015
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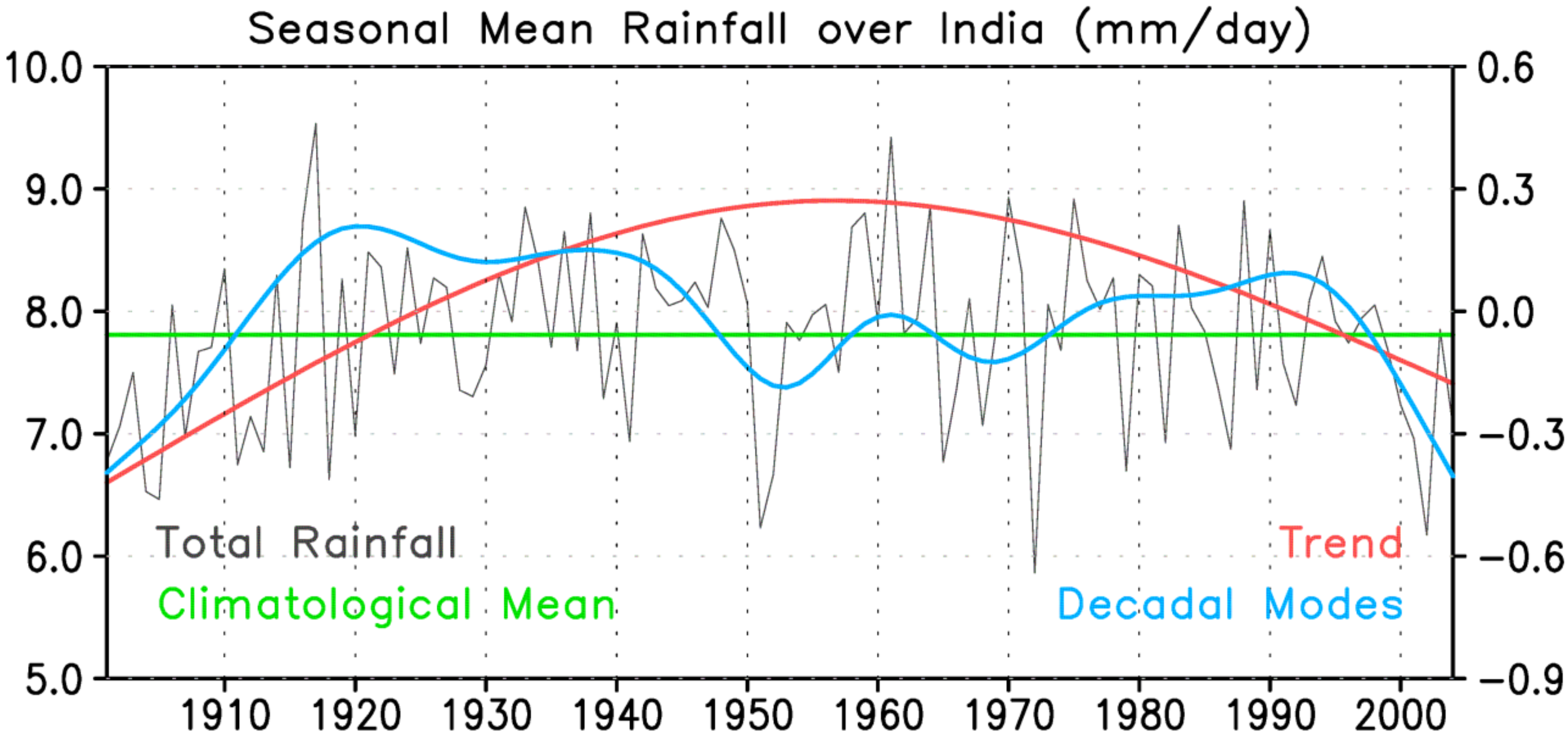
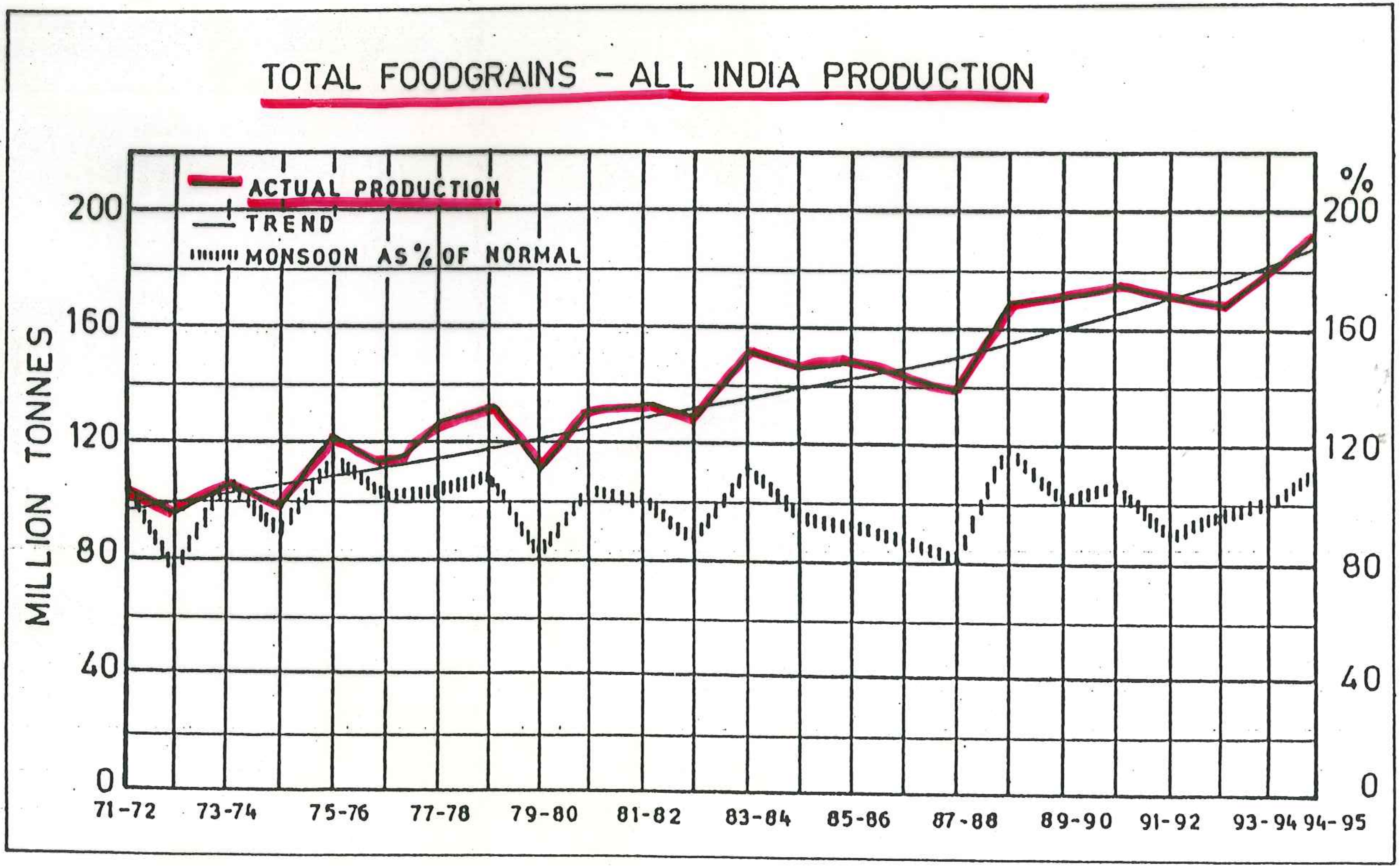
• 2. Support sustained research on modeling of physical, chemical, and biological processes for kilometer scale global models, data assimilation, unstructured adaptive grids, numerical methods, and, hardware and software for about a million cores and about a billion threads.

