The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

SMR/1849-33

Conference and School on Predictability of Natural Disasters for our Planet in Danger. A System View; Theory, Models, Data Analysis

25 June - 6 July, 2007

Predictability of Weather and Climate

Jagadish Shukla

George Mason University (GMU)
Institute of Global Environment and Society (IGES)
U S A

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A System View: Theory, Models, Data Analysis
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IGES

Center of Ocean-Land-Atmosphere studies COLA

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Outline

- **Weather and Climate for Poets**
- **Mechanisms of Variability of Weather and Climate**
- **Predictability and Prediction of Weather and Climate**
  - Weather
  - Climate (Seasonal, ENSO, Decadal)
  - Climate Change
- **Factors Limiting Predictability: Future Challenges**
  - Observational and Theoretical (Physics & Dynamics of the Coupled Climate System)
  - Computational and Numerical
- **Summary and Conclusions**

Physics of Weather and Climate
for Poets

Weather is what you get,
climate is what you expect.

(E. N. Lorenz)

Weather and Climate

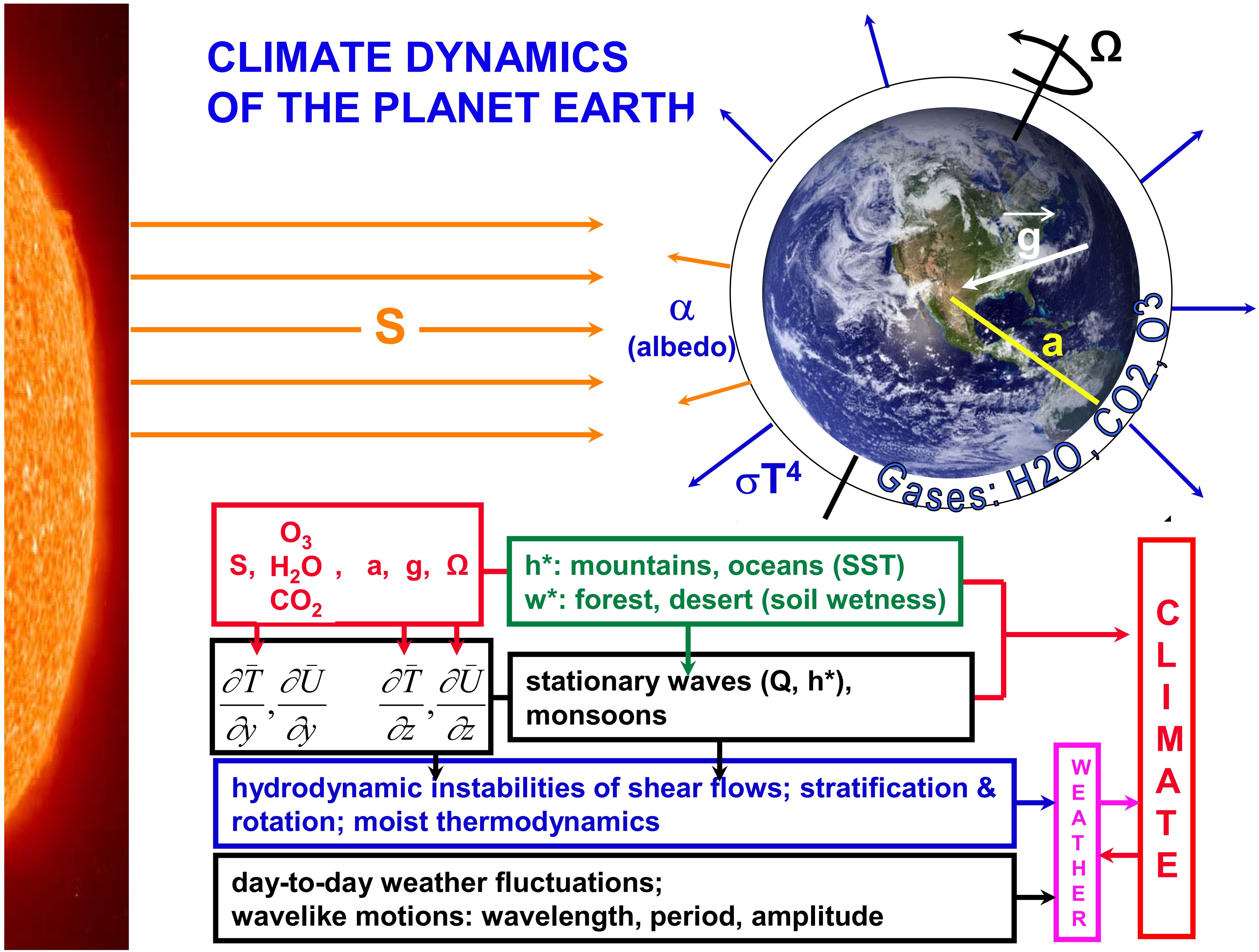
(Weather: Wind, Pressure, Temperature, Humidity & Precipitation)

Weather (x, y, z, t) = Expected Weather (x, y, z, t) + Unexpected Weather (x, y, z, t)

Expected Weather (x, y, z, t) → Climate

The Climate of a Planet Depends On …

1.	Energy from the Sun	S
	(energy from the interior)	
2.	Planetary Albedo	α
3.	Speed of Planet's Rotation	Ω
4.	Mass of the Planet	M
5.	Radius of the Planet	a
6.	Atmospheric Composition	H_2O, CO_2, O_3, clouds
7.	Ocean-Land, Topography	h*

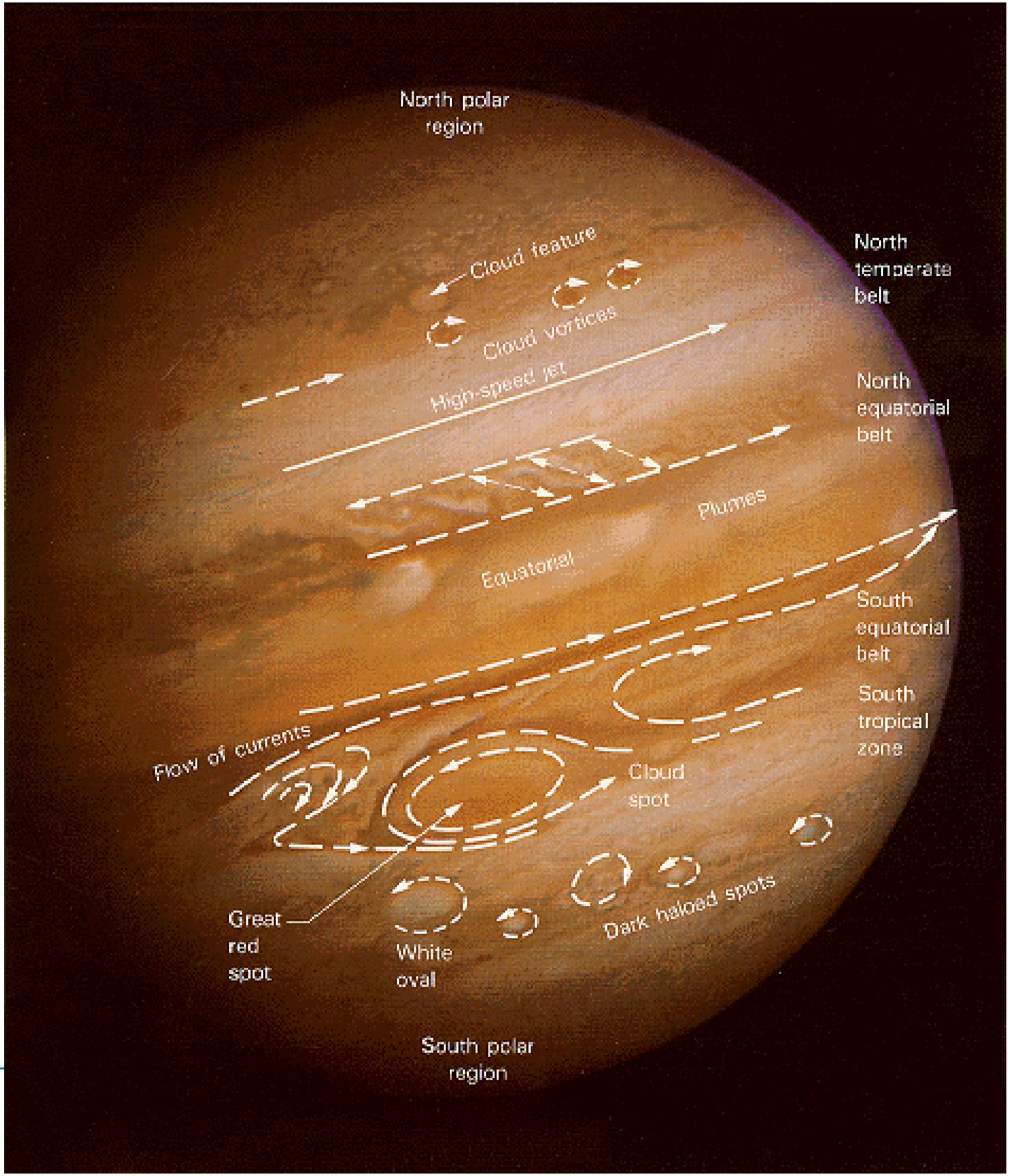

CLIMATE DYNAMICS
OF THE PLANET EARTH
S
α
(albedo)
σT4
Ω
g
a
Gases: H2O, CO2, O3
O3
S, H2O, a, g, Ω
CO2
h*: mountains, oceans (SST)
w*: forest, desert (soil wetness)
$\frac{\partial \bar{T}}{\partial y}, \frac{\partial \bar{U}}{\partial y}$
$\frac{\partial \bar{T}}{\partial z}, \frac{\partial \bar{U}}{\partial z}$
stationary waves (Q, h*),
monsoons
hydrodynamic instabilities of shear flows; stratification &
rotation; moist thermodynamics
day-to-day weather fluctuations;
wavelike motions: wavelength, period, amplitude
WEATHER
CLIMATE

What Determines the Climate of a Planet

	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
Mean Radius (km)	2440	6052	6371	3390	69911	58232	25362	24624
Mass ($\times 10^{24}$ kg)	0.3302	4.869	5.973	6.419	1898.6	568.46	86.832	102.43
Rotation Period	58.6d	−243d	23.93h	24.62h	9.93h	10.66h	17.24h	16.11h
Year Length (Earth days)	87.97	224.7	365.24	686.92	4330.6	10747	30589	59800
Equatorial Gravity ($m\ s^{-2}$)	3.701	8.870	9.780	3.690	23.12	8.96	8.69	11.00
Planetary Solar constant ($W\ m^{-2}$)	9936.9	2613.9	1367.6	589.0	50.5	15.04	3.71	1.47
Geometric Albedo	0.106	0.65	0.367	0.150	0.52	0.47	0.51	0.41
Obliquity to Orbit (deg.)	~0.1	177.3	23.45	25.19	3.12	26.73	97.86	29.56
Atmos. Temp.		735 K	270 K	210 K				
Atmos. Pressure (Bar)		90	1.0	0.0056				
Atmos. CO_2		96.5%	.035%	95.3%				
Atmos. H_2O		.015%	<4%	.021%				

AGU Reference Shelf 1; Global Earth Physics, A Handbook of Physical Constants (1995, T. J. Ahrens, Ed.)

Multiple Jets on Jupiter



Jupiter

Rotation Period: 9.93 hrs

Radius: 70,000 Km

Gravity: 23.12 ms^{-2}

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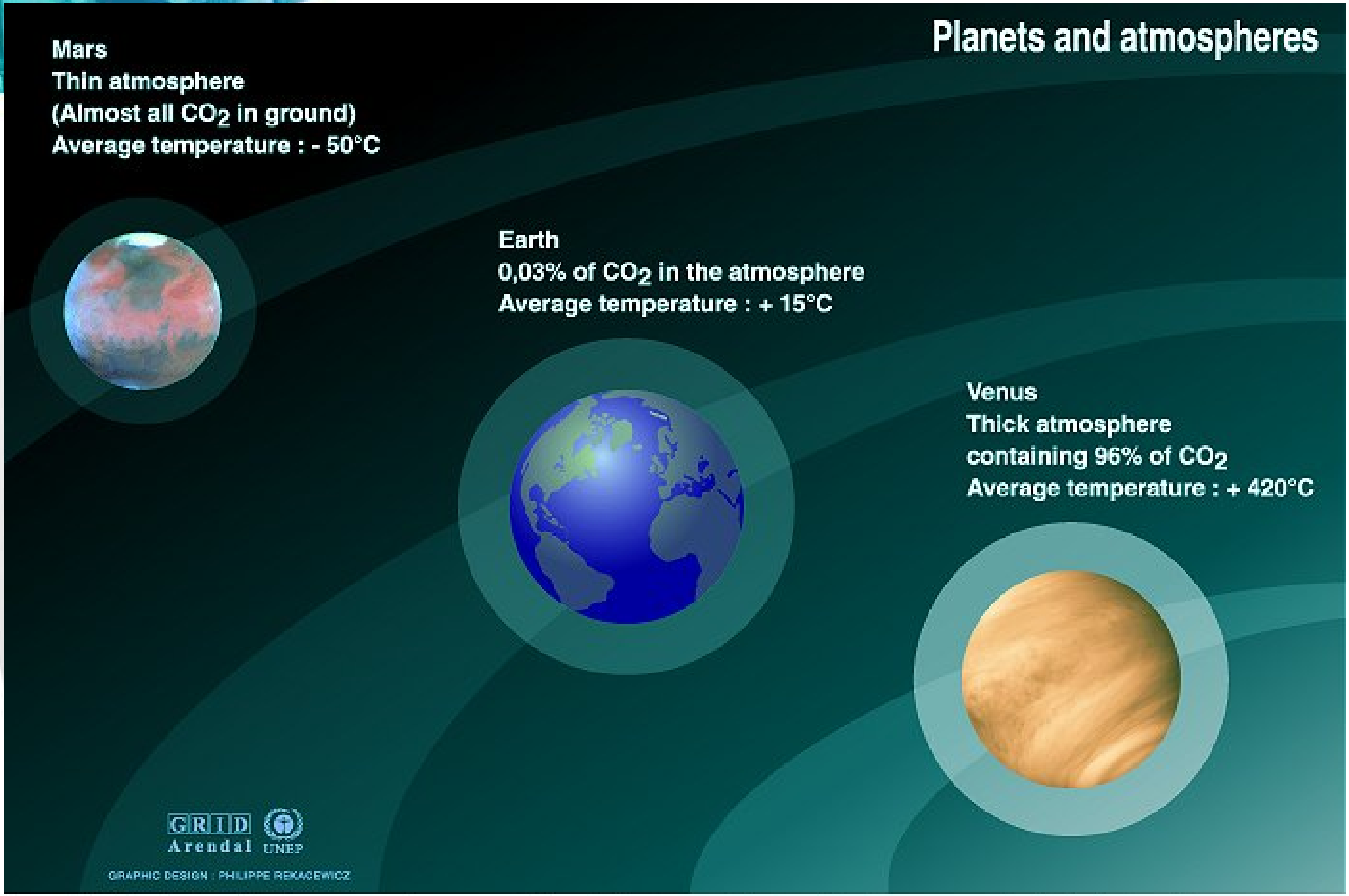
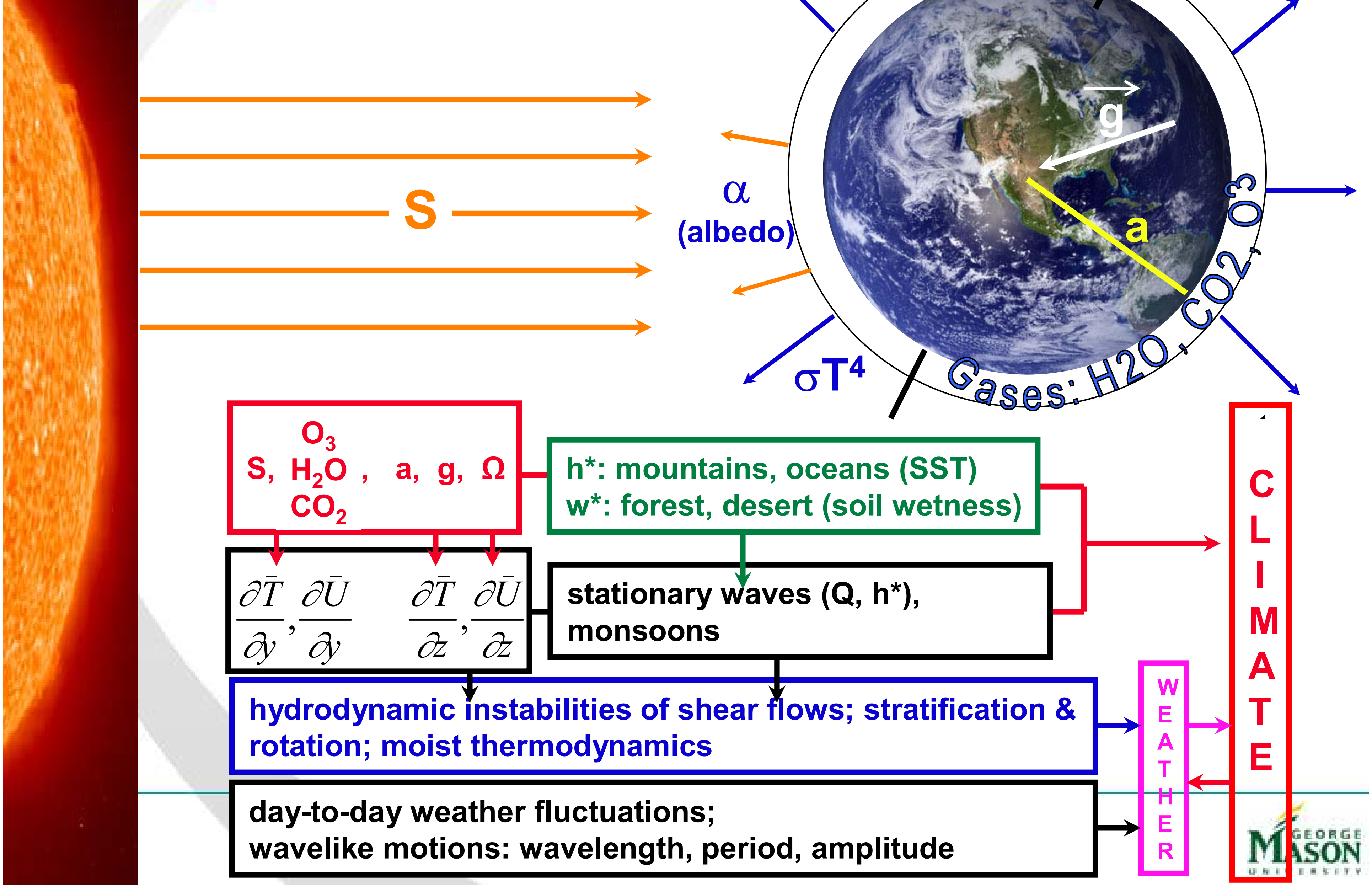
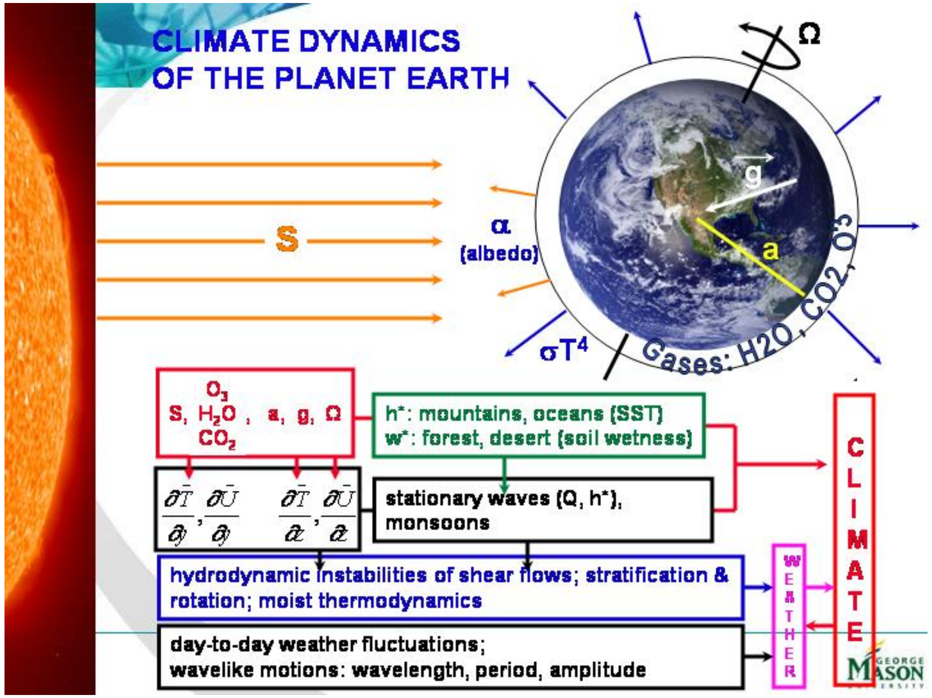


Sources: Calvin J. Hamilton, Views of the solar system, www.planetscapes.com; Bill Arnett , The nine planets, a multimedia tour of the solar system, www.seds.org/billa/tnp/nineplanets.html

CLIMATE DYNAMICS OF THE PLANET EARTH





The Climate of a Planet Depends On …

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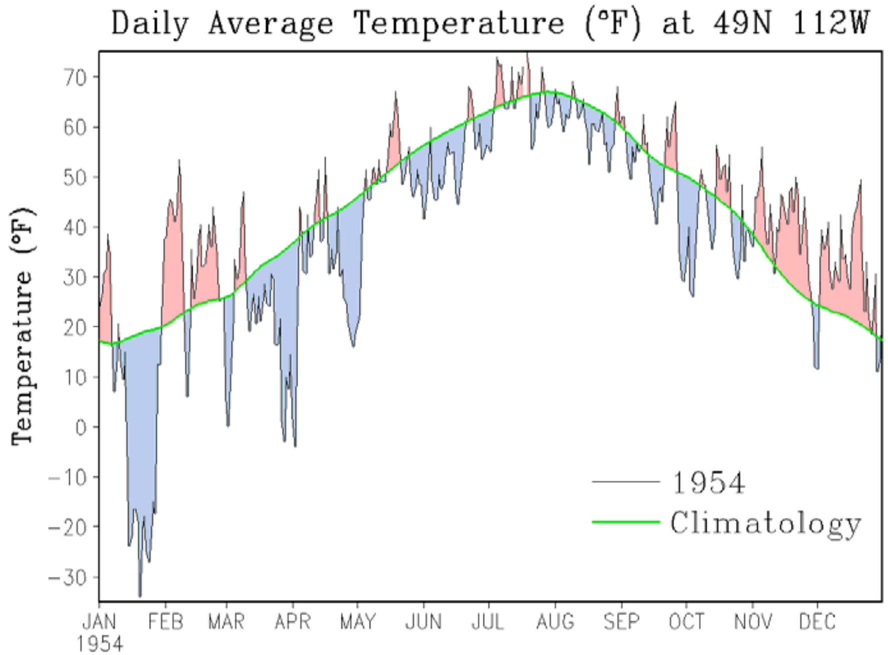
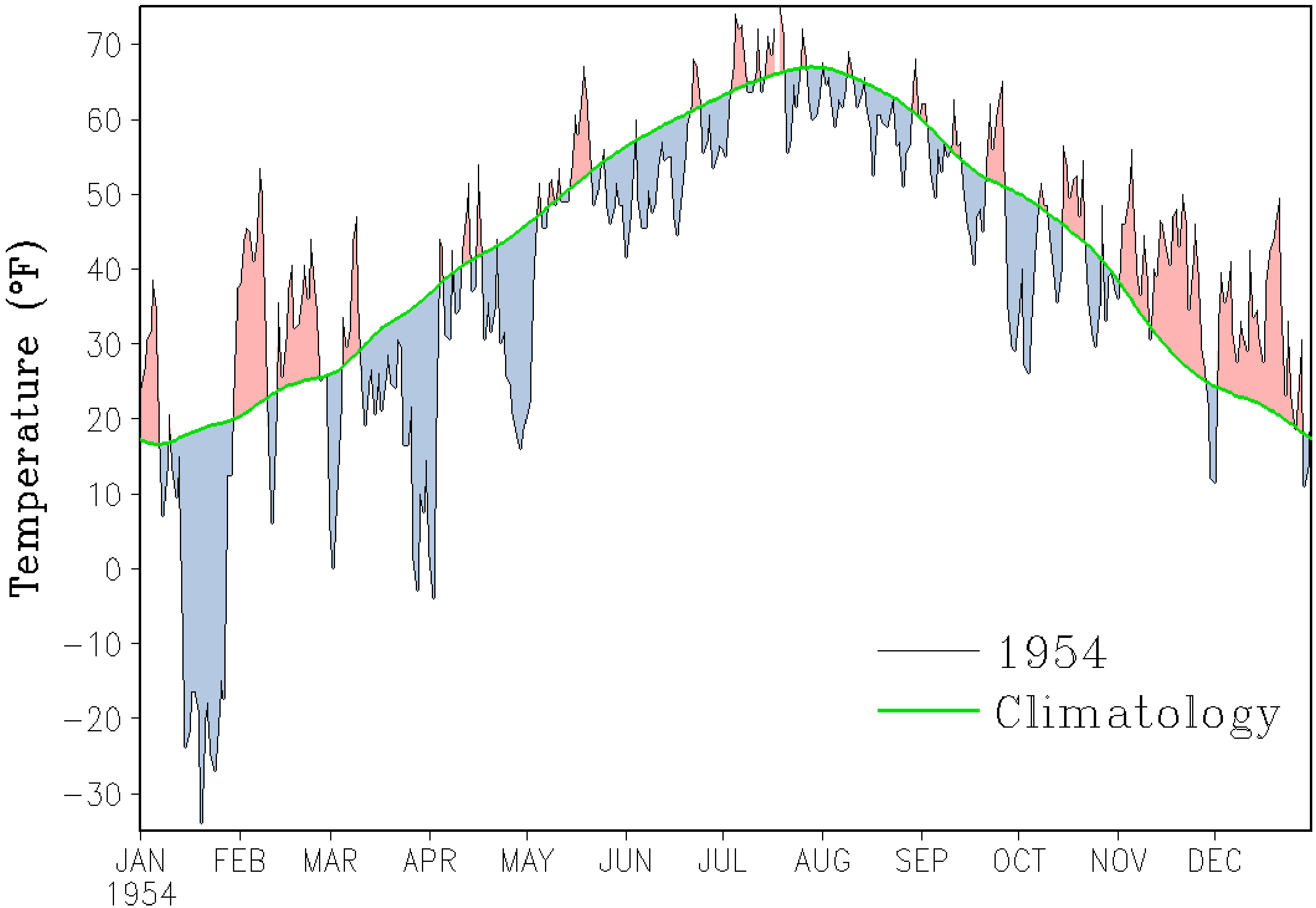


Examples of Weather and Climate Variability

- Annual Cycle
- Daily Weather
- Seasonal Climate
- Interannual (ENSO)
- Decadal
- Centennial (Climate Change)

Daily Average Temperature (°F) at 49N 112W



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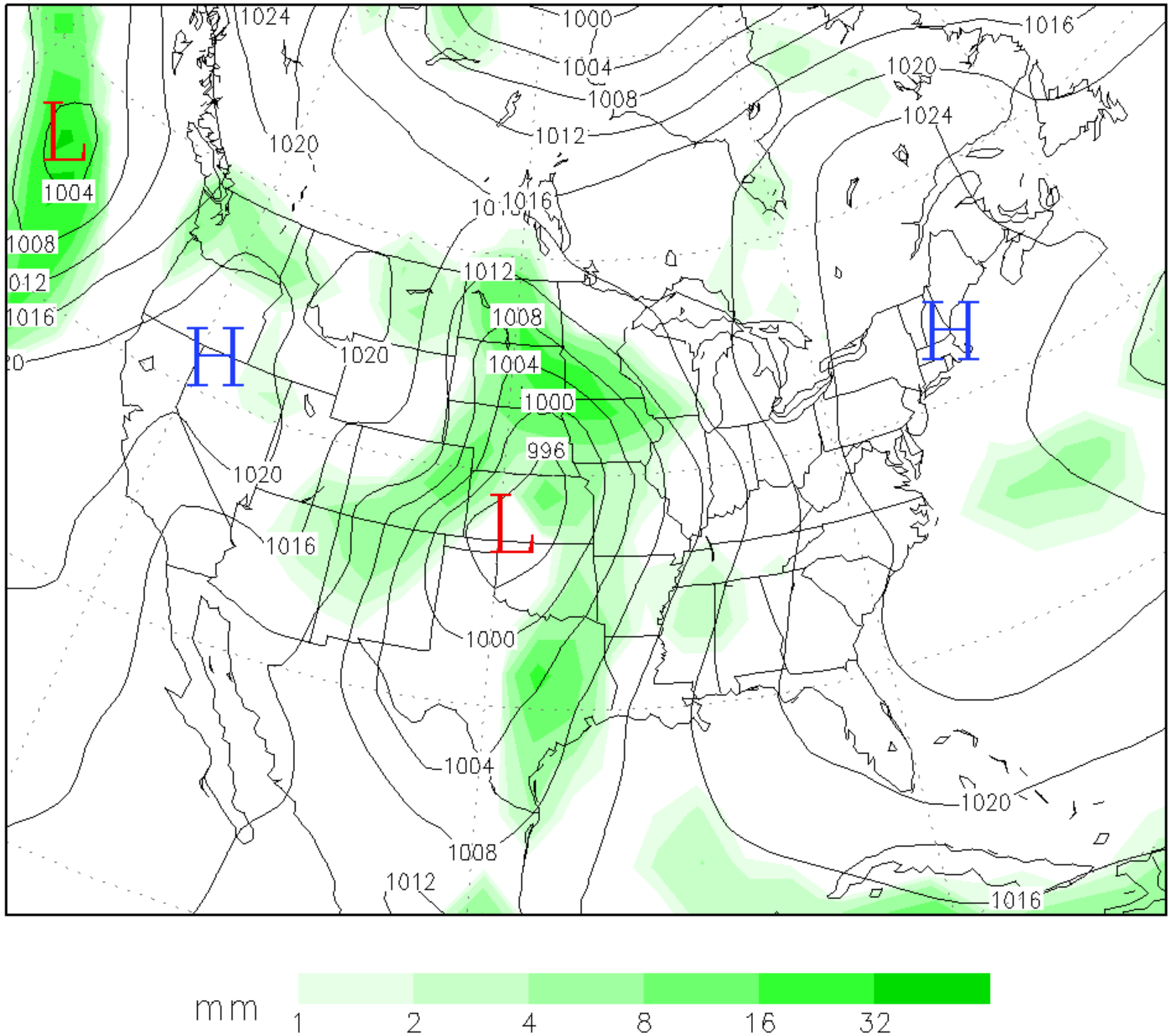
Sea Level Pressure (mb) and Precipitation Rate (mm/12Hr)
00Z Tue 10 NOV, 1998



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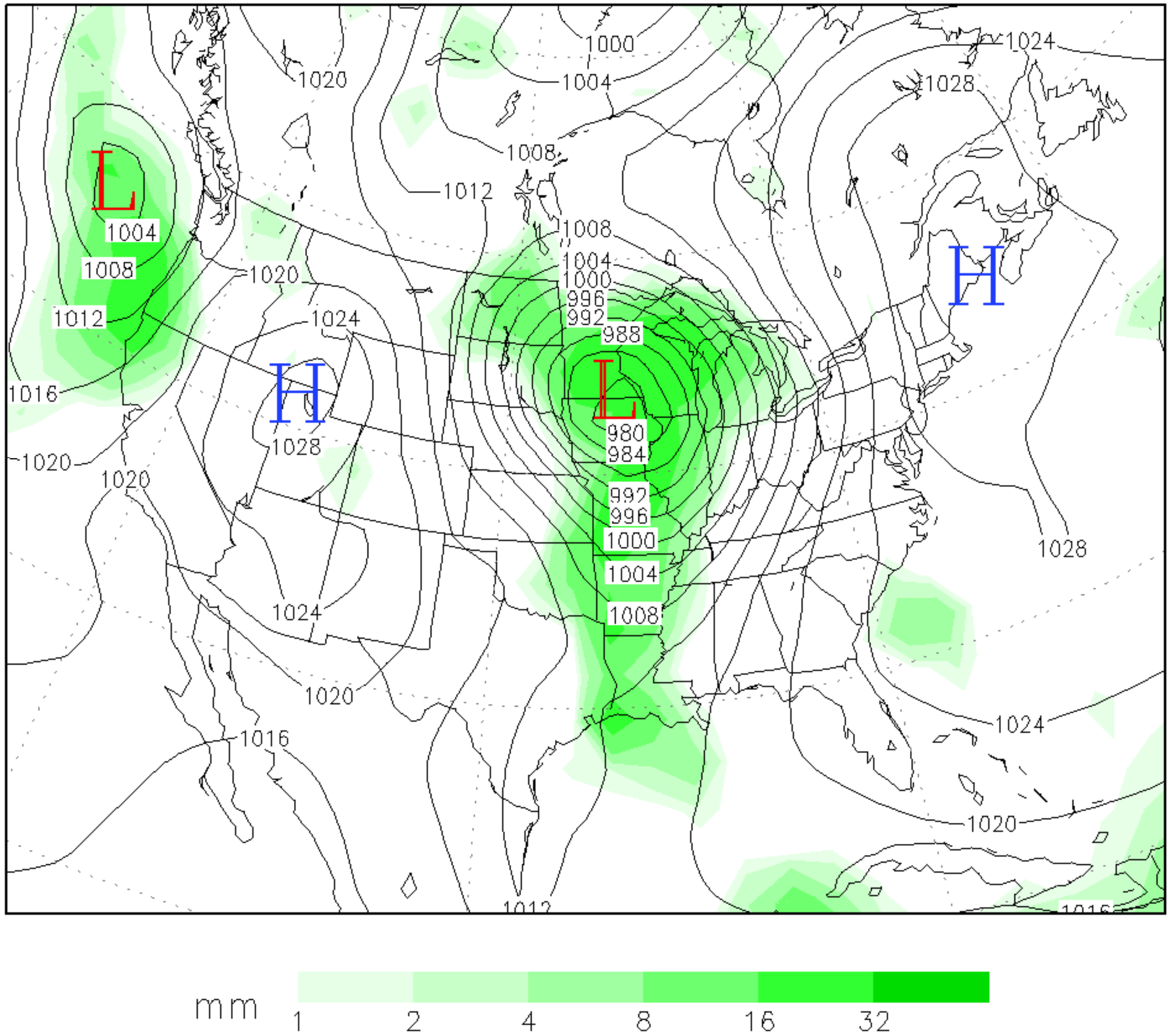
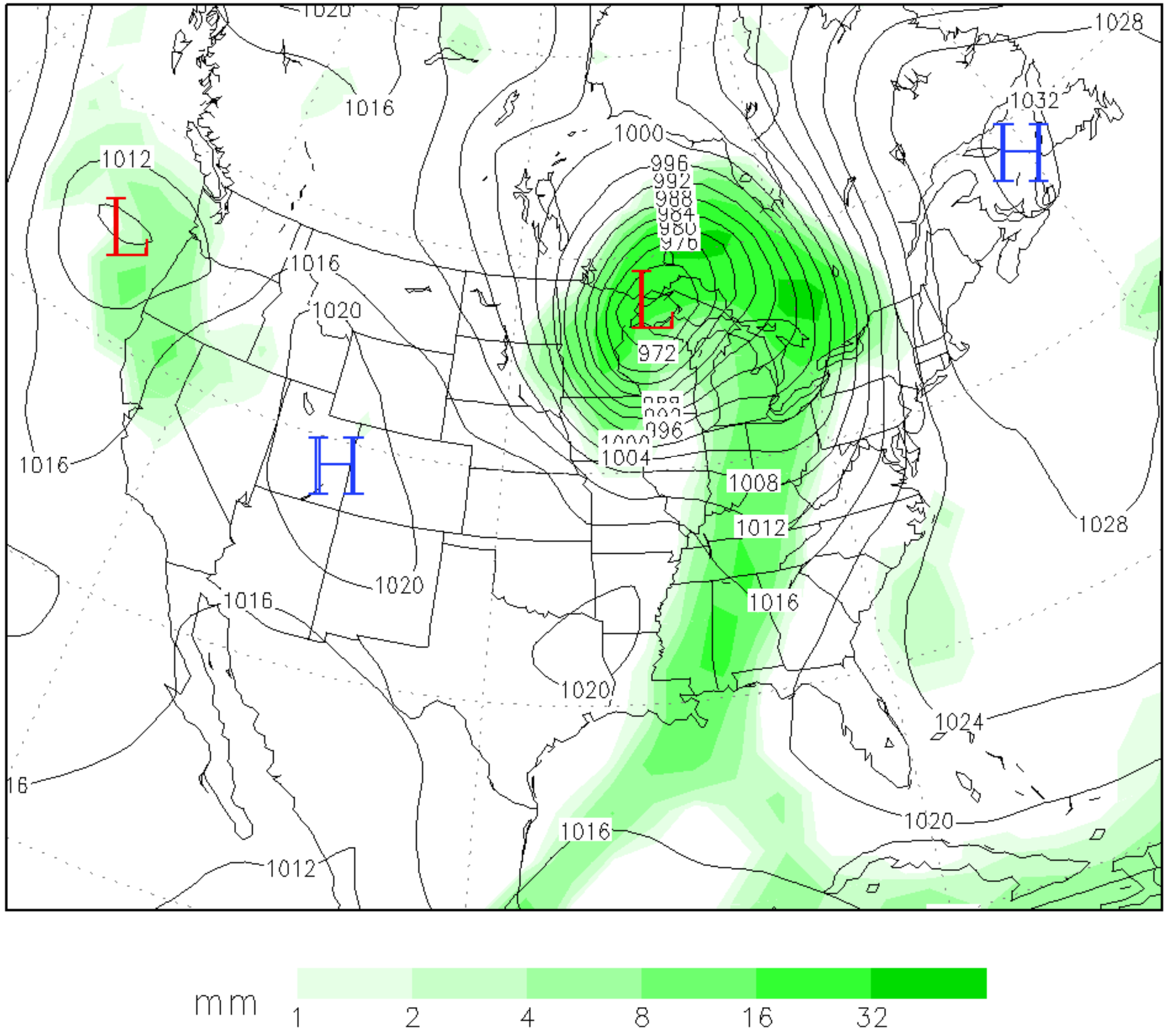


Sea Level Pressure (mb) and Precipitation Rate (mm/12Hr)
00Z Wed 11 NOV, 1998



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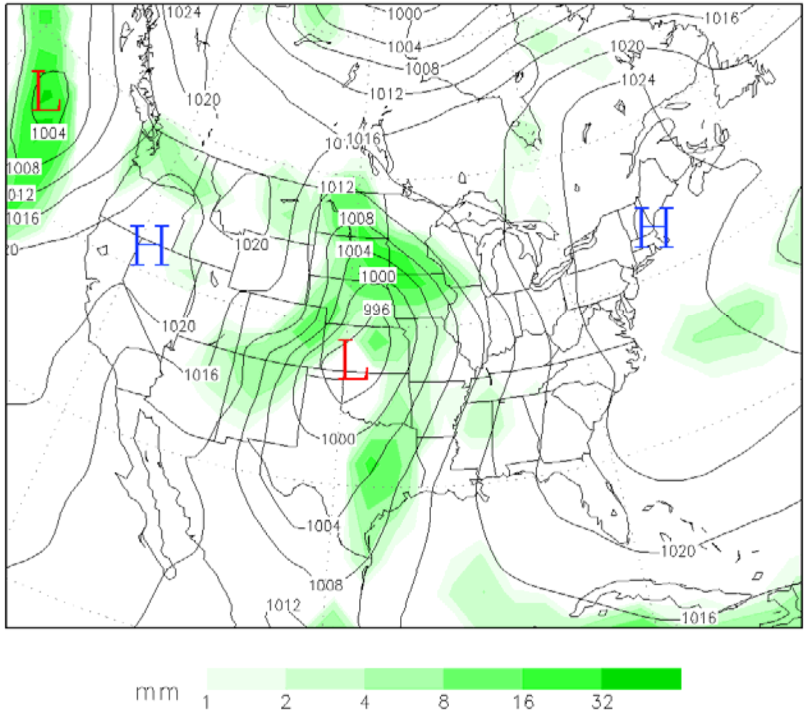

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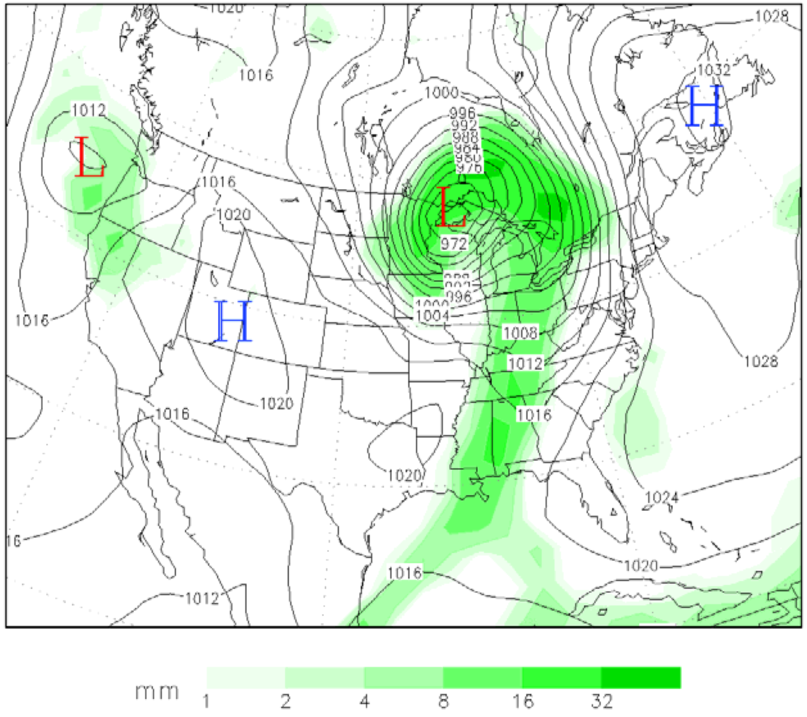
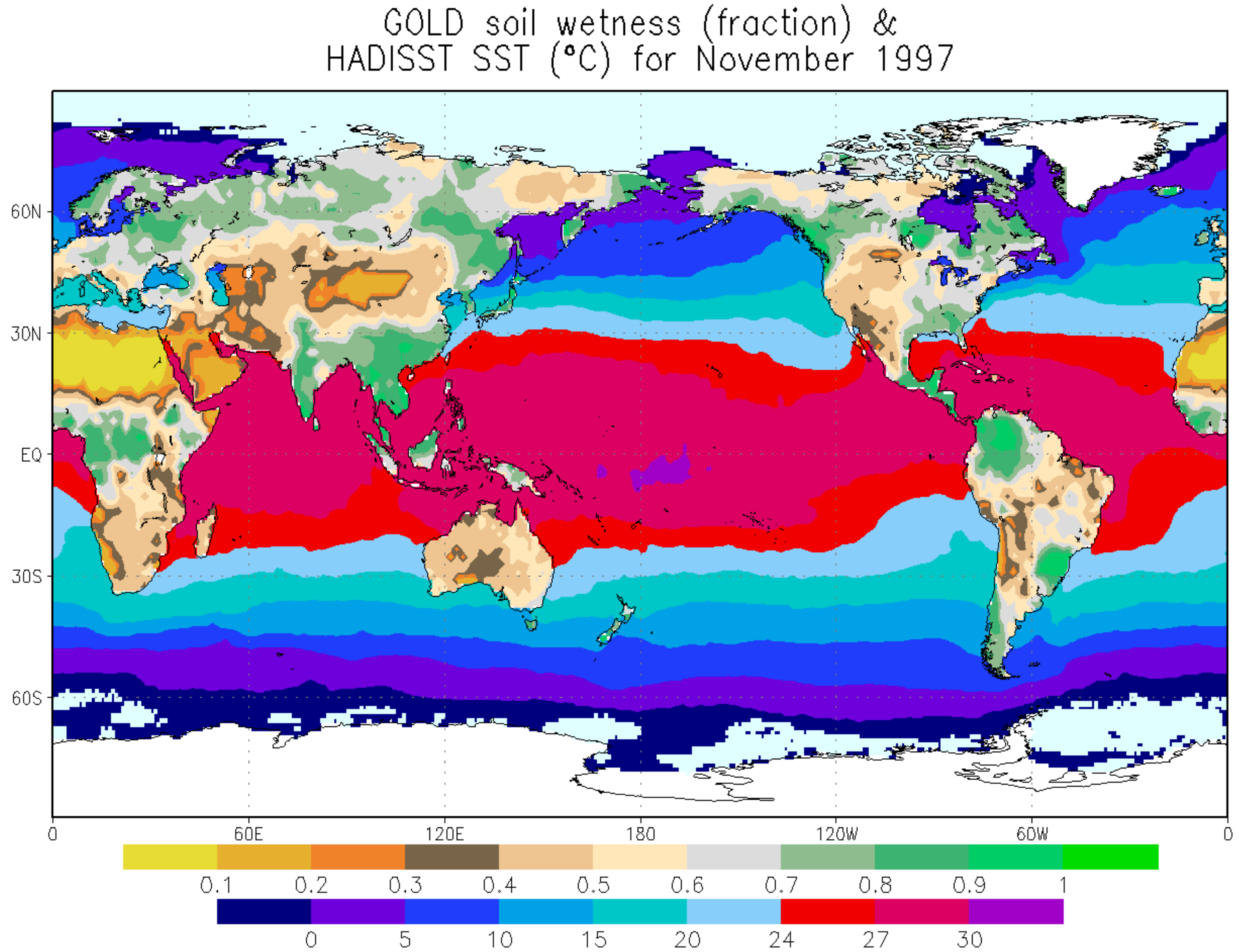
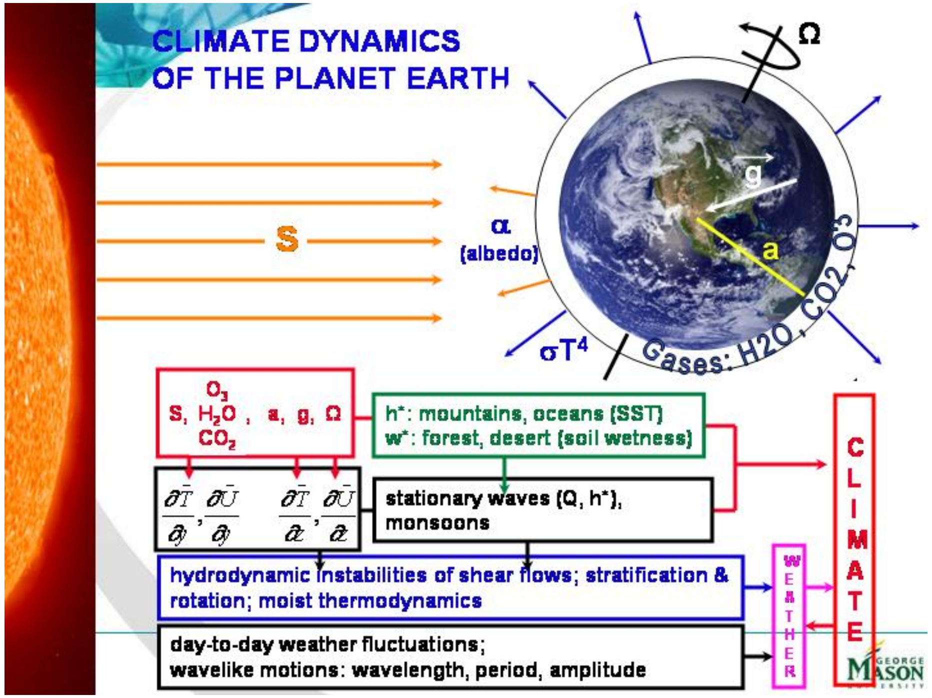



