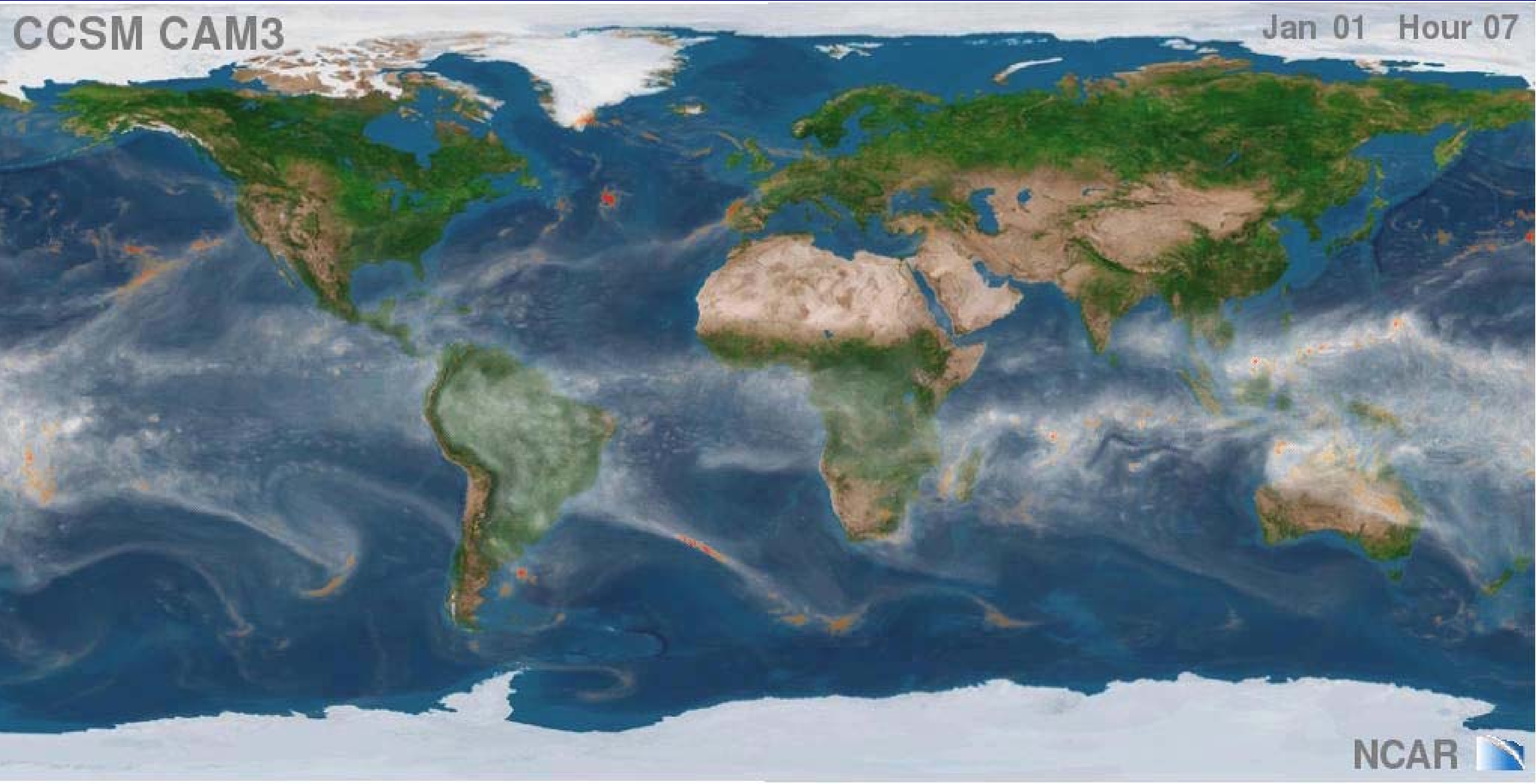
Climate Modeling in a Changed World

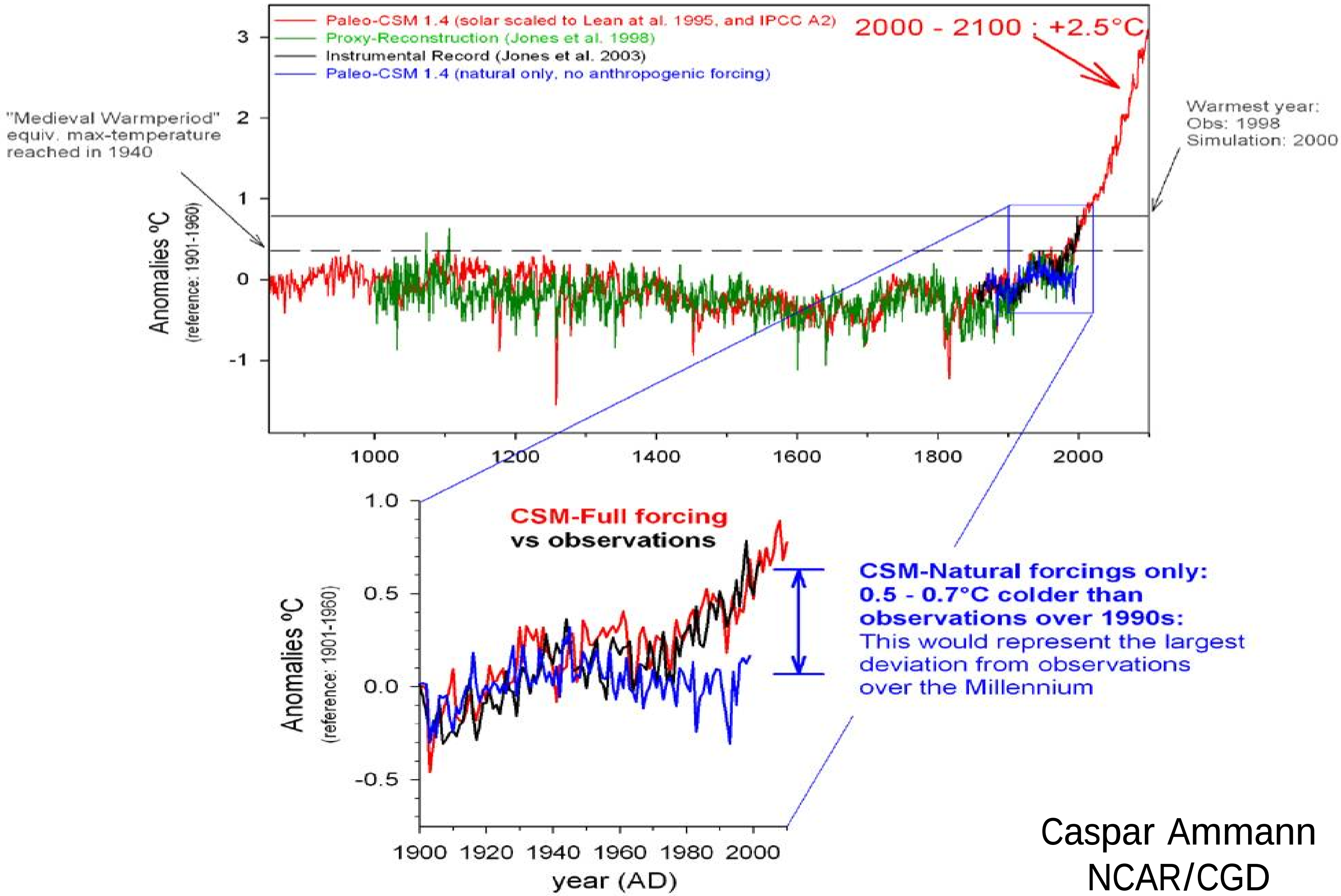
New Directions and Requirements for Climate following the breakthrough IPCC AR4