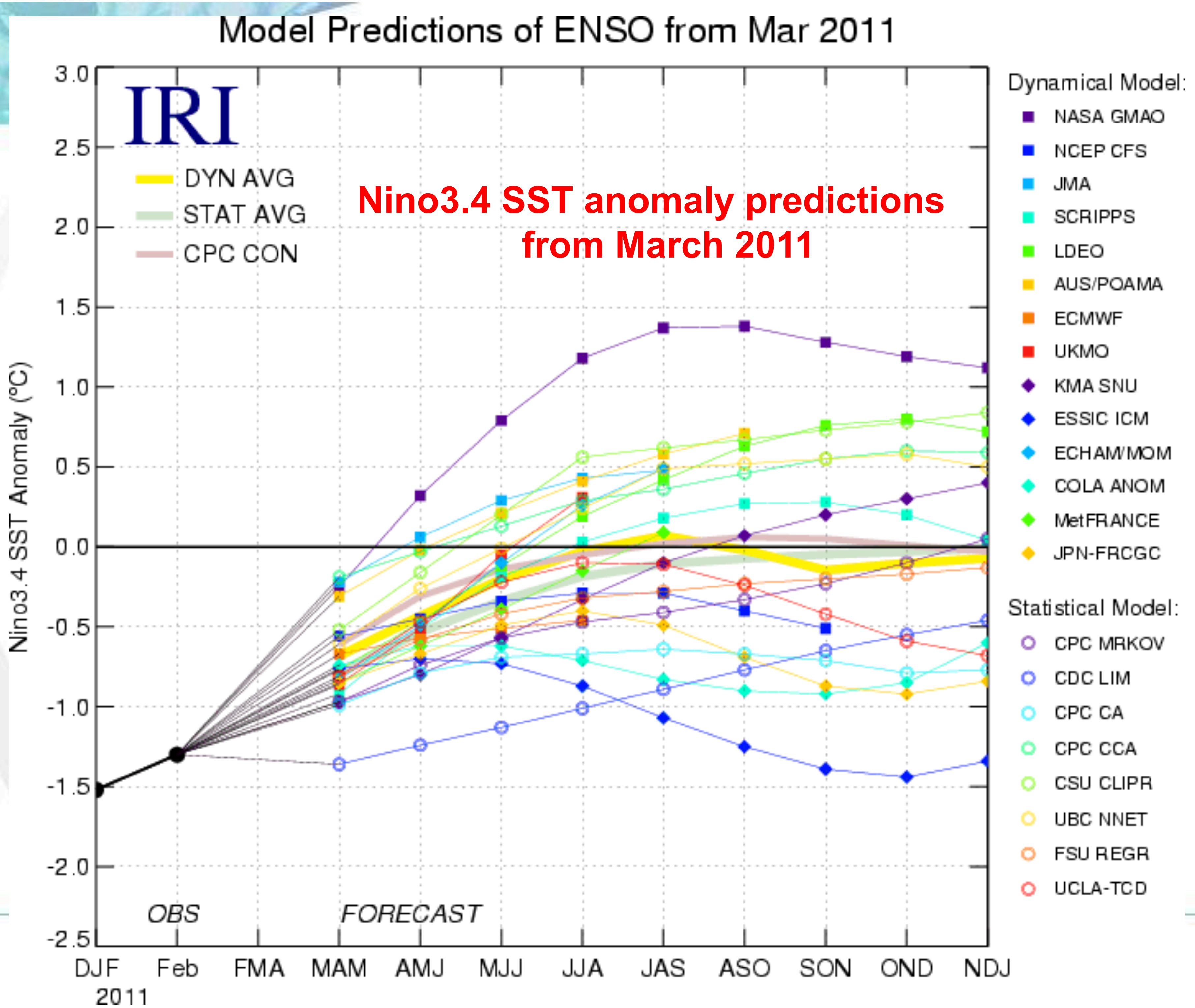
Long-term trend and decadal variations of all India JJAS rainfall