GOLD soil wetness (fraction) &
HADISST SST (°C) for November 1997
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
24
27
30



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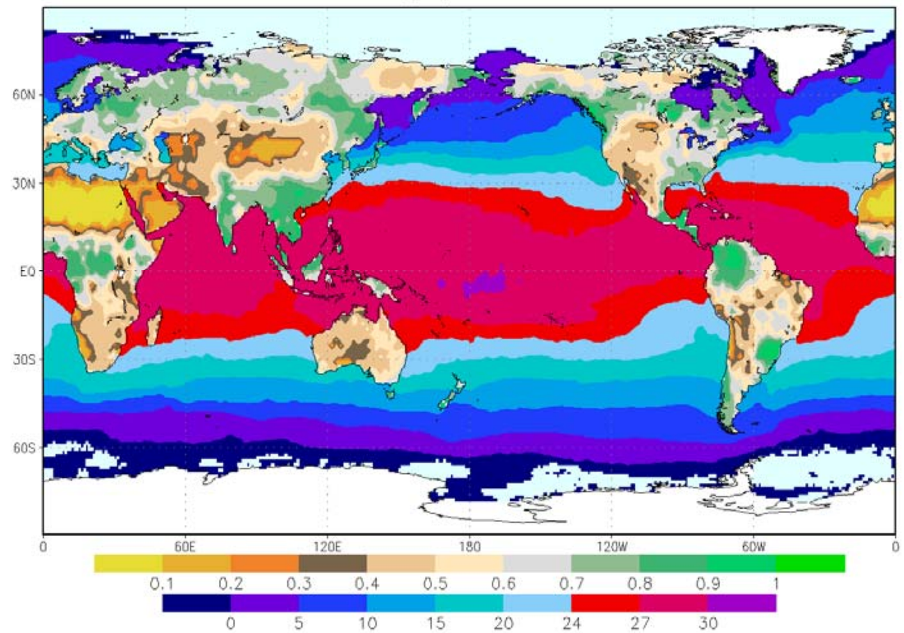
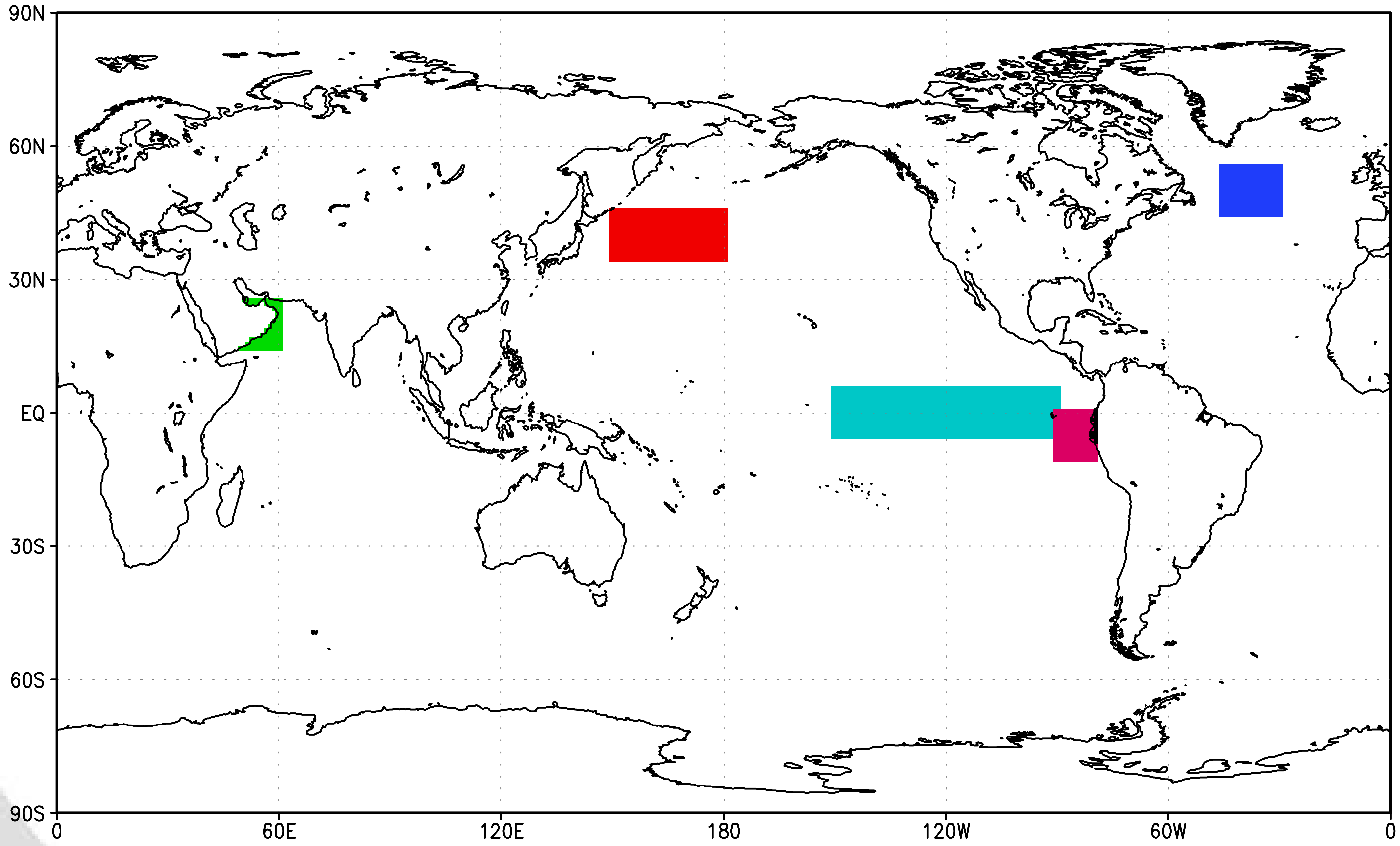
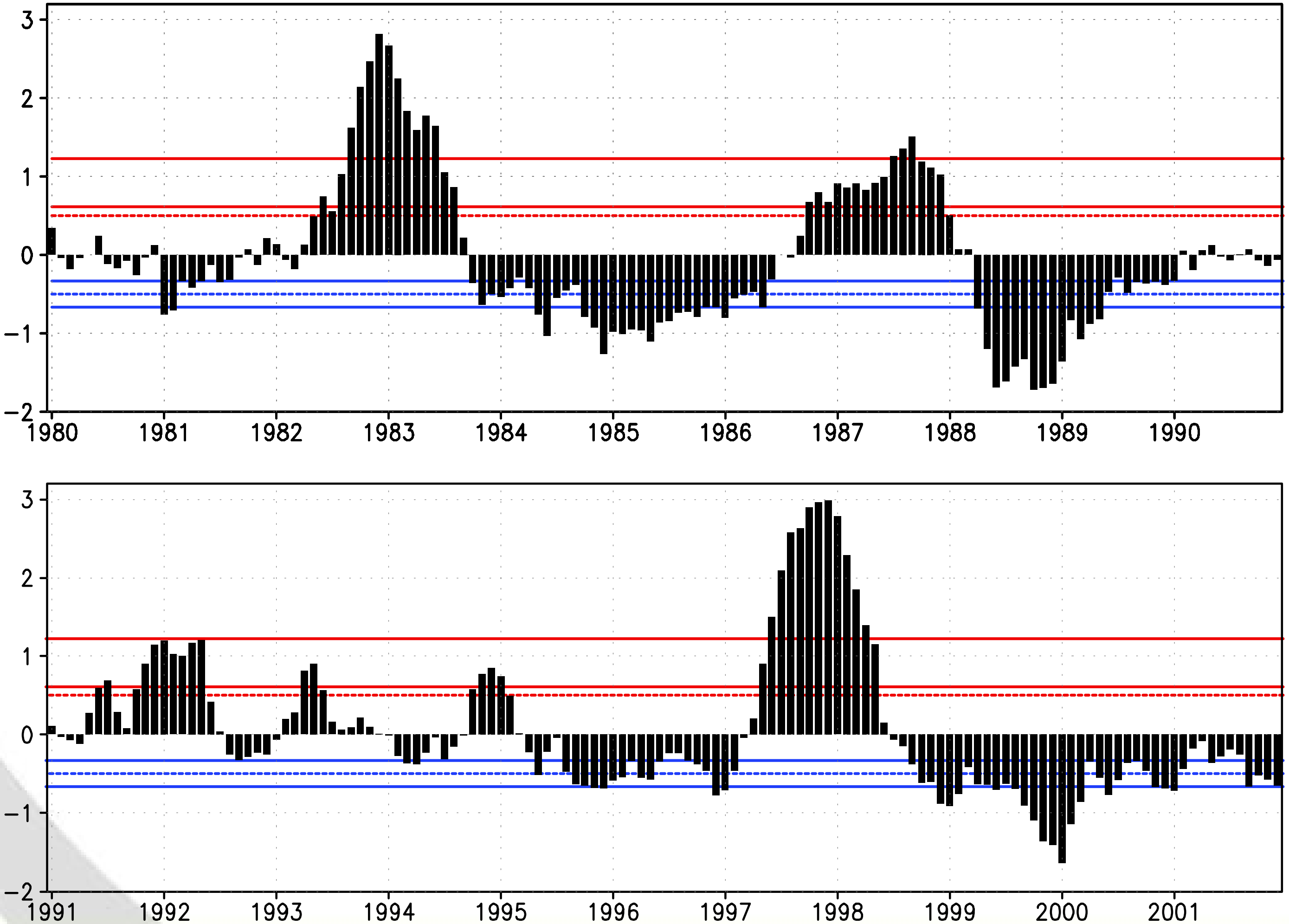



90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0

Interannual Variability of Tropical Pacific SSTA

(NINO3, 150°-90°W, 5°S-5°N)



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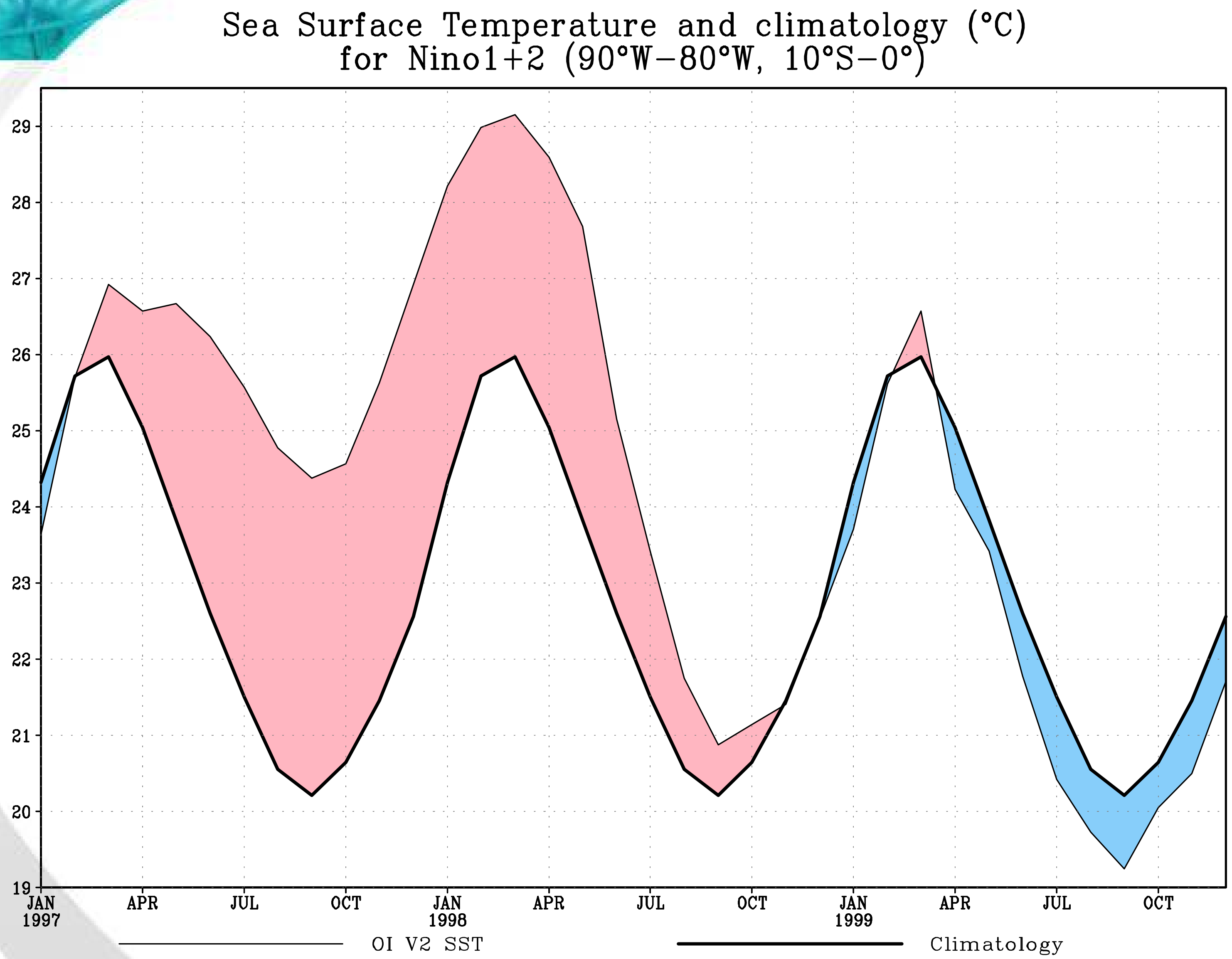
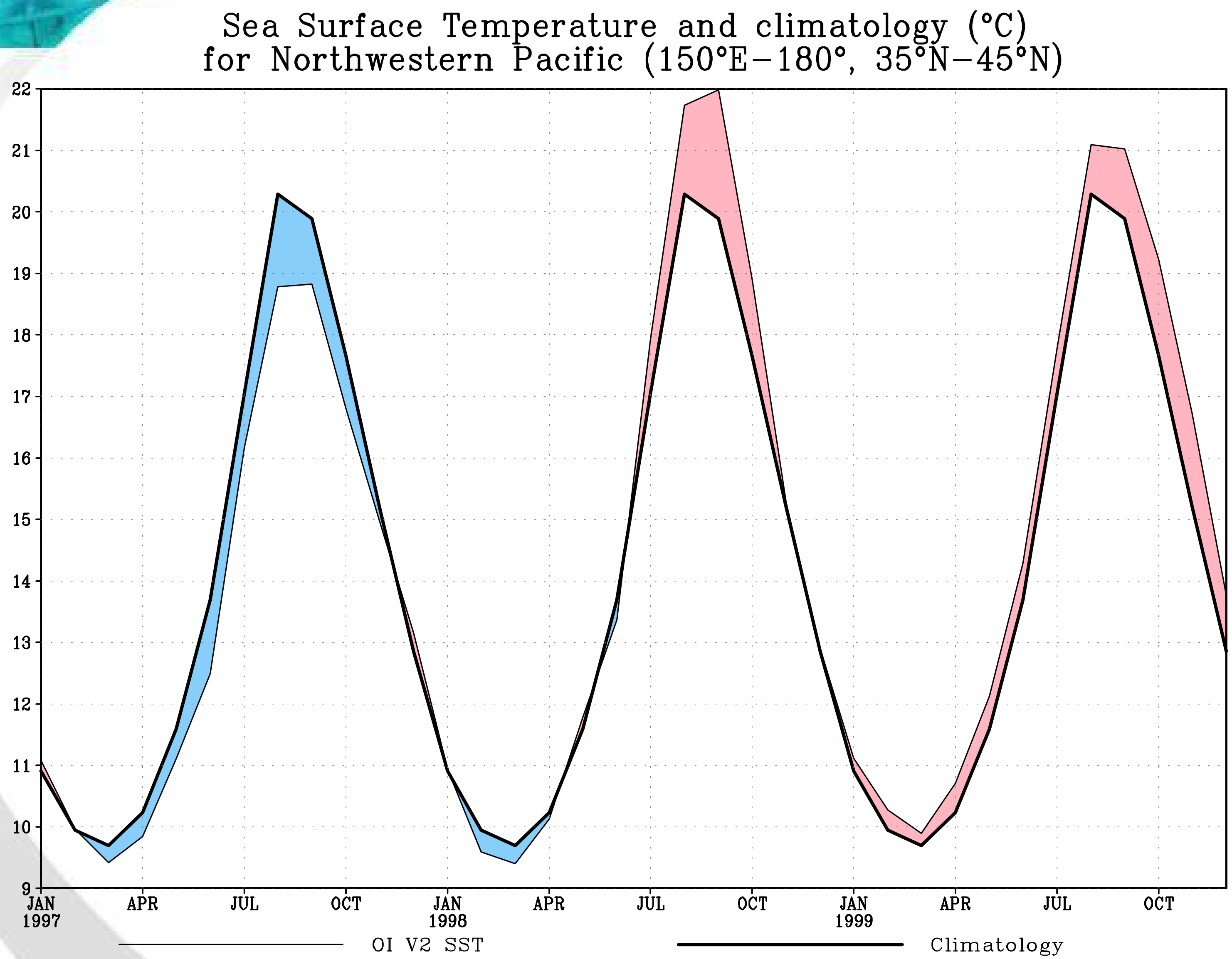
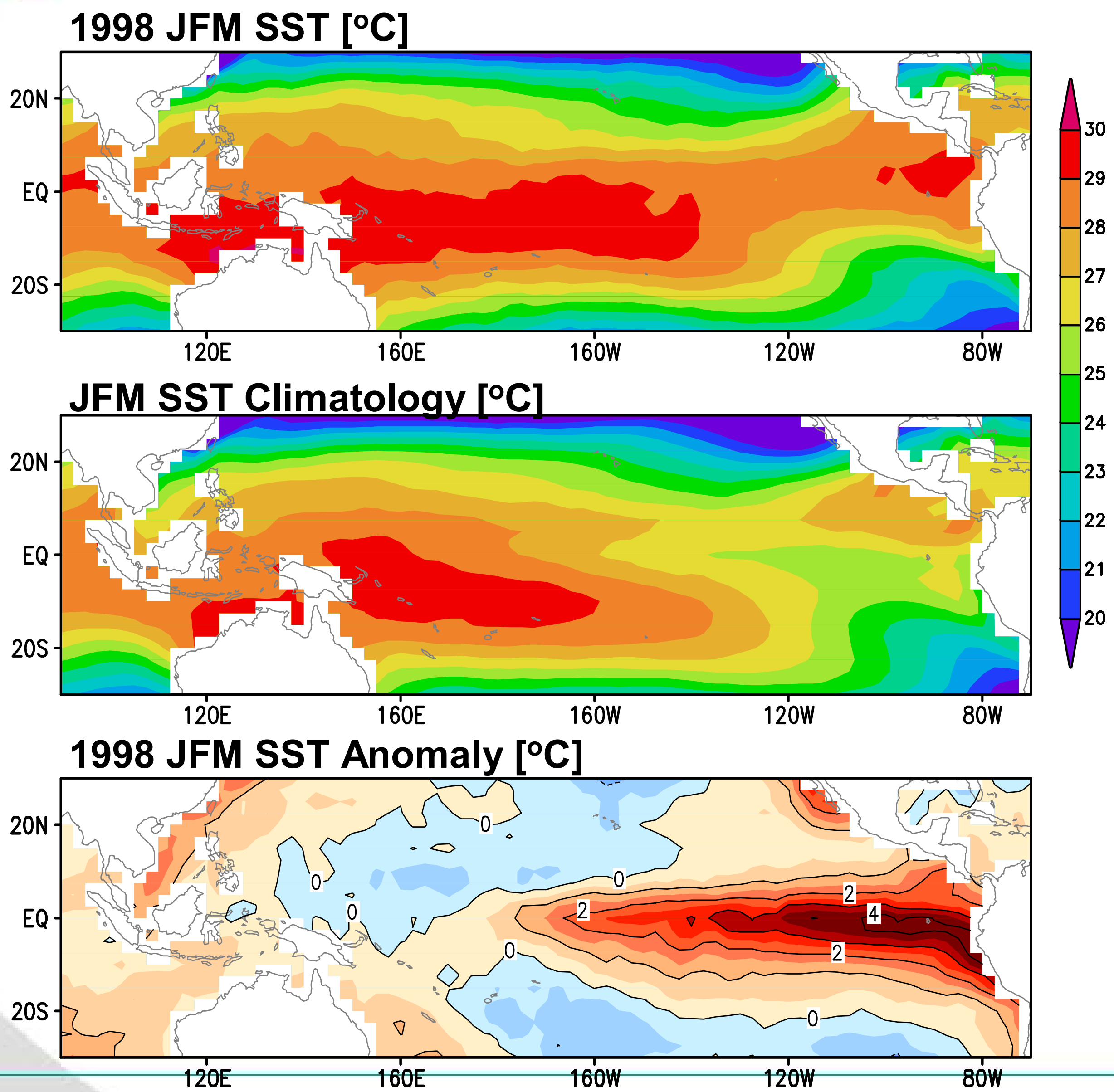

Sea Surface Temperature and climatology (°C)
for Nino1+2 (90°W–80°W, 10°S–0°)
29
28
27
26
25
24
23
22
21
20
19
JAN 1997
APR
JUL
OCT
JAN 1998
APR
JUL
OCT
JAN 1999
APR
JUL
OCT
OI V2 SST
Climatology

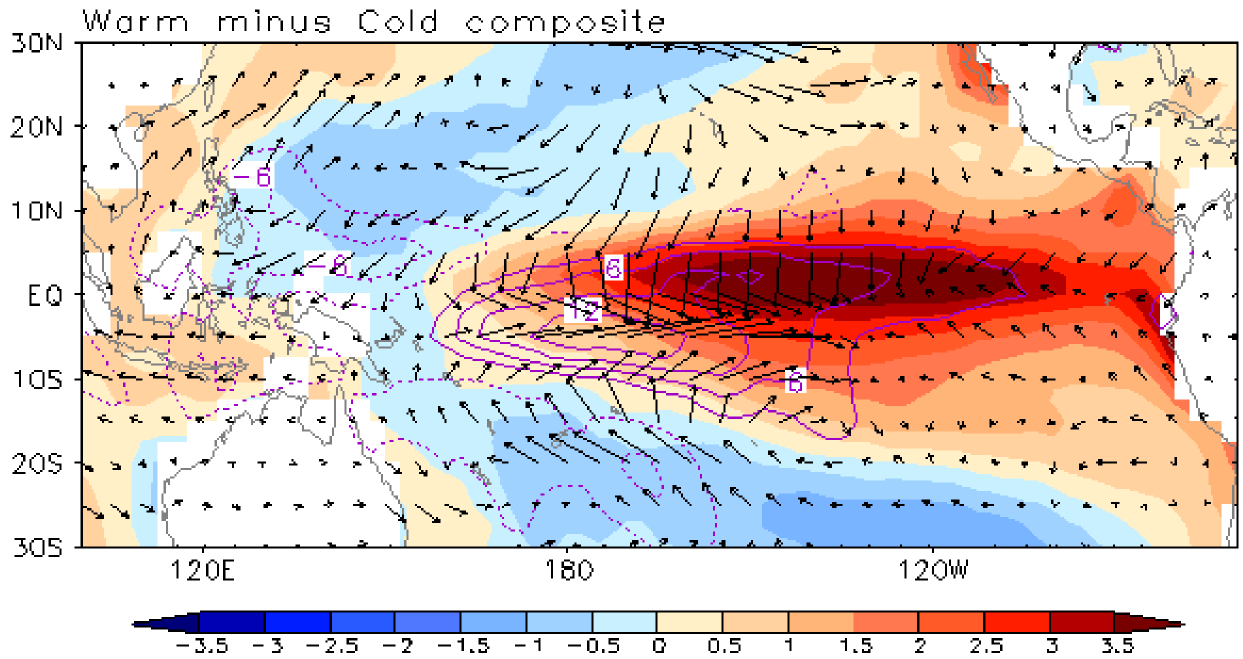


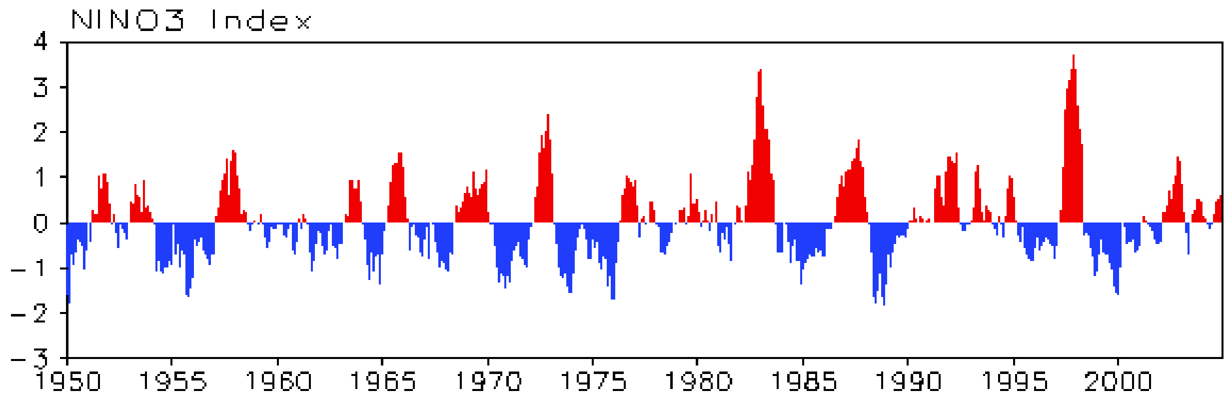
Sea Surface Temperature and climatology (°C)
for Northwestern Pacific (150°E–180°, 35°N–45°N)
22
21
20
19
18
17
16
15
14
13
12
11
10
9
JAN 1997
APR
JUL
OCT
JAN 1998
APR
JUL
OCT
JAN 1999
APR
JUL
OCT
OI V2 SST
Climatology

El Nino/Southern Oscillation



El Nino/Southern Oscillation





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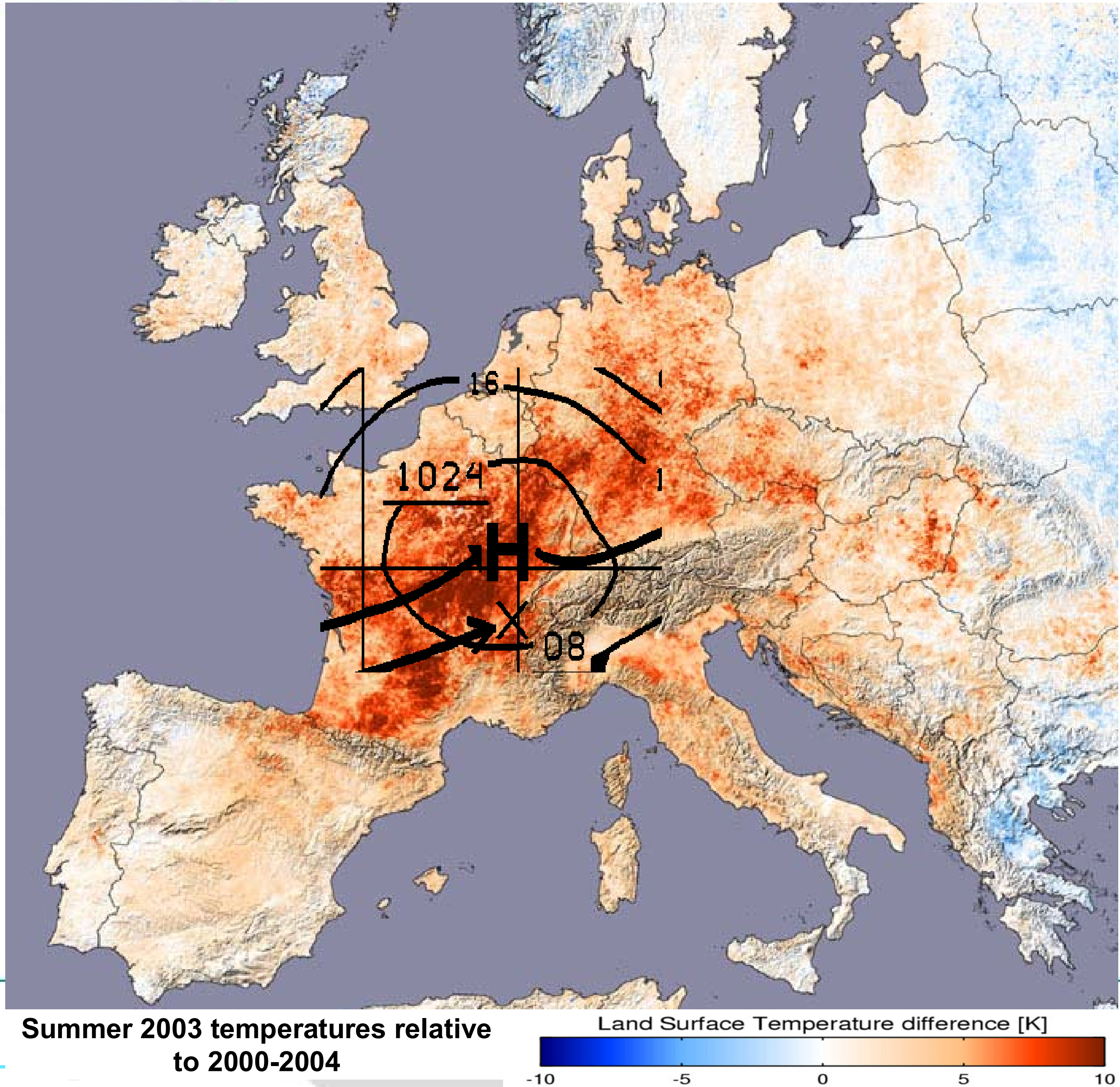
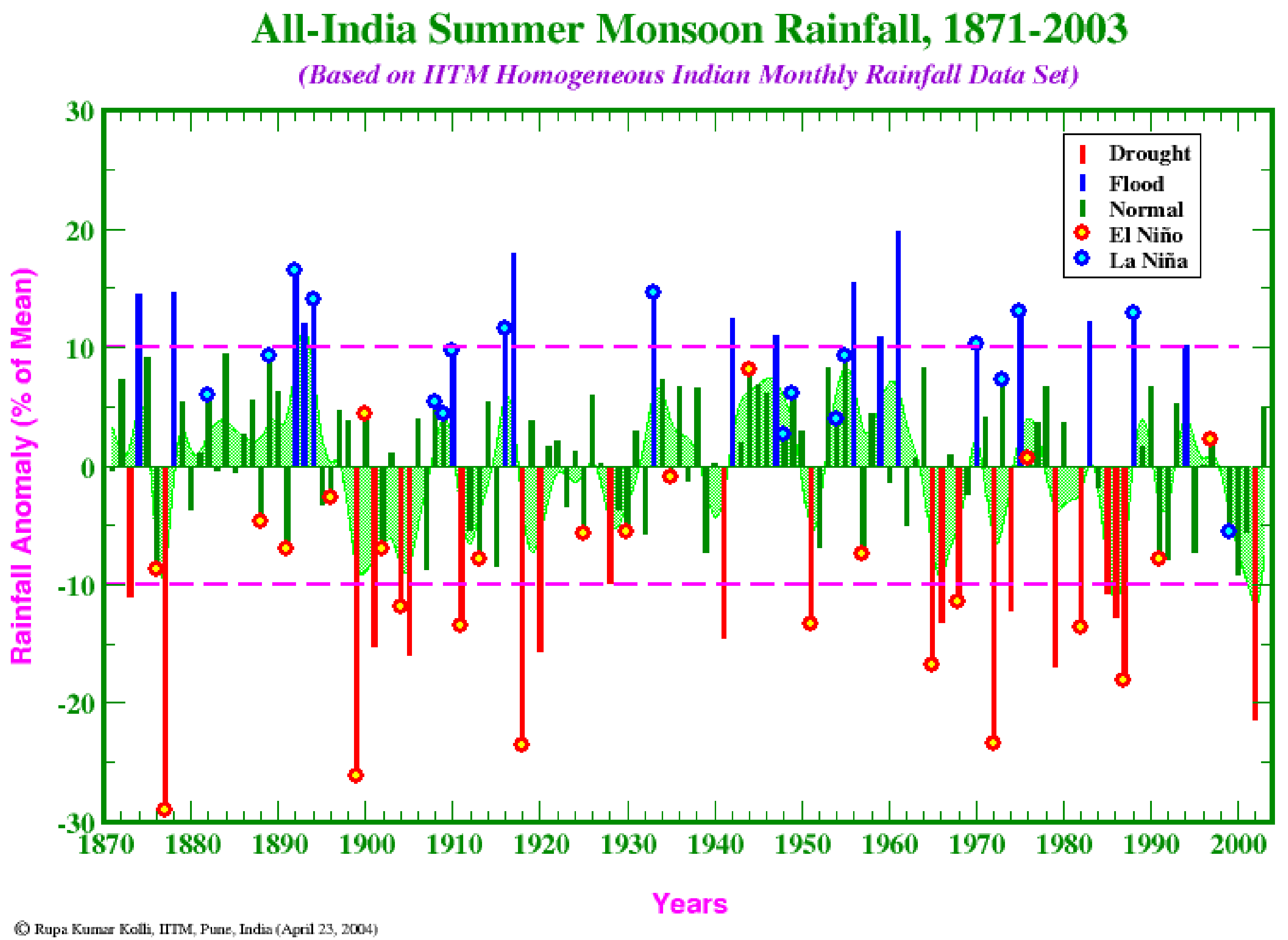
Summer 2003 European Heat Wave: Result of Global Warming?

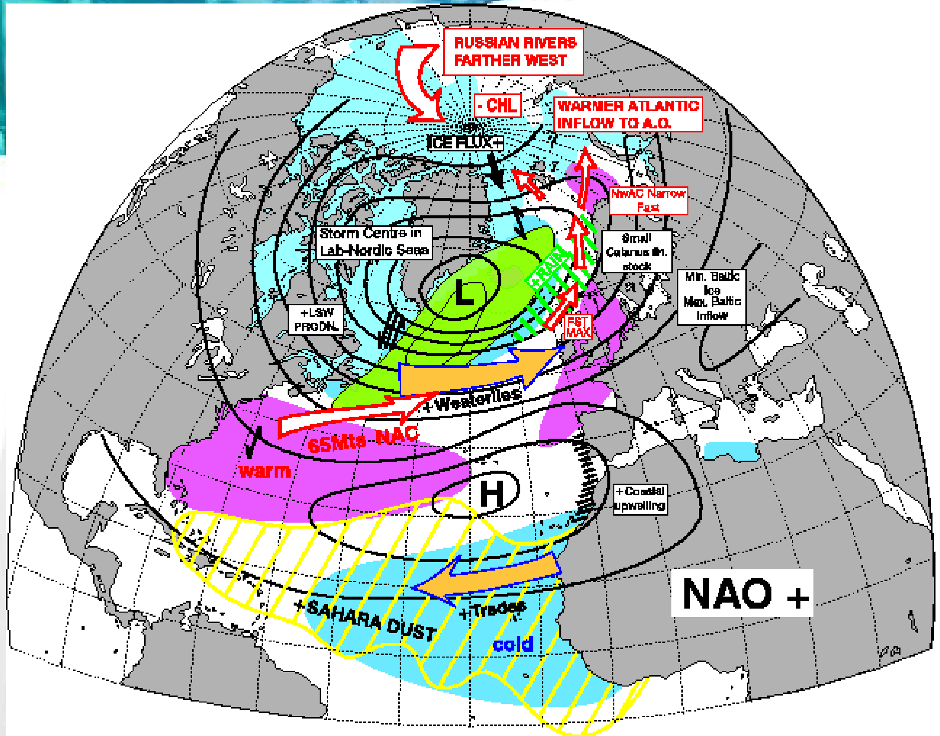


Summer 2003 temperatures relative to 2000-2004

- The immediate cause of the heat-wave was a persistent high pressure center over Northwest Europe.
- There is **currently no evidence** that human influence on climate makes such circulation patterns more likely.

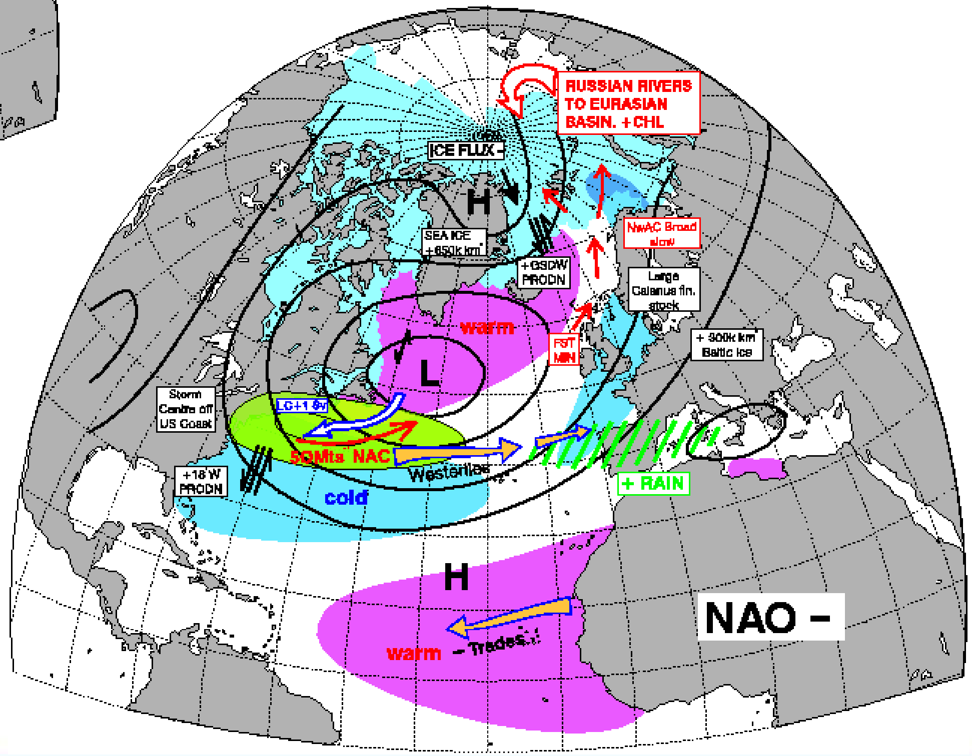


This figure shows the time series evolution of AISMR anomalies, expressed as percent departures from its long-term mean.

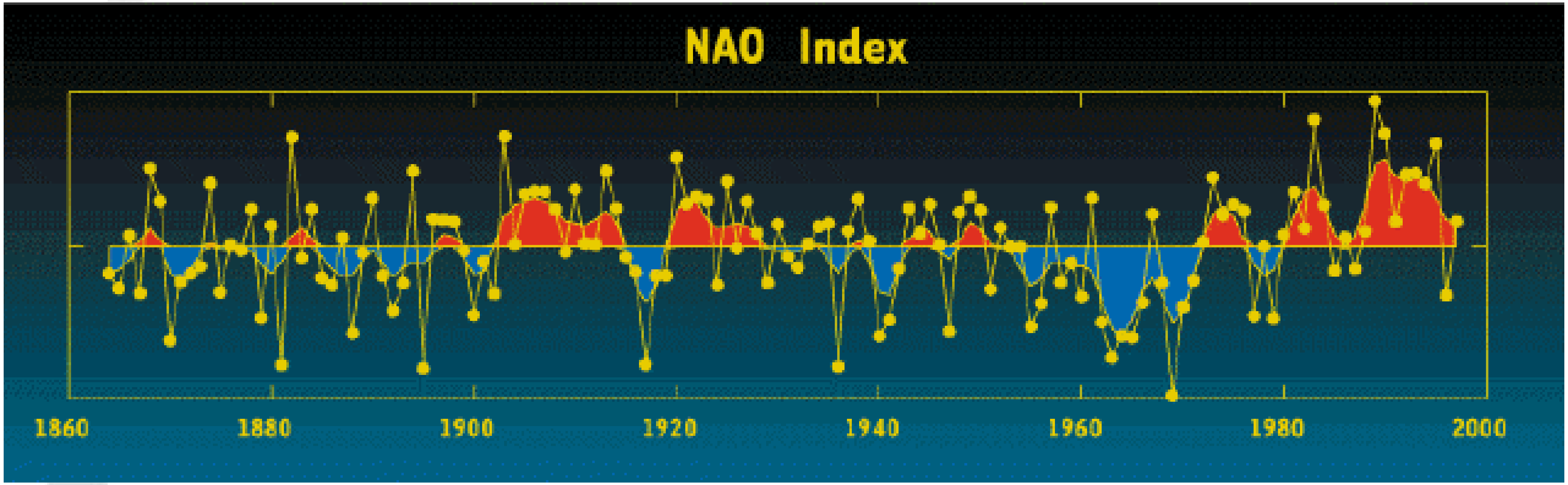


North Atlantic Oscillation:

the major mode of variation in the extra-tropical winter climate (contracted in summer)

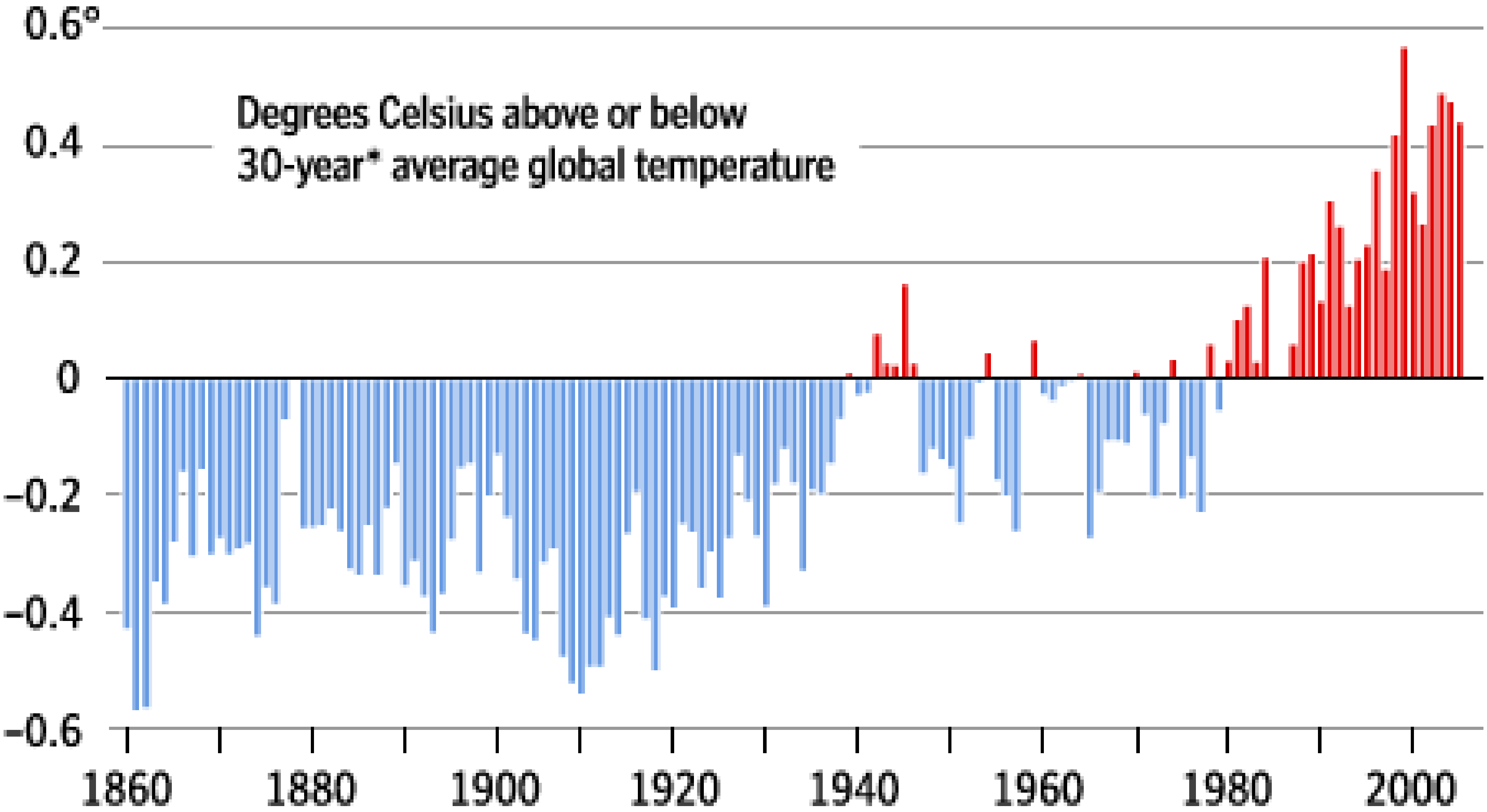


Decadal Variability of North Atlantic Oscillation



The NAO index is defined as the anomalous difference between the polar low and the subtropical high during the winter season (December through March).