Lawrence Buja
National Center for Atmospheric Research
Boulder, Colorado

CAM T341- Jim Hack

Climate of the last Millennium



Caspar Ammann
NCAR/CGD

NSF/DOE IPCC Project

NCAR, ORNL, NERSC, ES

Observations
of the
Earths Climate System

Simulations
Past, Present
Future Climate States

<u>6-Year Timeline</u>

2002: Climate Model/Data-systems development

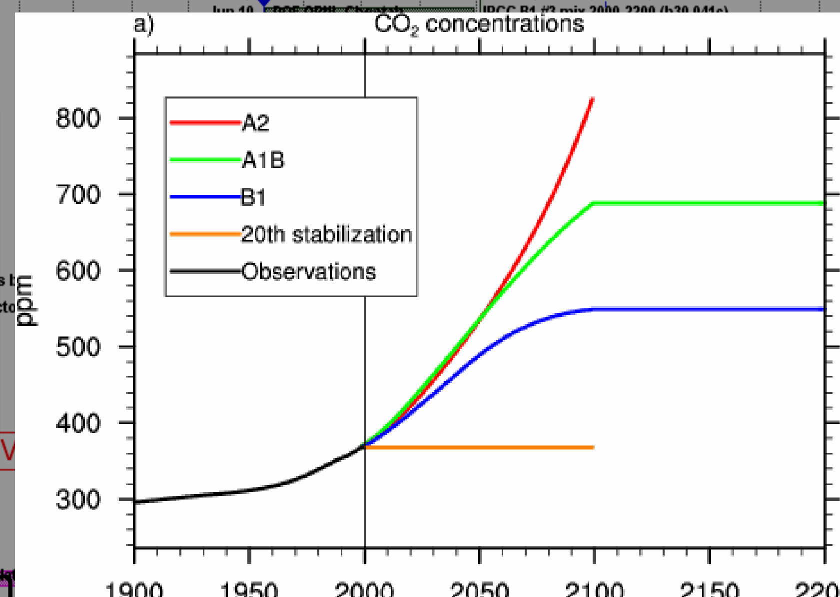
2003: Climate Model Control Simulations

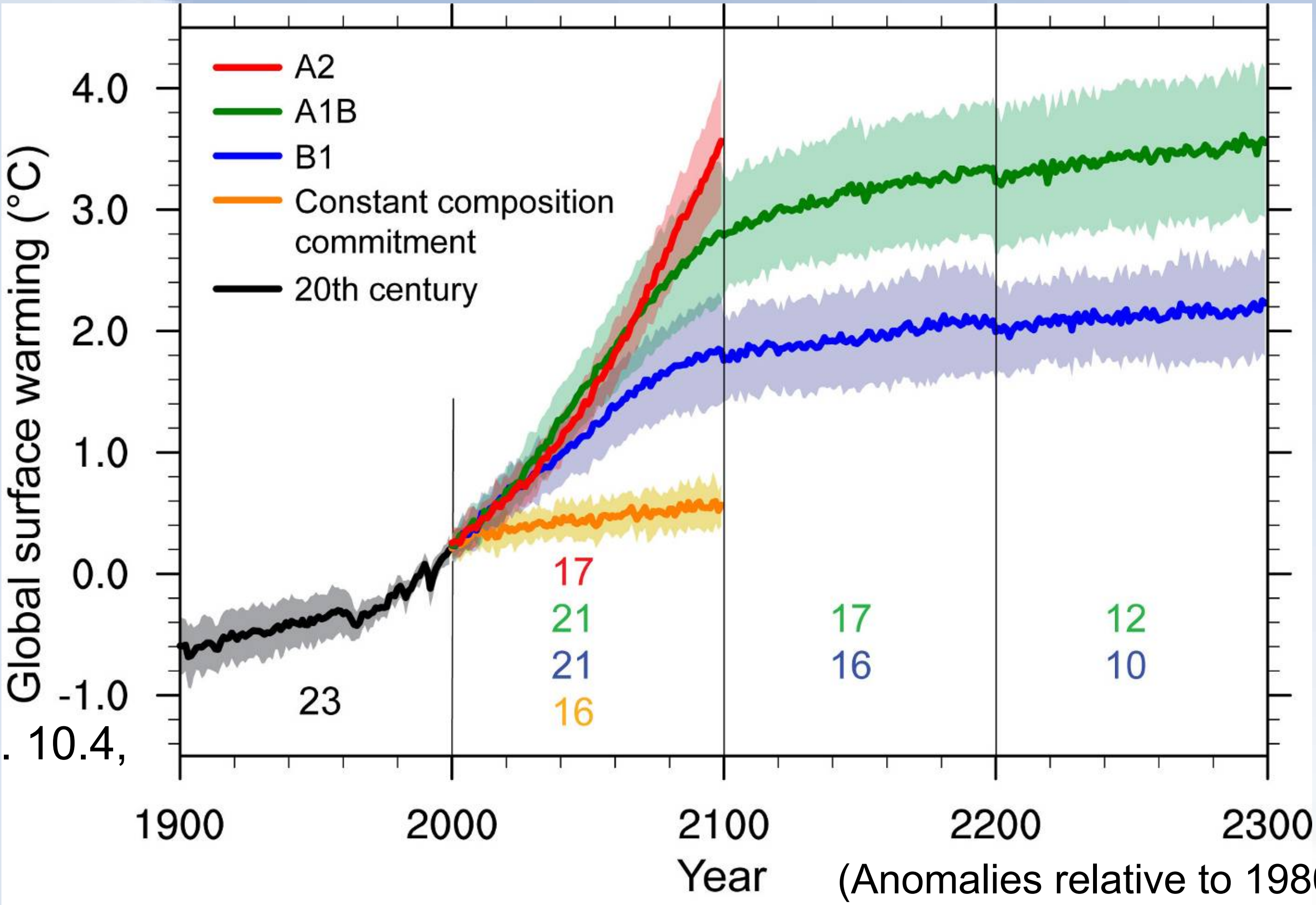
2004: IPCC Historical and Future Simulations