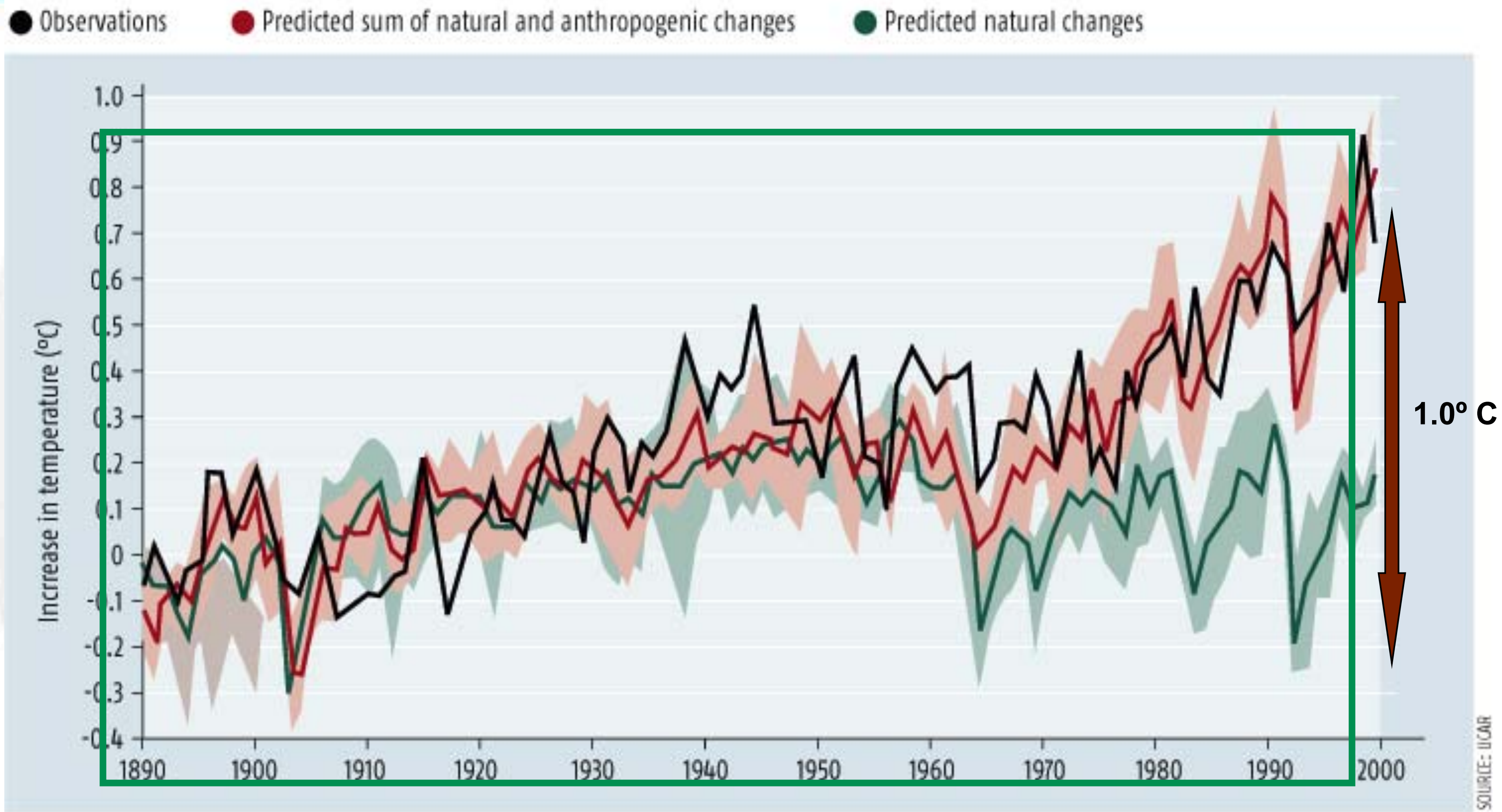


TOTAL FOODGRAINS - ALL INDIA PRODUCTION
ACTUAL PRODUCTION
TREND
MONSOON AS % OF NORMAL
MILLION TONNES
%
200
160
120
80
40
0
71-72
73-74
75-76
77-78
79-80
81-82
83-84
85-86
87-88
89-90
91-92
93-94
94-95