LAST CENTURY OR SO …



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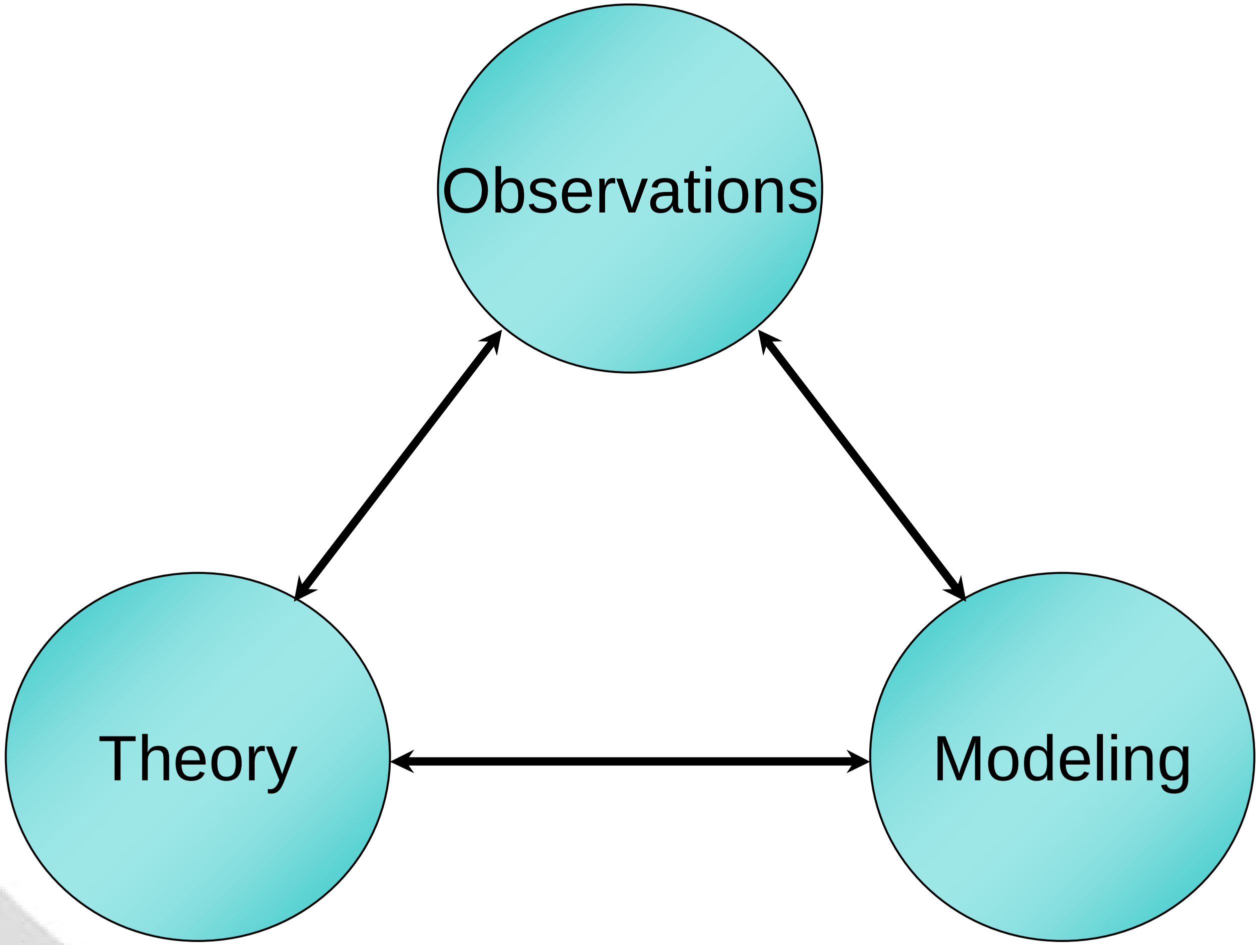
The “Charney” Diagram



Daily, Intraseasonal, Seasonal, Interannual, and Decadal Variations

ü "Short range" weather variation	• Hours; thunderstorms, tornadoes, squall lines, fronts, …. • Diurnal cycle; Organized convection • "Cyclones", Eeasterly waves, Depressions, ….
ü "Medium range" weather variations	• Blocking; Growth, decay of tropical, tropospherical disturbances
ü Intraseaonal variations	• Madden Julian "Oscillation" (MJO), Monsoon Intraseasonal variations, Pacific North American (PNA) variations, Annular modes
ü Seasonal mean variations	• Persistent droughts; Floods; Persistent "hot" and "cold" days; "Anomalous" number and tracks of cyclones
ü Interannual variations	• ENSO, QBO, TBO, NAO, NAM, SAM
ü Decadal variations	• PDO, Thermohaline circulation, Sahel drought, Decadal ENSO
ü Climate change	• Solar, Volcanoes, Greenhouse gases, Land use change

Mechanisms of Variability

	Internal	External
Weather:	1. Internal Dynamics of Atmosphere	• Boundary Condition of SST, Soil wetness, Snow, Sea ice, etc.
Climate: (seasonal-decadal)	2. Internal Dynamics of Coupled Ocean-Land-Atmospshere	• Solar, Volcanoes
Climate Change:	3. Internal Dynamics of Sun-Earth System	• Human effects: (Greenhouse gases, land use changes)

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Laplacian Determinism

We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes.

Laplace

Essai philosophique sur les probabilités

Historical Views of Predictability (1)

1.The Austrian School ~ 1893

The meteorologist of Austrian School considered forecasting to be unscientific.

Evoking the attitude of some members of this school: forecasting is immoral, a danger to the character of a meteorologist, and an affair for romantics.

(BAMS, 2006, Vol.87, pp1662-1667)

Historical Views of Predictability (2)

2. The Norwegian School (V. Bjerknes) ~1904

- Presented a set of equations that should be solved to calculate the future weather, as an application of Laplacian determinism.
- Considered weather to be predictable in principle.

3. The Chicago School ~ 1950s

- Optimistic followers of the Laplacian determinism (V. Bjerknes)
- Considered the limit of predictability of the weather restricted only by the imperfections of observations of the initial conditions and the imperfections in the models.

(BAMS, 2006, Vol.87, pp1662-1667)

Historical Views of Predictability (3)

4. Lorenz (Deterministic Chaos, Predictability) ~ 1960s

- **An irrefutable theory of the predictability of weather, nonlinear dynamical systems.**
- **Showed that for some physical systems, while Laplacian determinism holds, the prediction of future behavior will necessarily be imperfect.**

(BAMS, 2006, Vol.87, pp1662-1667)

Historical Views of Predictability (4)

5. Predictability in the midst of Chaos ~ 1980s

- **Atmosphere-ocean interactions and atmosphere-land interactions enhance predictability of the coupled system far beyond the limits of predictability of weather.**
- **Forced response of the tropical atmosphere is so strongly determined by the underlying ocean, and the forced response of the tropical ocean is so strongly determined by the overlying atmosphere, that there is no sensitive dependence on the initial conditions.**
- **Coupled ocean-land-atmosphere system is predictable.**

A simple model to predict weather and climate

$$Y_{n+1} = f(Y_n)$$

Three examples:

1. A discrete nonlinear system with one variable (one equation)

2. A continuous nonlinear system with three variables (the Lorenz model)

3. Weather and climate models with one million equations (GCM)

A simple model of climate

(Lorenz, E. N., 1964: The problem of deducing the climate from the governing equations. *Tellus*, 16, 1-11)

Quadratic Map: A discrete deterministic nonlinear system
(Also called Logistic map in other fields.)

$$Y_{n+1} = f(Y_n)$$

$$Y_{n+1} = rY_n(1 - Y_n)$$

Using a linear transformation $Y_n = -X_n/r + 1/2$ and $c = r^2/4 - r/2$,

we obtain an alternate form of the quadratic map: $X_{n+1} = X_n^{\,2} - c$

For specified values of c and X_0, we get a sequence

$X_0, X_1, X_2, X_3, X_4, \ldots$ **at time steps** $n = 0, 1, 2, \ldots$

Predictability experiments with quadratic map $X_{n+1} = X_n^{\,2} - c$

n	c=1.8000	c=1.8000	c=1.8010	c=1.800
0	0.5000	0.5010	0.5000	0.500
1	-1.5500	-1.5489	-1.5510	-1.550
2	0.6025	0.5990	0.6046	0.602
3	-1.4369	-1.4411	-1.4354	-1.437
4	0.2646	0.2767	0.2593	0.264
5	-1.7299	-1.7234	-1.7337	-1.730
6	1.1925	1.1701	1.2047	1.192
7	-0.3779	-0.4308	-0.3496	-0.379
8	-1.6571	-1.6144	-1.6787	-1.656
9	0.9459	0.8062	1.0170	0.942
10	-0.9052	-1.1500	-0.7667	-0.912
11	-0.9806	-0.4775	-1.2131	-0.968
12	-0.8384	-1.5719	-0.3293	-0.862
13	-1.0970	0.6708	-1.6925	-1.056
14	-0.5965	-1.3500	1.0635	-0.684
15	-1.4441	0.0225	-0.6699	-1.332
16	0.2854	-1.7994	-1.3522	-0.025
17	-1.7185	1.4378	0.0274	-1.799
18	1.1532	0.2672	-1.8002	1.436

Predictability experiments with quadratic map

n	c=1.8000	c=1.8000	c=1.8010	c=1.800
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
85	0.0373	0.2580	-1.7333	-1.302
86	-1.7986	-1.7334	1.2033	-0.104
87	1.4349	1.2046	-0.3530	-1.789
88	0.2589	-0.3489	-1.6763	1.400
89	-1.7329	-1.6782	1.0089	0.159
90	1.2029	1.0163	-0.7831	-1.774
91	-0.3530	-0.7671	-1.1877	1.347
92	-1.6753	-1.2115	-0.3903	0.014
93	1.0066	-0.3322	-1.6486	-1.799
94	-0.7867	-1.6896	0.9168	1.436
95	-1.1811	1.0547	-0.9604	0.262
96	-0.4050	-0.6876	-0.8786	-1.731
97	-1.6359	-1.3272	-1.0290	1.196
98	0.8761	-0.0385	-0.7421	-0.369
99	-1.0324	-1.7985	-1.2502	-1.663
100	-0.7341	1.4346	-0.2379	0.965

Lorenz's Empirical Formula for Error Growth

Introduce an ensemble of small initial errors and allow it evolve.

If E is the mean error, the exponential growth is given by the equation

$$\frac{dE}{dt} = \lambda E$$

Doubling time of the errors $td = (\ln 2)/\lambda.$

The errors do not grow forever. The nonlinearities limit the error growth.

Lorenz introduced a simple assumption that nonlinear error growth is quadratic in E.

The modified error equation is

$$\frac{dE}{dt} = \lambda E - sE^2$$

where λ is the growth rate and s is so chosen that $E_s = \lambda/s$ is the saturation value of E.

λ is usually the largest Lyapunov exponent.

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

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

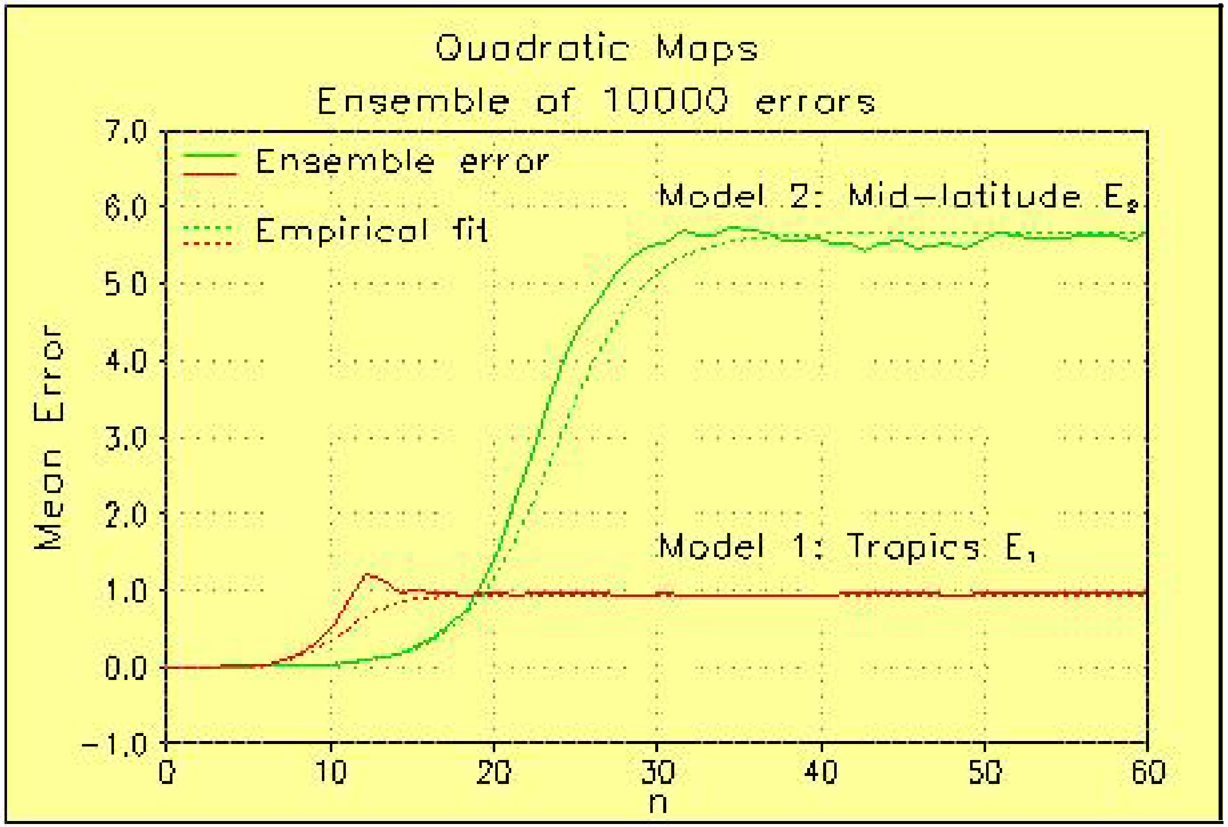
$$\frac{dE_1}{dt} = \lambda_1 E_1 - s_1 E_1^{\,2}$$

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

$$\lambda_1 > \lambda_2$$

$$\lambda_1 = 0.63$$

$$\lambda_2 = 0.37$$



Lorenz Model

Lorenz model is a low-order convection model described by just three ordinary differential equations. It is one of the simplest forced dissipative nonlinear systems.

$$\frac{dX}{dt} = -\sigma X + \sigma Y$$
$$\frac{dY}{dt} = -XZ + rX - Y$$
$$\frac{dZ}{dt} = XY - bZ$$

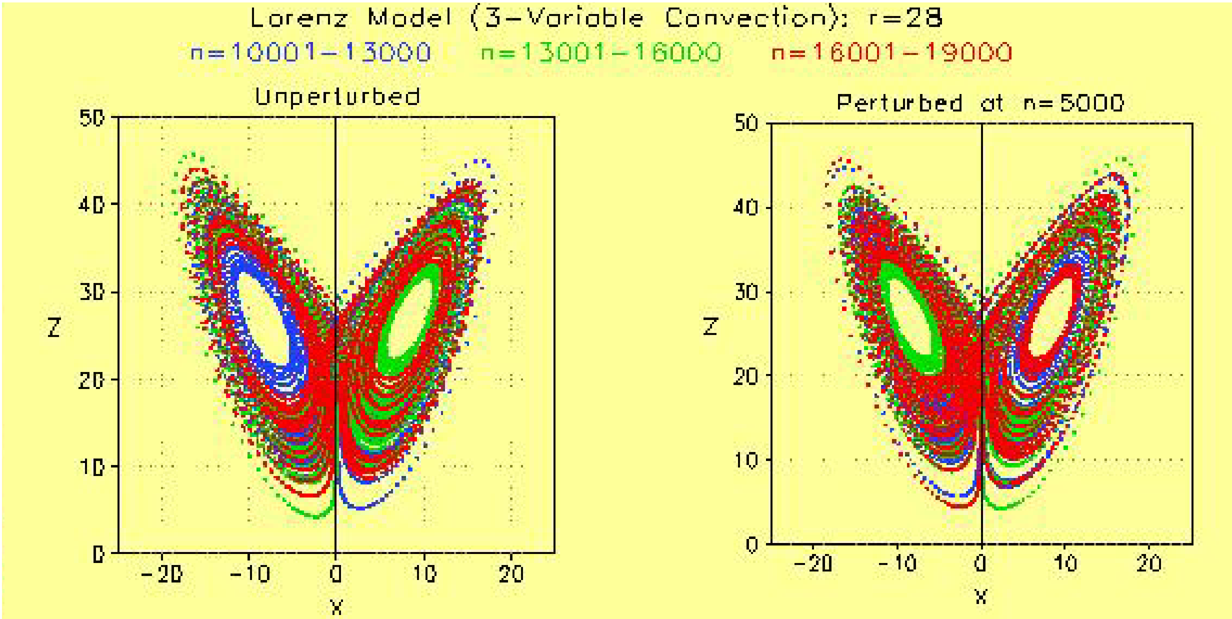
X, Y, Z: Dynamical variables
r: Forcing
σ, b: Dissipation
Parameter values: $\sigma = 10, \quad b = 8/3, \quad r = 28$
Initial condition: $X = 0.0, \ Y = 1.0, Z = 0.0$
Time increment for integration: $\Delta t = 0.01$

Predictability Experiment 1 in Lorenz Model

The Lorenz model is first integrated up to the time step *n* = 10000.

At *n* = 10001, this unpertubed integration is continued, and a new integration is carried out with a small perturbation added to the state from the unpertubed integration.

The same projections of unperturbed and perturbed trajectories are shown in different colors for different segments of time, the divergence of trajectories become clear.



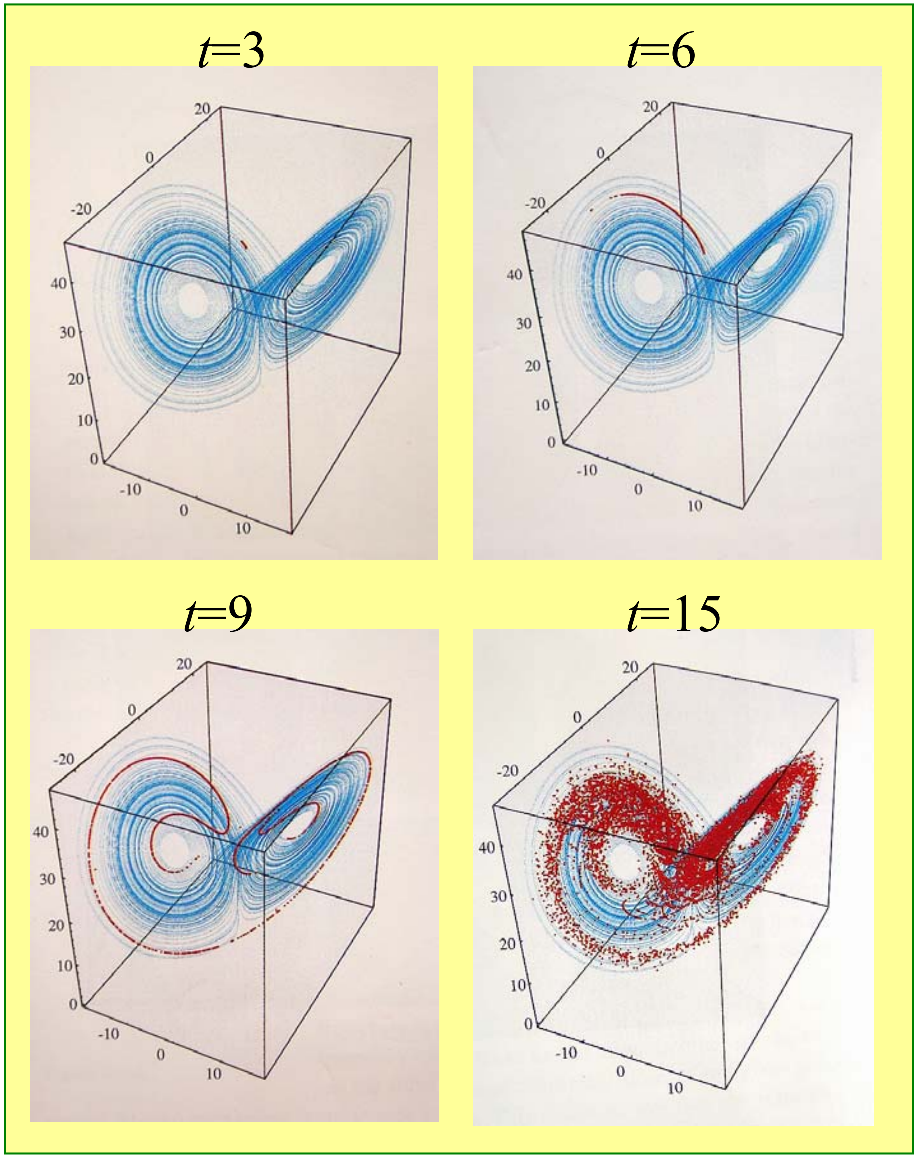
Predictability Experiment 2 in Lorenz Model

From Strogatz, S. H., 1994: *Nonlinear dynamics and chaos*, Westview Press

An ensemble of 10000 nearby points at an initial $t = 0$ around a basic state is allowed to evolve in Lorenz model.

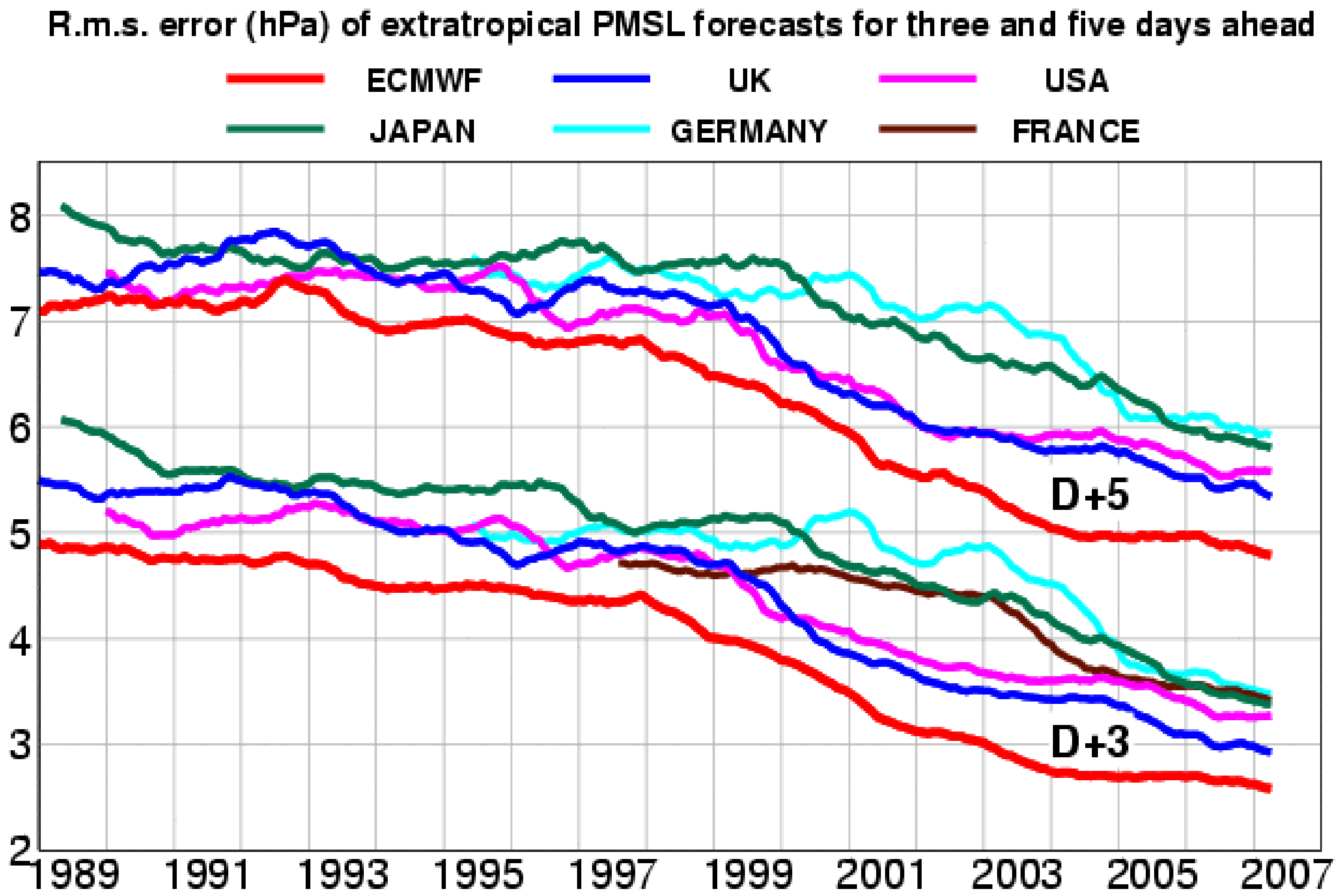
Blue points are from unperturbed integration.
Red points show the evolution of the perturbed initial states.

"As each point moves according to Lorenz equations, the blob is stretched into a thin filament… Ultimately, the points spread over … showing that the final state could be almost anywhere, even though the initial conditions were almost identical."



Historical Evolution: 1904-1954

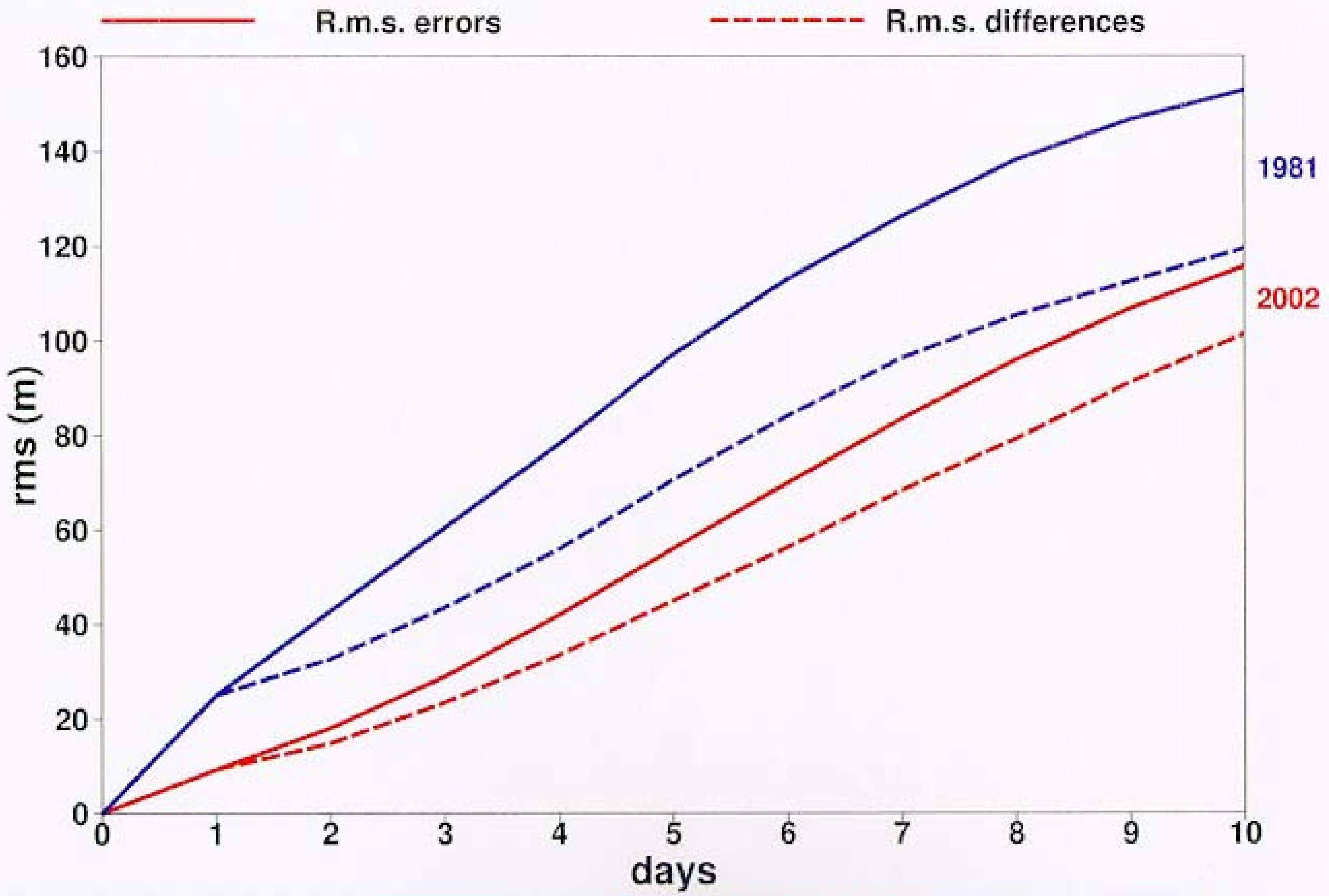
- V. Bjerknes (1904) — Equations of Motion
  - Father of J. Bjerknes, son and research assistant of C. Bjerknes (Hertz, Helmholtz)
- L. F. Richardson (1922) — Manual Numerical Weather Prediction
  - Military background, later a pacifist, estimated death toll in wars
- C. G. Rossby (1939) — Barotropic Vorticity Equation
  - First "Synoptic and Dynamic" Meteorologist; Founder of Meteorology Programs at MIT, Chicago, Stockholm
- J. Charney (1949) — Filtered Dynamical Equations for NWP
  - First Ph.D. student at UCLA; Chicago, Oslo, Institute for Advanced Study, MIT
- N. A. Phillips (1956) — General Circulation Model
  - Father of Climate Modeling; Chicago, Institute for Advanced Study, MIT



(Thanks to ECMWF!)

R.m.s. errors and differences between successive forecasts

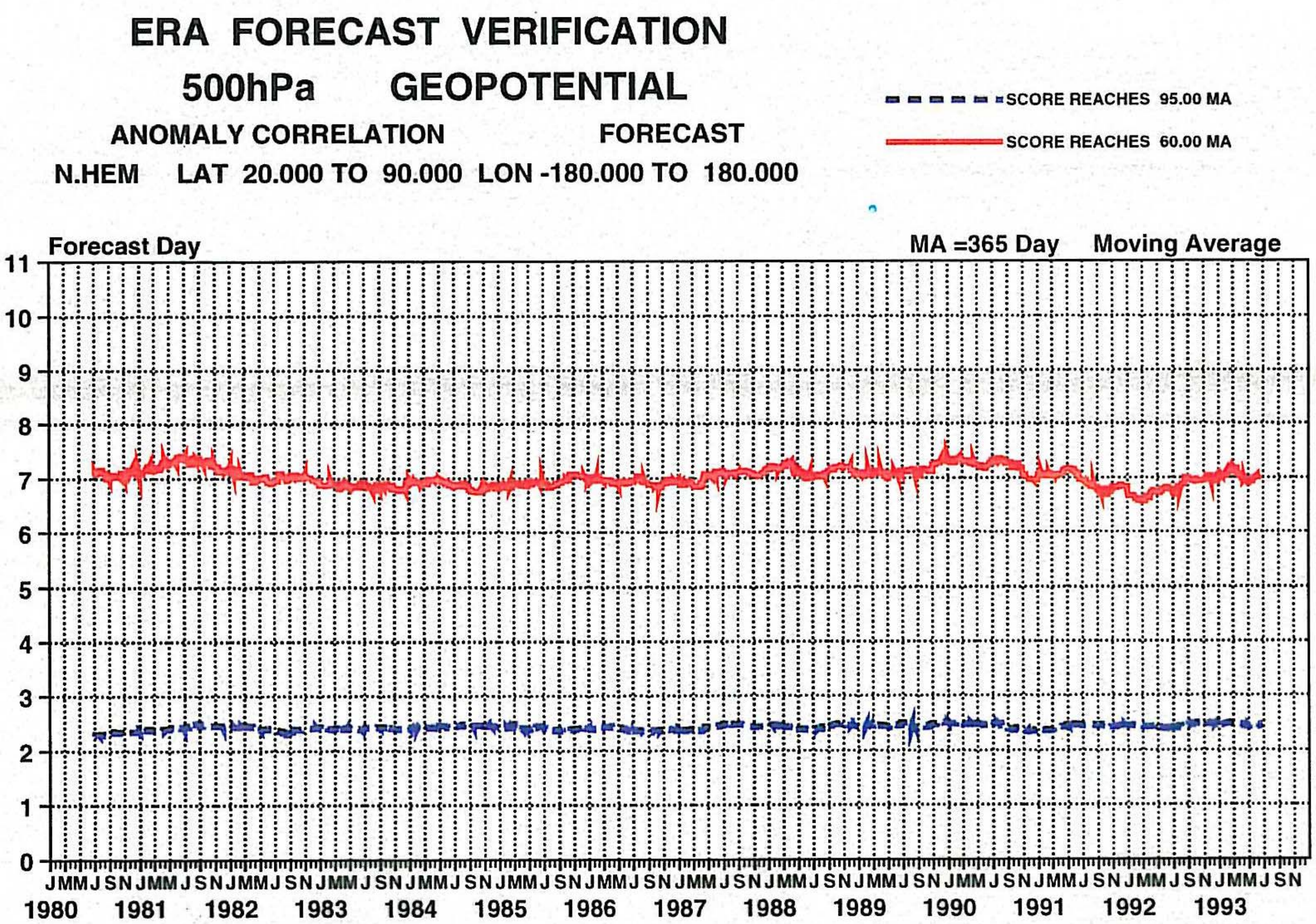
Northern hemisphere   500hPa height   Winter



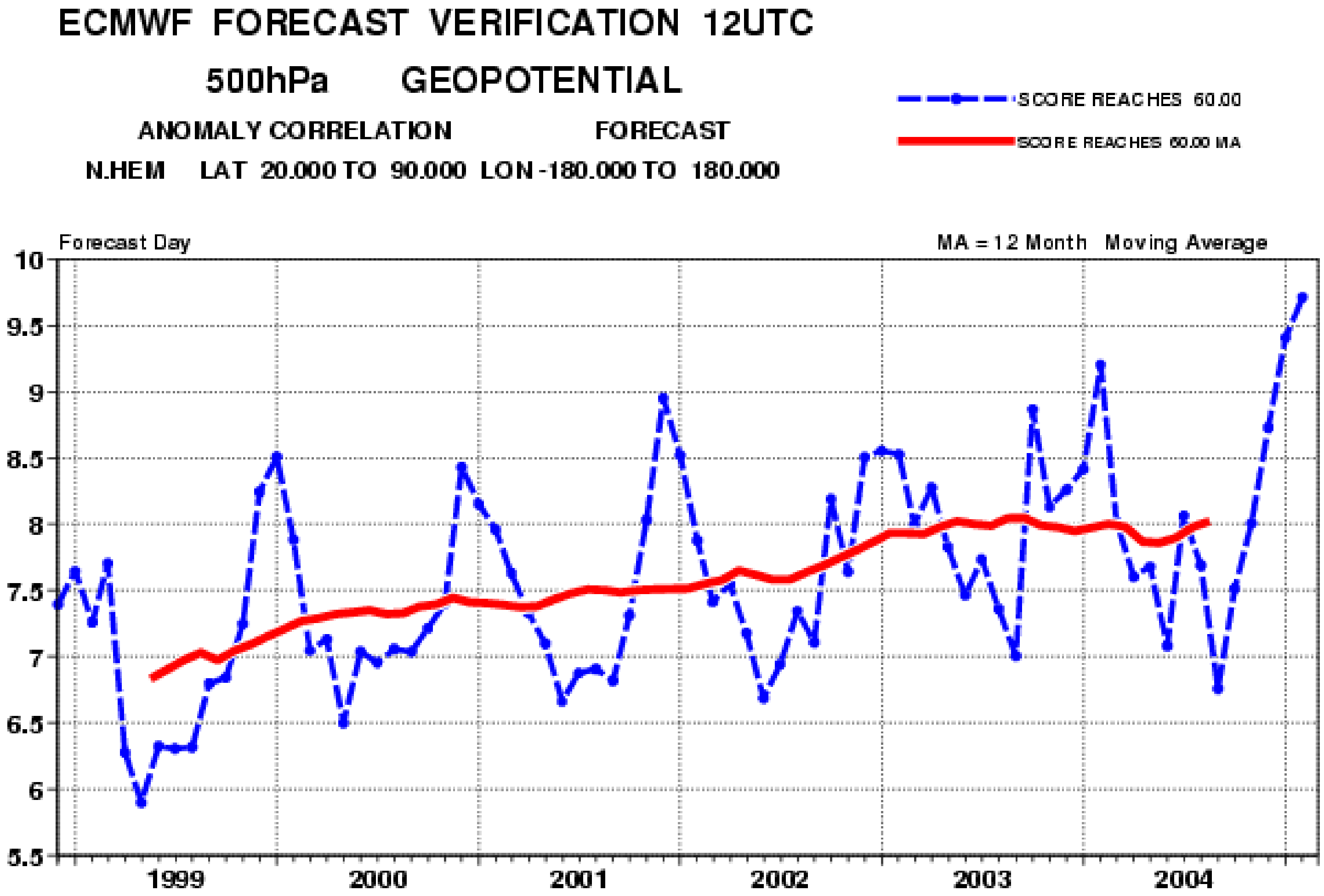
Evolution of 1-Day Forecast Error, Lorenz Error Growth, and Forecast Skill for ECMWF Model

(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
500hPa GEOPOTENTIAL
ANOMALY CORRELATION FORECAST
N.HEM LAT 20.000 TO 90.000 LON -180.000 TO 180.000
SCORE REACHES 95.00 MA
SCORE REACHES 60.00 MA
Forecast Day
MA =365 Day Moving Average
11
10
9
8
7
6
5
4
3
2
1
0
JMMJSNJMMJSNJMMJSNJMMJSNJMMJSNJMMJSNJMMJSNJMMJSNJMMJSNJMMJSNJMMJSNJMMJSNJMMJSNJMMJSN
1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993



Center of Ocean-Land-Atmosphere studies

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

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

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$$\lambda_1 > \lambda_2$$

$$\lambda_1 = 0.63$$

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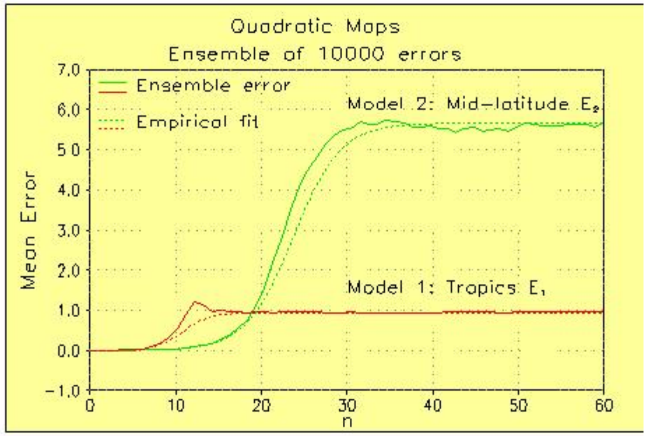
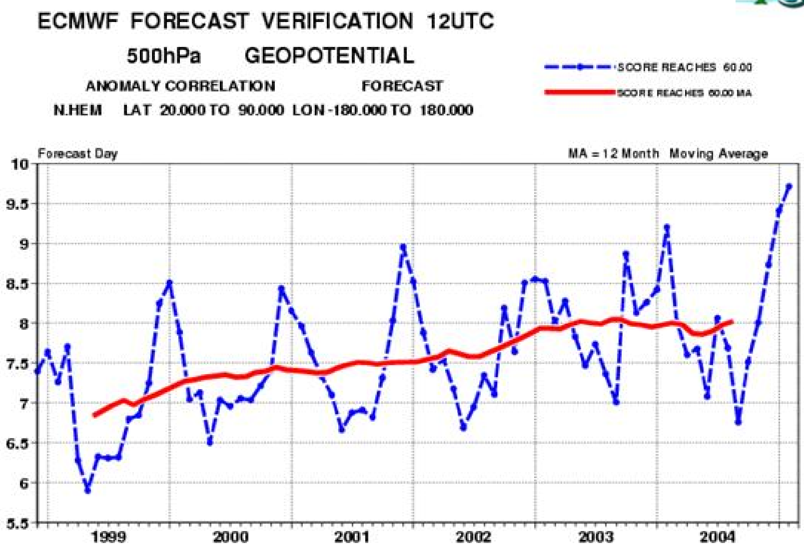


IGES COLA CREW GEORGE MASON UNIVERSITY



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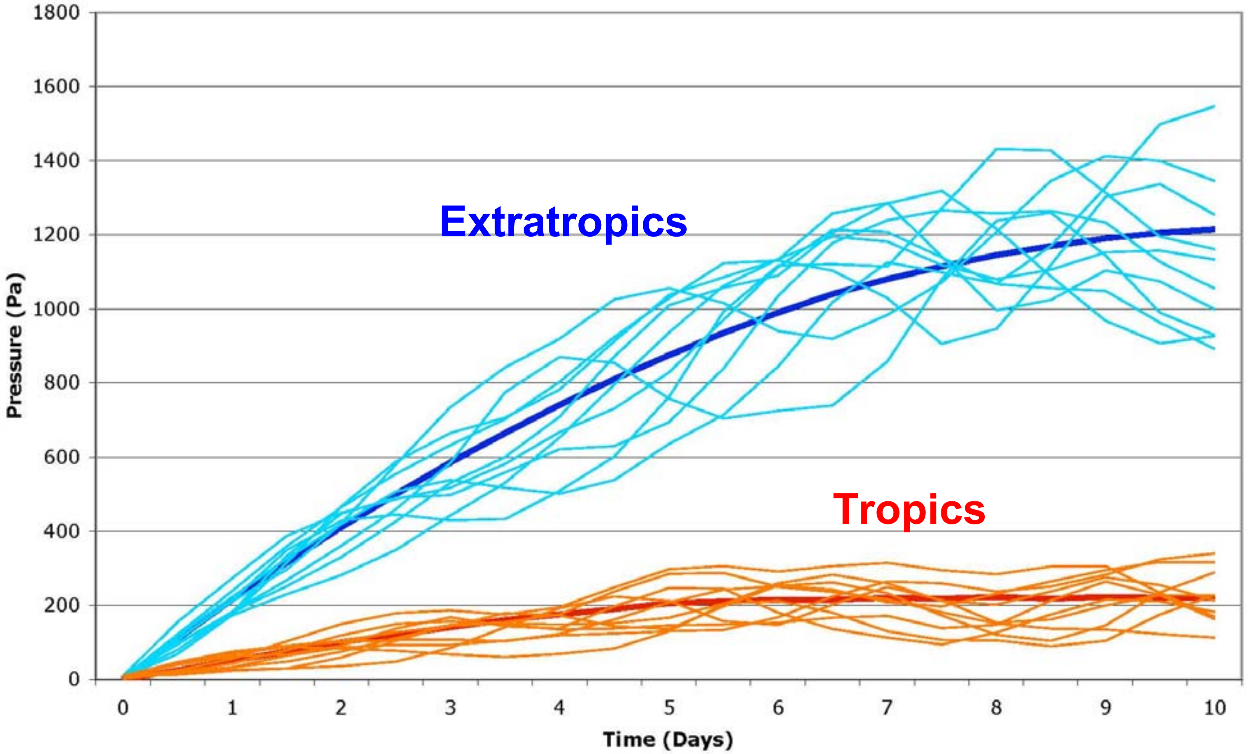
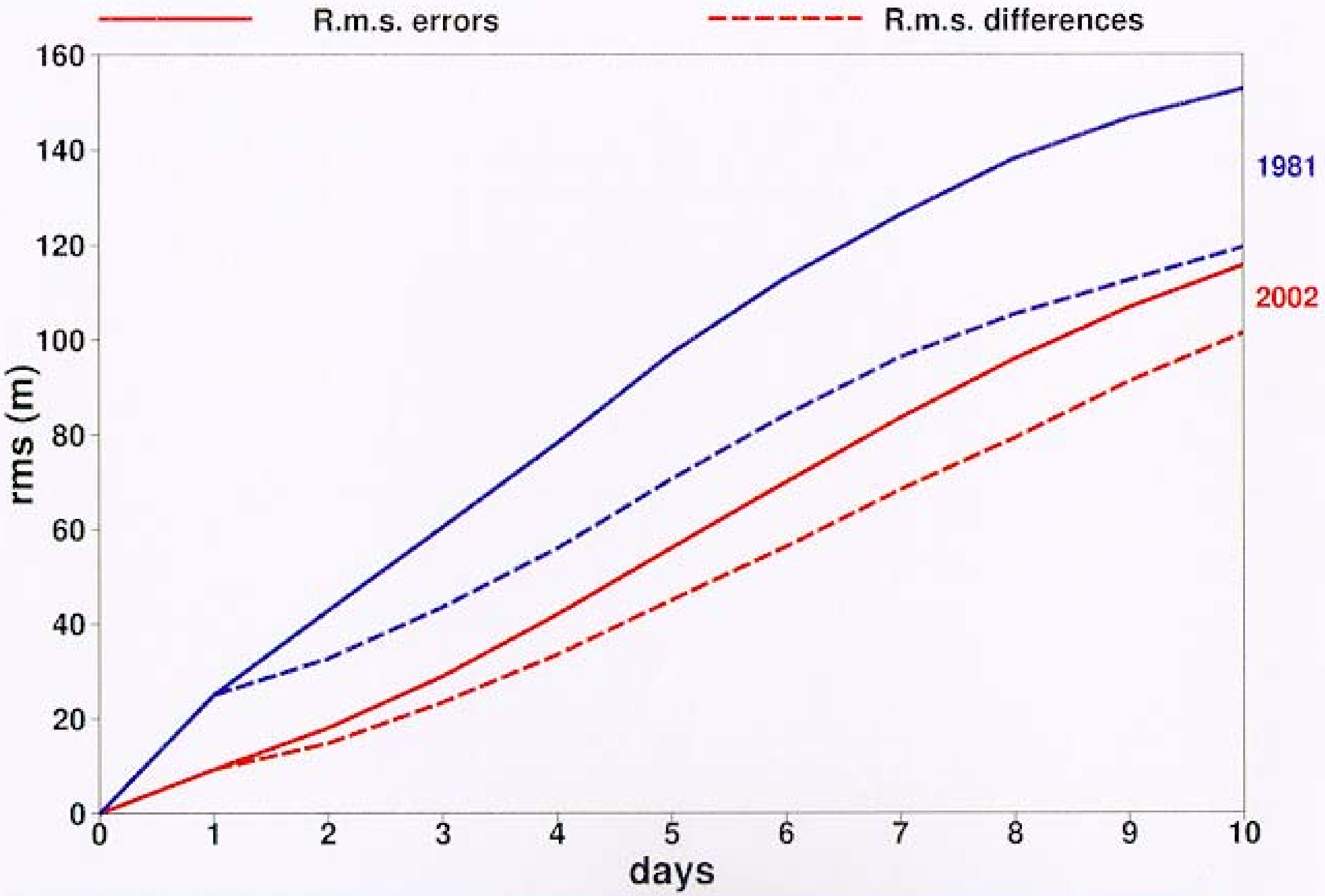
Schematic Error Growth for the Tropics (Red) & Extratropics (Blue)



Schematic diagram illustrating the error growth in the tropics (red) and the extratropics (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.