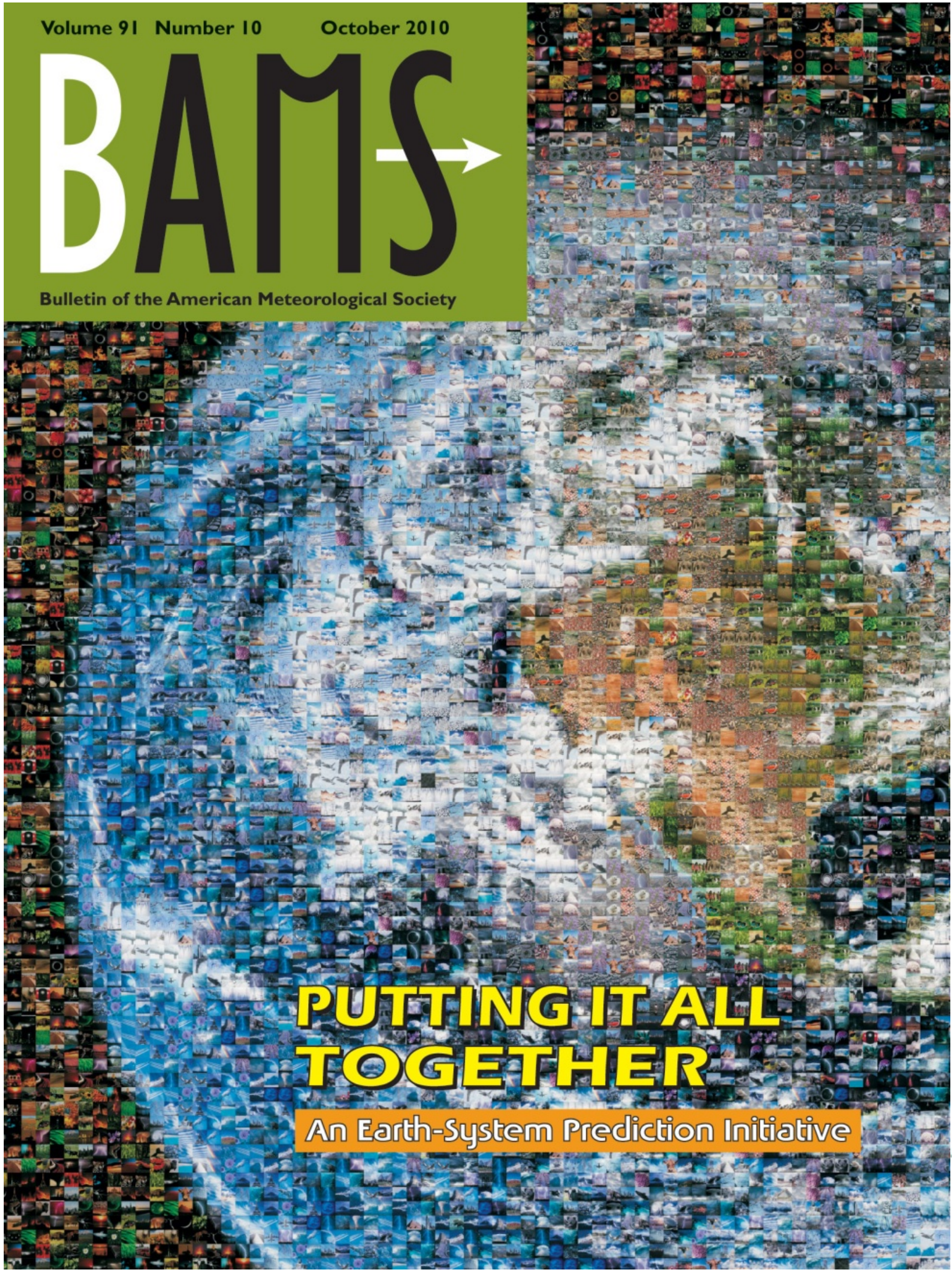
Fig. 16



Model Predictions of ENSO from Mar 2011
IRI
DYN AVG
STAT AVG
CPC CON
Nino3.4 SST anomaly predictions
from March 2011
Nino3.4 SST Anomaly (°C)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
OBS
FORECAST
DJF
2011
Feb
FMA
MAM
AMJ
MJJ
JJA
JAS
ASO
SON
OND
NDJ
Dynamical Model:
NASA GMAO
NCEP CFS
JMA
SCRIPPS
LDEO
AUS/POAMA
ECMWF
UKMO
KMA SNU
ESSIC ICM
ECHAM/MOM
COLA ANOM
MetFRANCE
JPN-FRCGC
Statistical Model:
CPC MRKOV
CDC LIM
CPC CA
CPC CCA
CSU CLIPR
UBC NNET
FSU REGR
UCLA-TCD



Courtesy of UCAR



Brunet, G., et al, 2010: Collaboration of the Weather and Climate Communities to Advance Sub-Seasonal to Seasonal Prediction. *BAMS, Vol. 91, 1397-1406*

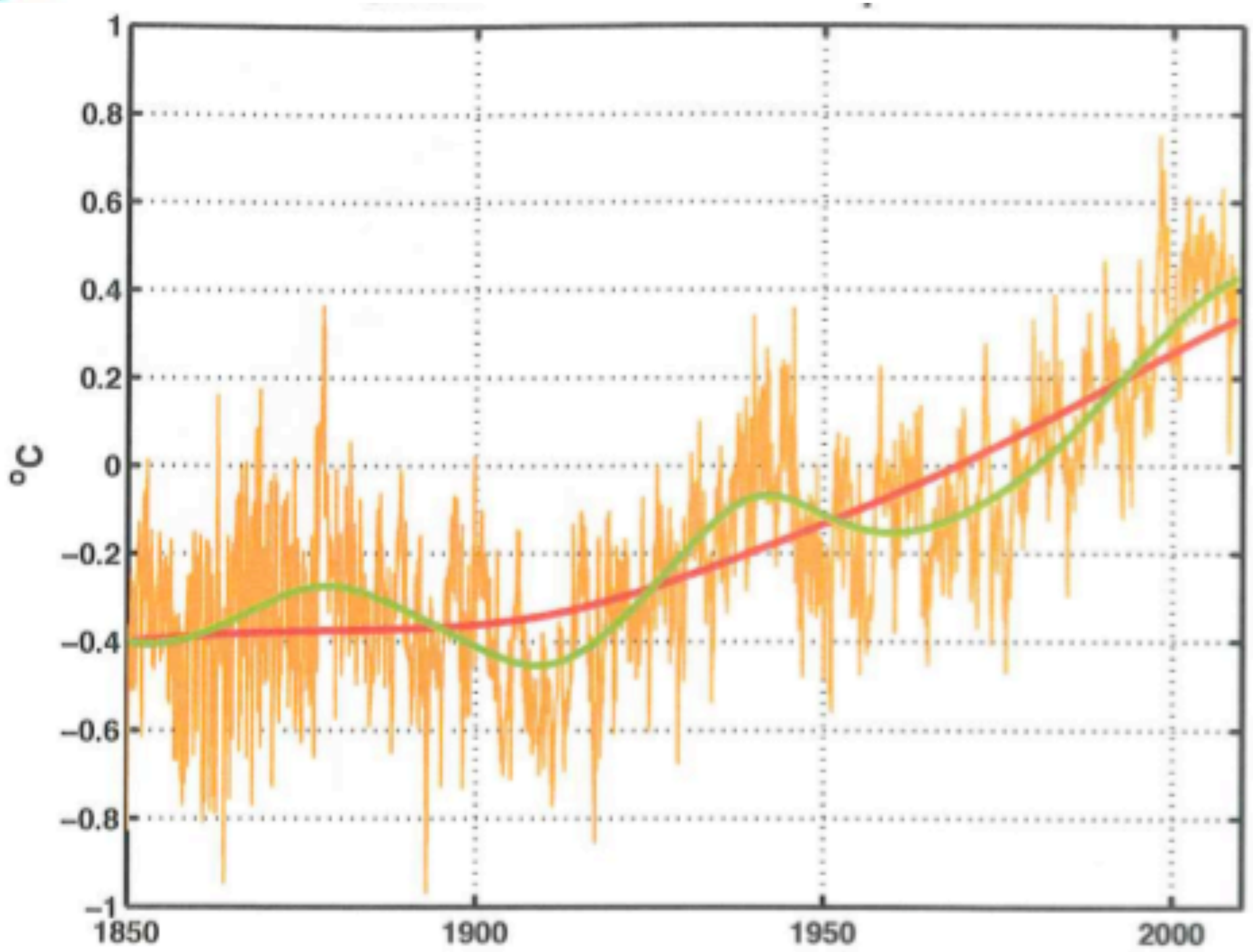
Shapiro, M., J. Shukla, et al, 2010: An Earth-System Prediction Initiative for the 21st Century. *BAMS, Vol.91, 1377-1388*

Shukla, J., T.N. Palmer, R. Hagedorn, B. Hoskins, J. Kinter, J. Marotzke, M. Miller, and J. Slingo, 2010: Towards a New Generation of World Climate Research and Computing Facilities. *BAMS, Vol.91, 1407-1412*

Shukla, J., R. Hagedorn, B. Hoskins, J. Kinter, J. Marotzke, M. Miller, T.N. Palmer, and J. Slingo, 2009: Revolution in climate Prediction is Both Necessary and Possible: A Declaration at the World Modelling Summit for Climate Prediction. *BAMS, Vol.90,* 16-19

An Earth system Prediction Initiative

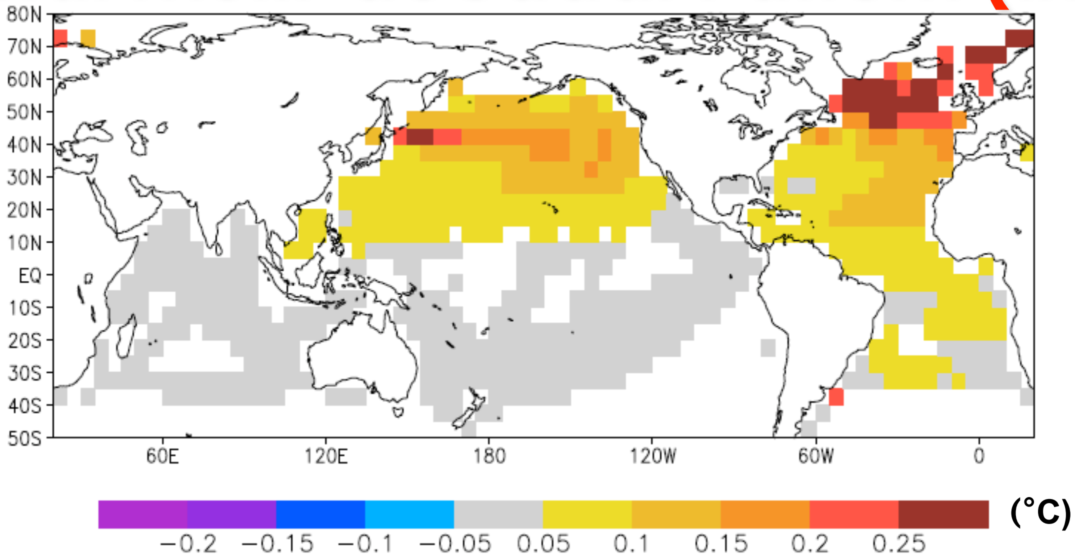
Global-mean Surface Temperature

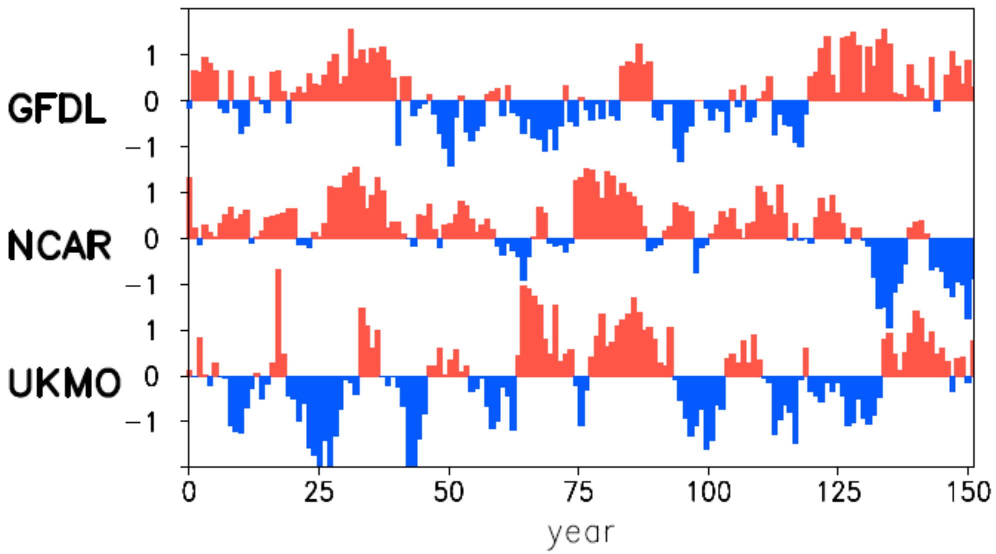


On the Time-Varying Trend in Global-Mean Surface Temperature
by Huang, Wu, Wallace, Smoliak, Chen, Tucker
EEMD: Ensemble Empirical Mode Decomposition; MDV: Multi Decadal Variability

Figure 4: Reconstruction of the raw GST time series (brown lines) using ST only (red lines) and ST + MDV (green lines).

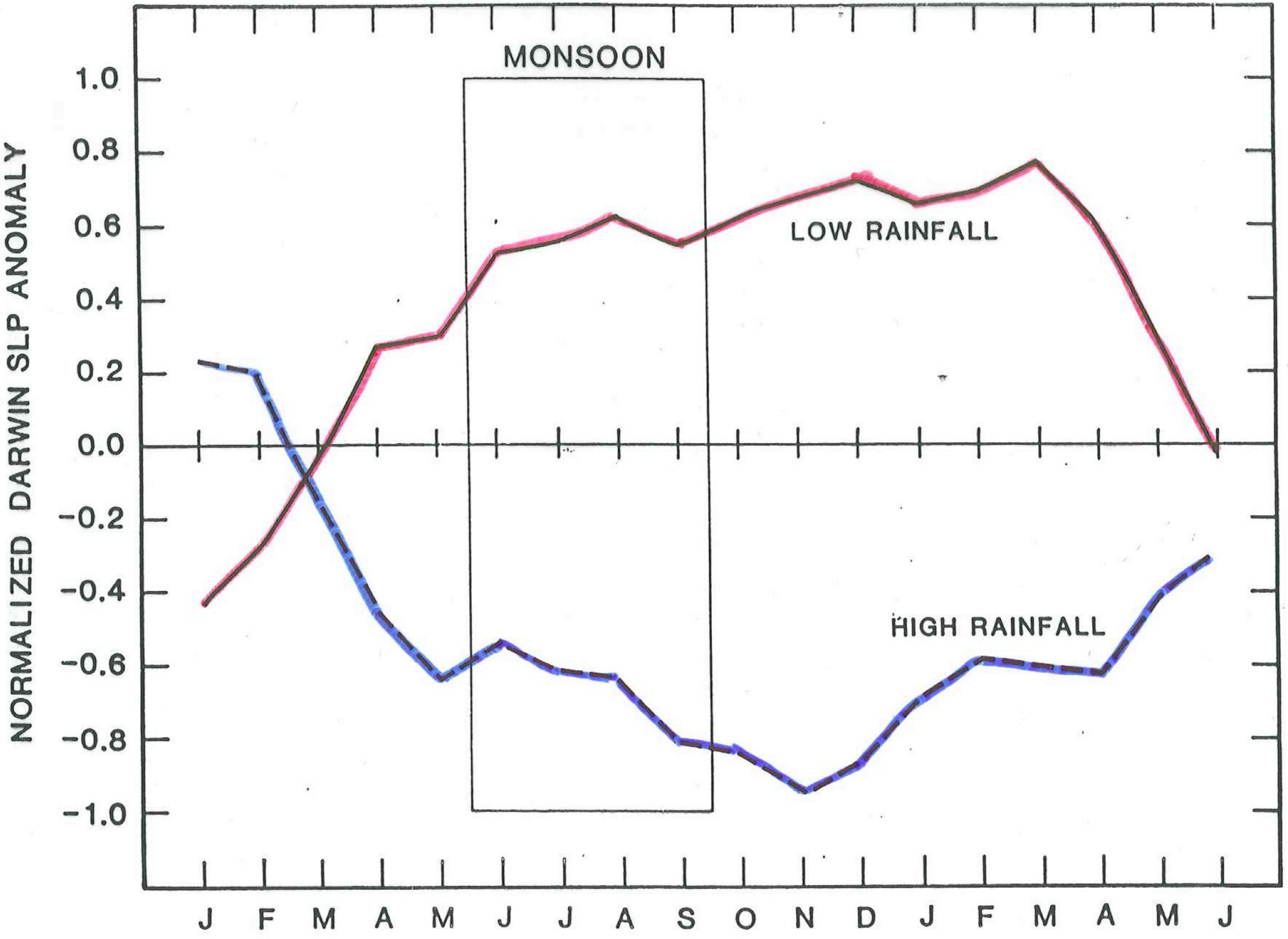
Leading Predictable Component (APT): Internal Multi-decadal Pattern (IMP)