R.m.s. errors and differences between successive forecasts

Northern hemisphere 500hPa height Winter



Outline

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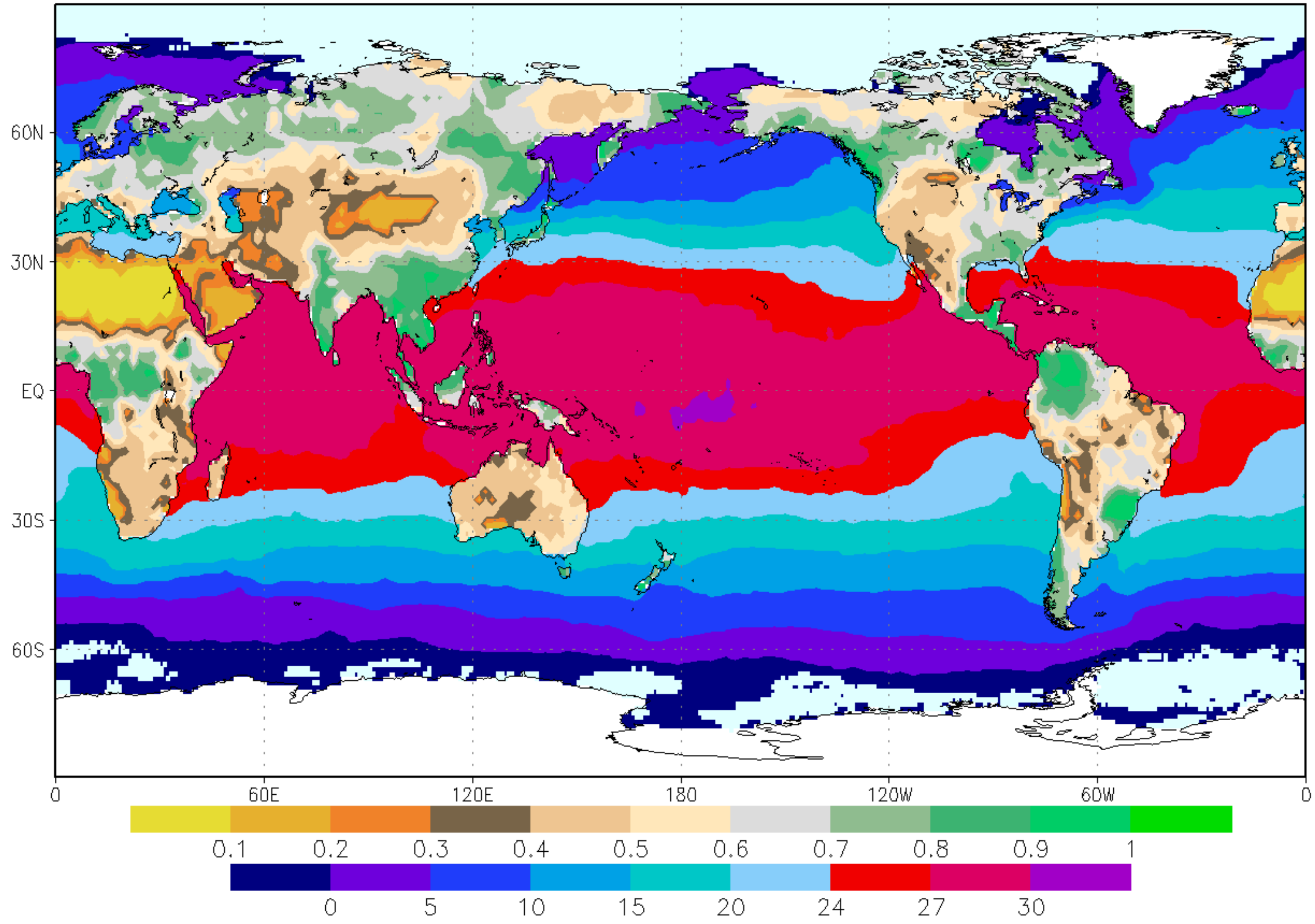
- Mechanisms of Variability of Weather and Climate
- **Predictability and Prediction of Weather and Climate**
  - Weather
  - **Climate (Seasonal, ENSO, Decadal)**
  - Climate Change
- Factors Limiting Predictability: Future Challenges
  - Observational and Theoretical (Physics & Dynamics of the Coupled Climate System)
  - Computational and Numerical
- Summary and Conclusions

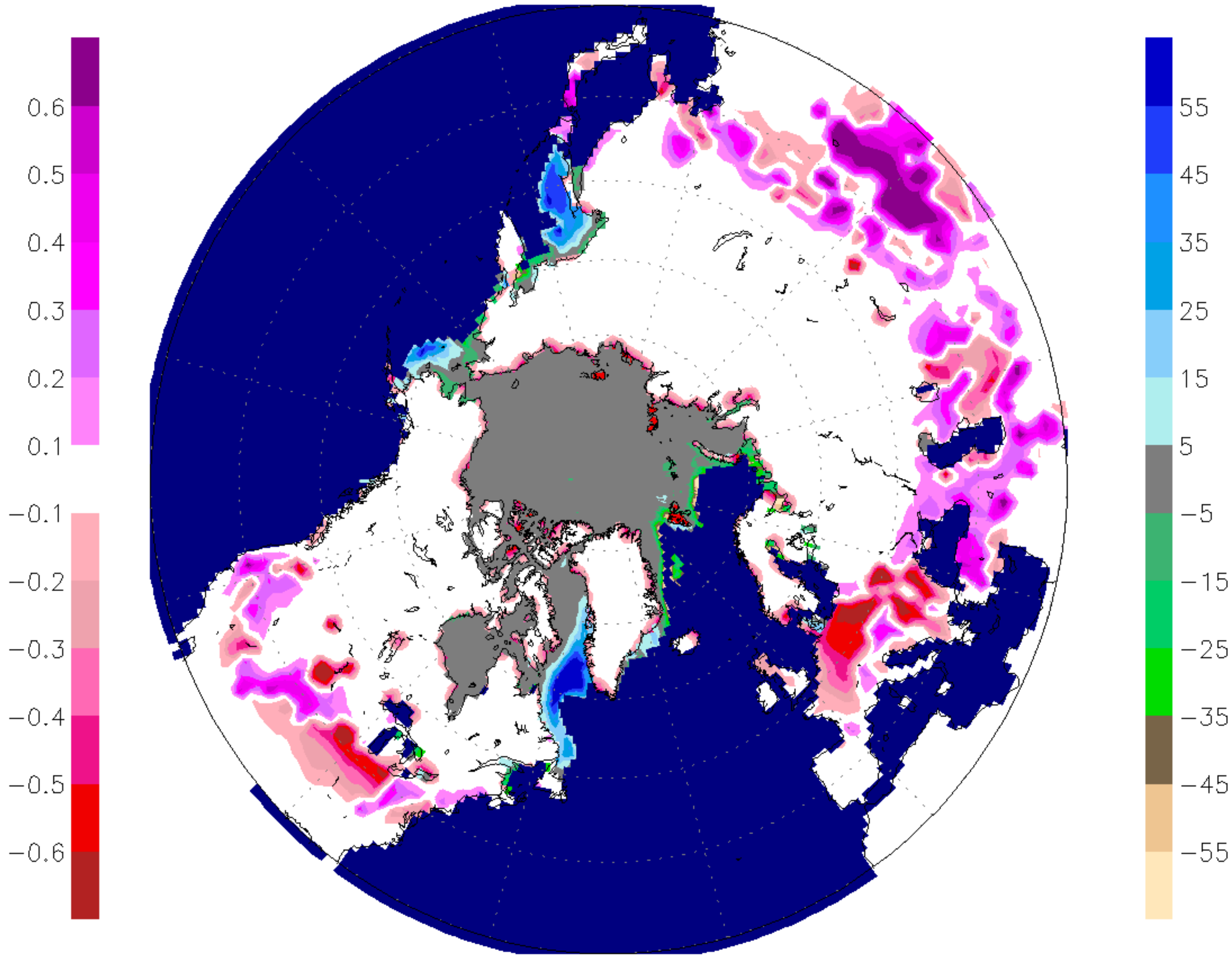
From Numerical Weather Prediction (NWP) To Dynamical Seasonal Prediction (DSP) (1975-2004)

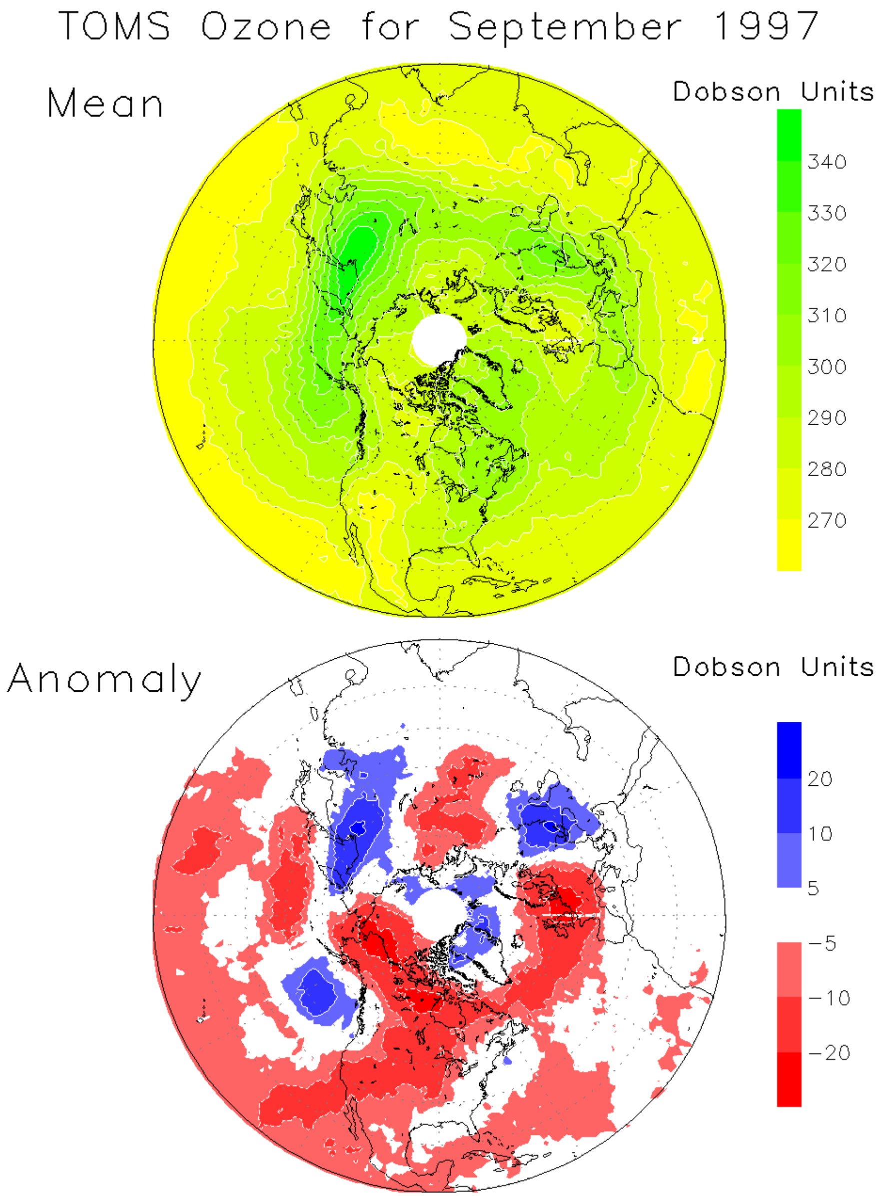
- **Operational Short-Range NWP:** was already in place
- **15-day & 30-day Mean Forecasts**: demonstrated by Miyakoda (basis for creating ECMWF-10 days)
- **Dynamical Predictability of Monthly Means**: demonstrated by analysis of variance
- **Boundary Forcing**: predictability of monthly & seasonal 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

GOLD soil wetness (fraction) & HADISST SST (°C) for November 1997

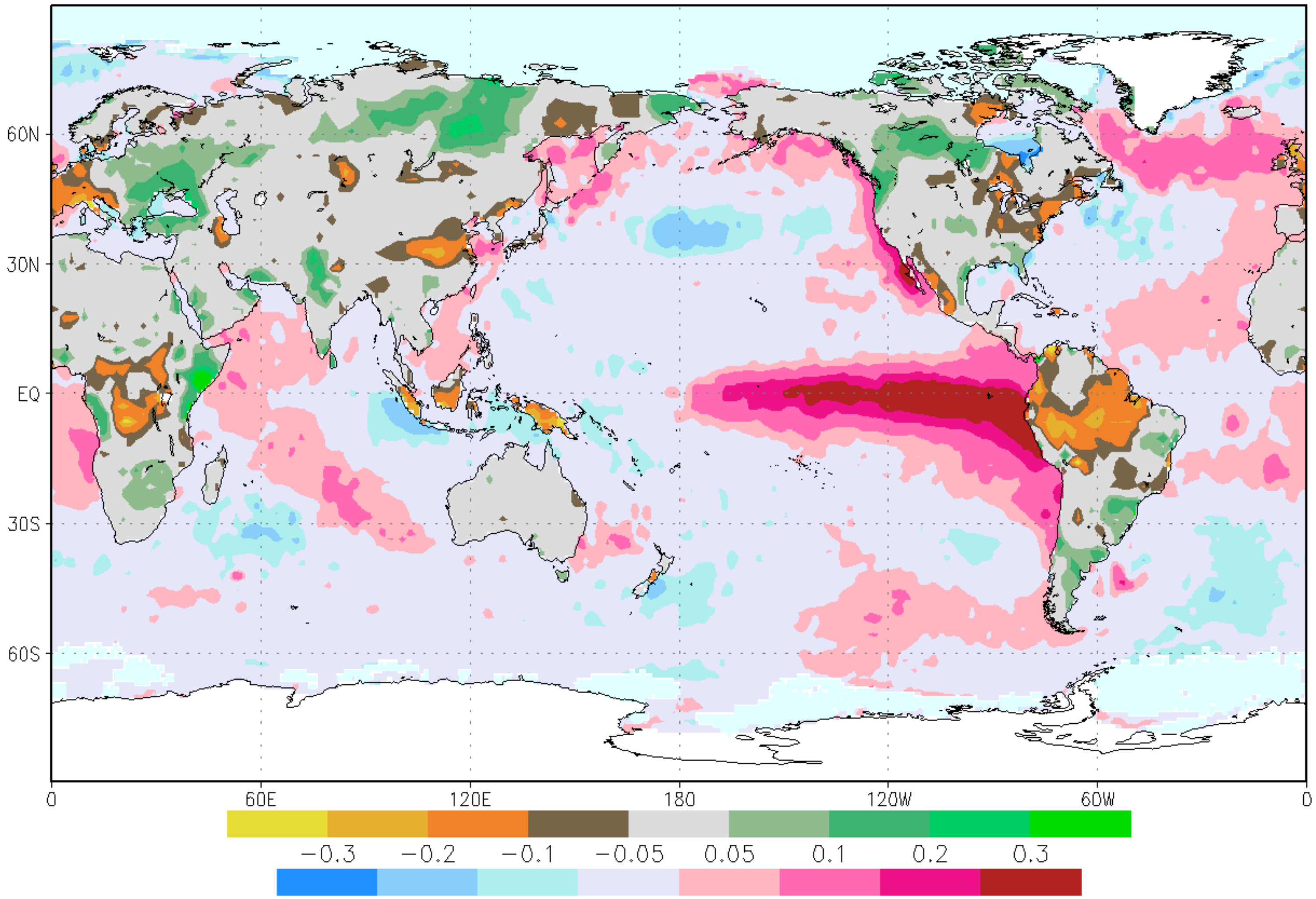


NESDIS snow cover (fraction) anomaly (1966–90 mean) & HADISST Sea Ice (%) anomaly (1966–90 mean) for January 1983




TOMS Ozone for September 1997
Mean
Dobson Units
340
330
320
310
300
290
280
270
Anomaly
Dobson Units
20
10
5
−5
−10
−20

GOLD soil wetness (fraction) anomaly (1979–99 mean) &
HADISST SST (°C) anomaly (1979–99 mean) for November 1997



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!)

EFFECTS OF SST ANOMALY

$\delta T(x,y)$ → $\delta Q(x,y,z)$ → δV

SST anomaly — heating anomaly — circulation anomaly

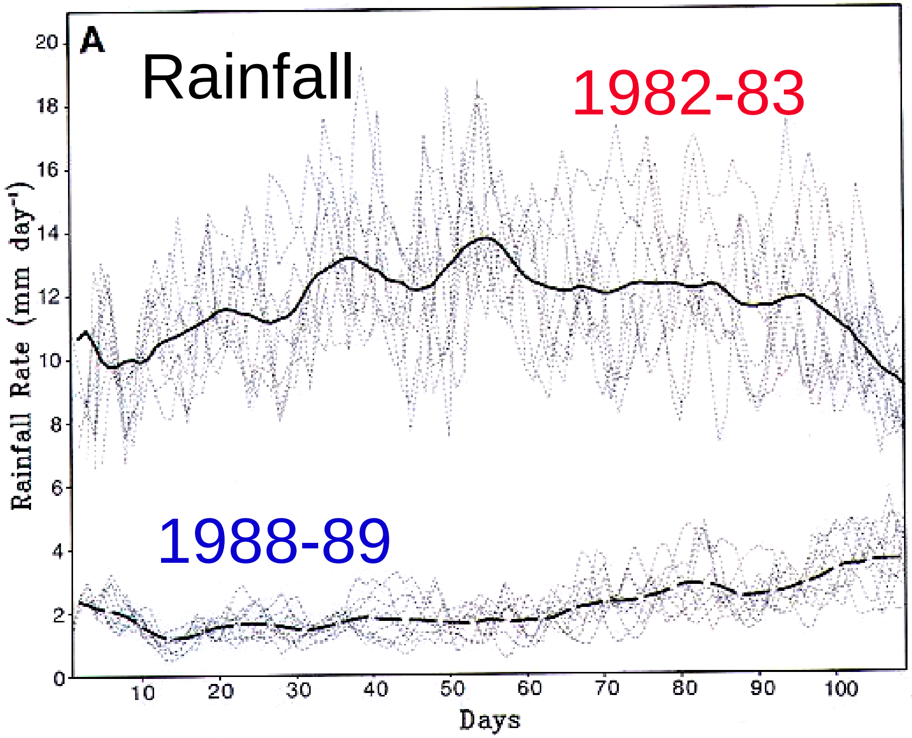
~ 5-7 days

- δT (magnitude, structure)
- T (magnitude, structure)
- V (x,y,z): large scale flow
- δ (conv., div.):
  latitude regime (f)
- instability

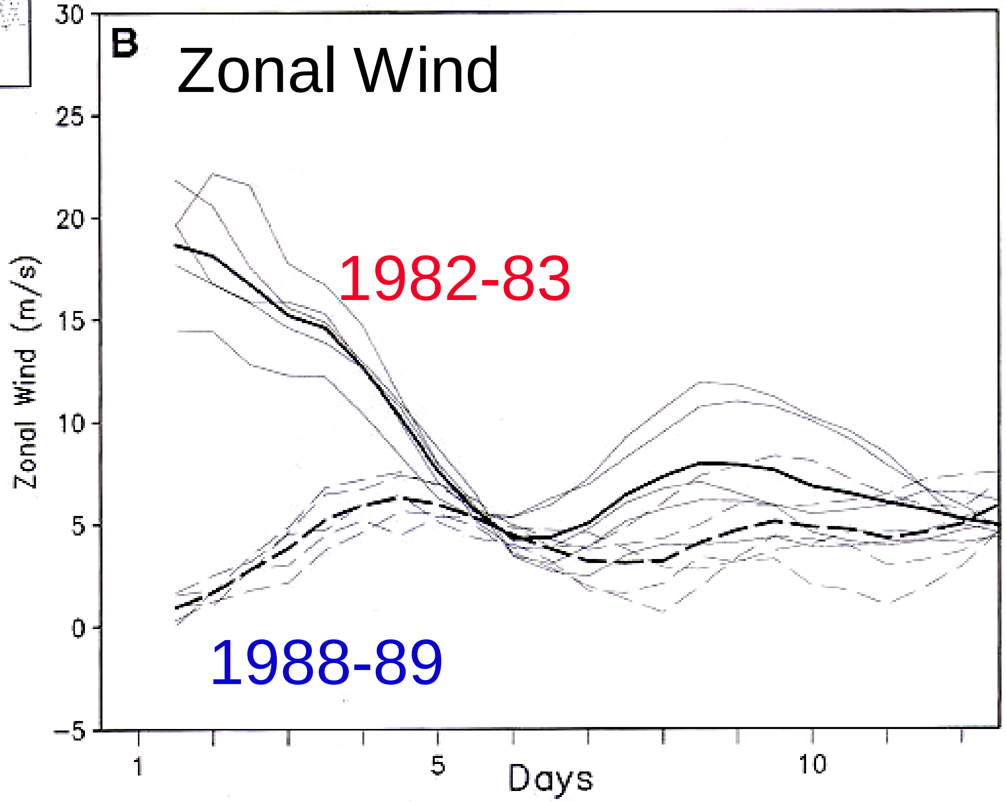
~ 10-30 days

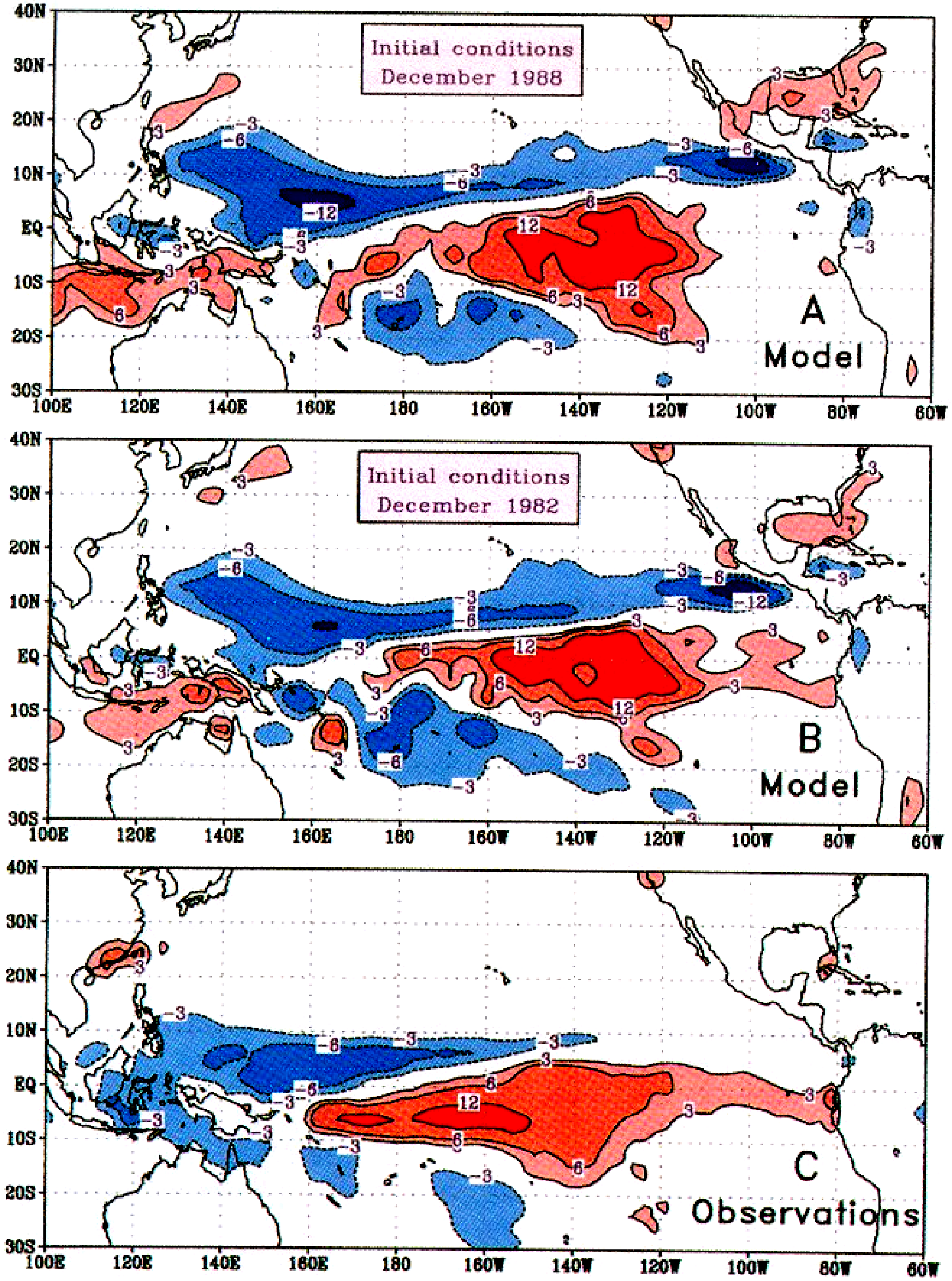
- δQ (magnitude, structure)
- location of δQ w.r.t. V
  - tropics: Hadley, Walker, monsoon
  - extratropics: quasi-stationary waves, forcings and instability
- U(y,z): resonance, propagation
  ($\delta Q \Leftrightarrow \delta U$)

1. $\delta Q \Rightarrow \delta$(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).

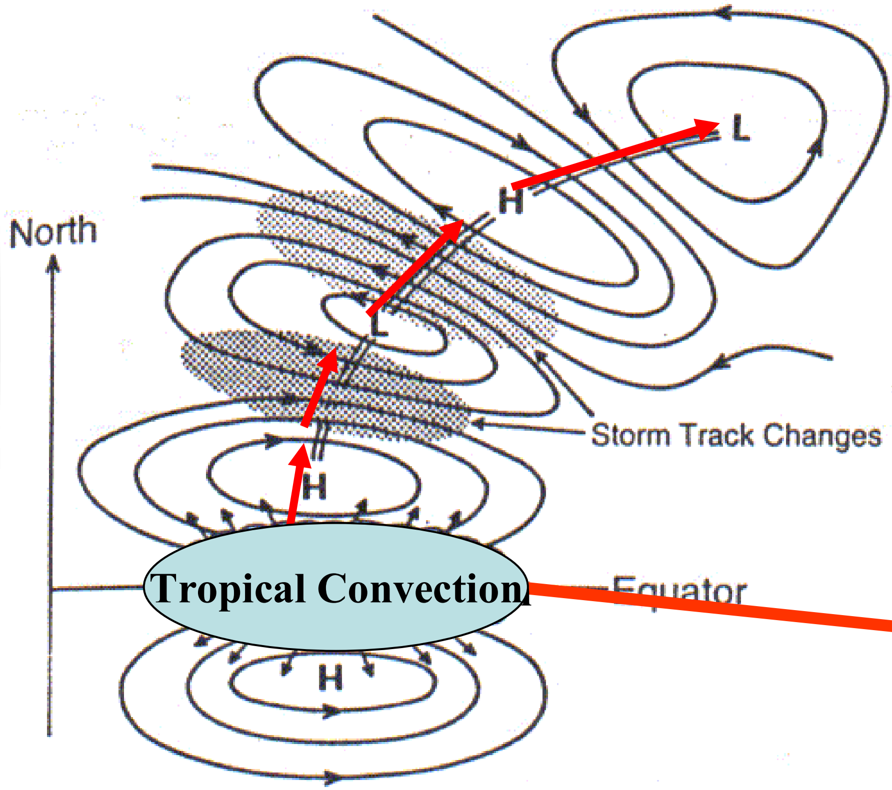


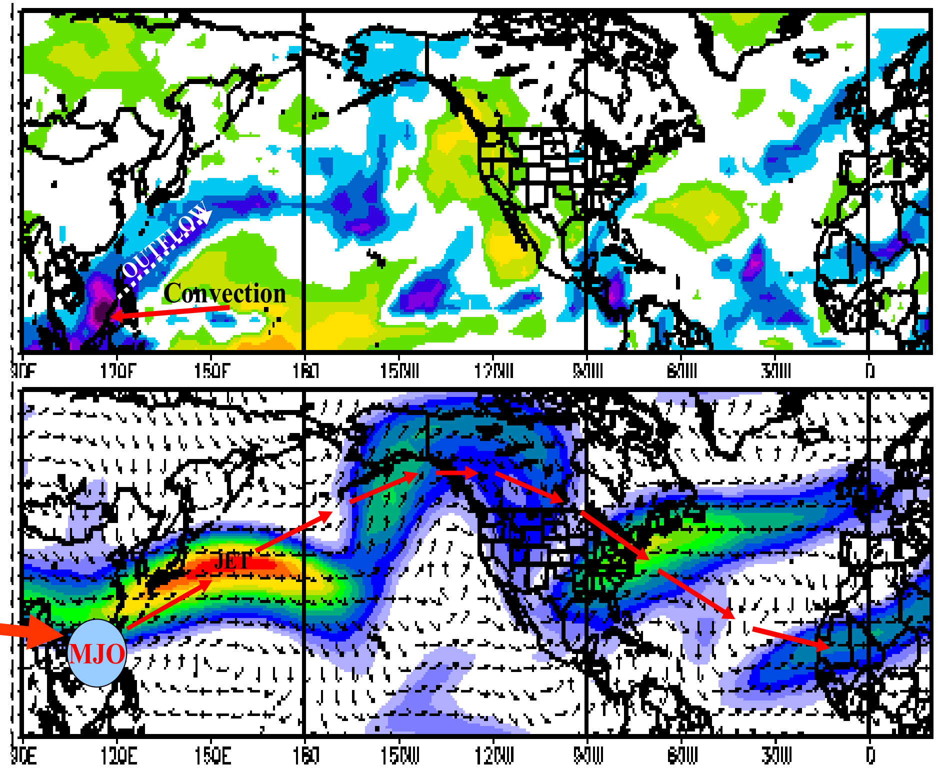

Initial conditions
December 1988
A
Model
Initial conditions
December 1982
B
Model
C
Observations
40N
30N
20N
10N
EQ
10S
20S
30S
100E
120E
140E
160E
180
160W
140W
120W
100W
80W
60W

Some Examples of Seamless Processes

1.	Tropical Convection (SST) →	Rossby Waves (Atmosphere) →	North America Forest Fires (Land)
2.	Persistent Drought (Land) →	Surface Wind (Atmosphere) →	Influence ENSO (Ocean)
3.	Eurasian Snow (Cryosphere) →	Wet/Dry soil, Ts (Land) →	Monson Droughts (Atmosphere)
4.	Pacific/IO SST (Ocean) →	Walker cell (Atmosphere) →	Asian Monsoon (Land)
5.	Upp. Stratosphere Circ. →	Propagation down →	Extra Trop. Surface Winds
6.	ISO/MJO →	ENSO →	Global Warming
7.	Global change →	Regional SSTA →	Hurricanes

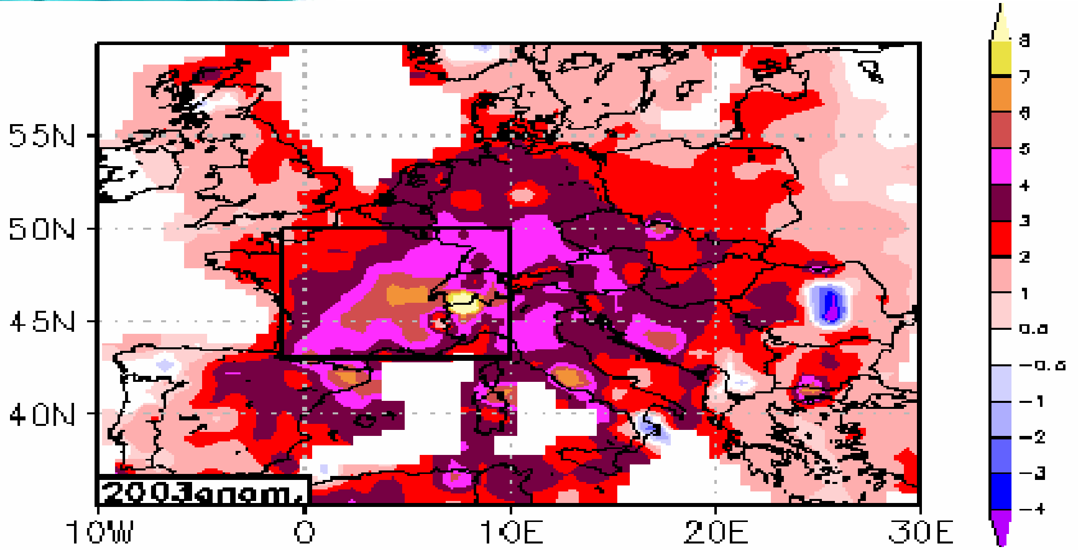
Northward Propagating Rossby-Wave Train

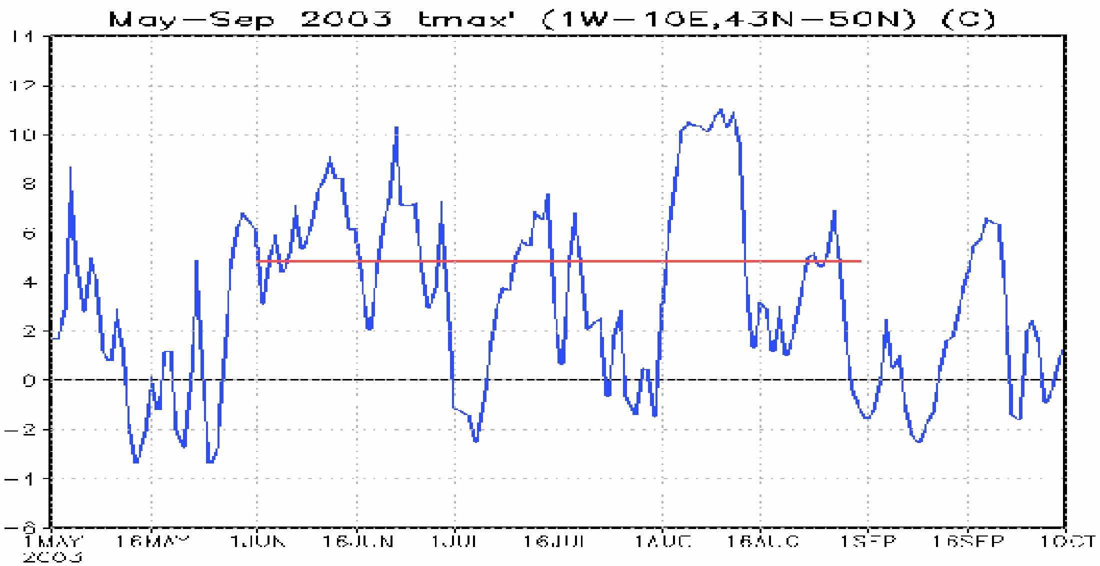




(Trenberth, et al. 1998)

European Heat Wave of summer 2003



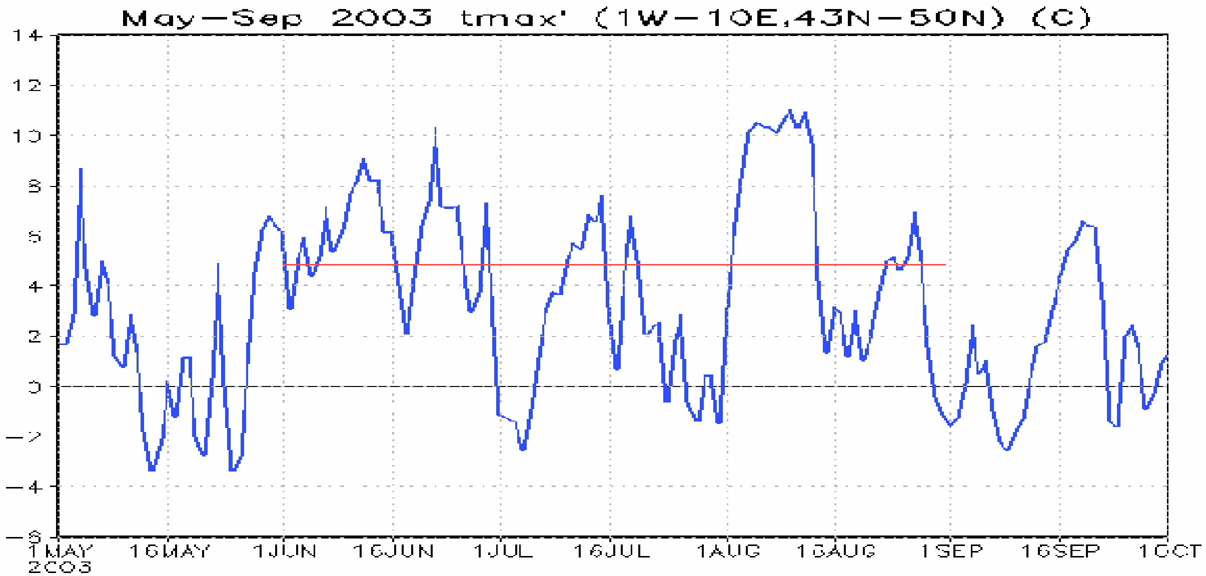


Tcmx JJA 2003

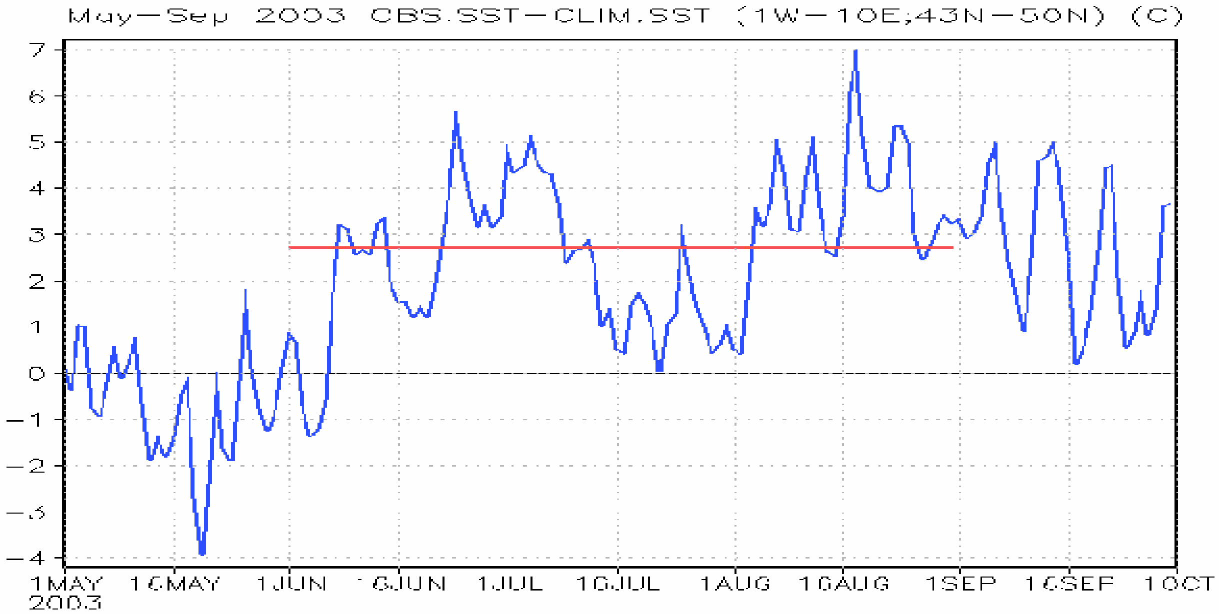
(Xie Pingping data)

Anomaly of maximum surface temperature

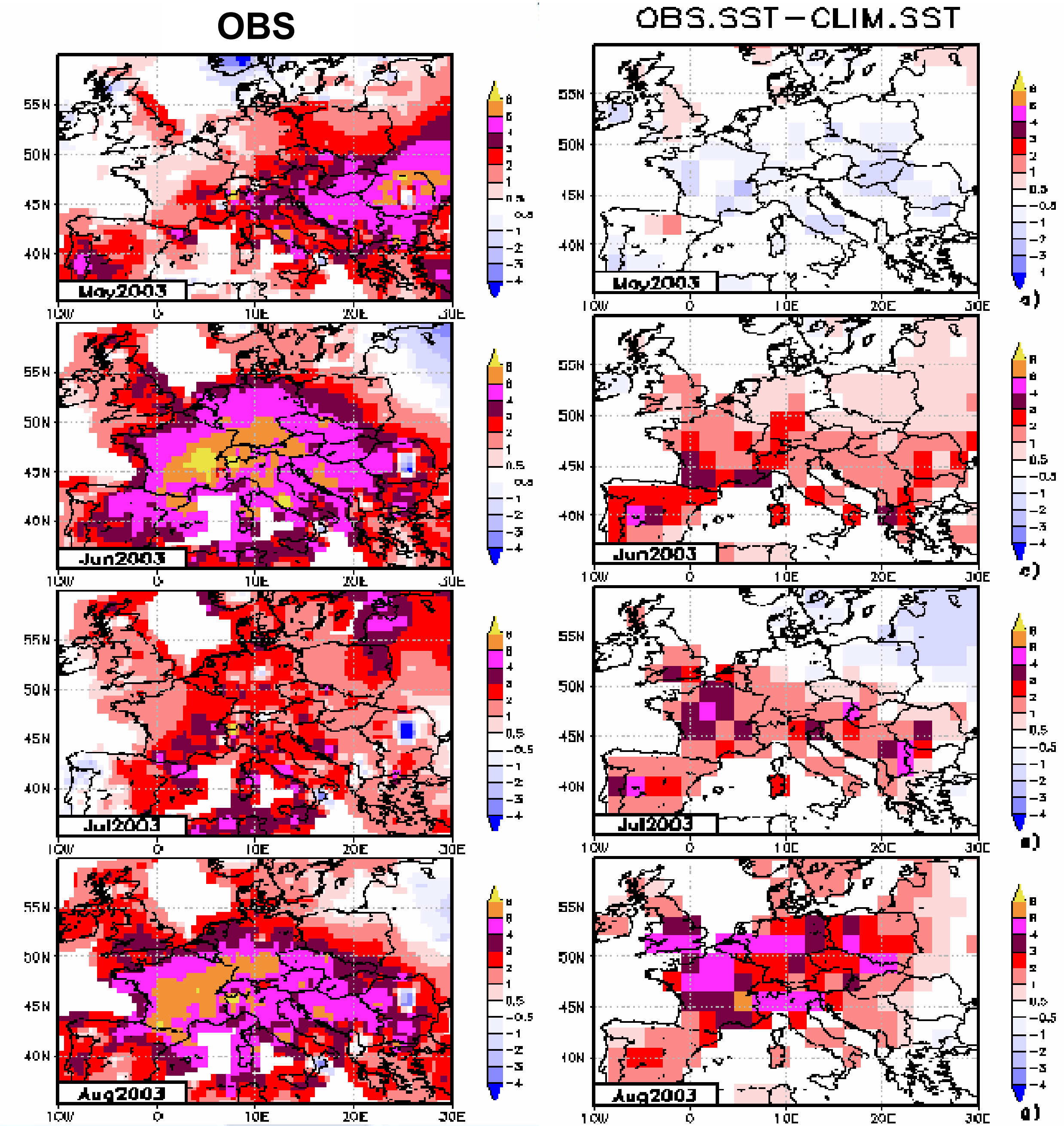
OBSERVATIONS



OBS.SST-CLIM.SST
- Global SST effect -



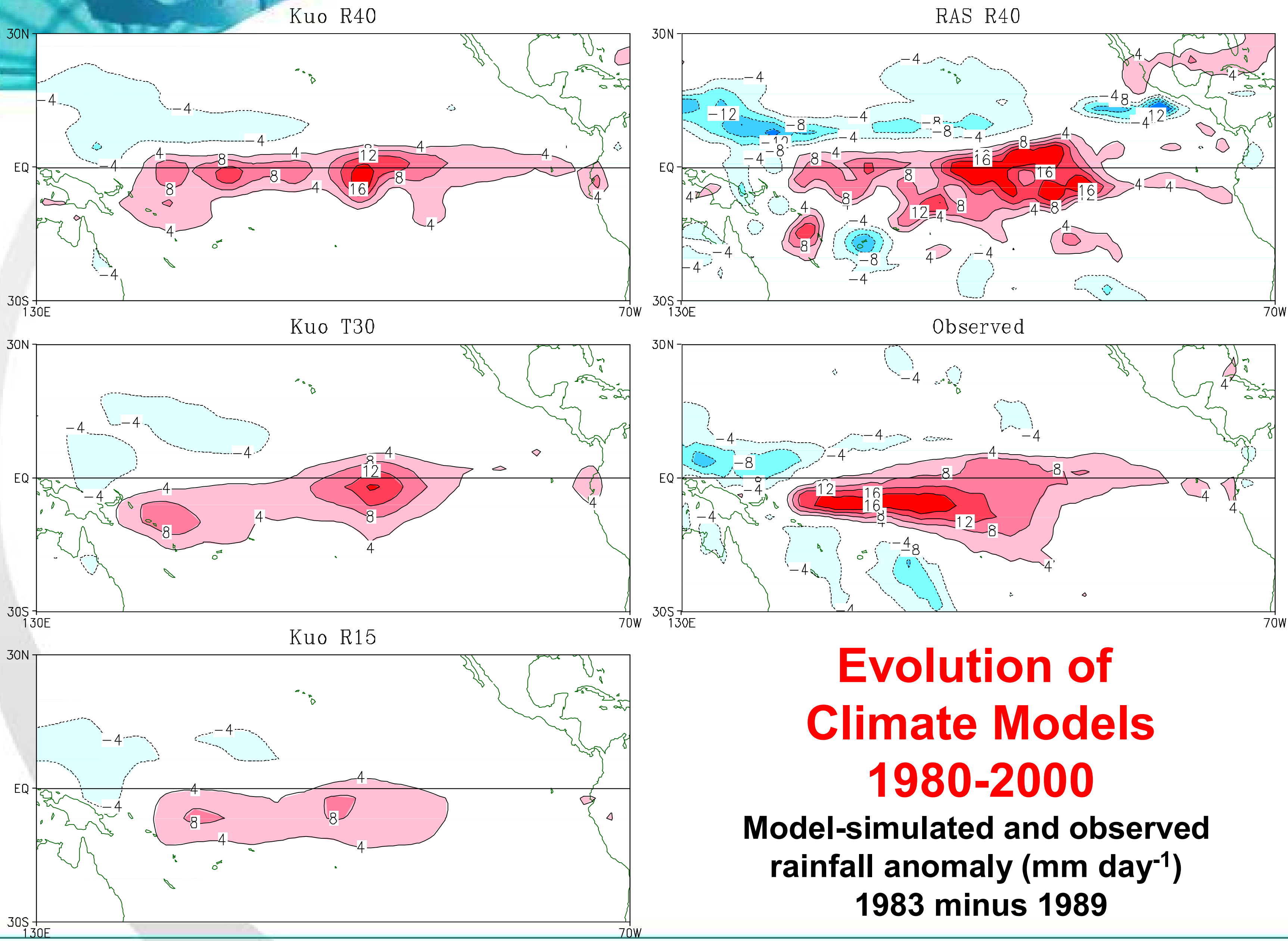
Anomaly of maximum surface temperature on (1W-10E;43N-50N)



T_{MAX} anomaly:

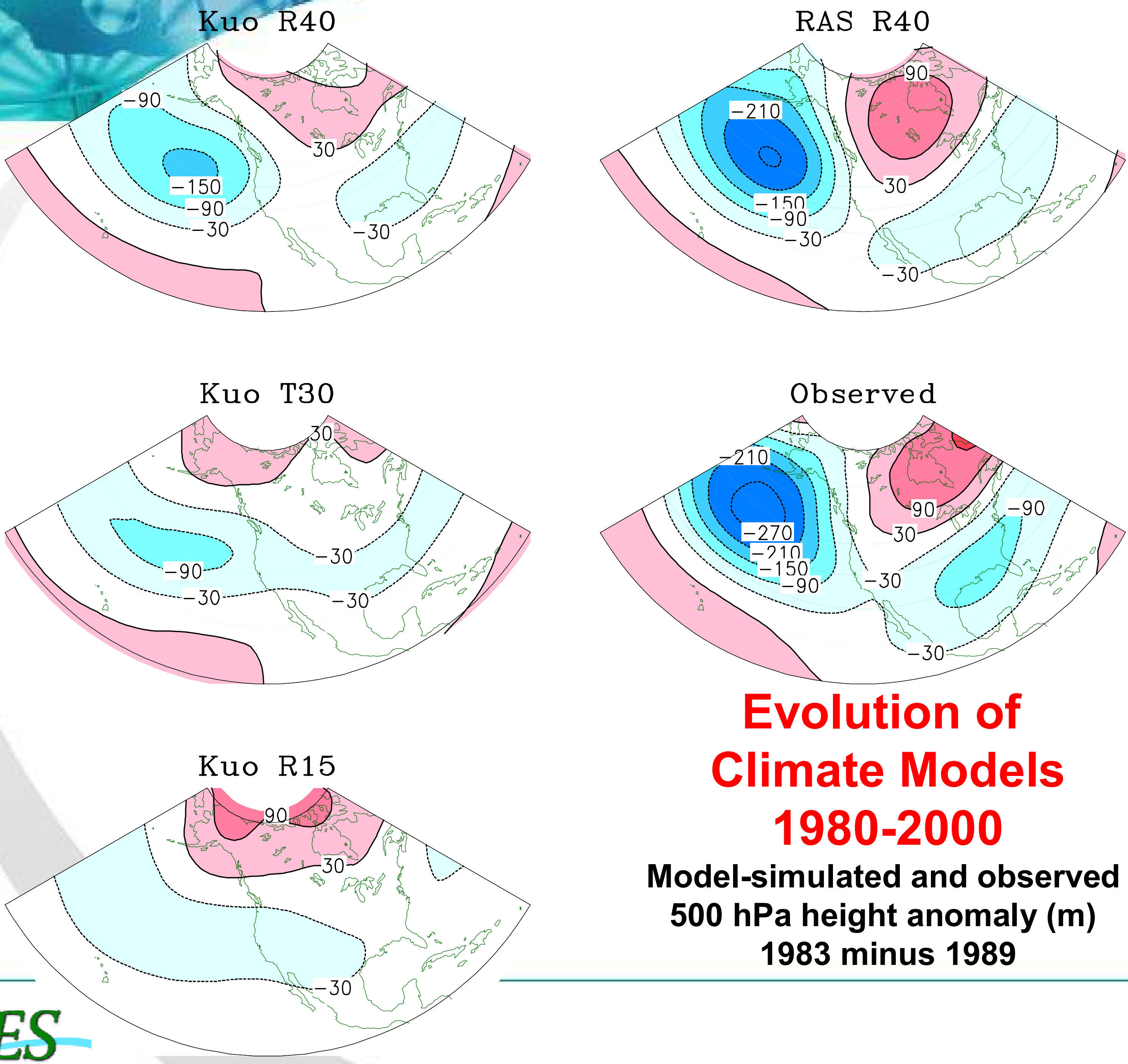
comparison between ***observations*** *and*

global SST run



Evolution of Climate Models 1980-2000

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



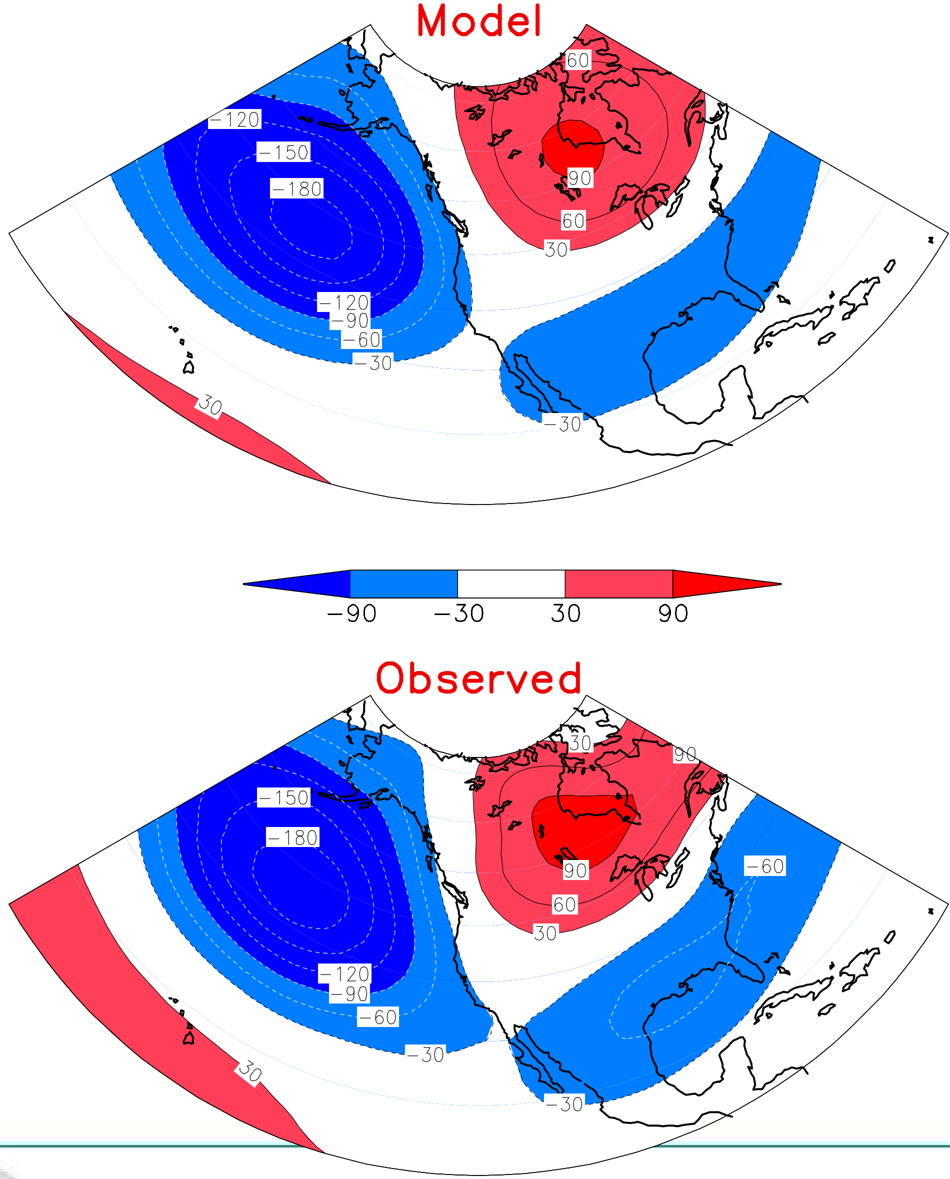
Evolution of Climate Models 1980-2000

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

Model Simulation of ENSO Effects

500 hPa height (meters) anomalies

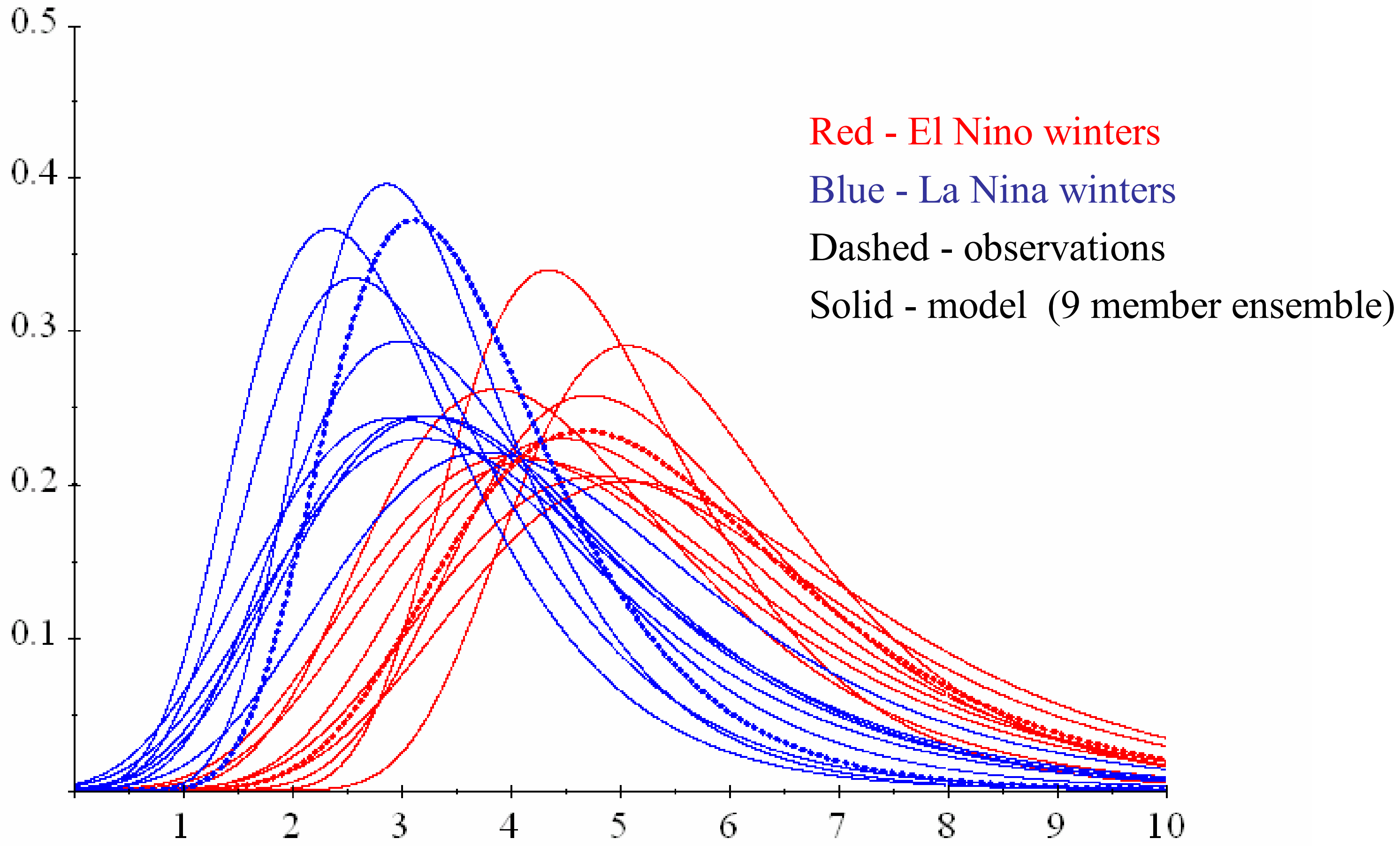
ACC = 0.98



Vintage 2000 AGCM

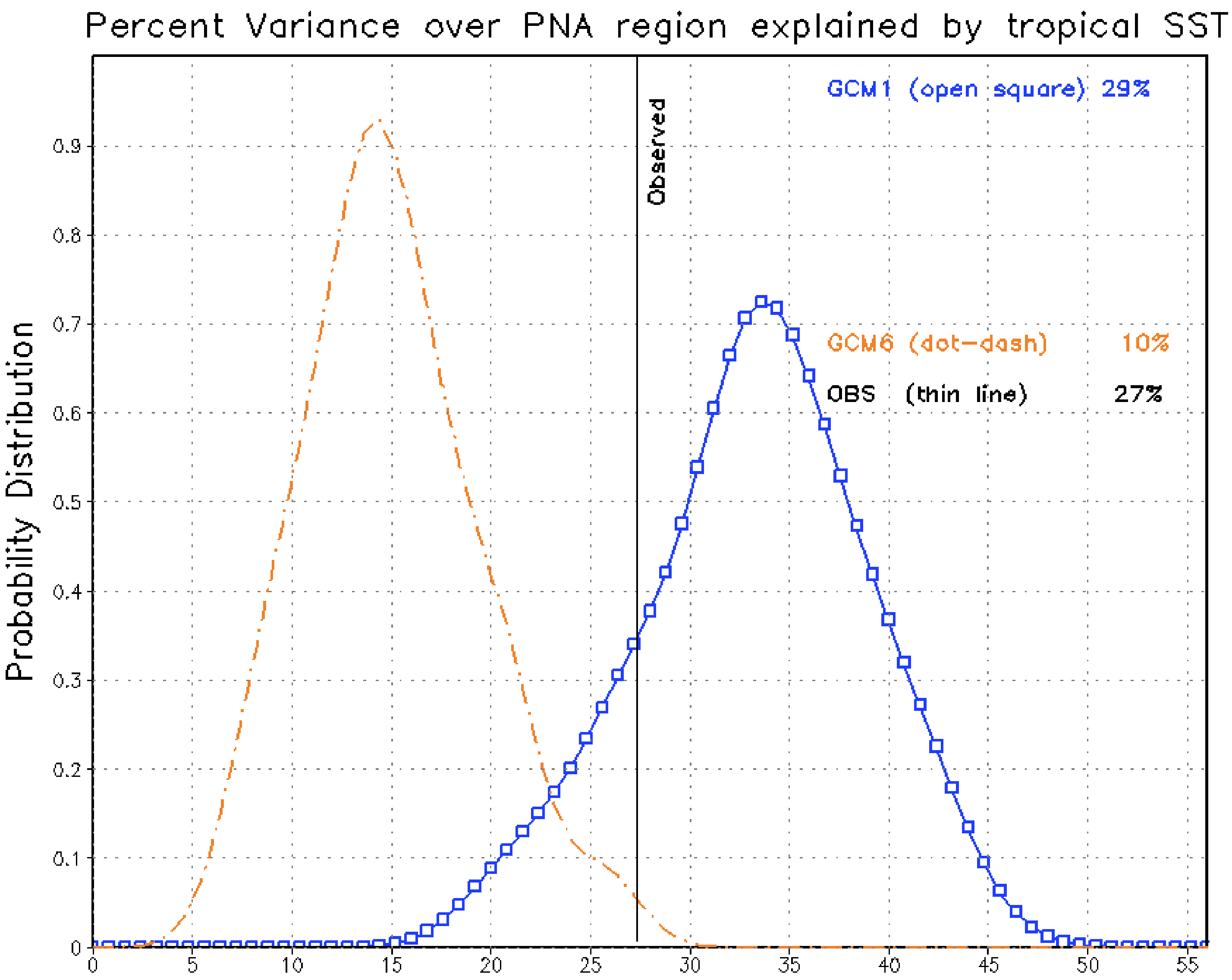
NINO3 Warm(83,87,92) – Cold(85,89)

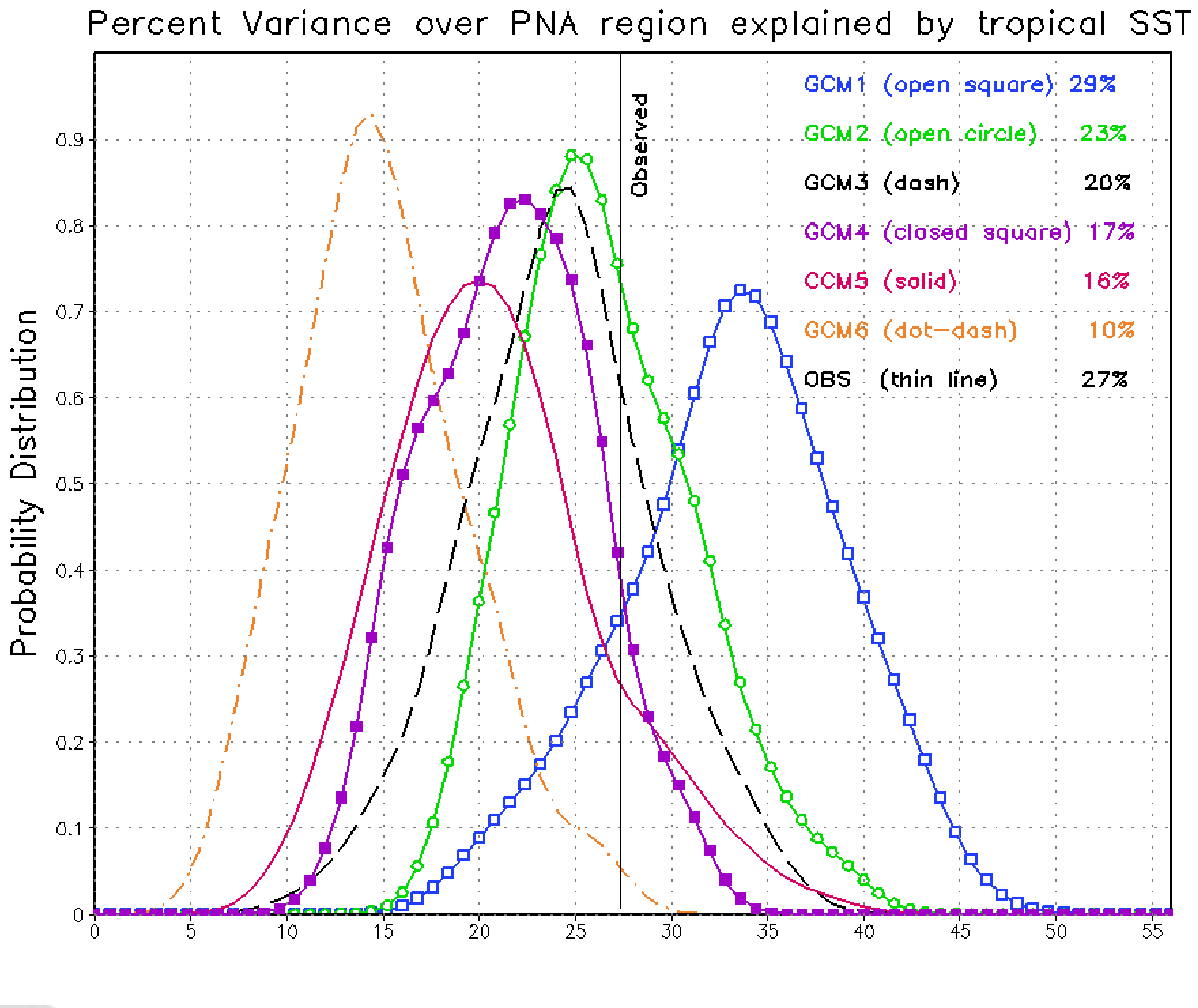
Probability Density Function of Extreme Winter Storms in Southeastern US (DJF 1949-1998)



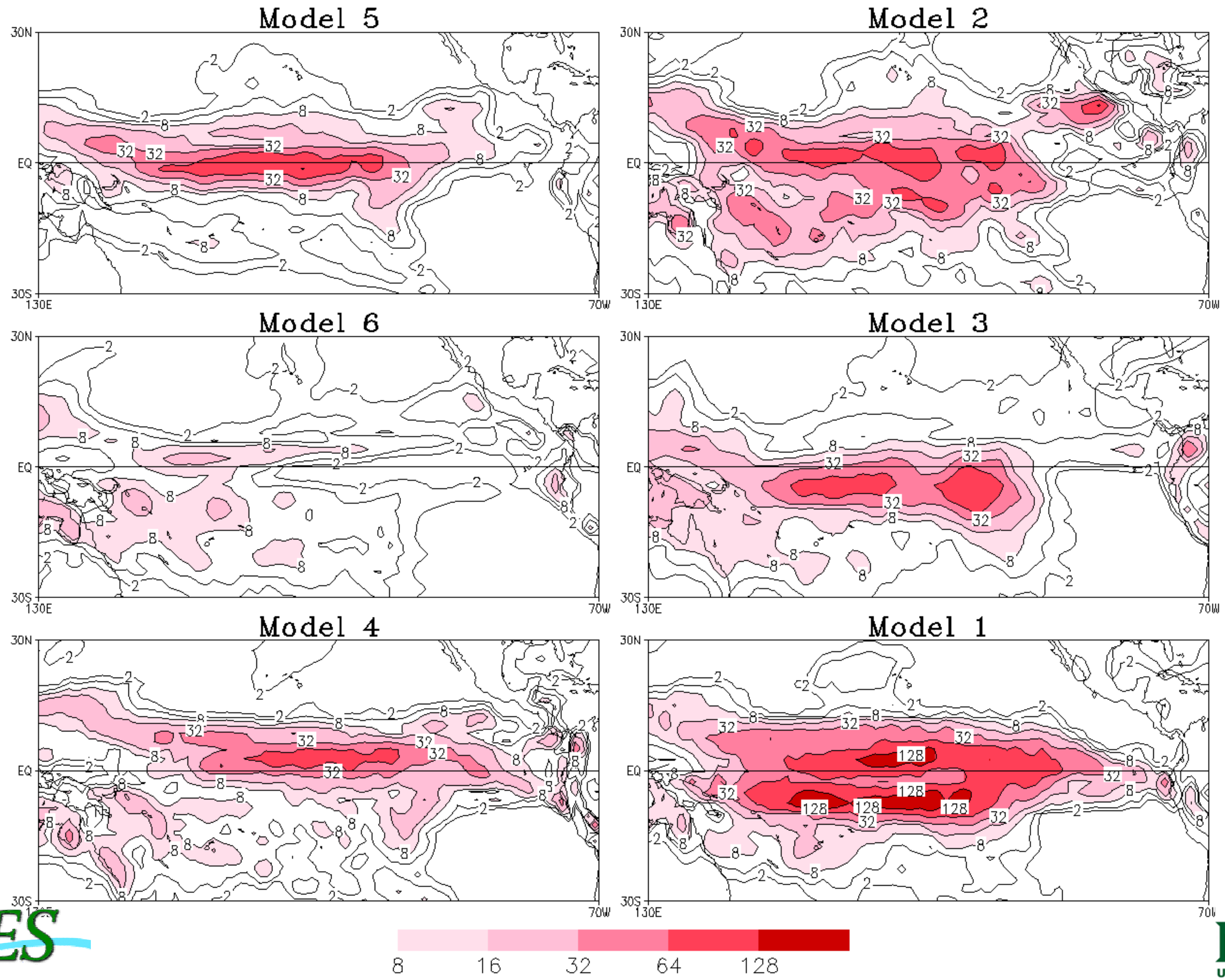
Maximum value of the intensity of storms affecting the southeastern United States (storms are identified from an EOF analysis of daily precipitation). Values are the principal components scaled so that the model and observed EOFs have the same total variance. Units are arbitrary. The PDFs are the fits to a Gumbel Distribution.

Factors Limiting Predictability: Future Challenges

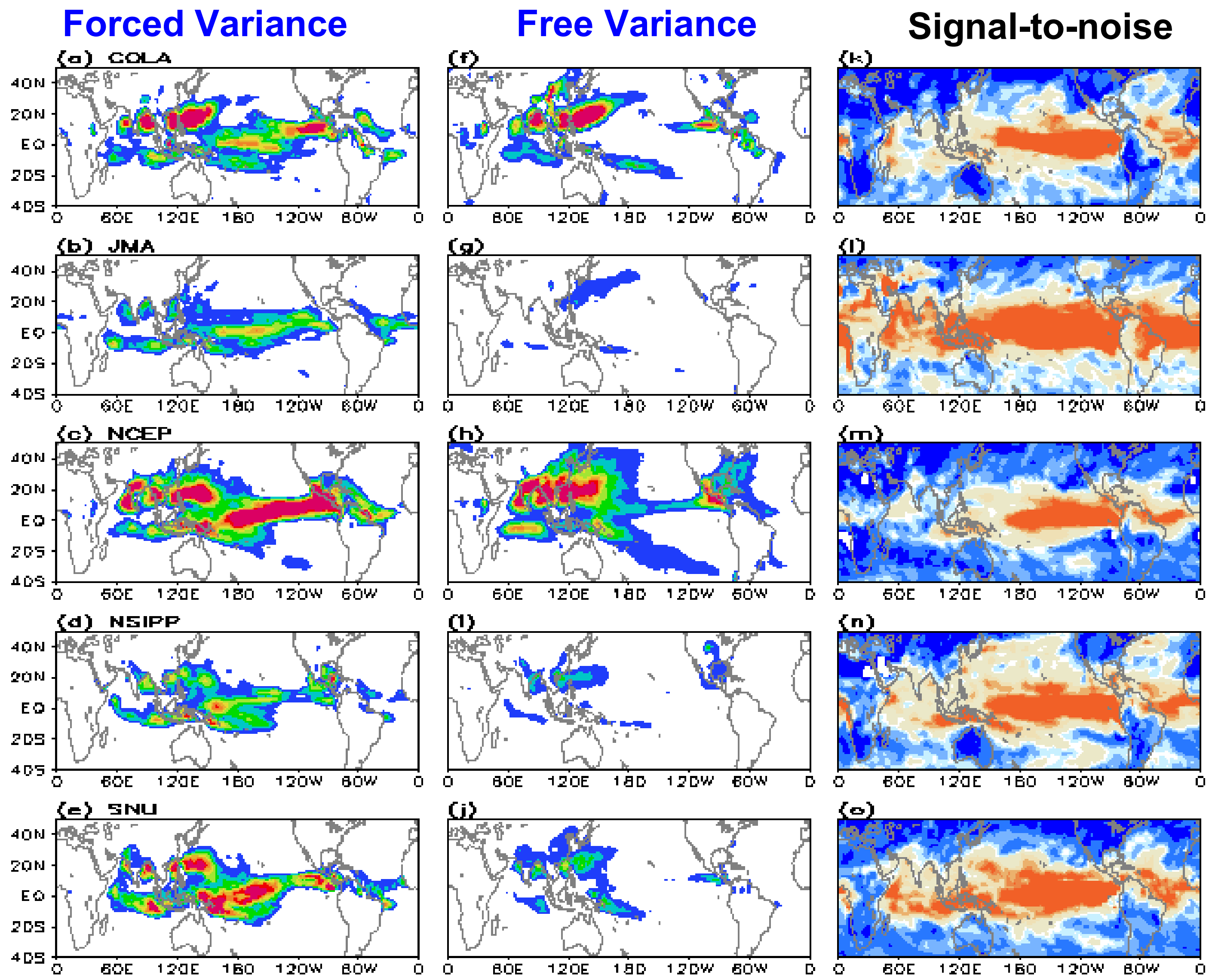

Percent Variance over PNA region explained by tropical SST
Probability Distribution
Observed
GCM1 (open square) 29%
GCM6 (dot-dash) 10%
OBS (thin line) 27%
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
10
15
20
25
30
35
40
45
50
55


Percent Variance over PNA region explained by tropical SST
Probability Distribution
Observed
GCM1 (open square) 29%
GCM2 (open circle) 23%
GCM3 (dash) 20%
GCM4 (closed square) 17%
CCM5 (solid) 16%
GCM6 (dot-dash) 10%
OBS (thin line) 27%
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 5 10 15 20 25 30 35 40 45 50 55
GrADS: COLA/IGES

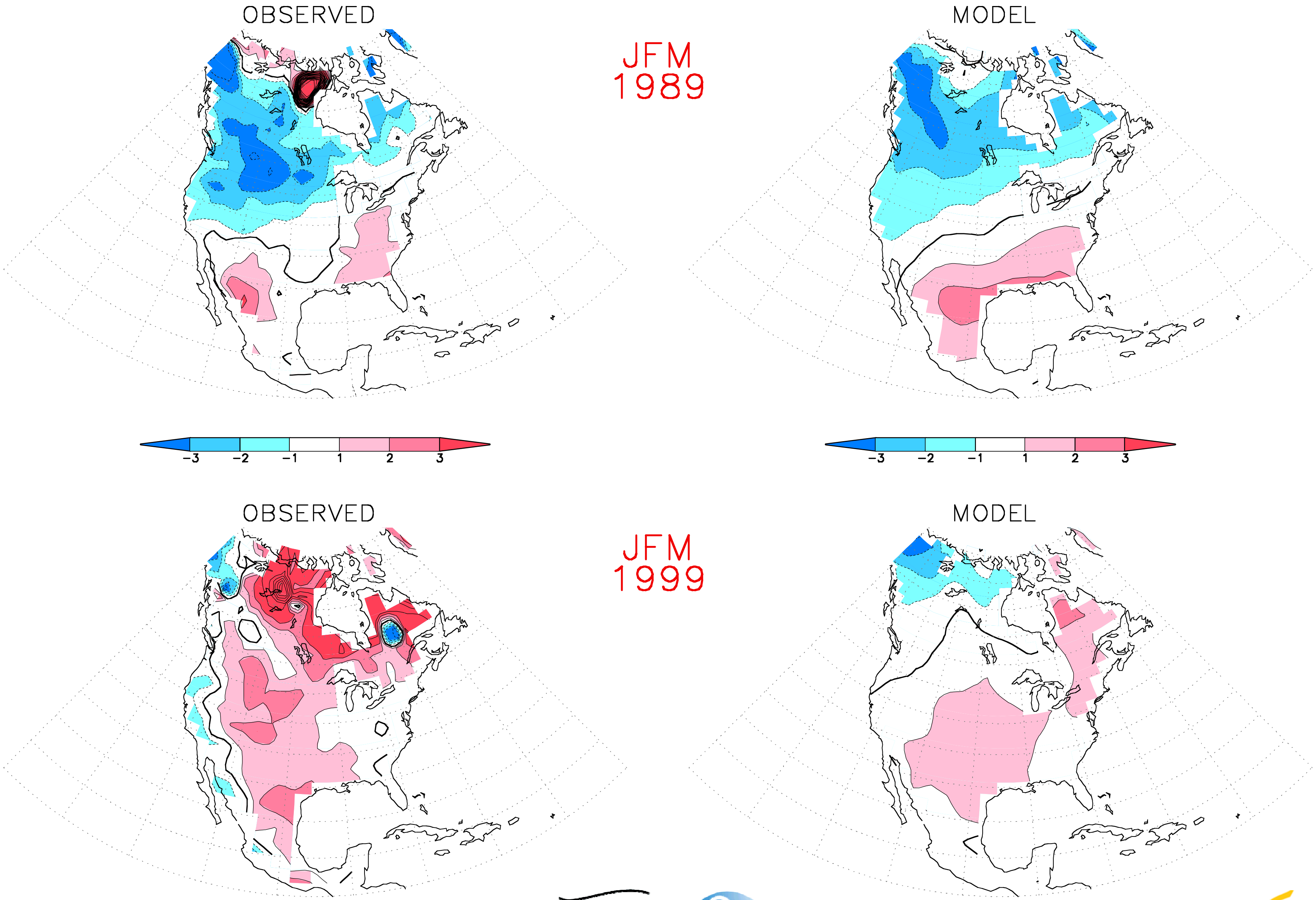
Variance of Model-Simulated Seasonal (JFM) Rainfall (mm^2)



Boreal Summer (JJA) Rainfall Variance in AGCMs



Observed and Simulated Surface Temperature (°C)



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- Factors Limiting Predictability: Future Challenges
  - Observational and Theoretical (Physics & Dynamics of the Coupled Climate System)
  - Computational and Numerical
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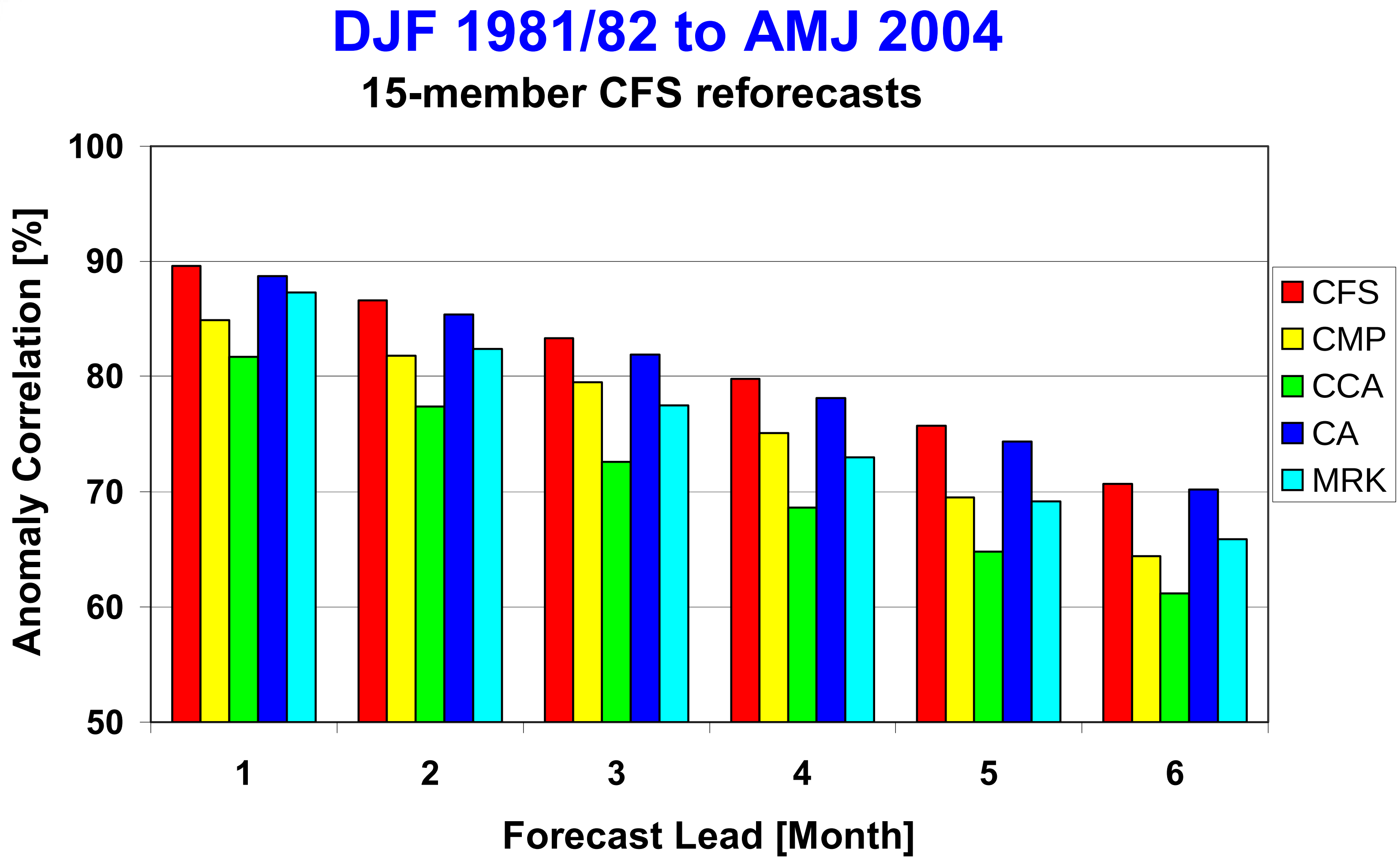
Evolution of Climate Models: 1955-2004

- **Atmospheric General Circulation Models (1960-1965)**
  - Smagorinsky, Manabe, Arakawa and Mintz, Leith, …
- **Oceanic General Circulation Models (1963-1967)**
  - Bryan, Sarkisyan, Bryan and Cox, Takano and Mintz, Semtner, …
- **Land Surface Processes Models**
  - Manabe (1965); Dickinson (1984), Sellers et al. (1986), …
- **Coupled Climate Models**
  - Manabe and Bryan (1969); Gates, Hansen, Hasselmann, Meier-Reimer, Mitchell, Washington, …

(Thanks to GFDL!)

Skill in SST Anomaly Prediction for Nino3.4



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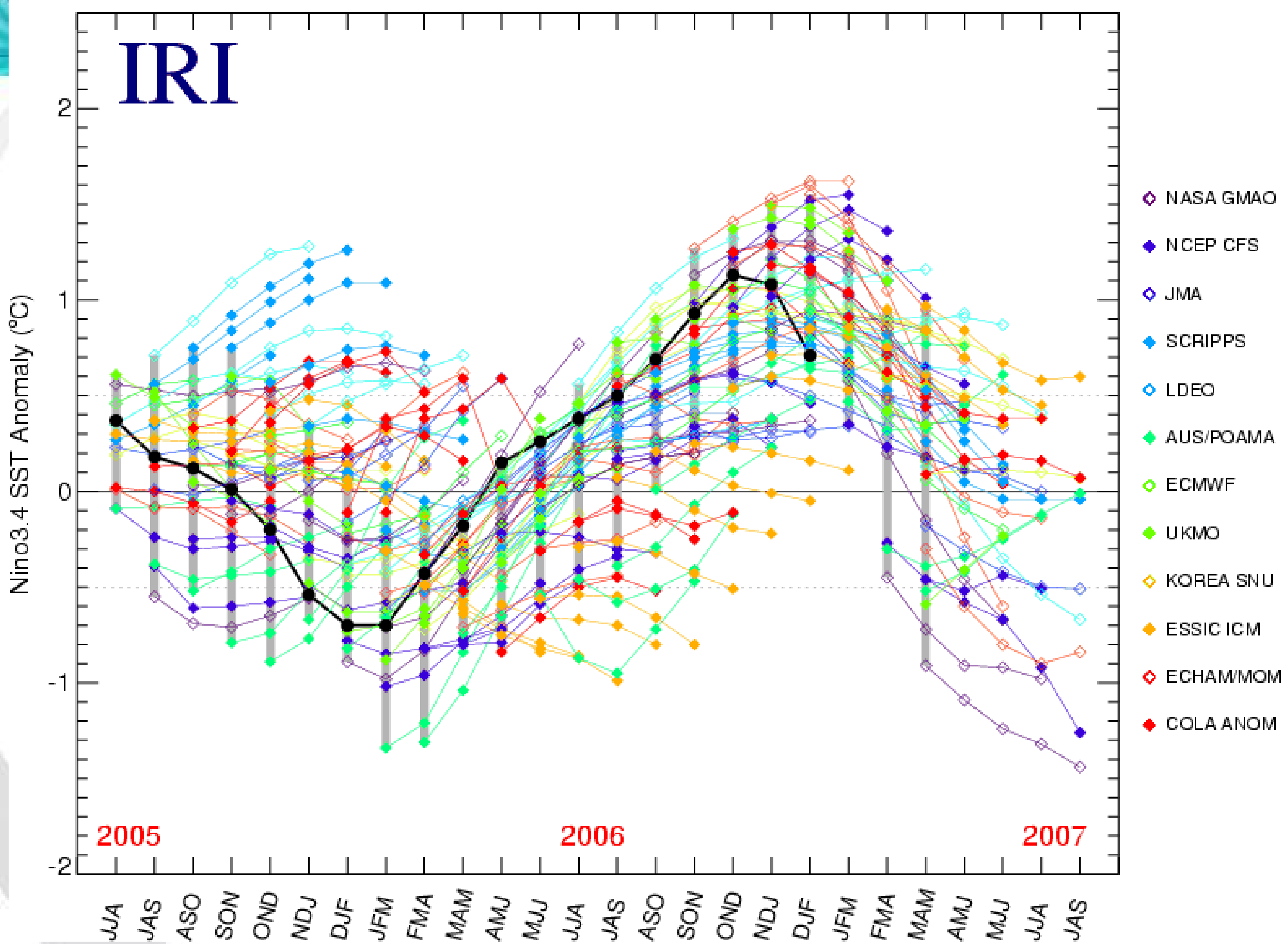
ENSO Forecast for dynamical models, Jun 05 - Mar 07



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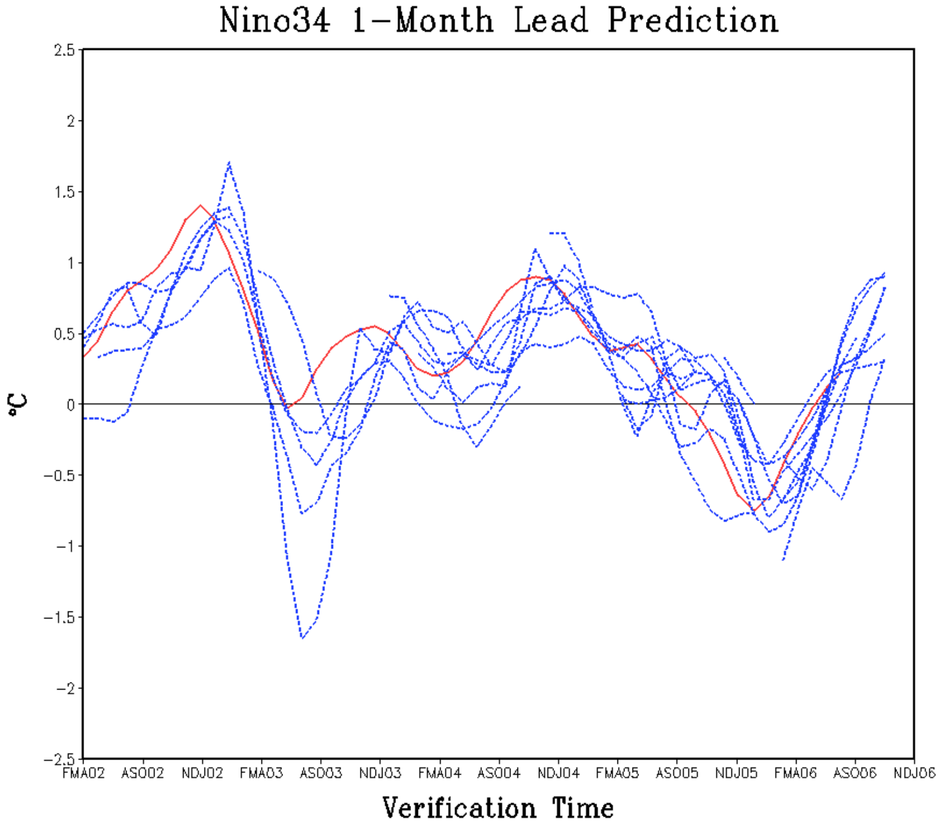
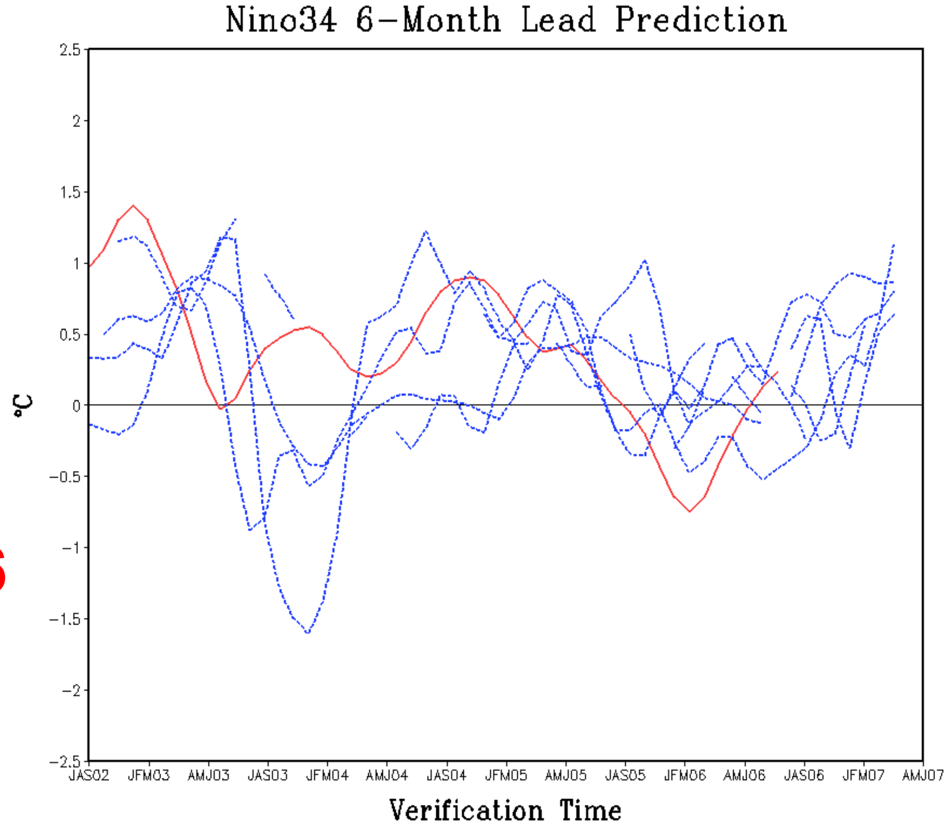