Center of Ocean-Land-Atmosphere studies

ENSO has large amplitude after the monsoon season: to predict monsoon, we must predict ENSO first



Dynamical Seasonal Prediction (DSP)

Source of predictability: Dynamical memory of atmos. IC
+ Boundary forcing (SST, SW, snow, sea ice)

DSP = NWP + IC of Ocean, Land, Atmosphere

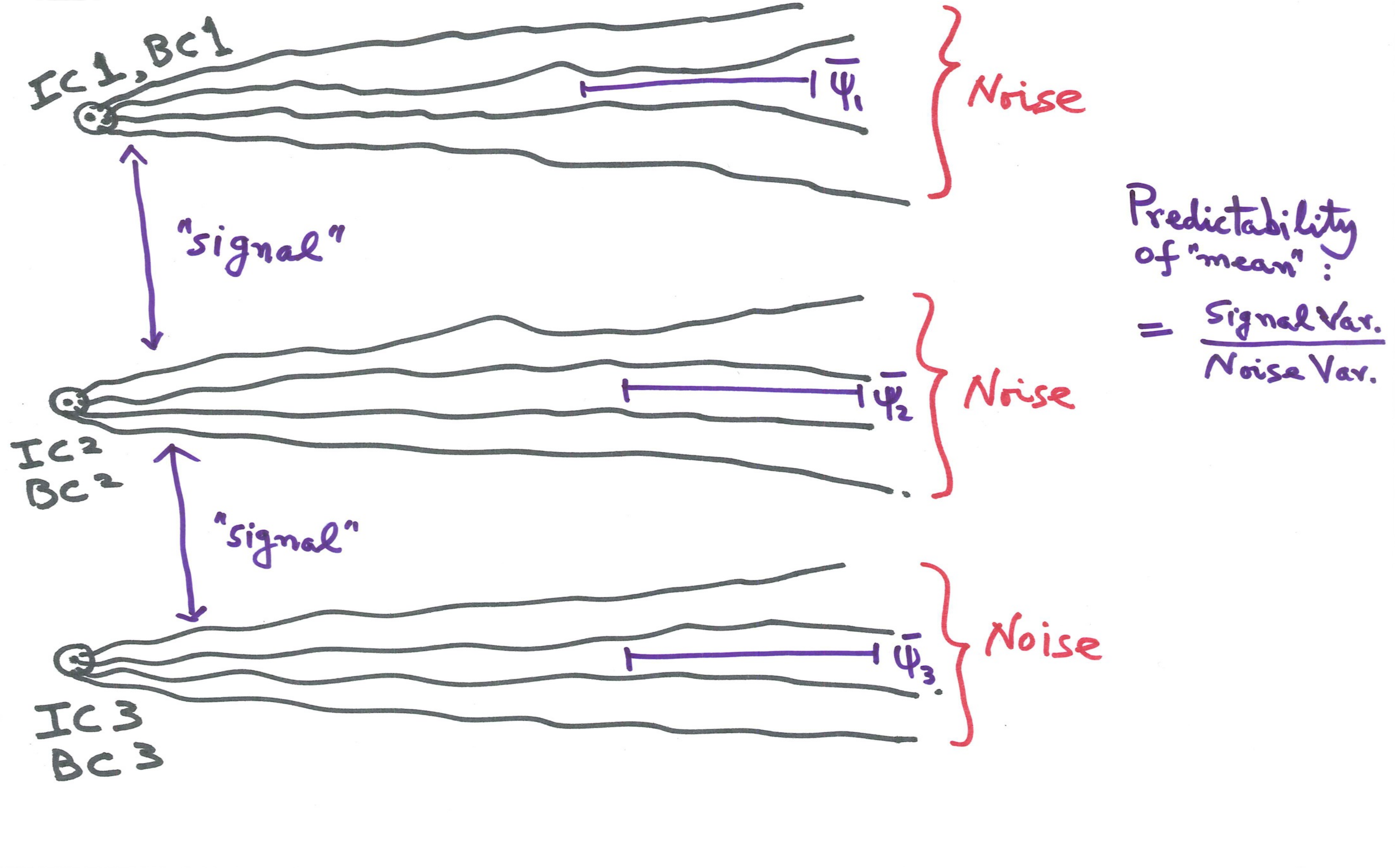
- *dynamically coupled and consistent IC*
- *Global ocean (especially upper ocean); sea ice (volume)*
- *Global Atmos. including stratosphere (IC)*
- *Global GHG (especially CO_2, O_3)*
- *Global land (soil moisture, vegetation, snow depth) IC*

Tier 1: Fully coupled models (CGCM) to predict Boundary Forcing

Tier 2: Predict Boundary Forcing separately; use AGCM

- **(NWP=Atmos. IC + SST IC)**

Predictability of Time (Seasonal) Mean



Analysis of Variance: F as a measure of predictability
5 CGCMs, 46 years, 9 ensembles