Dynamic CGCMs Only



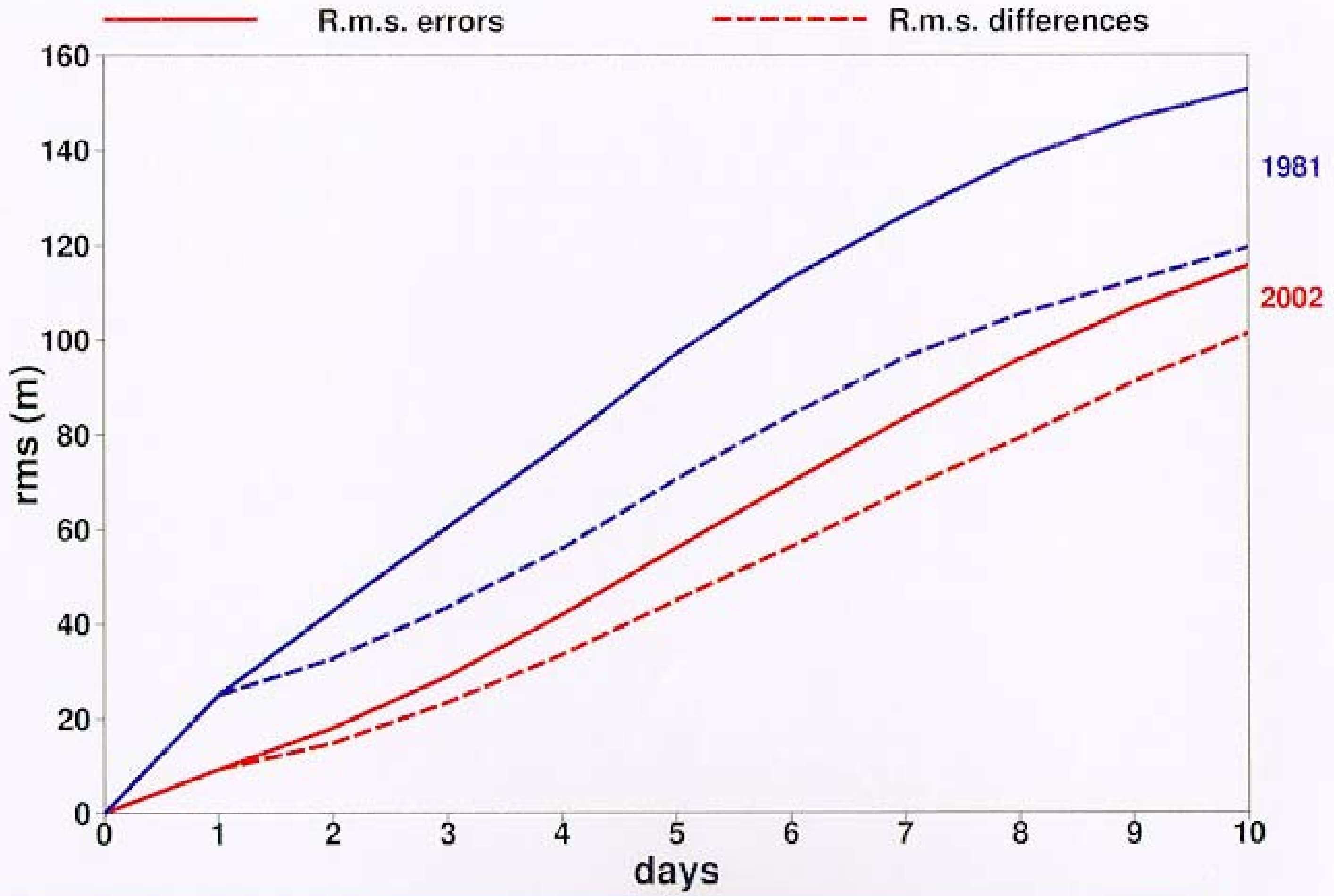
IRI Nino34 Forecast Archive
February 2002-September 2006

Running Seasonal Means

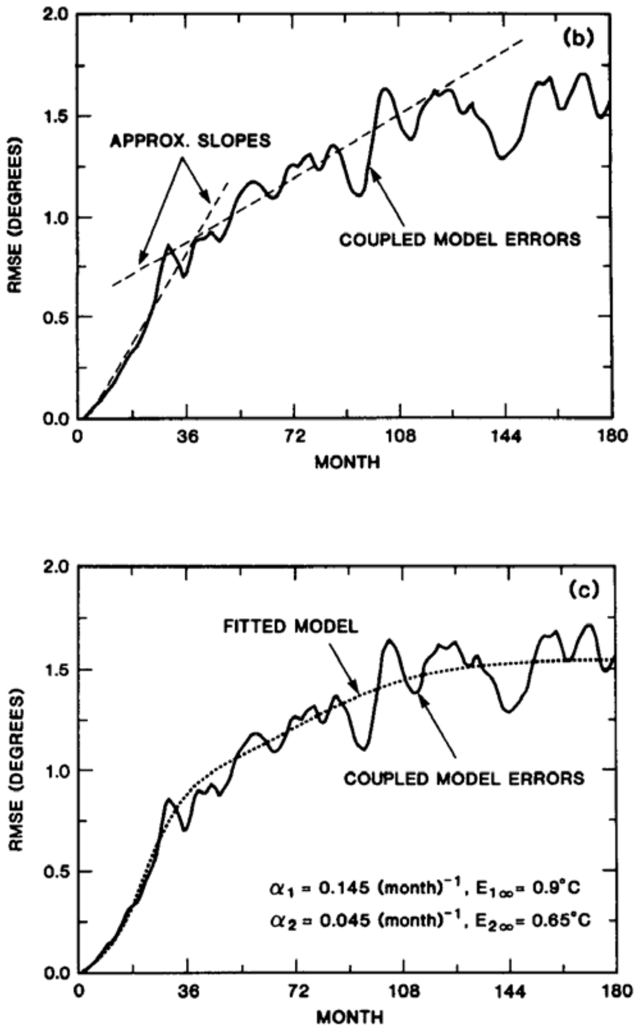
Understanding Variations in Forecast Skill

- **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

R.m.s. errors and differences between successive forecasts
Northern hemisphere 500hPa height Winter



Predictability Limited Due to Initial Condition Uncertainty: Two Time Scales in the Error Growth?



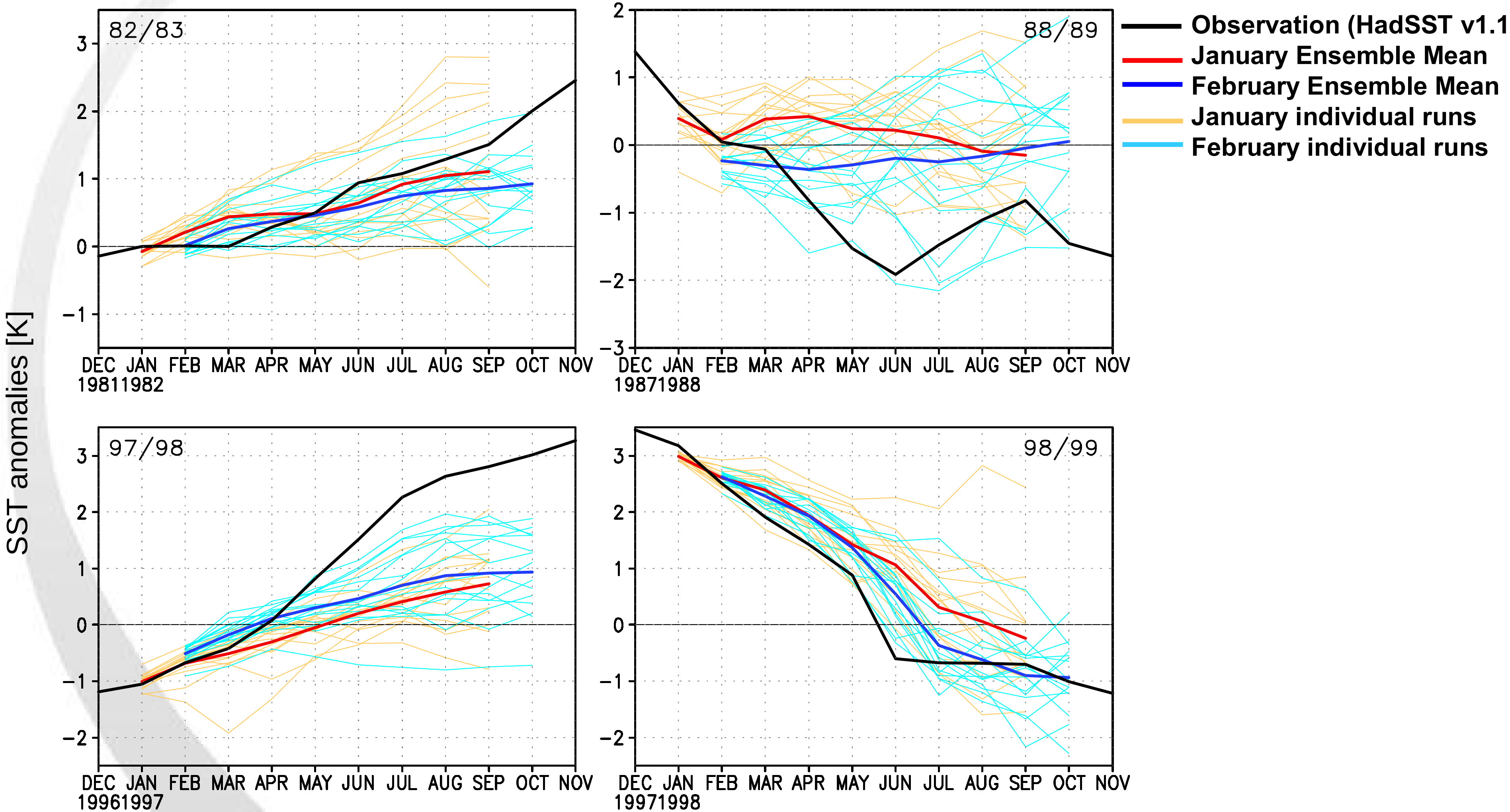
$$E(t) = E_1(t) + E_2(t)$$

$$\frac{dE_1}{dt} = \alpha_1 E_1 - \alpha_1 E_1^2 \Big/ E_{1\infty}$$

$$\frac{dE_2}{dt} = \alpha_2 E_2 - \alpha_2 E_2^2 \Big/ E_{2\infty}$$

Goswami and Shukla (1991)
J. Clim.

Examples: 4 ENSO cases of NINO3 index in CFS

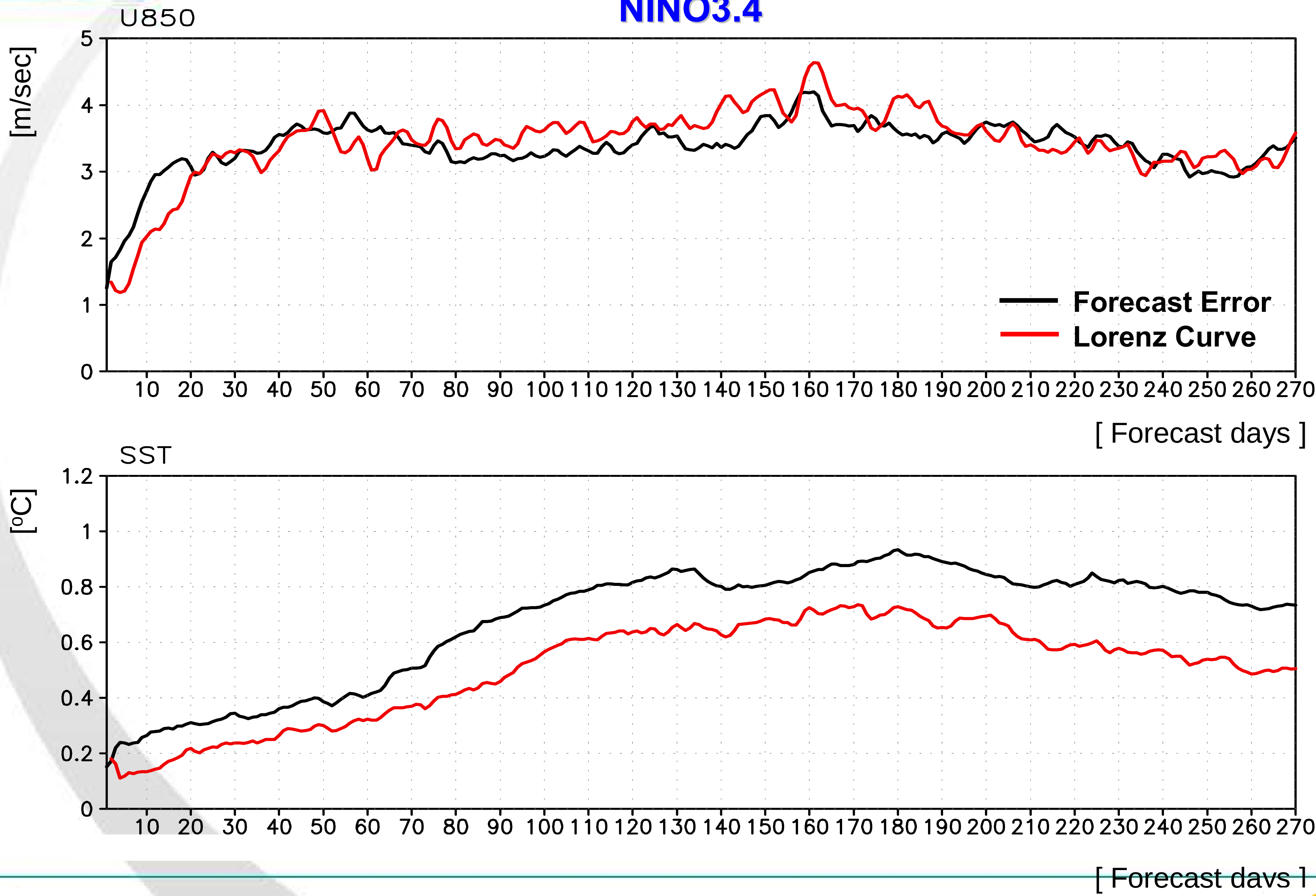


Jin and Kinter, 2007

Forecast Error and Lorenz Curve

NCEP CFS daily forecast start from 9Apr to 3May (15 members)

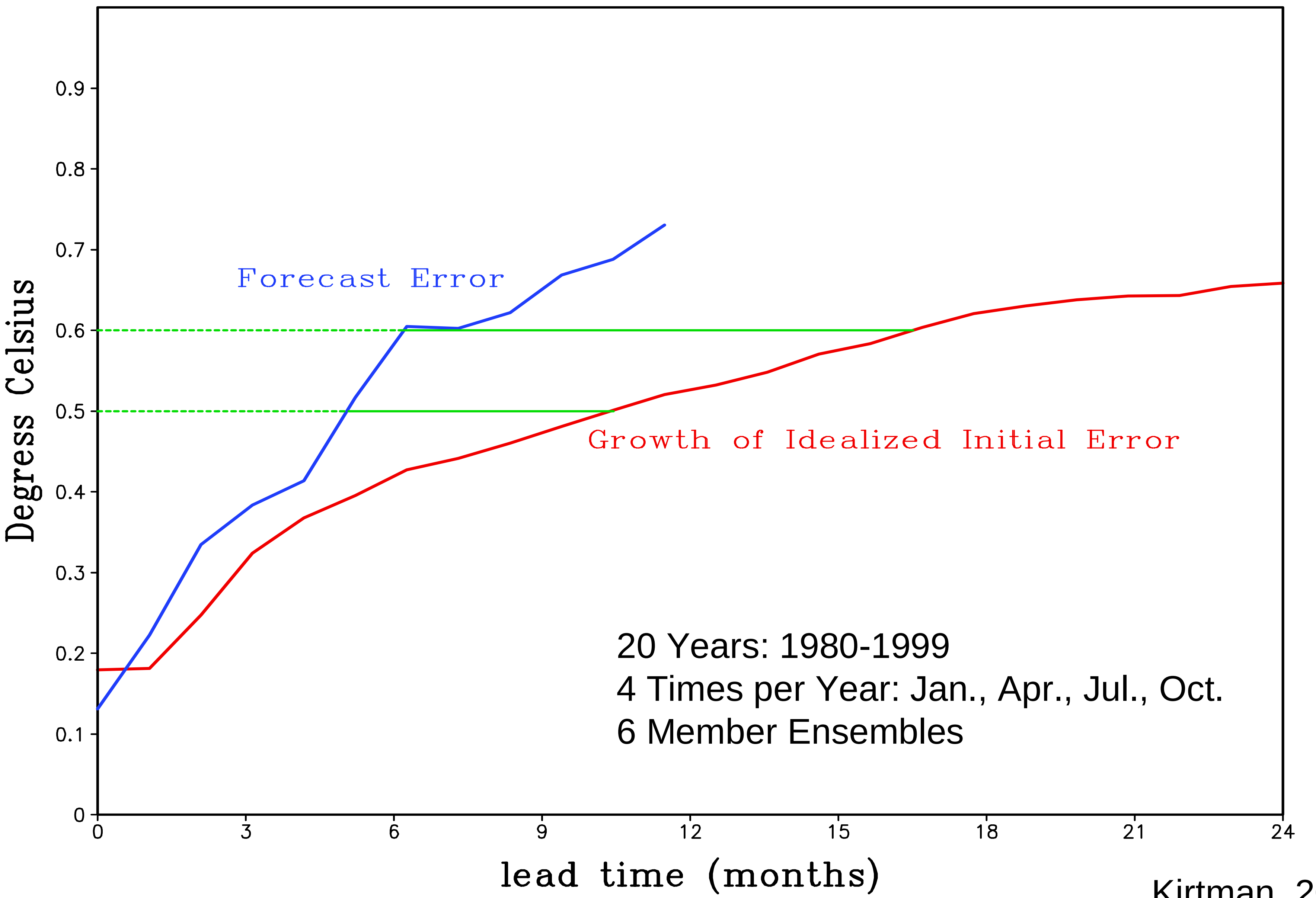
NINO3.4



IGES

GEORGE MASON UNIVERSITY

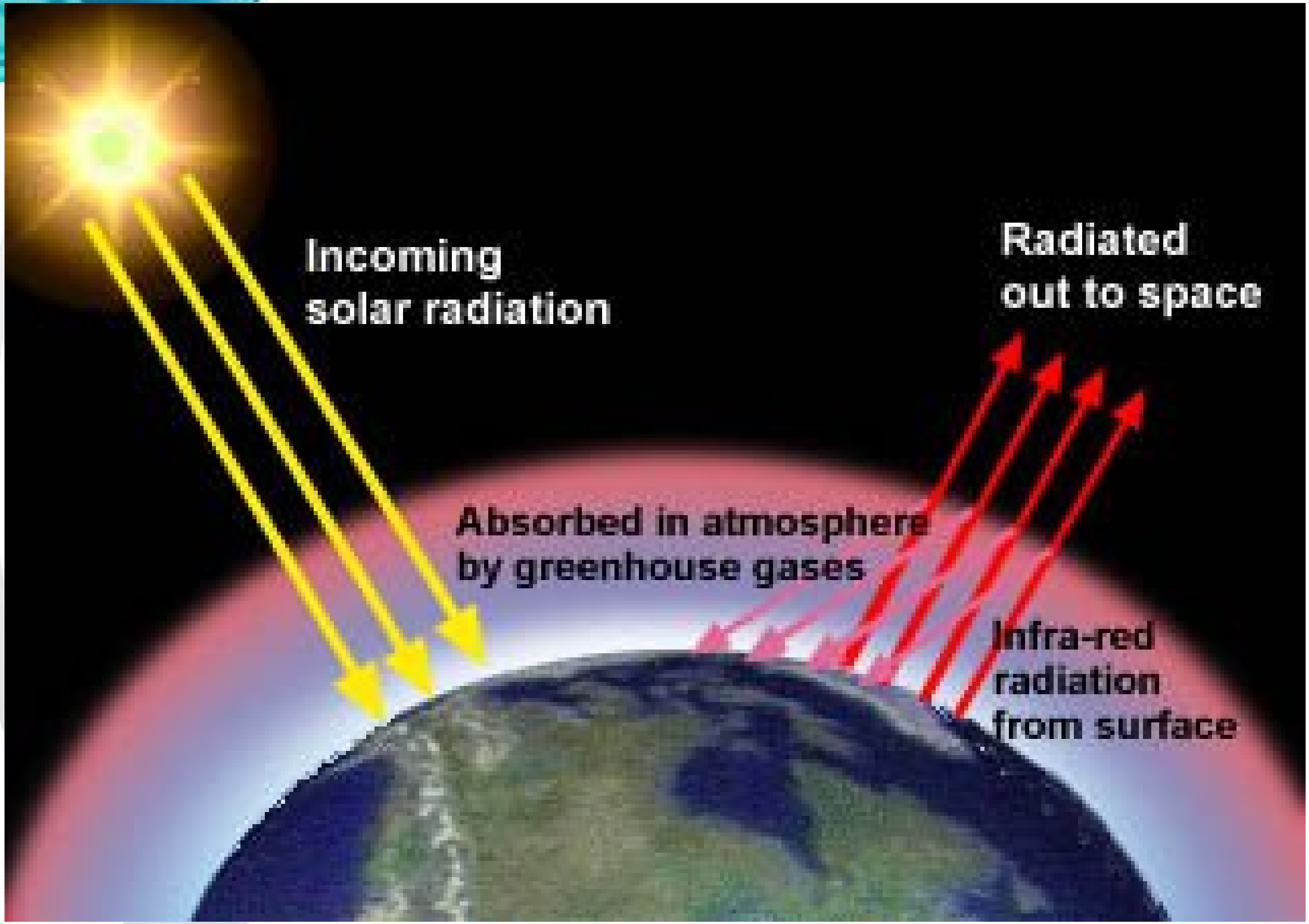
Current Limit of Predictability of ENSO (Nino3.4)
Potential Limit of Predictability of ENSO



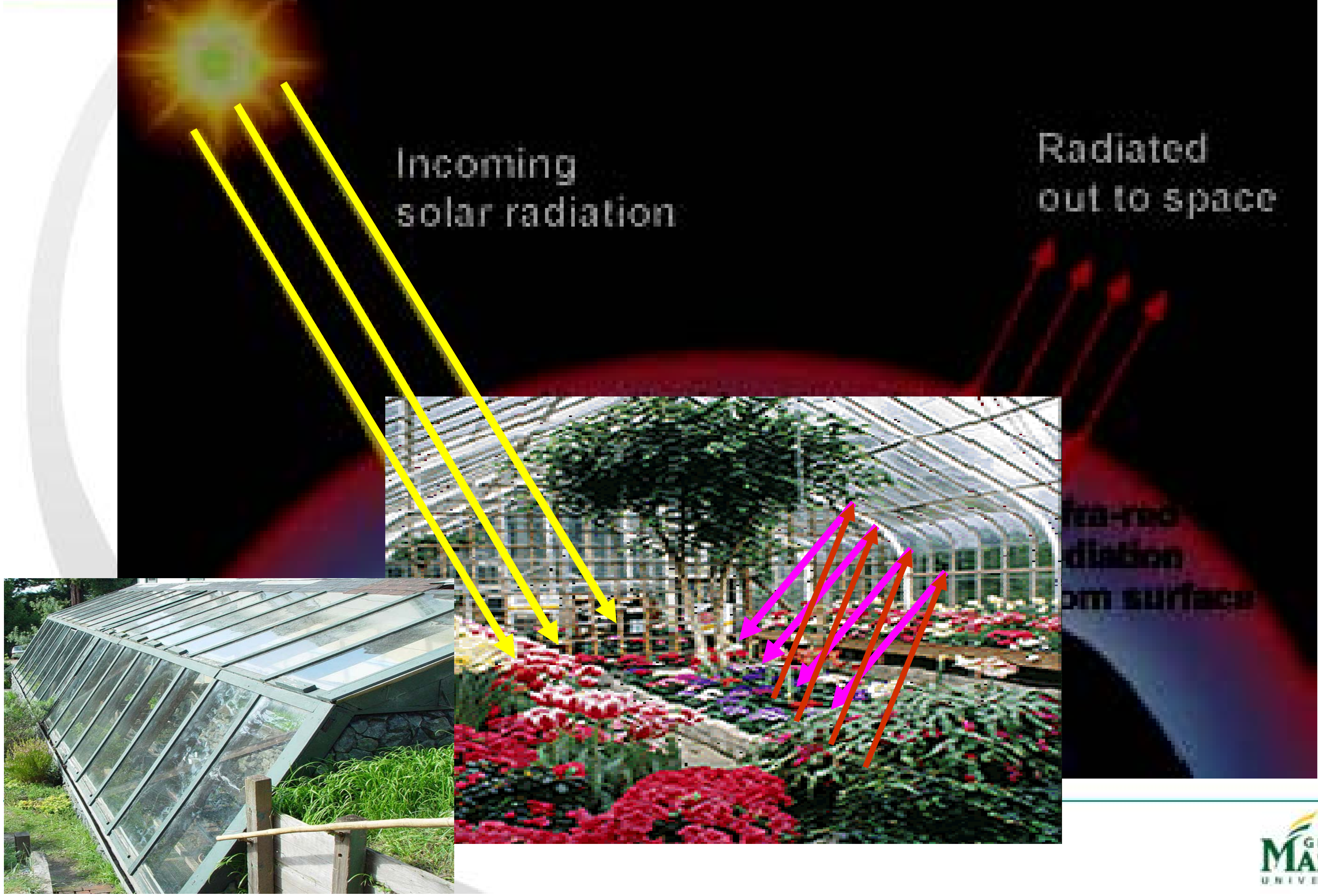
Kirtman, 2003

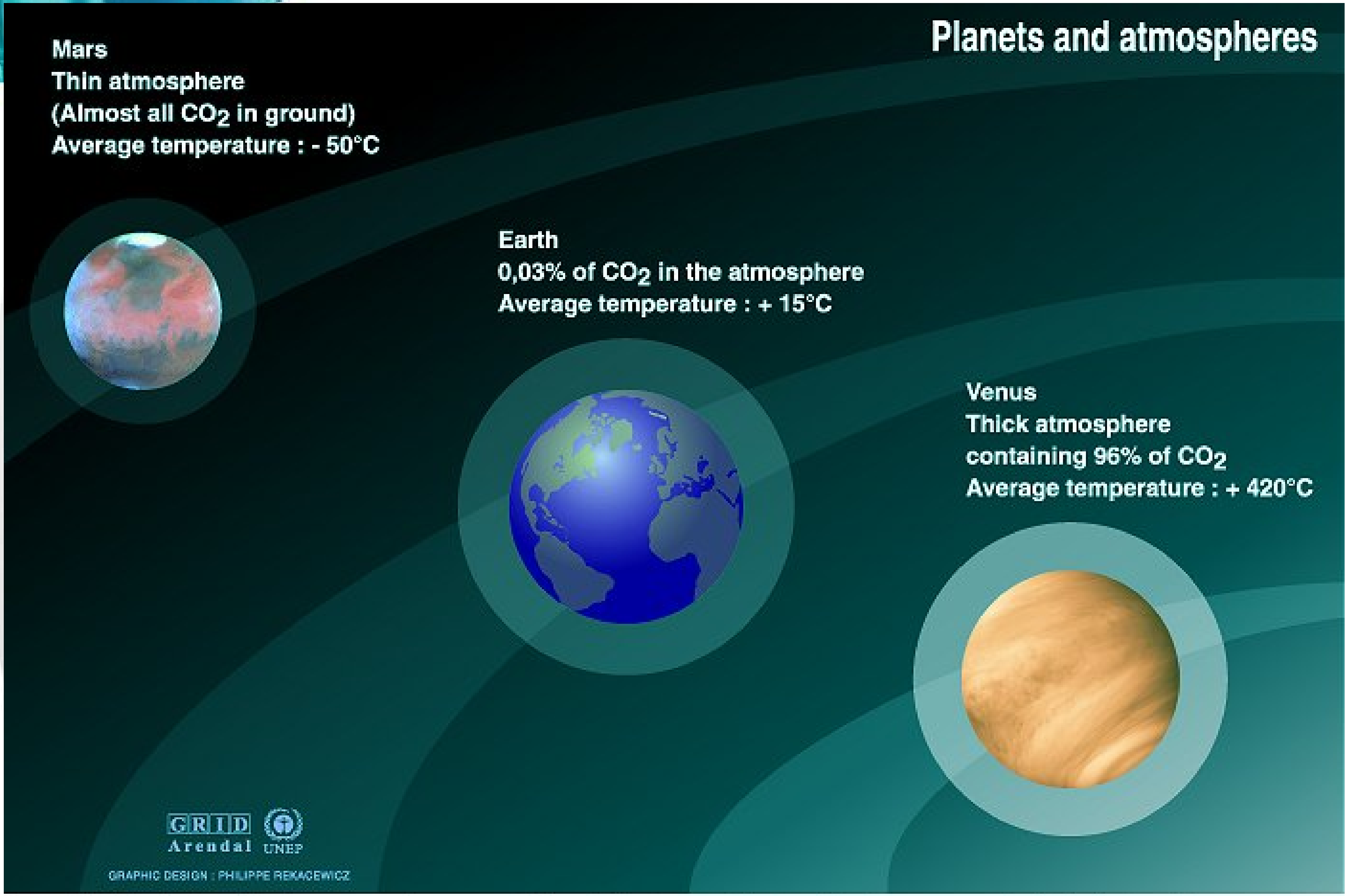
Outline

- Weather and Climate for Poets
- Mechanisms of Variability of Weather and Climate
- Predictability and Prediction of Weather and Climate
  - Weather
  - Climate (Seasonal, ENSO, Decadal)
  - Climate Change
- Factors Limiting Predictability: Future Challenges
  - Observational and Theoretical (Physics & Dynamics of the Coupled Climate System)
  - Computational and Numerical
- Summary and Conclusions

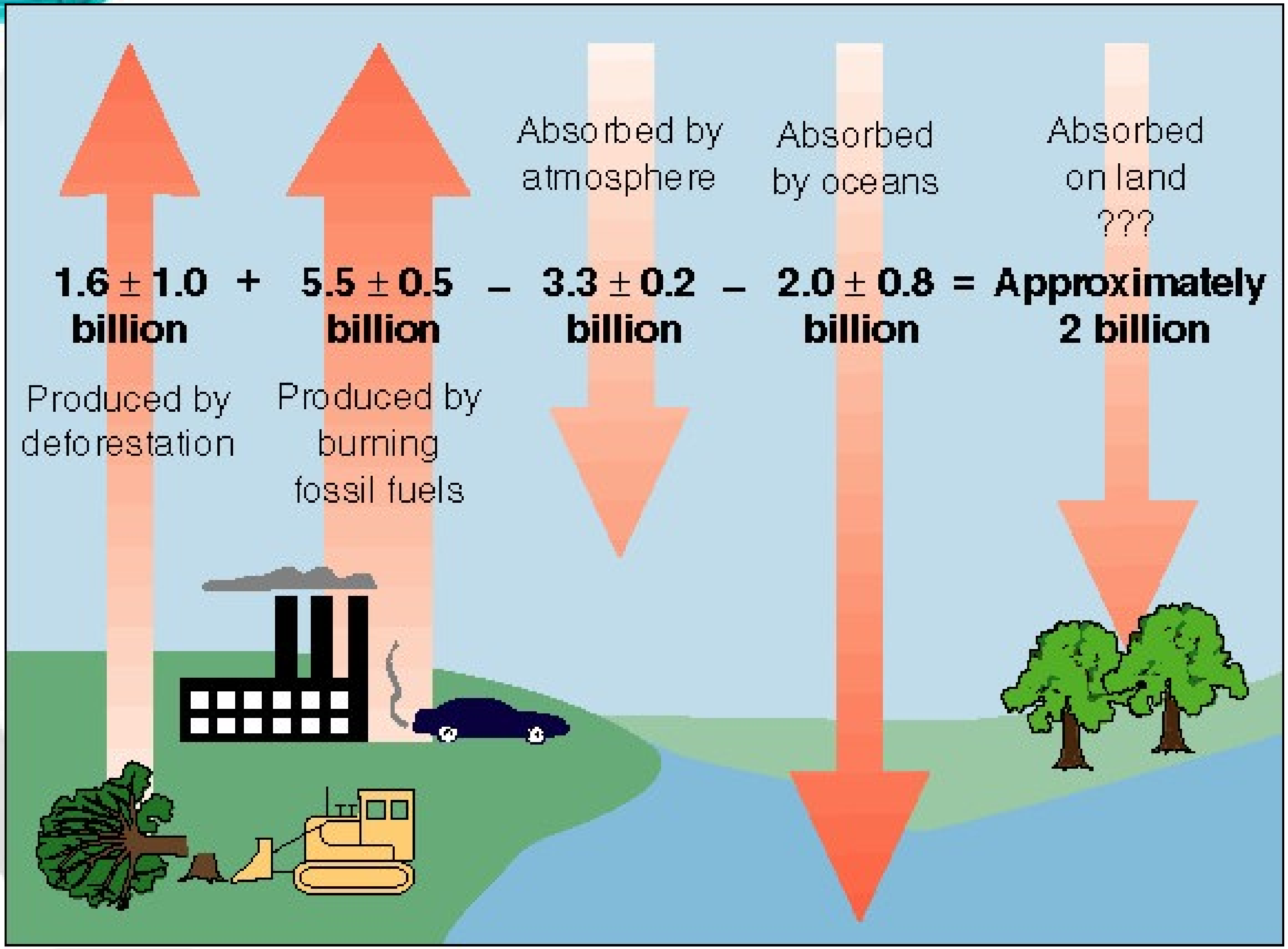

Incoming
solar radiation
Radiated
out to space
Absorbed in atmosphere
by greenhouse gases
Infra-red
radiation
from surface

Hence the term, “Greenhouse Effect”

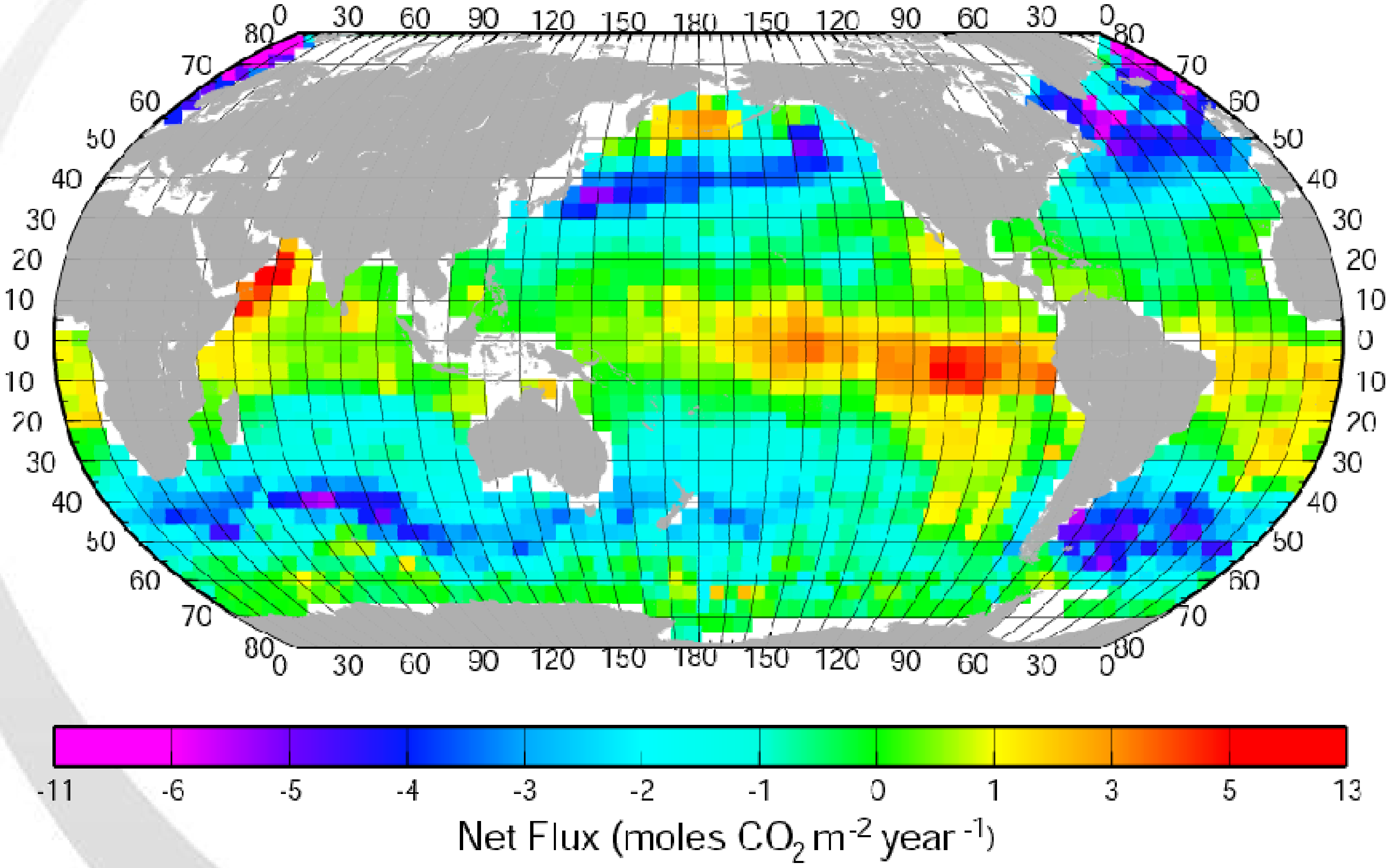




Sources: Calvin J. Hamilton, Views of the solar system, www.planetscapes.com; Bill Arnett , The nine planets, a multimedia tour of the solar system, www.seds.org/billa/tnp/nineplanets.html


Absorbed by atmosphere
Absorbed by oceans
Absorbed on land ???
1.6 ± 1.0 billion + 5.5 ± 0.5 billion – 3.3 ± 0.2 billion – 2.0 ± 0.8 billion = Approximately 2 billion
Produced by deforestation
Produced by burning fossil fuels

Net CO_2 Flux from Takahashi et al., 2002



Radiative Forcing Components

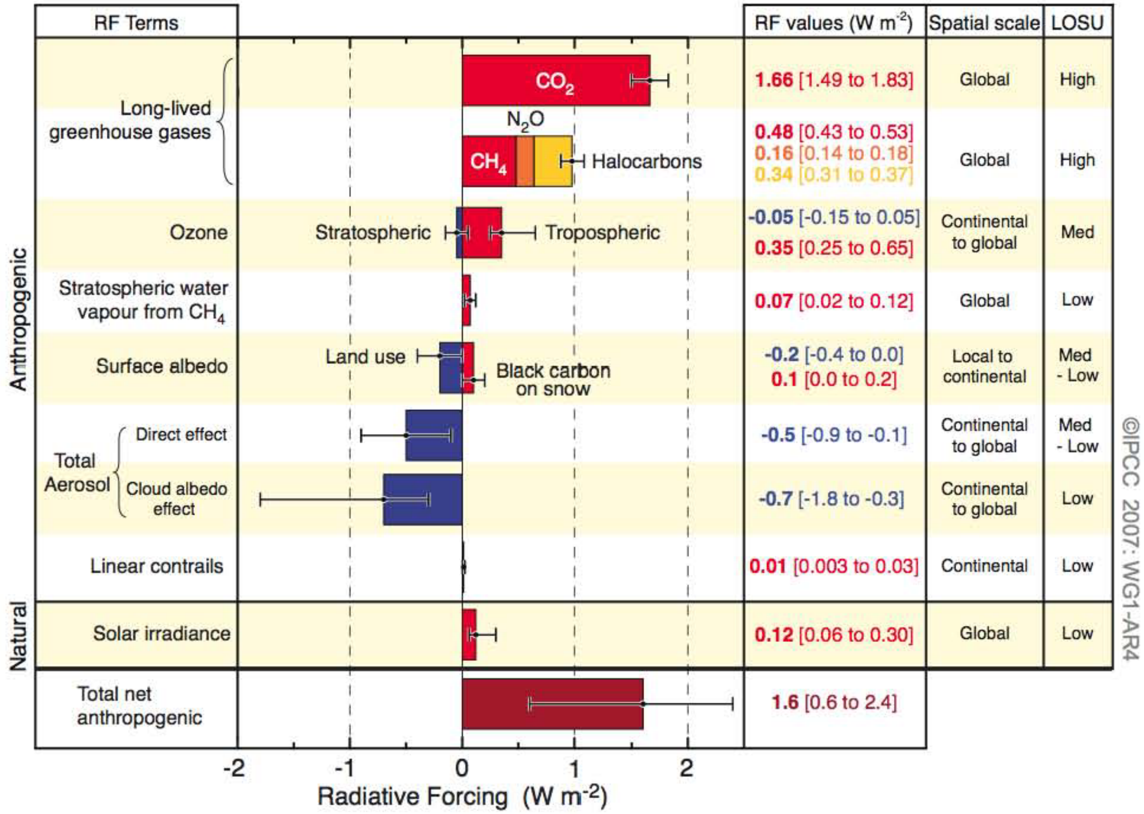
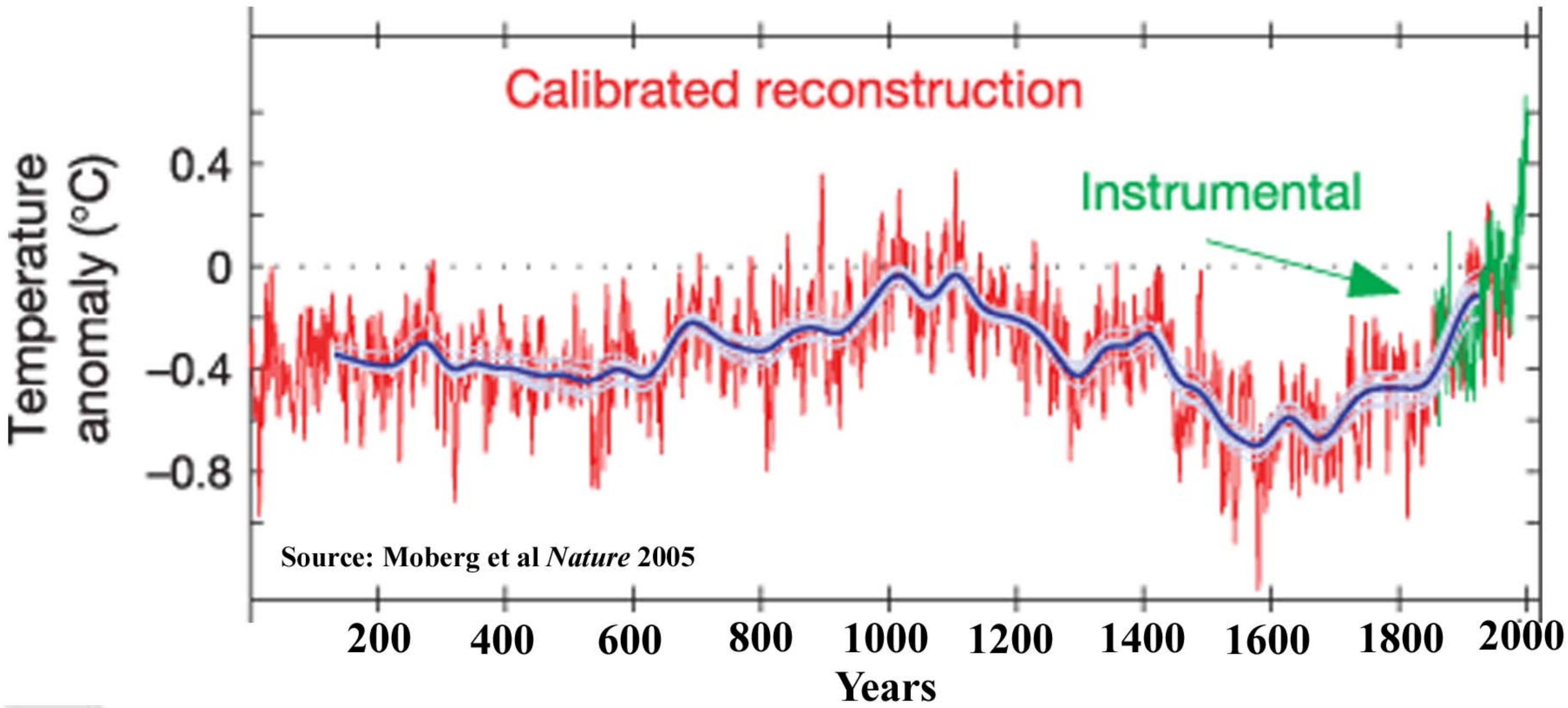