Measure of predictability is

$$F = E\frac{\hat{\sigma}_S^2}{\hat{\sigma}_N^2}$$

where

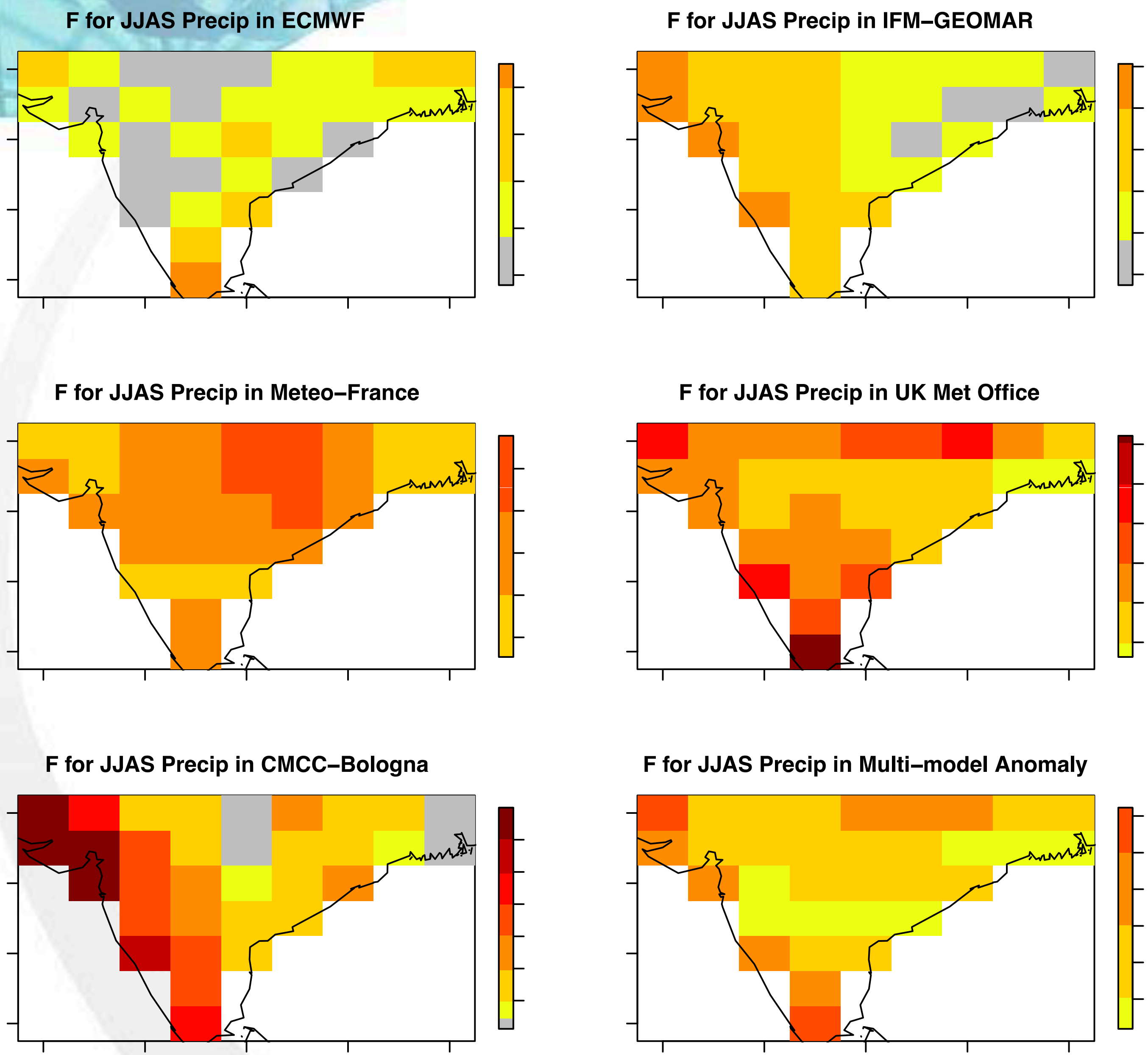
$$\hat{\sigma}_S^2 = \frac{1}{Y-1}\sum_{y=1}^{Y}\left(P_{y,e} - \overline{\overline{P}}\right)^2$$

$$\hat{\sigma}_N^2 = \frac{1}{Y(E-1)}\sum_{y=1}^{Y}\sum_{e=1}^{E}\left(P_{y,e} - \overline{P}_y\right)^2$$

$$\overline{P}_y = \frac{1}{E}\sum_{e=1}^{E} P_{y,e}$$

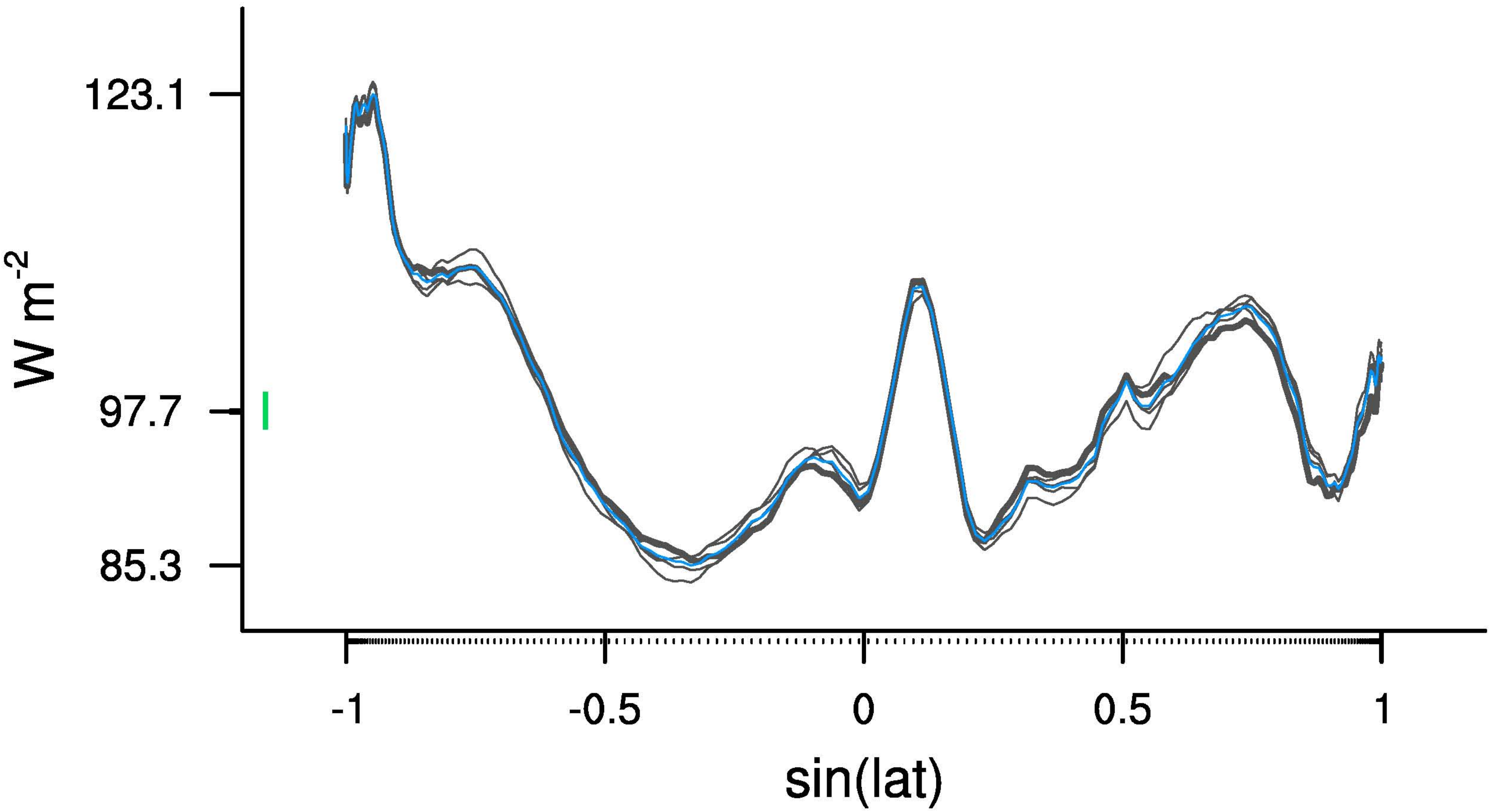
$$\overline{\overline{P}} = \frac{1}{Y}\sum_{y=1}^{Y}\overline{P}_y$$

For samples drawn independently from the same normal distribution, and for $Y = 46$ and $E = 9$, the 5% significance threshold of F is 1.40



F-values for JJAS precip. For 46-years and 9 ensemble members the 5% significance is F=1.4. Gray color indicates not statistically significant at 95% confidence interval.

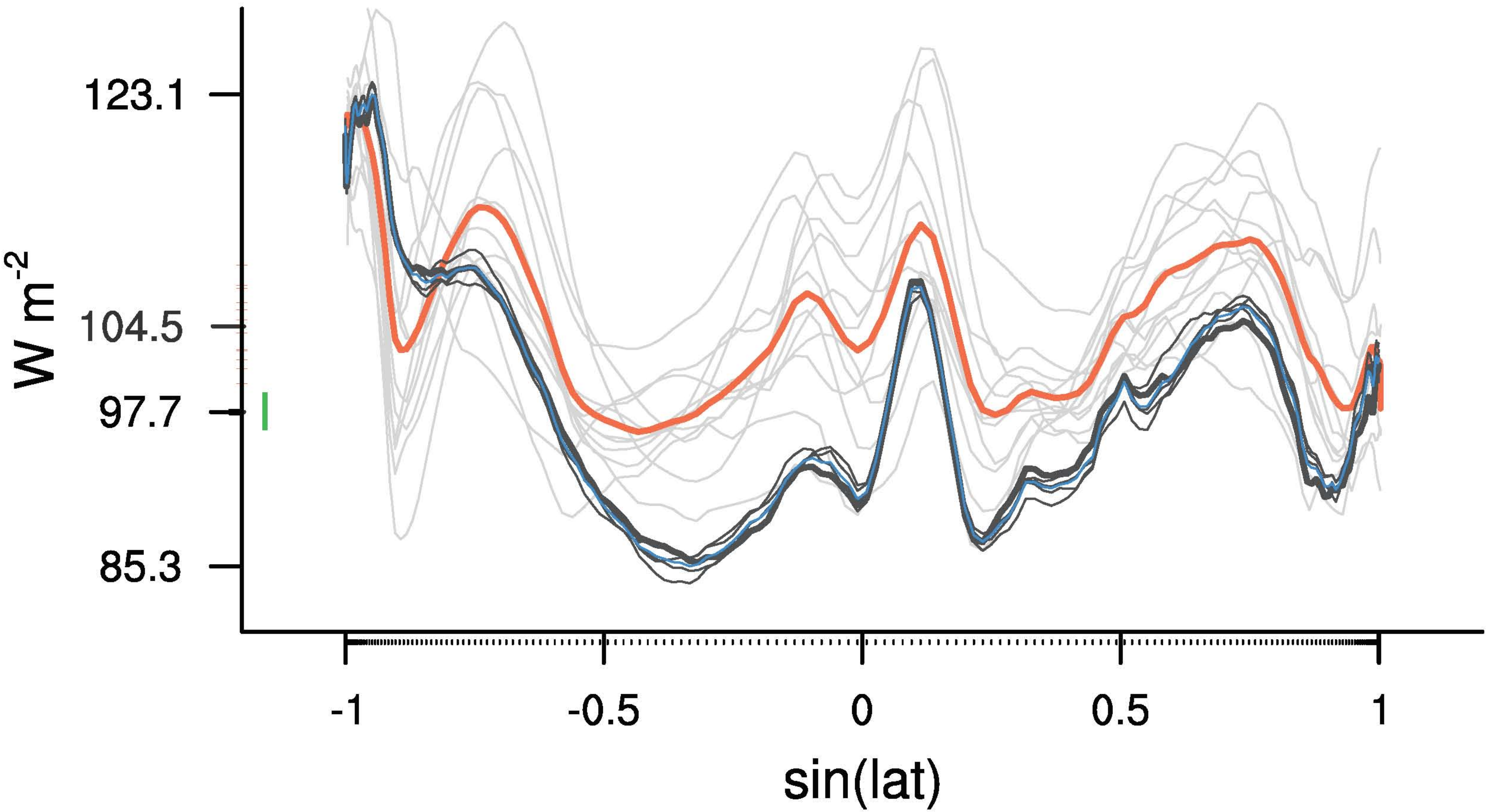
Annually & Zonally Averaged Reflected SW Radiation



Bjorn Stevens, UCLA
World Modelling Summit, ECMWF, May 2008

IGES
Center of Ocean-Land-Atmosphere studies
COLA
GEORGE MASON UNIVERSITY

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

Impediments to Progress in Earth System Prediction

1. The science community uses low-resolution inadequate climate models for prediction, not only because of a lack of knowledge of science, but also because of the lack of appropriate Earth System Modeling infrastructure with sufficient computational capacity and critical mass of qualified scientists.

2. Major national modeling centers (NCAR, GFDL) use one set of models, and national prediction centers (NCEP, FNMOC) use another set of models (insufficient or no interaction).

3. Operational centers have been less successful than research centers in attracting young talented scientists.

Dynamical Prediction Experience

Model predictability depends on model fidelity