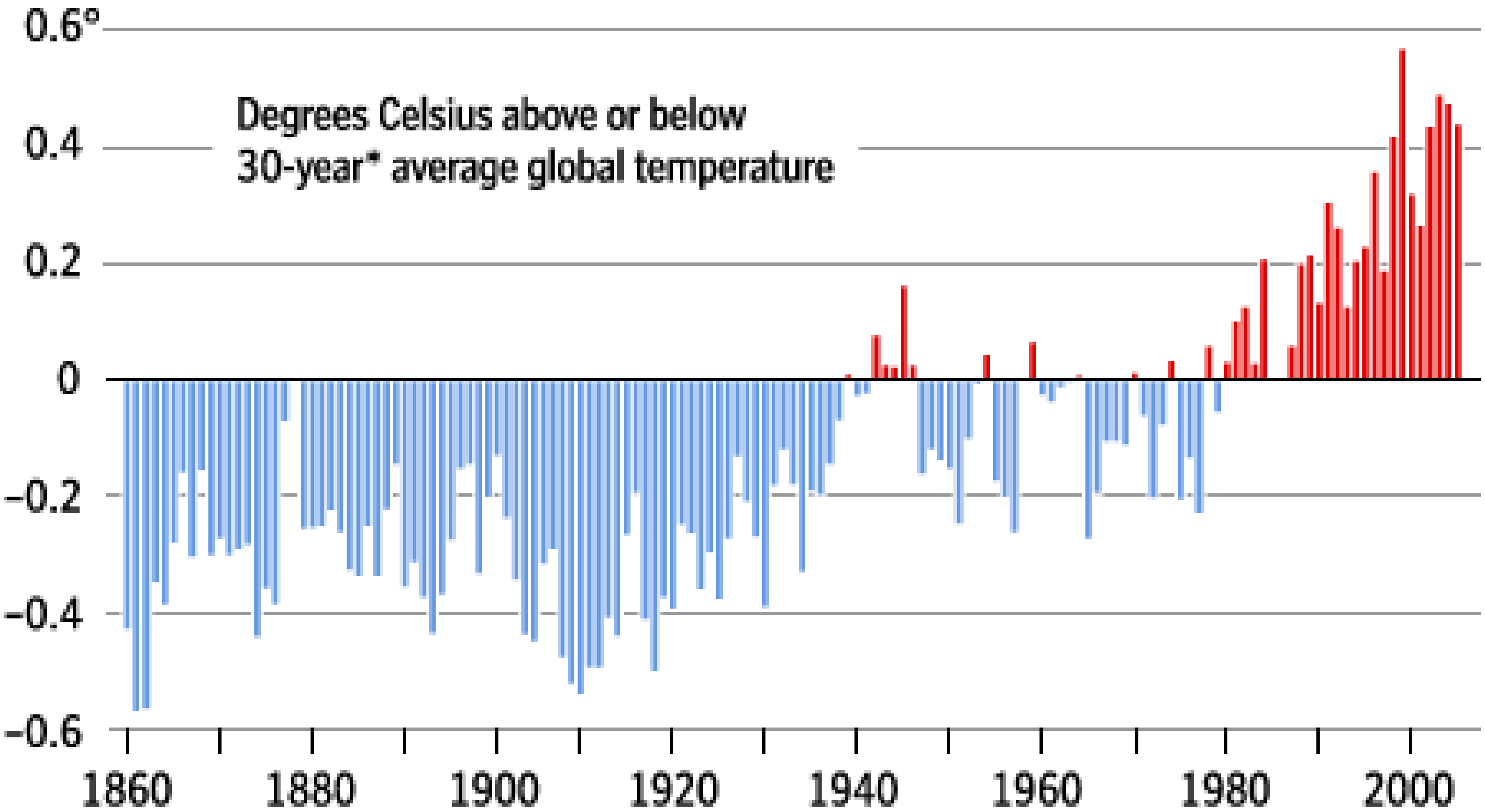
FIGURE SPM-2. Global-average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. Range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}

2000 Year Northern Hemisphere Reconstruction of Surface Air Temperatures



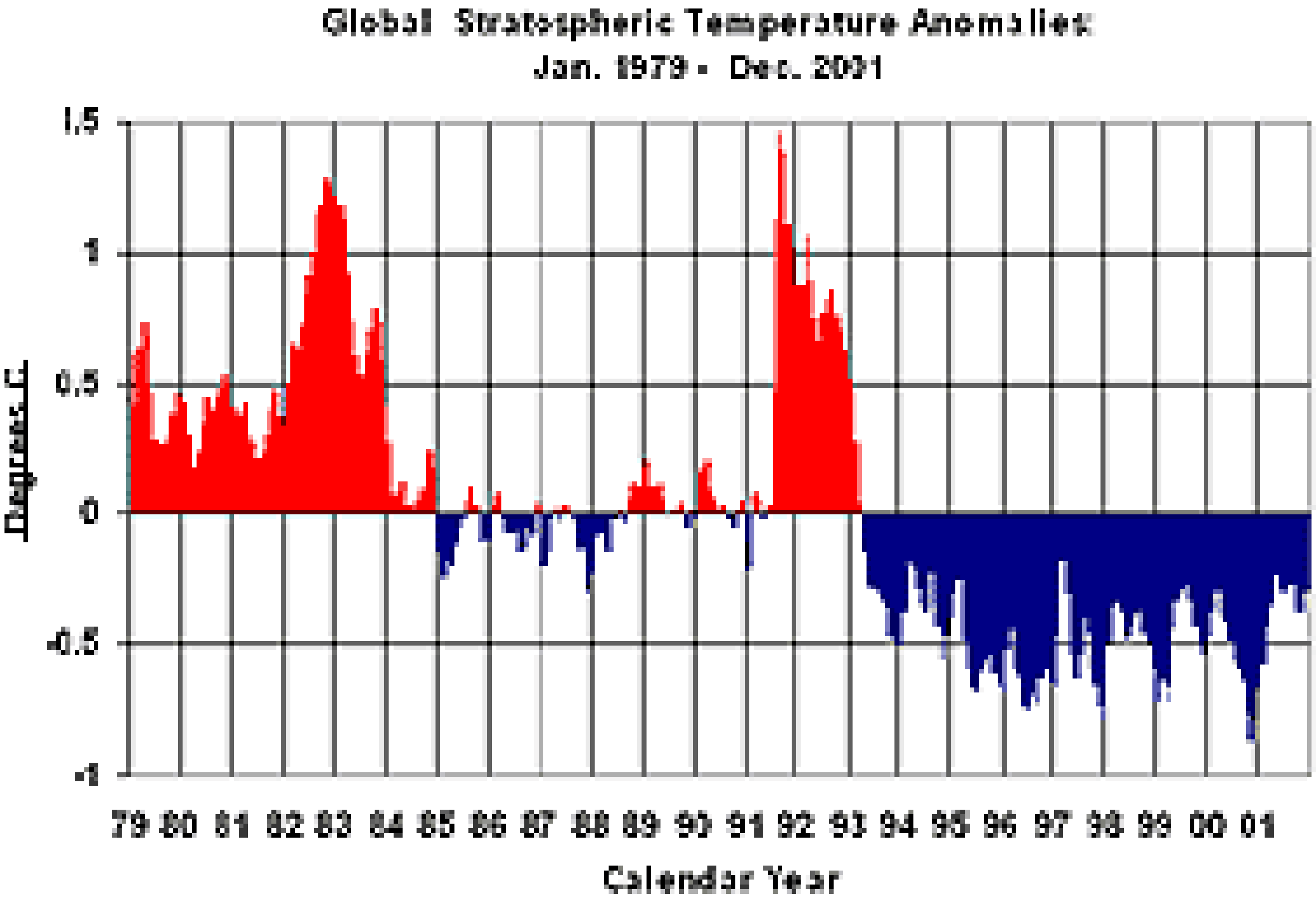
LAST TWO MILLENIA OR SO …

LAST CENTURY OR SO …

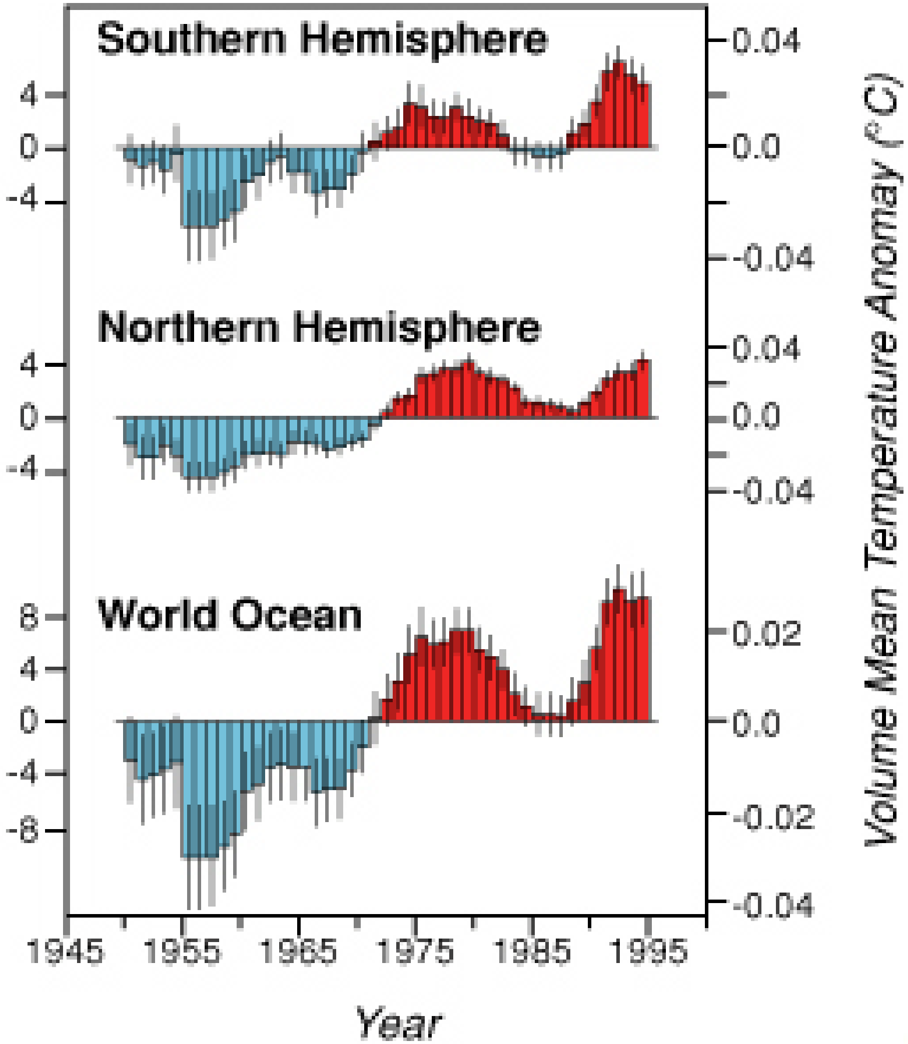


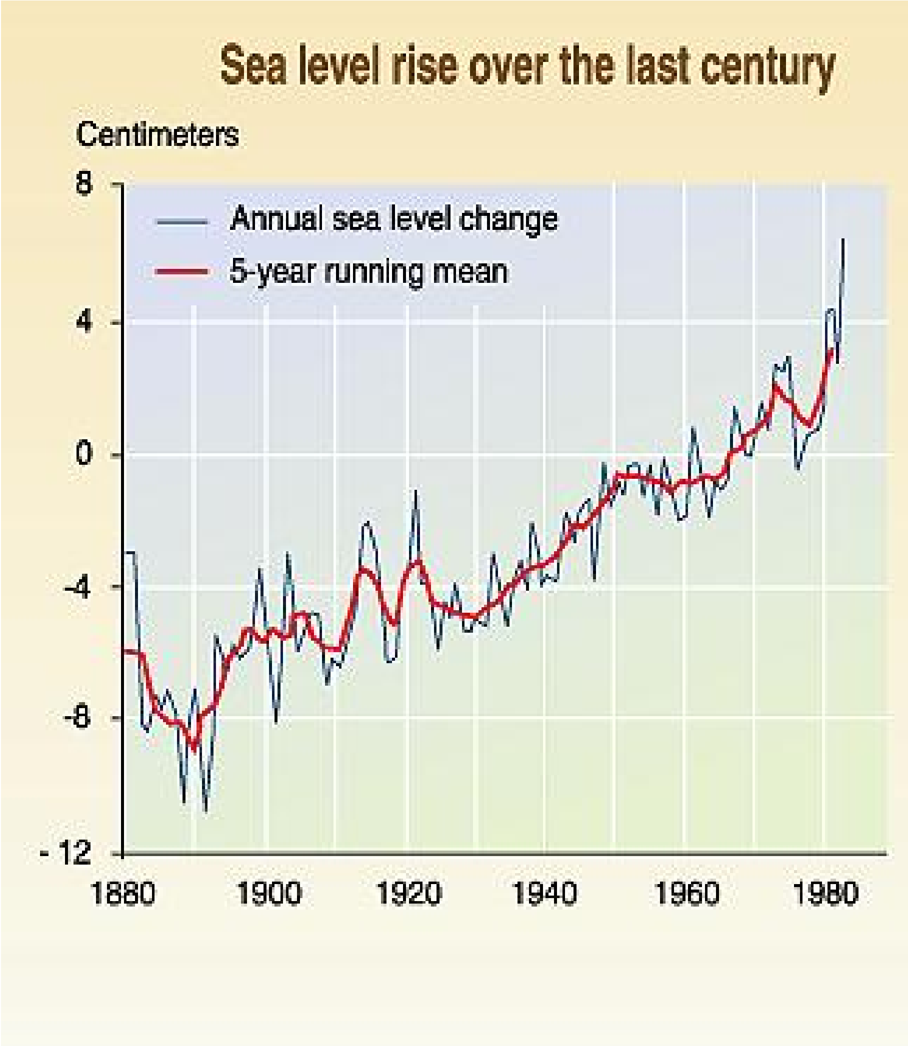
Center of Ocean-Land-Atmosphere studies
COLA
CREW
Center for Research on Environment and Water

What's Happening in the Upper Atmosphere?

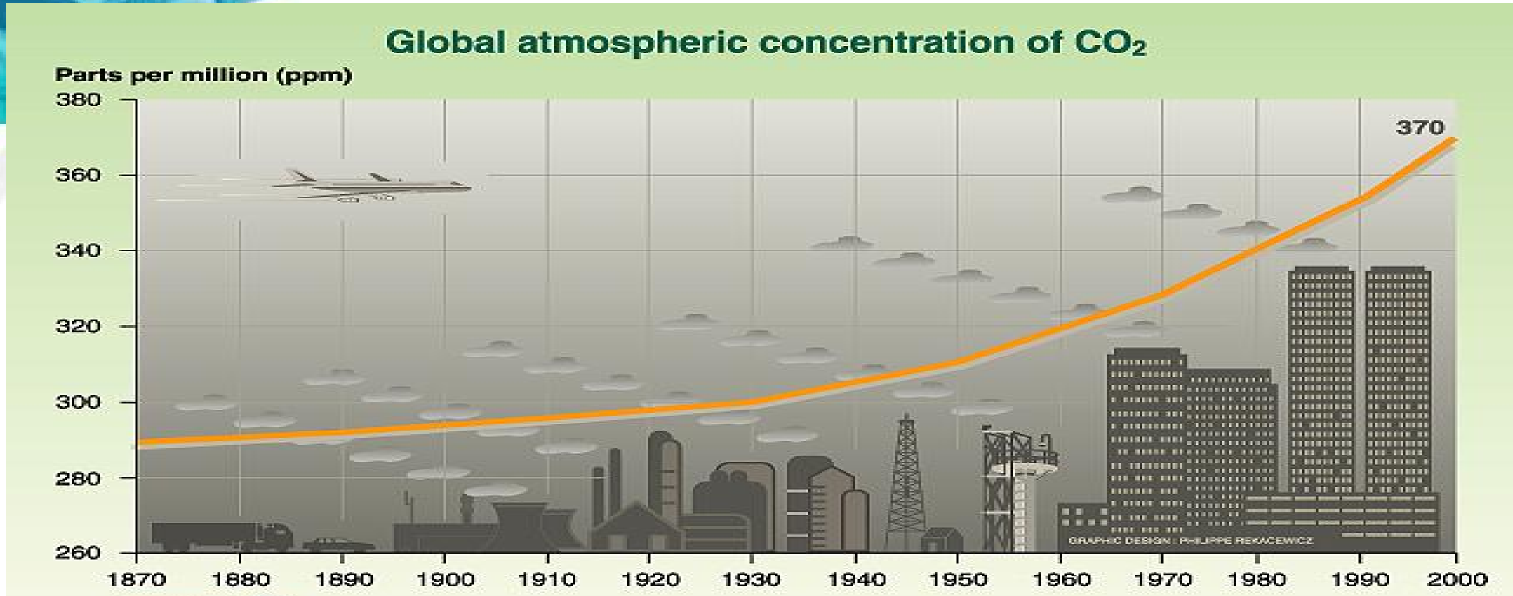


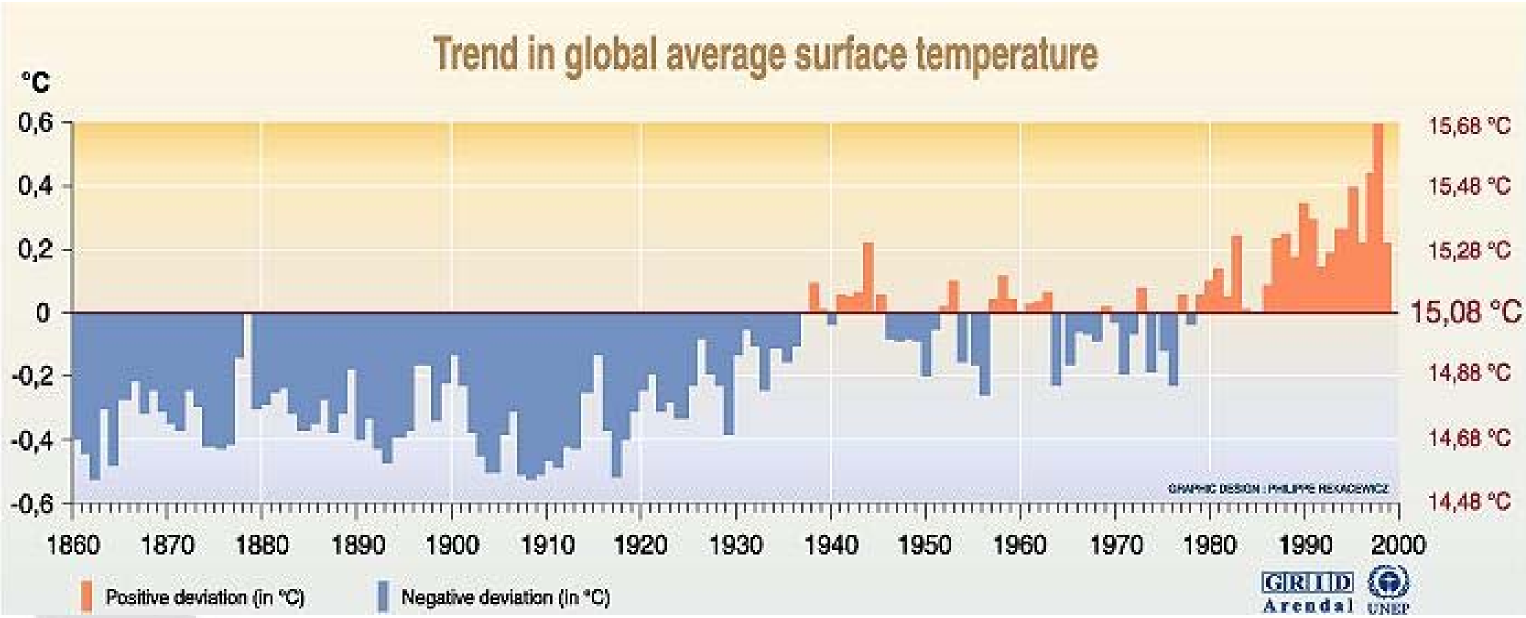
What's Happening in the Ocean?

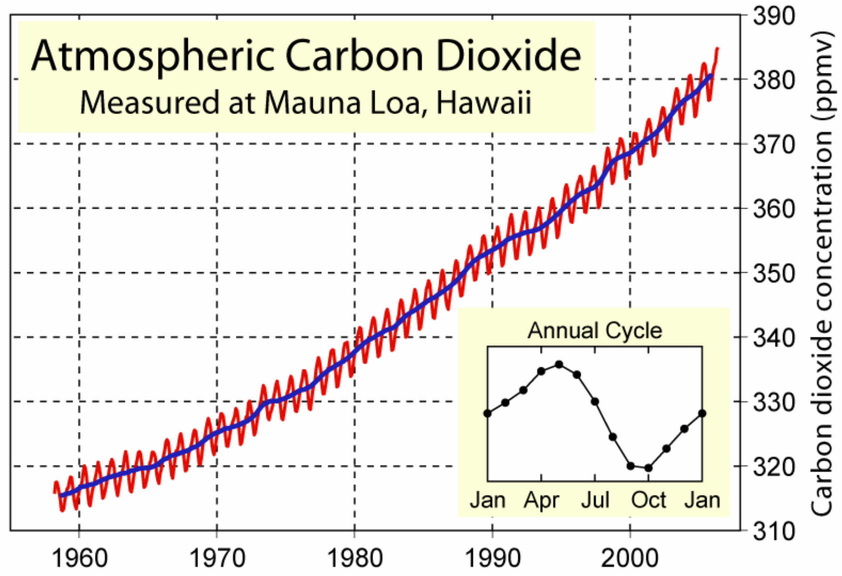


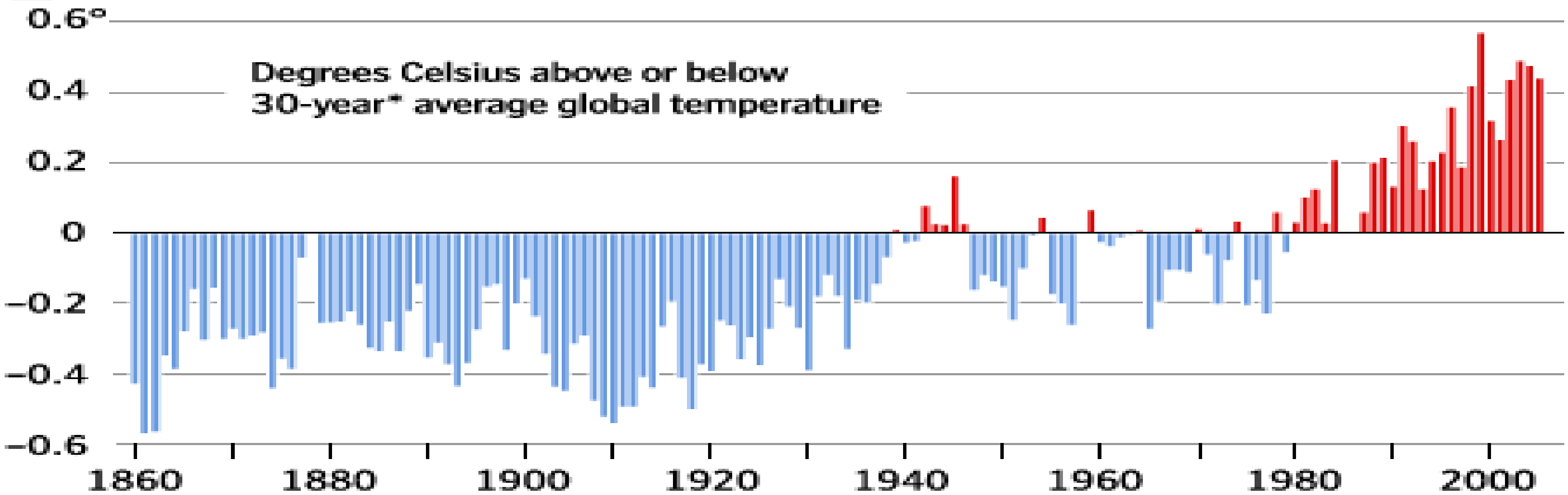


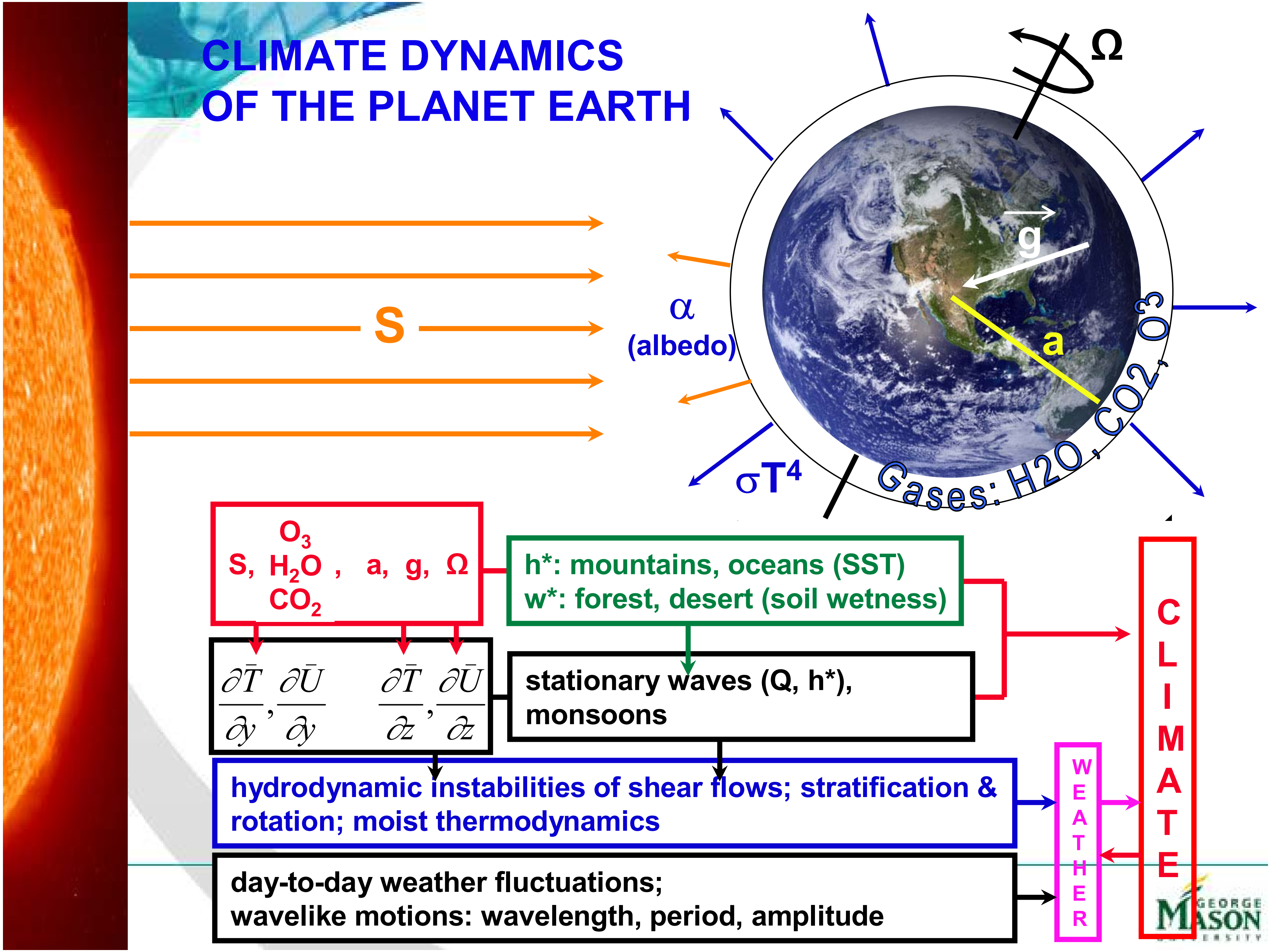
Source: Climate change 1995, The science of climate change, contribution of working group 1 to th
university press, 1996; Sea level rise over the last century, adapted from Gornitz and Lebedeff, 19


Global atmospheric concentration of CO2
Parts per million (ppm)
380
360
340
320
300
280
260
370
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
GRAPHIC DESIGN : PHILIPPE REKACEWICZ

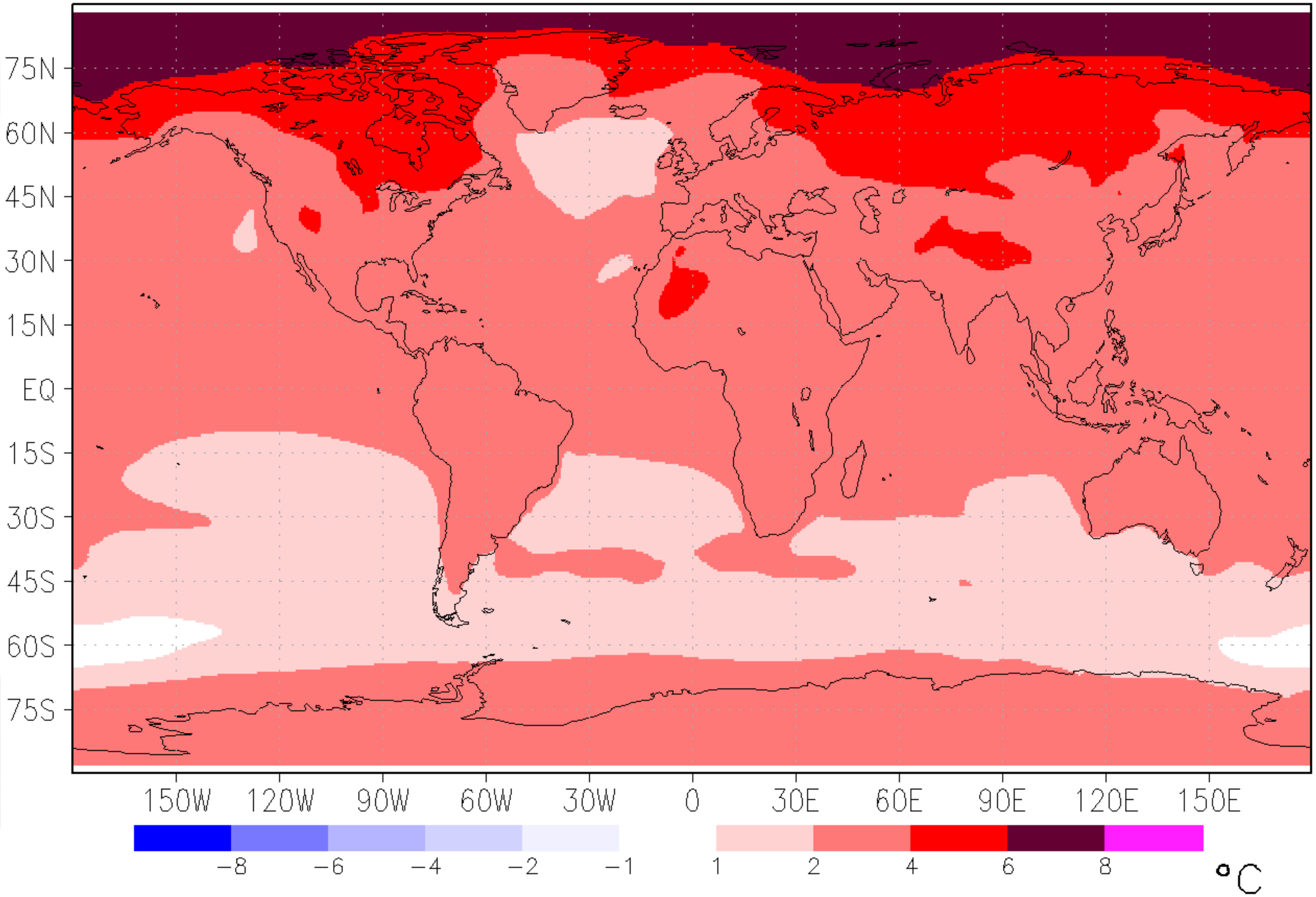

Trend in global average surface temperature
°C
0,6
0,4
0,2
0
-0,2
-0,4
-0,6
15,68 °C
15,48 °C
15,28 °C
15,08 °C
14,88 °C
14,68 °C
14,48 °C
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
GRAPHIC DESIGN : PHILIPPE REKACEWICZ
Positive deviation (in °C)
Negative deviation (in °C)
GRID Arendal
UNEP


Atmospheric Carbon Dioxide
Measured at Mauna Loa, Hawaii
Annual Cycle
Jan Apr Jul Oct Jan
Carbon dioxide concentration (ppmv)
390
380
370
360
350
340
330
320
310
1960 1970 1980 1990 2000


Degrees Celsius above or below
30-year* average global temperature
0.6°
0.4
0.2
0
−0.2
−0.4
−0.6
1860 1880 1900 1920 1940 1960 1980 2000


CLIMATE DYNAMICS
OF THE PLANET EARTH
S
α
(albedo)
σT4
g
a
Ω
Gases: H2O, CO2, O3
O3
S, H2O, a, g, Ω
CO2
h*: mountains, oceans (SST)
w*: forest, desert (soil wetness)
$\frac{\partial \bar{T}}{\partial y}, \frac{\partial \bar{U}}{\partial y}$
$\frac{\partial \bar{T}}{\partial z}, \frac{\partial \bar{U}}{\partial z}$
stationary waves (Q, h*),
monsoons
hydrodynamic instabilities of shear flows; stratification &
rotation; moist thermodynamics
day-to-day weather fluctuations;
wavelike motions: wavelength, period, amplitude
WEATHER
CLIMATE
GEORGE MASON

Mean of 15 Models Sfc Air Temp Difference
(sresa1b YR 71–100)–(20c3m 1969–98) Glbl Ave = 2.61



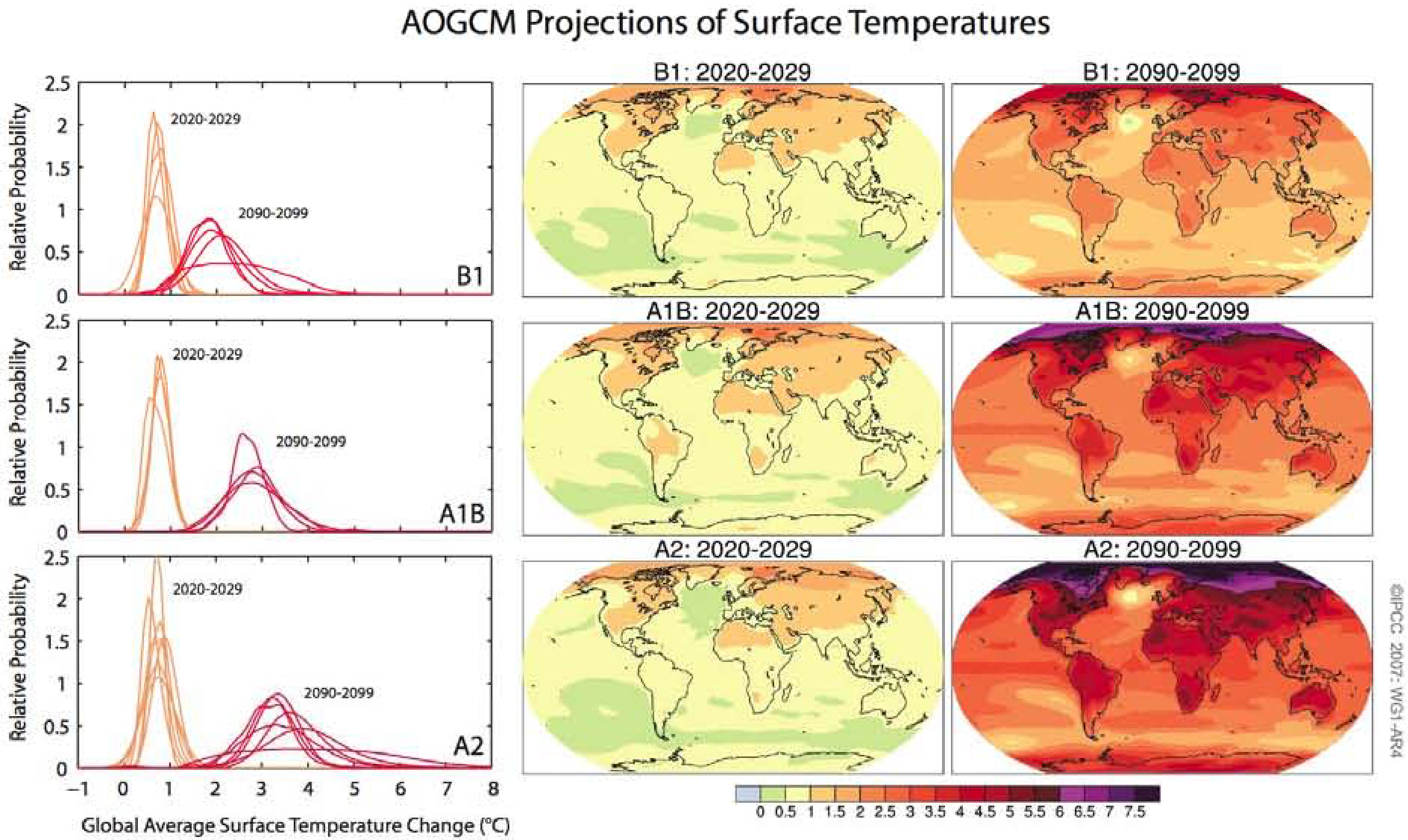
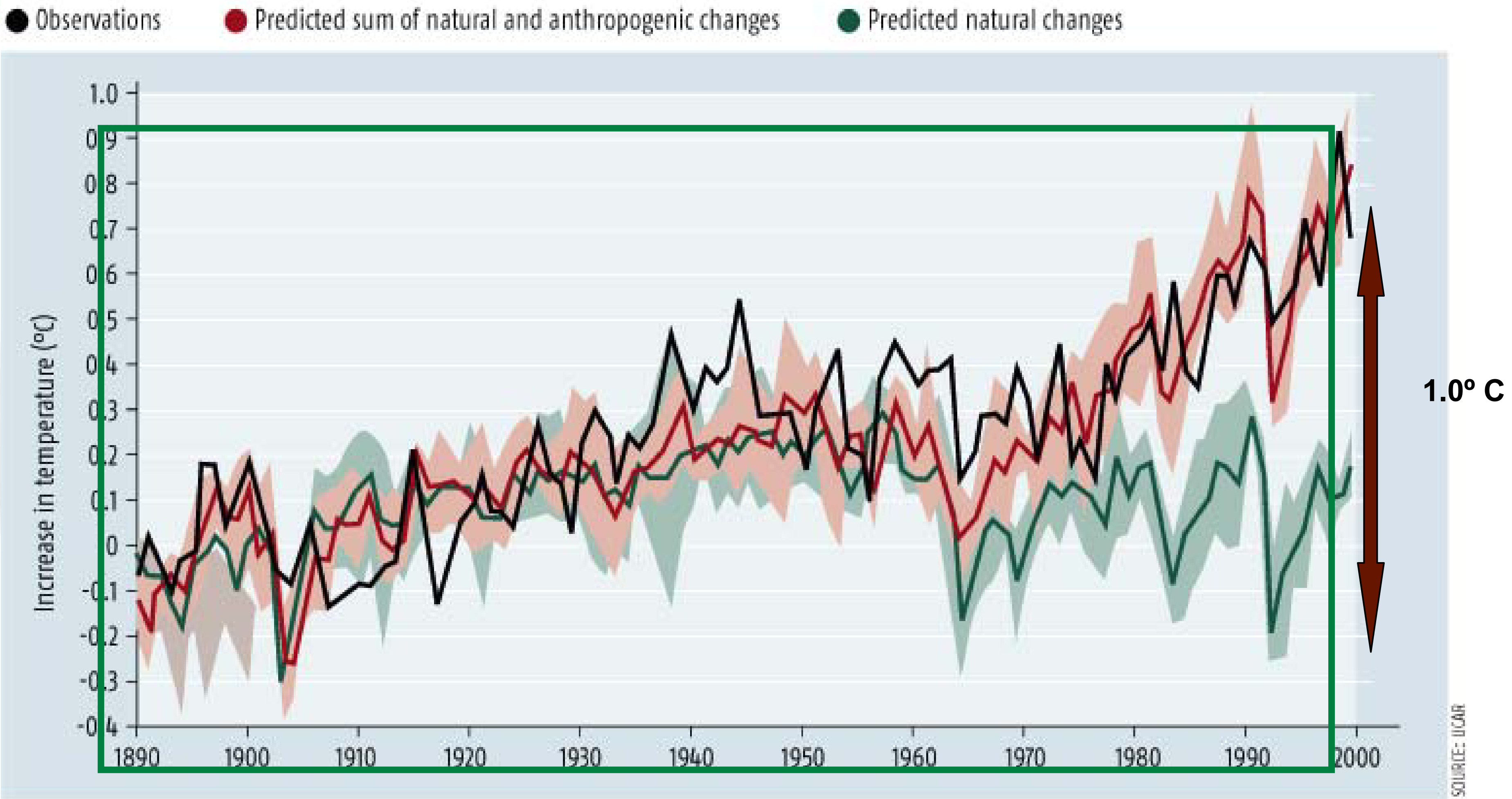
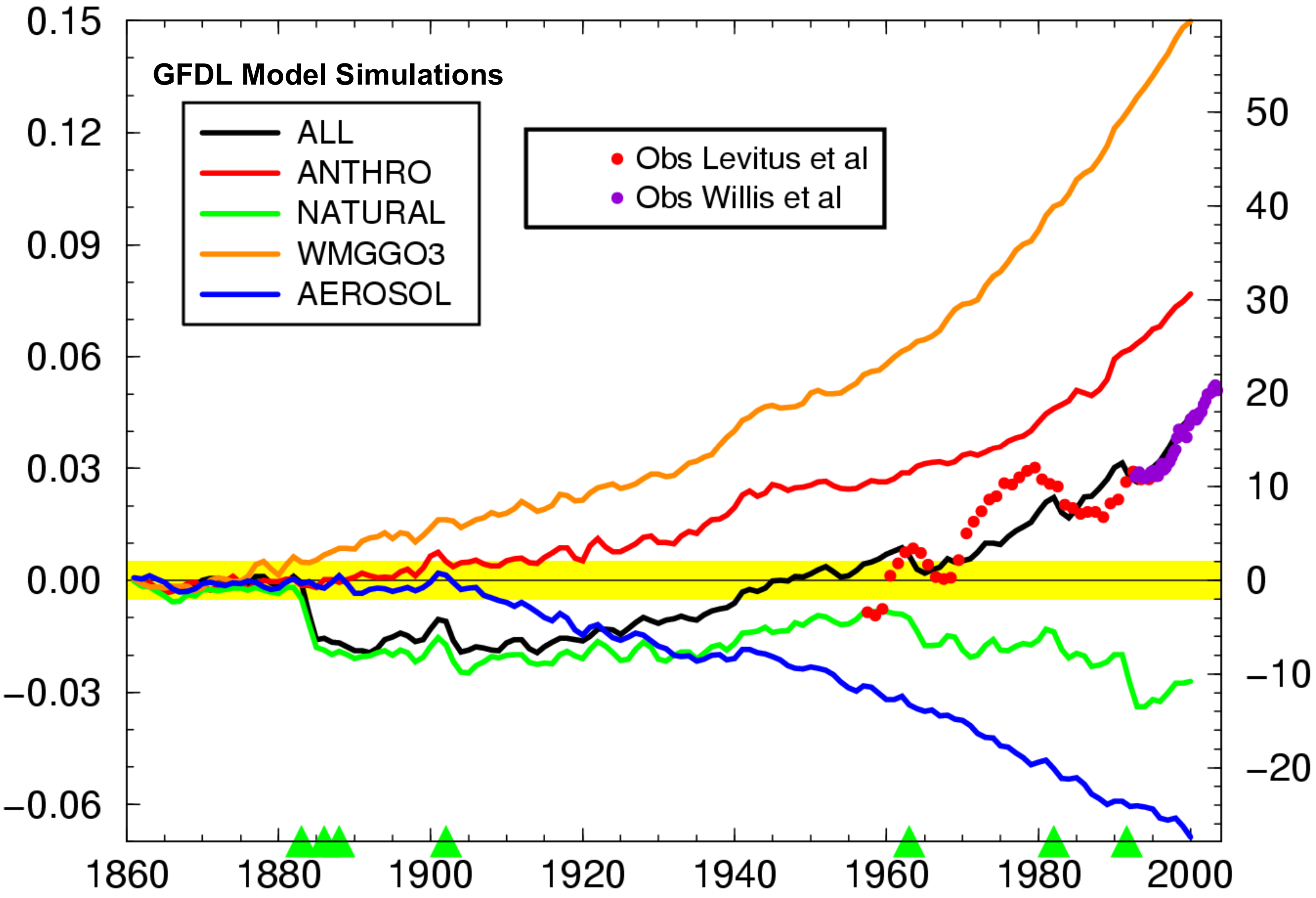


FIGURE SPM-6. Projected surface temperature changes for the early and late 21st century relative to the period 1980–1999. The central and right panels show the Atmosphere-Ocean General Circulation multi-Model average projections for the B1 (top), A1B (middle) and A2 (bottom) SRES scenarios averaged over decades 2020–2029 (center) and 2090–2099 (right). The left panel shows corresponding uncertainties as the relative probabilities of estimated global average warming from several different AOGCM and EMICs studies for the same periods. Some studies present results only for a subset of the SRES scenarios, or for various model versions. Therefore the difference in the number of curves, shown in the left-hand panels, is due only to differences in the availability of results. {Figures 10.8 and 10.28}



Courtesy UCAR

Global mean, volume mean ocean temperature



Courtesy of Tom Delworth (GFDL)

Multi-model Averages and Assessed Ranges for Surface Warming

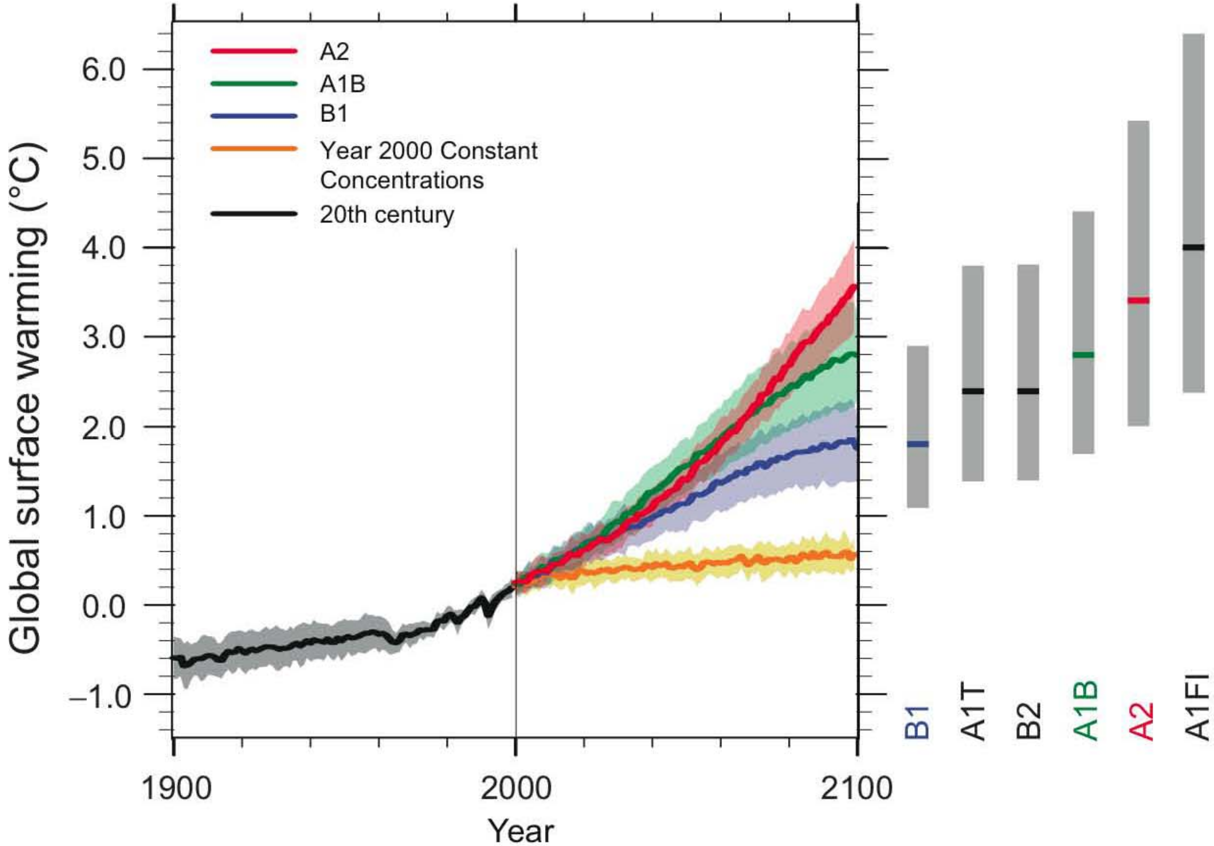


FIGURE SPM-5. Solid lines are multi-model global averages of surface warming (relative to 1980-99) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the plus/minus one standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The gray bars at right indicate the best estimate (solid line within each bar) and the *likely* range assessed for the six SRES marker scenarios. The assessment of the best estimate and *likely* ranges in the gray bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. {Figures 10.4 and 10.29}

Global and Continental Temperature Change

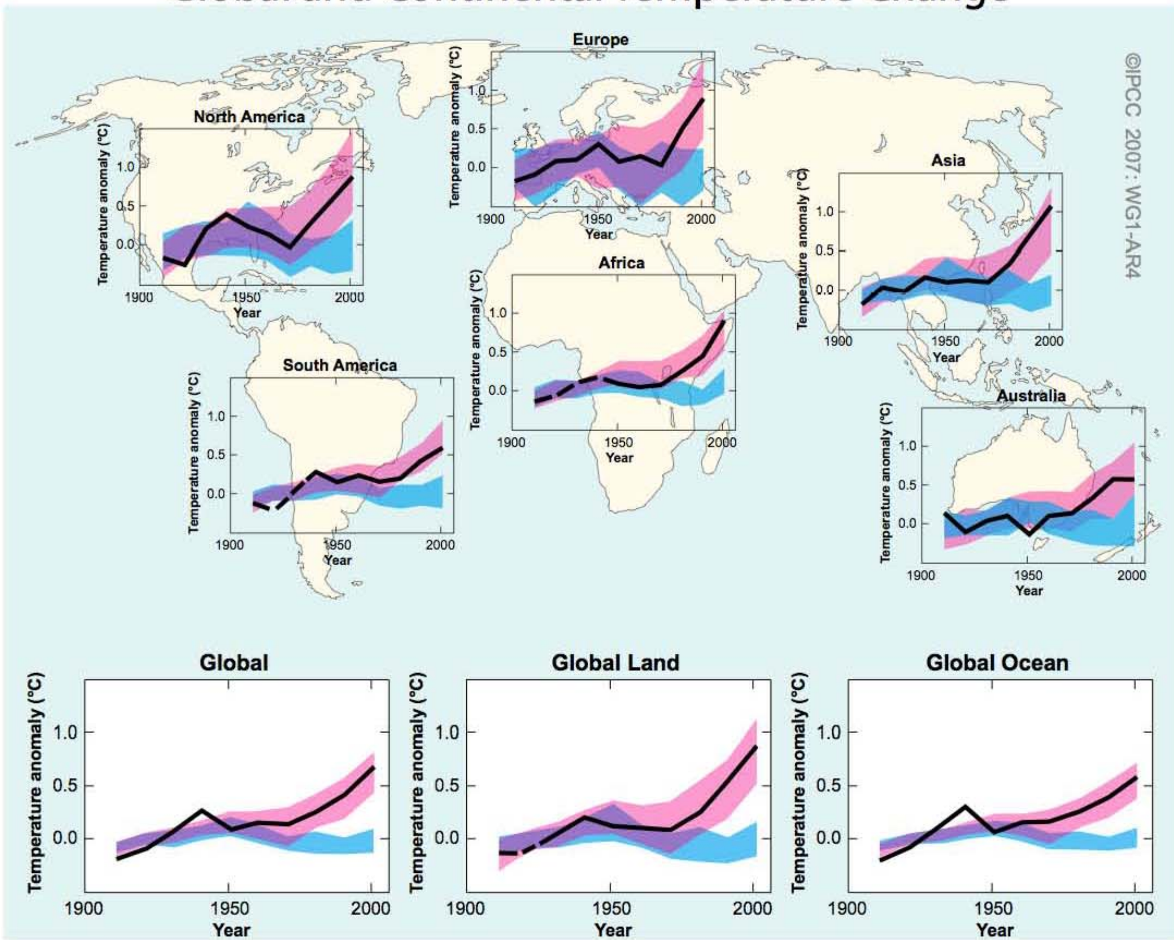
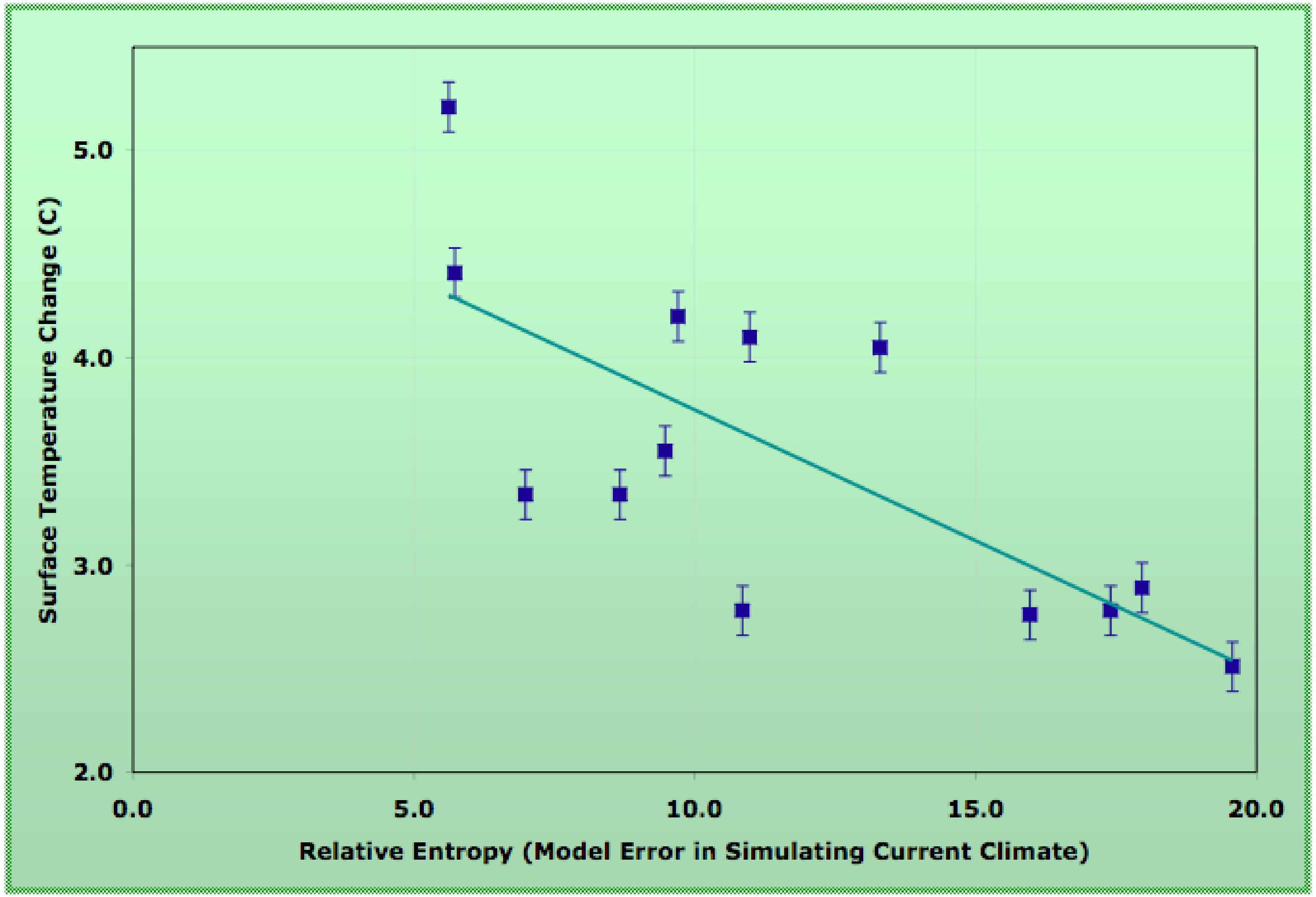


FIGURE SPM-4. Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906–2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5–95% range for 19 simulations from 5 climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings. {FAQ 9.2, Figure 1}

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.

Summary

• If we conjecture that models that better simulate the present climate should be considered more credible in projecting the future climate change, then this study suggests that the actual changes in global warming will be closer to the highest projected estimates (4-5 ^{o}C) among the current generation of models used in IPCC Assessment Report 4.

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

Climate Modeling and Computing

Models Today

- **Weather**
  - T254: 5 d/hr on 144 CPUs
  - T511: 2.5 d/hr on 288 CPUs
- **Climate**
  - T85/ 1°: 2.0 yrs/d on 96 CPUs
  - 2°X2.5°/1°: 5.25 yrs/d on 180 CPUs

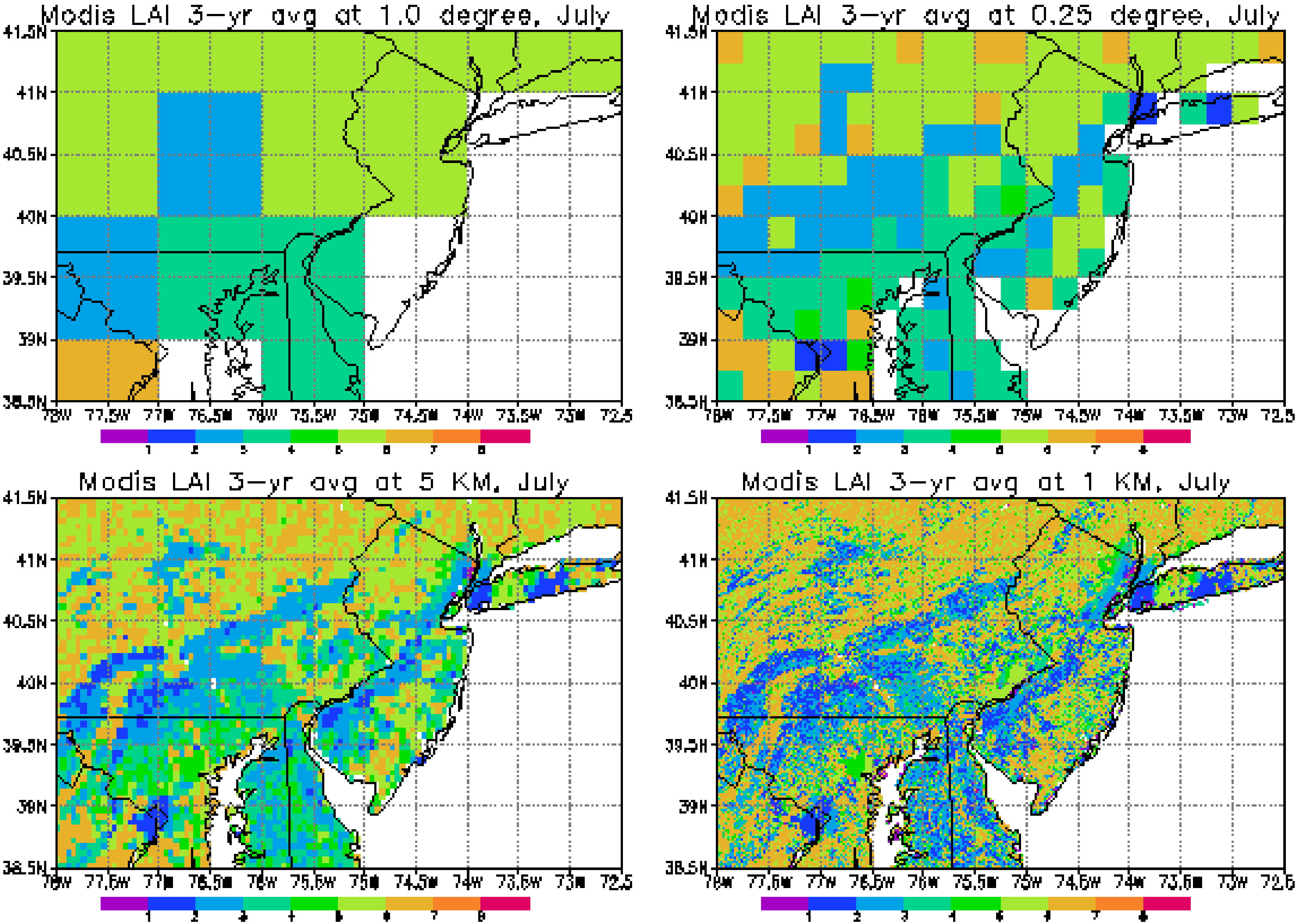
Models in 2015

- **Weather**
  - T3800 (5 km): 4 d/hr (2,160 CPUs)

    - or -
  - T825 (25 km): 4 d/hr (468 CPUs)
- **Climate**
  - T420/ 0.5°: 2.4 yrs/d (2,500 CPUs)

    -or-
  - T420/0.5°: 2 mo/d (2,500 CPUs)

[43%/yr (Moore's Law) -OR- 10%/yr]

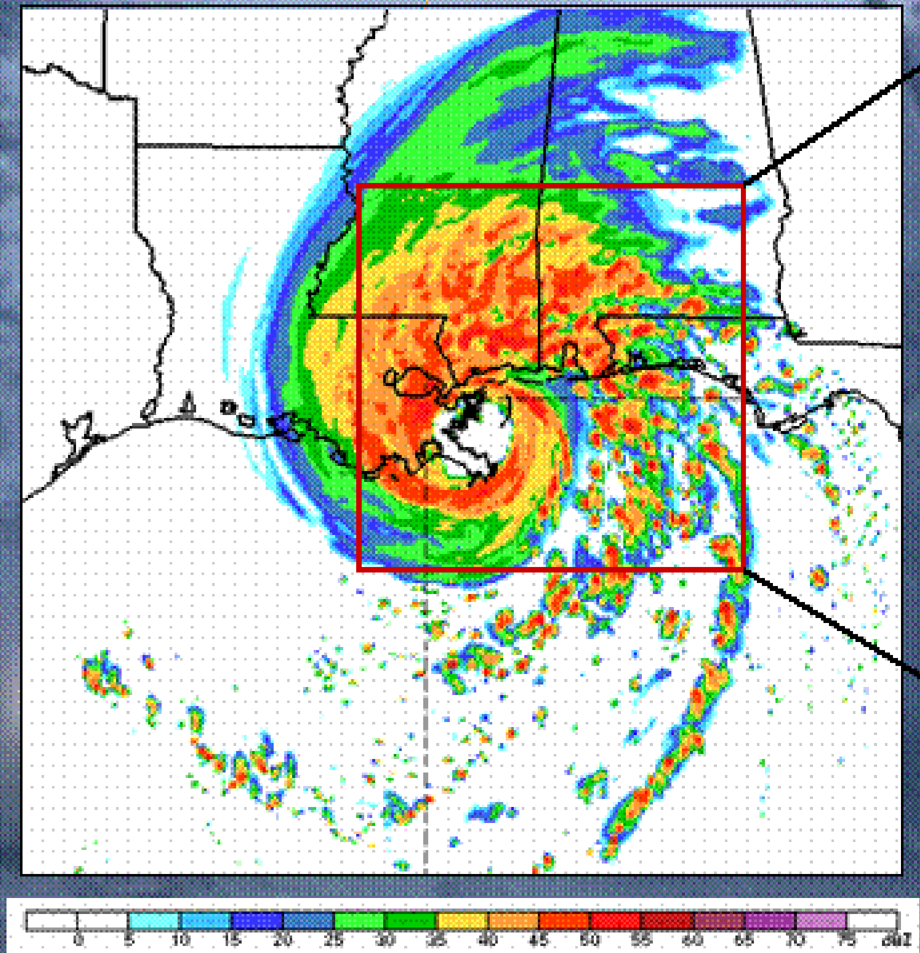


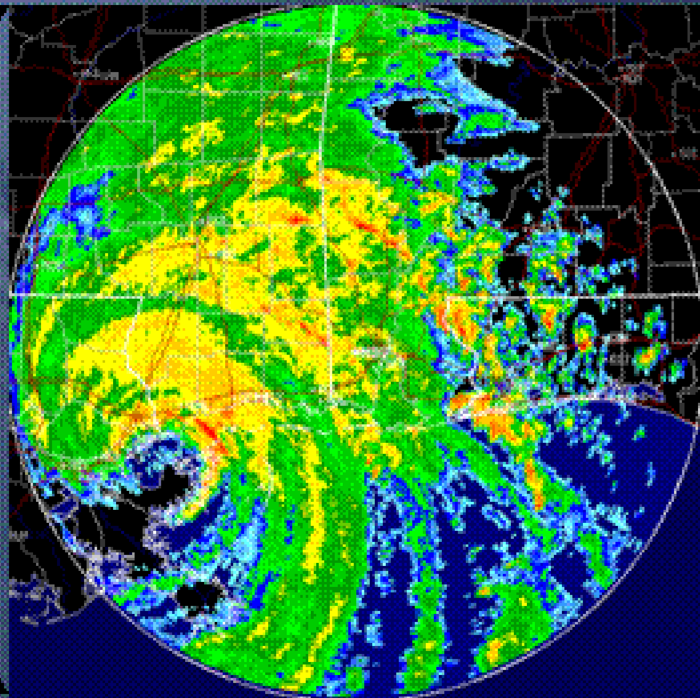
Courtesy of P. Houser (GMU)

Hurricane Katrina Reflectivity at Landfall

29 Aug 2005 14 Z

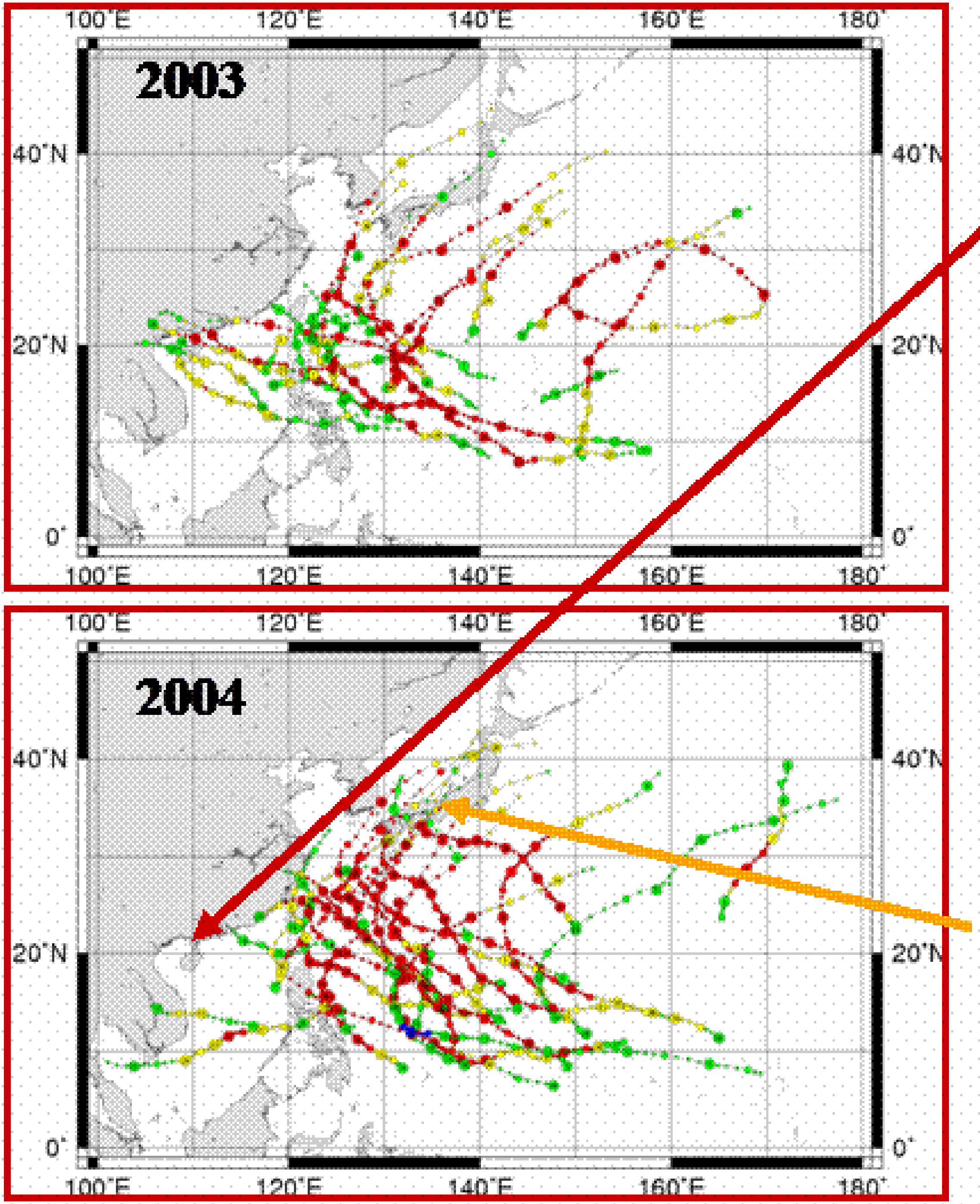
4 km WRF , 62 h forecast





Mobile Radar

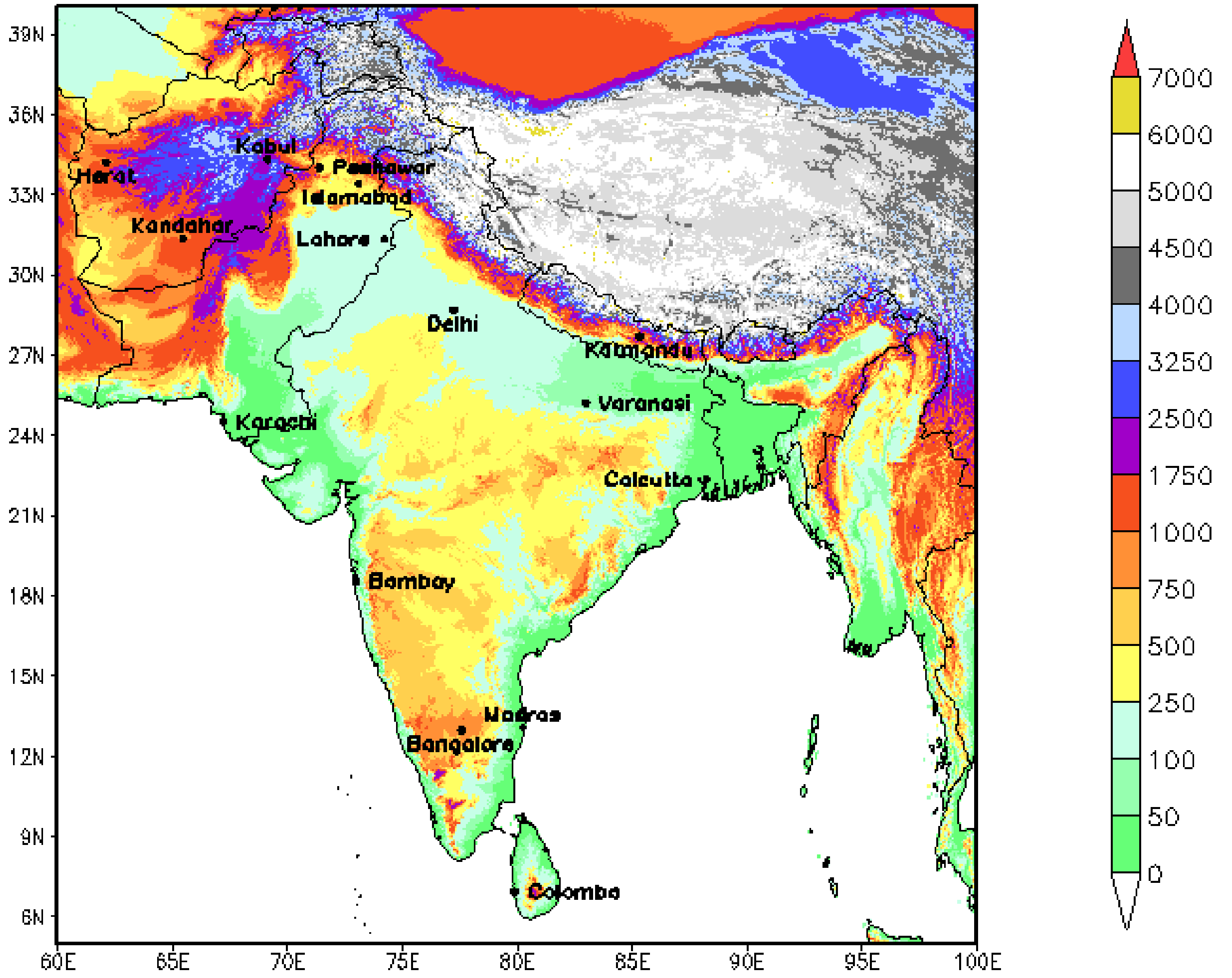
Courtesy of P. Fox (NCAR)

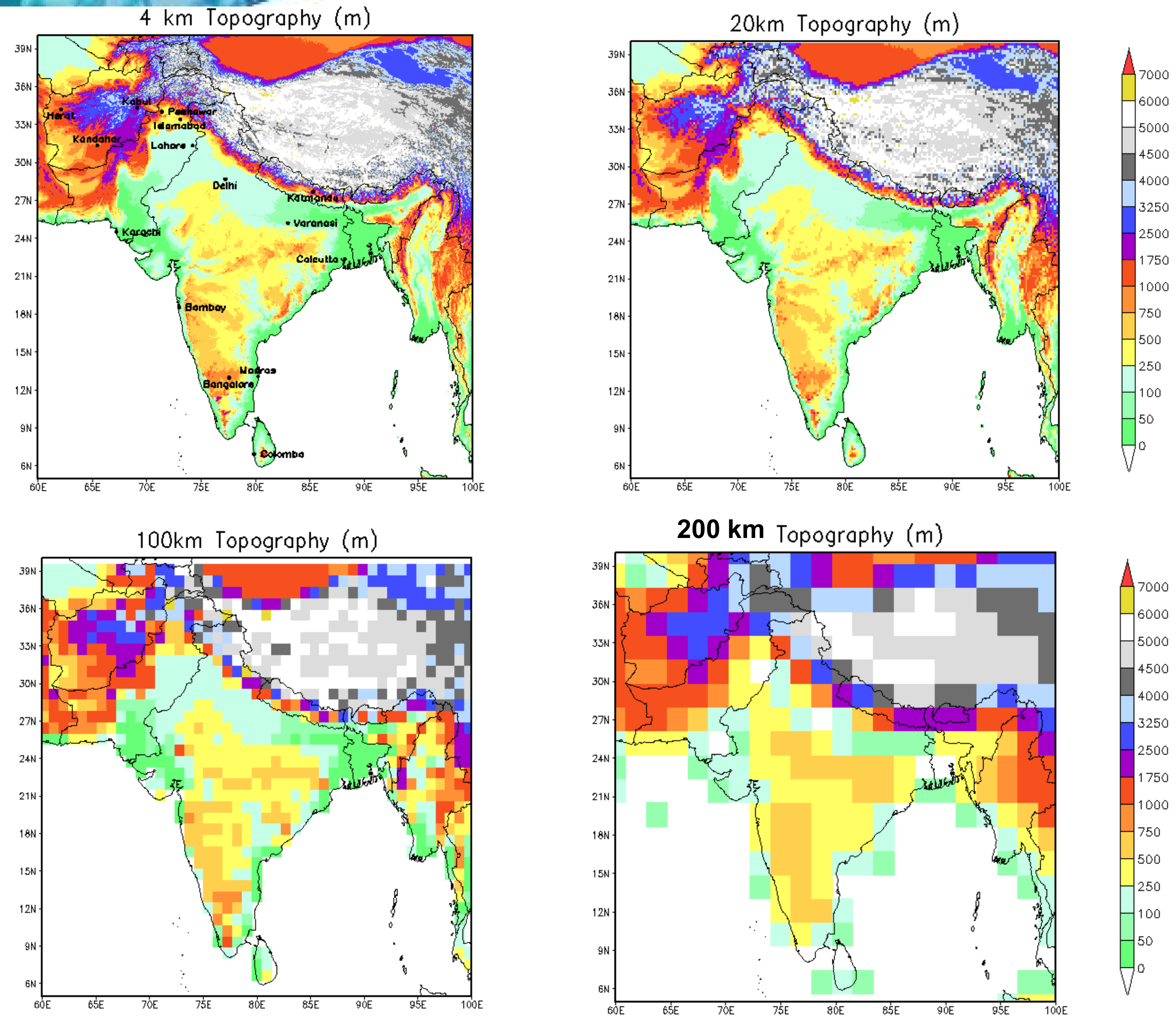


Some parts of China are experiencing the worst drought in 50 years. Some 9 million people are facing a shortage of drinking water while farmers across the country are looking out over parched land. Even though irrigation systems are in place there is little water to supply it.

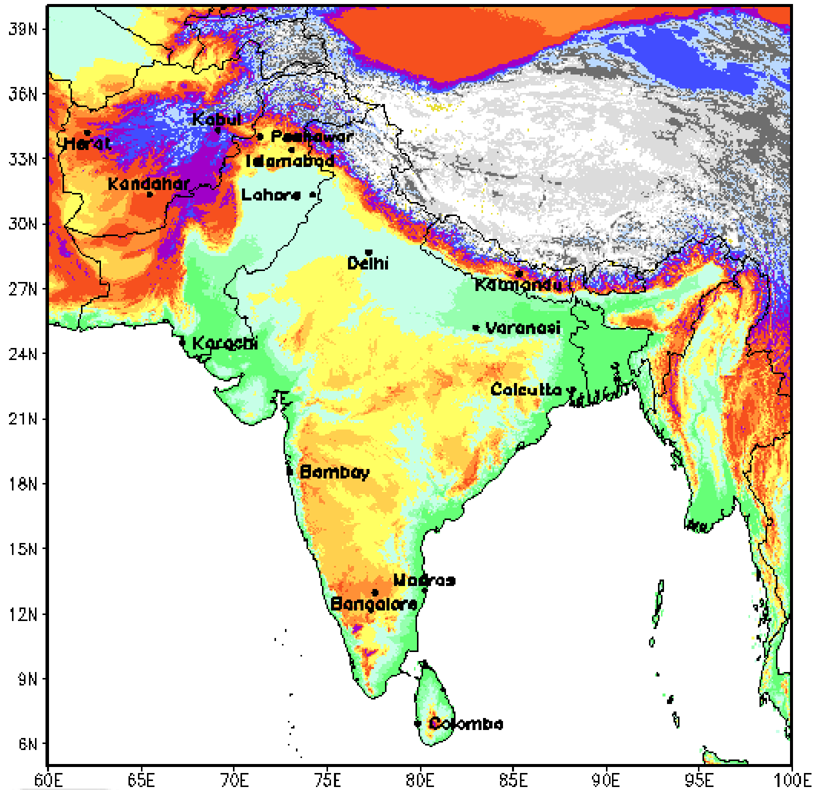
For Japanese people, this year may be remembered as "the year of disasters" because of the unprecedented number of typhoon strikes against Japan and subsequent disasters.

4 km Topography (m)

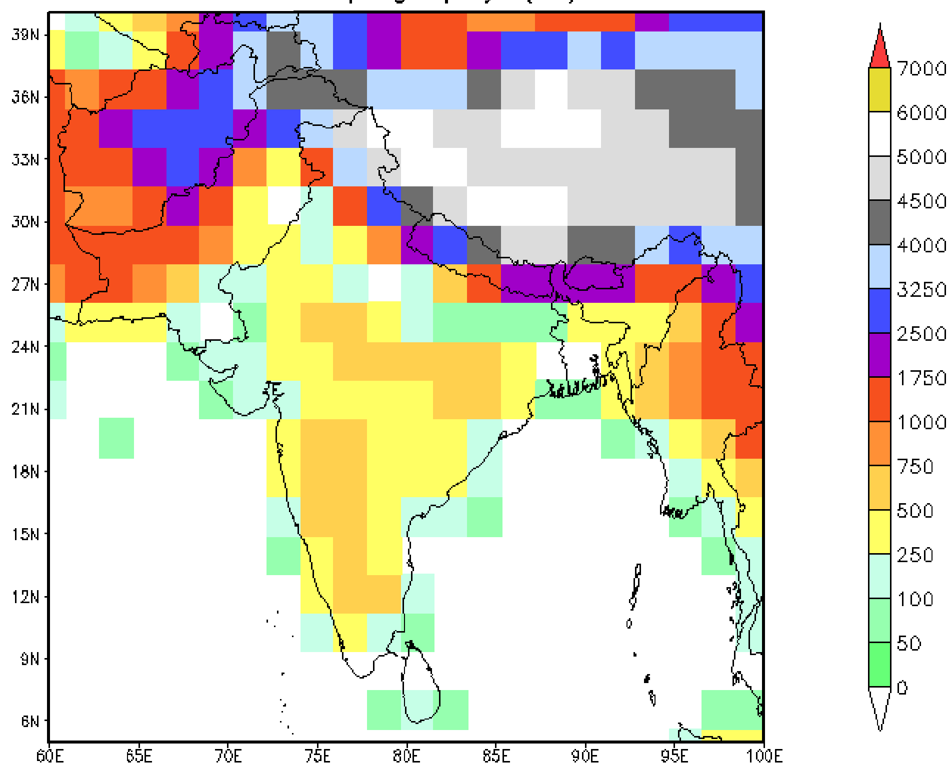



4 km Topography (m)
20km Topography (m)
100km Topography (m)
200 km Topography (m)
Herat
Kabul
Peshawar
Islamabad
Kandahar
Lahore
Delhi
Katmandu
Varanasi
Karachi
Calcutta
Bombay
Madras
Bangalore
Colombo
39N 36N 33N 30N 27N 24N 21N 18N 15N 12N 9N 6N
60E 65E 70E 75E 80E 85E 90E 95E 100E
7000 6000 5000 4500 4000 3250 2500 1750 1000 750 500 250 100 50 0

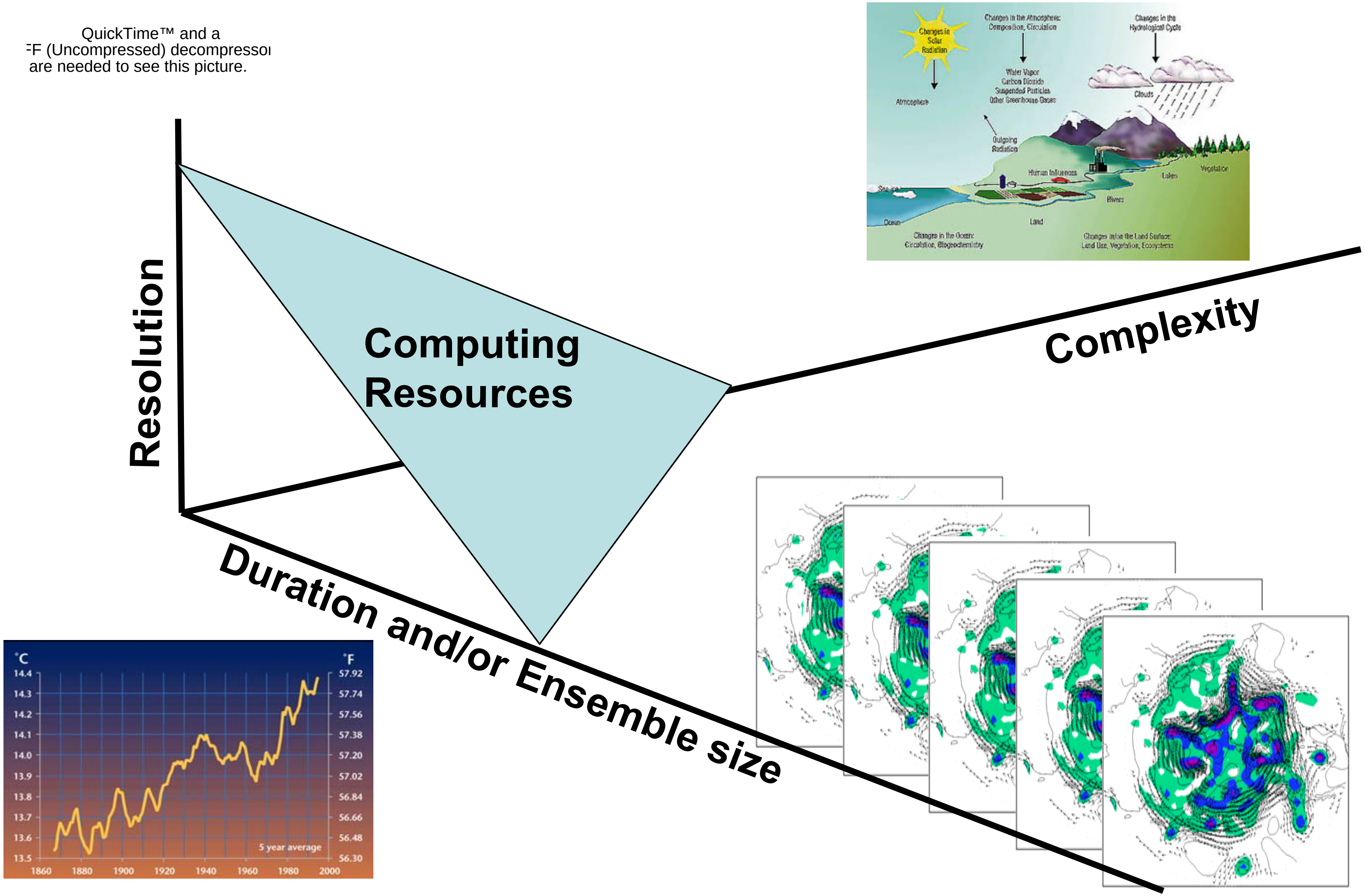
4 km Topography (m)

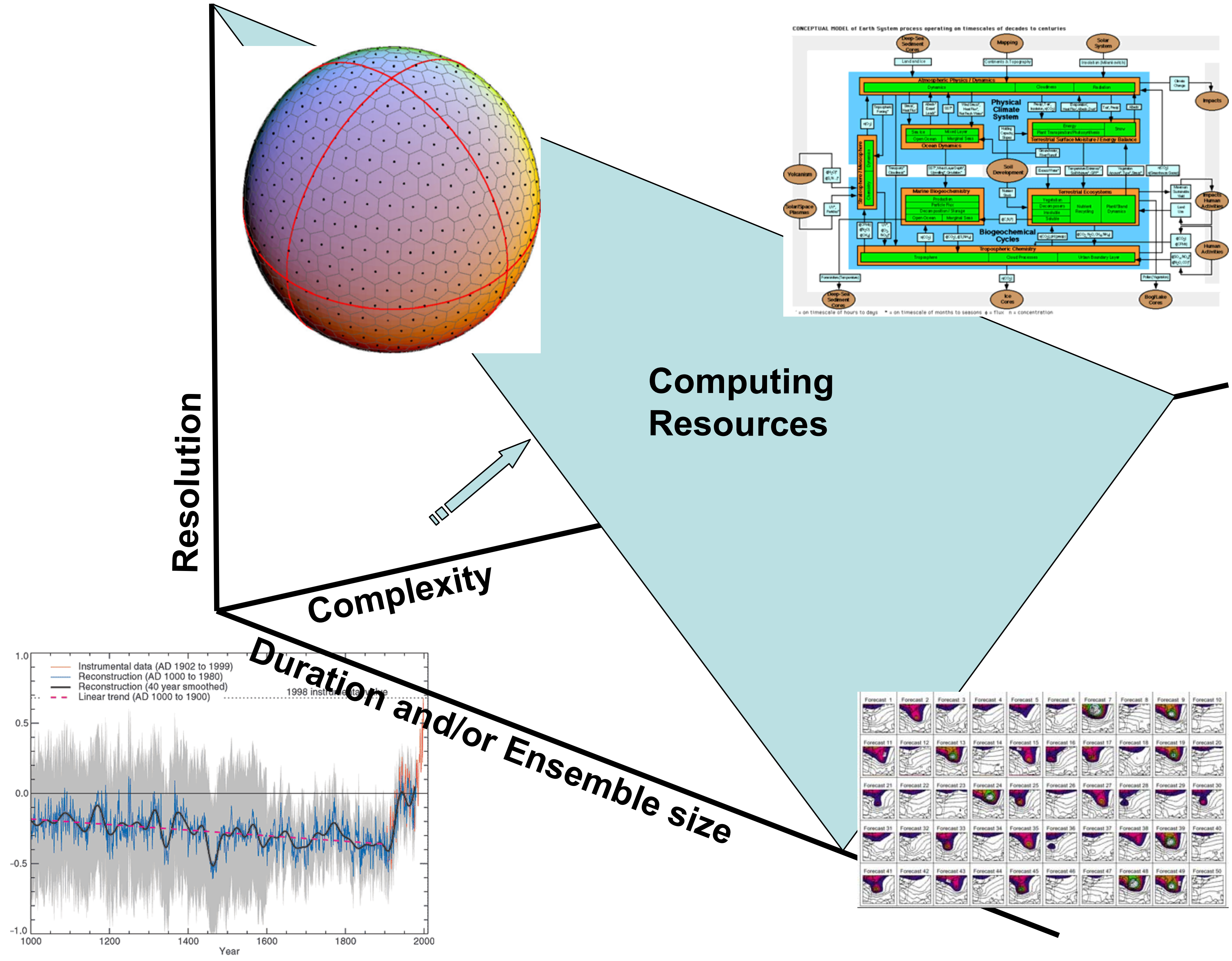


200 km Topography (m)



Resources Tradeoffs




CONCEPTUAL MODEL of Earth System process operating on timescales of decades to centuries
Physical Climate System
Biogeochemical Cycles
Computing Resources
Resolution
Complexity
Duration and/or Ensemble size
Instrumental data (AD 1902 to 1999)
Reconstruction (AD 1000 to 1980)
Reconstruction (40 year smoothed)
Linear trend (AD 1000 to 1900)
1998 instrumental value
Year

Technology Trends

Current:

- **Peak speed: ~2-3 Gflops per chip**
- **System integration: ~10,000 processors**
- **Sustained performance: ~ 5-15% of peak (fluid codes)**
- **Model examples:**
  - **ECMWF T511L60 1X/day**
  - **NCEP T382L64 4X/day**
  - **NCAR CCSM T85L26 AGCM with 1° global OGCM**

By 2010:

- **Peak speed: ~30-50 Gflops per chip (↑ 8X - Moore's Law)**
- **System integration: ~30,000 or more chips**
- **Fluid codes are expected to continue to achieve sustained performance of up to 15% of peak**
- **Expected sustained capability: 150 TFLOPs (15% of 1 petaflops)**

Suggestion for Accelerating Progress in Modeling and Prediction of the Physical Climate System

- National Efforts

- Multi-National Efforts

- **National**: (5-10 efforts worldwide)
  - Reanalyze and reforecast (1-2 seasons) for the past 50 years each year (one year per week)

Weather Prediction Model of ~2020

Coupled Ocean-Land-Atmosphere Model

~1 km x ~1 km
100 levels
Unstructured, adaptive grids

Landscape-resolving
(~100 m)

~1 km x ~1 km
50 levels
Unstructured, adaptive grids

Assumption: Computing power enhancement by a factor of 10^3-10^4

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 (??)

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 about 200 scientists co-located with central facility
- Distributed team of 200 scientists among interconnected centers

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

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

Conclusions, Conjectures and Suggestions

Conclusions, Conjectures and Suggestions

- 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.

Conclusions, Conjectures and Suggestions

- Improvements in dynamical weather prediction over the past 30 years **did not occur because of any major scientific breakthroughs** in our understanding of the physics or dynamics of the atmosphere
- **Dynamical weather prediction is challenging**: progress takes place slowly and through a great deal of hard work that is not necessarily scientifically stimulating, performed in an environment that is characterized by frequent setbacks and constant criticism by a wide range of consumers and clients
- Nevertheless, scientists worldwide have made tremendous progress in improving the skill of weather forecasts by **advances in data assimilation, improved parameterizations, improvements in numerical techniques and increases in model resolution and computing power**

Conclusions, Conjectures and Suggestions

- **Improve understanding of physics and dynamics of (small scale) cloud-system, and technique to assimilate and initialize them is necessary to advance skill of weather and climate prediction.**

- **Coordinate world effort is needed to transition from cyclone resolving models to cloud-system resolving global models.**

- **Global teleconnections put a limit on the utility of regional models.**

- **Predictability of regional decadal variations remains a challenging research problem.**

THANK YOU!

ANY QUESTIONS?