2005: Data Postprocessing & Analysis

2006: Scientific Synthesis

2007: Publication



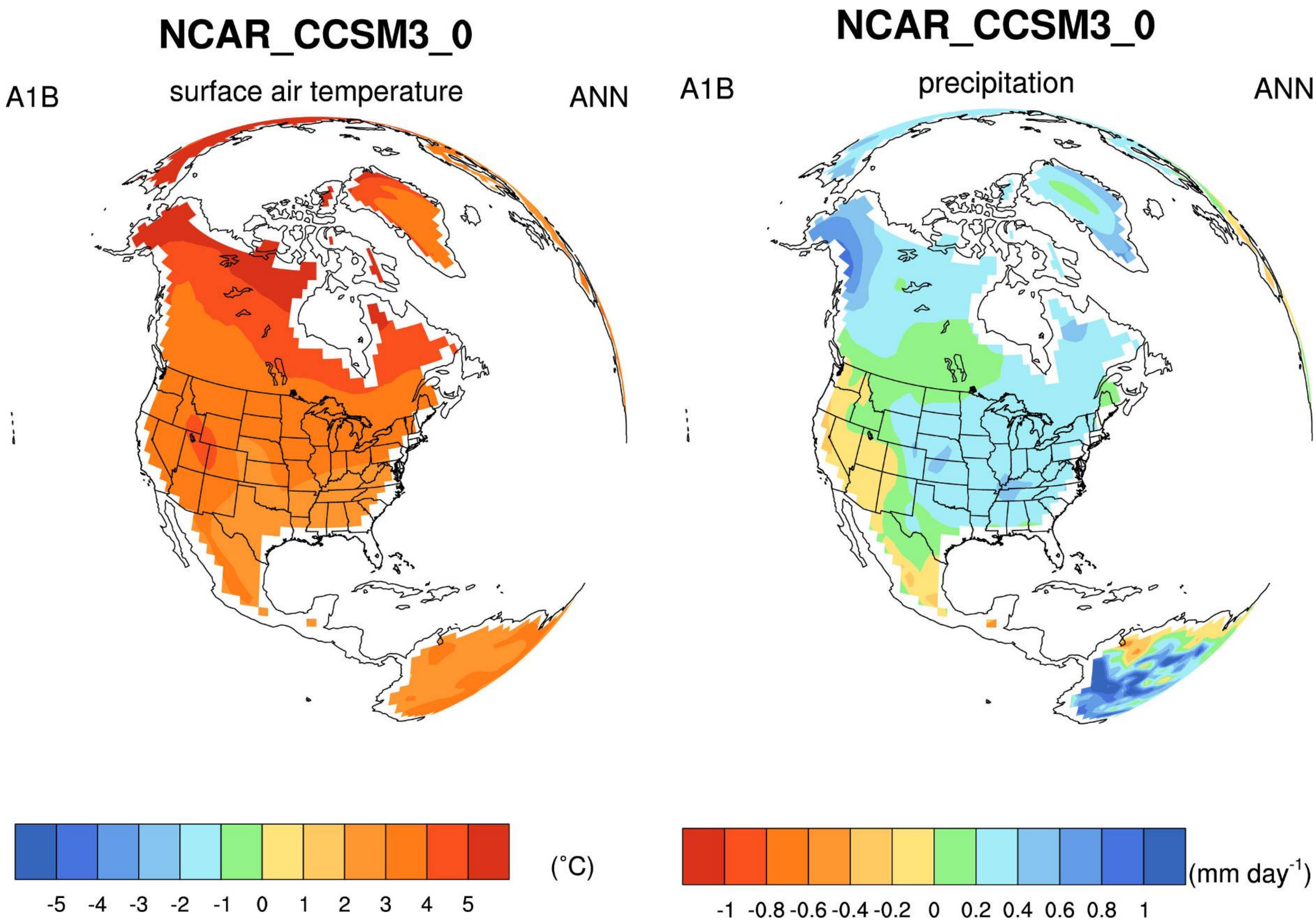


Ch. 10, Fig. 10.4, TS-32

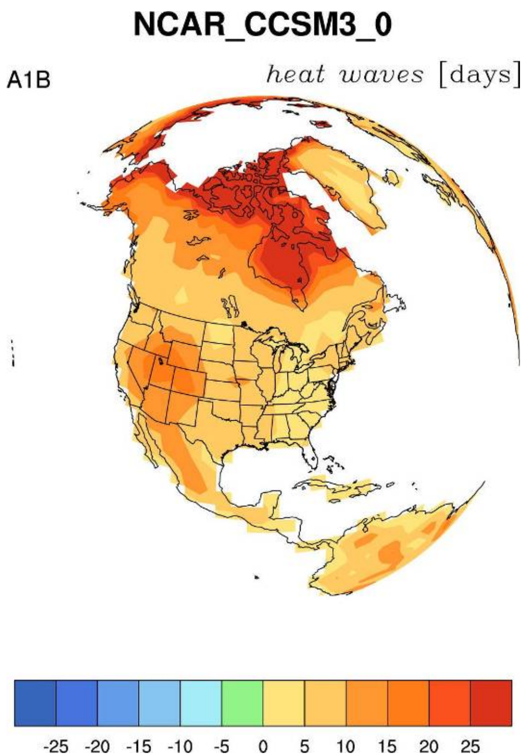
(Anomalies relative to 1980-99)

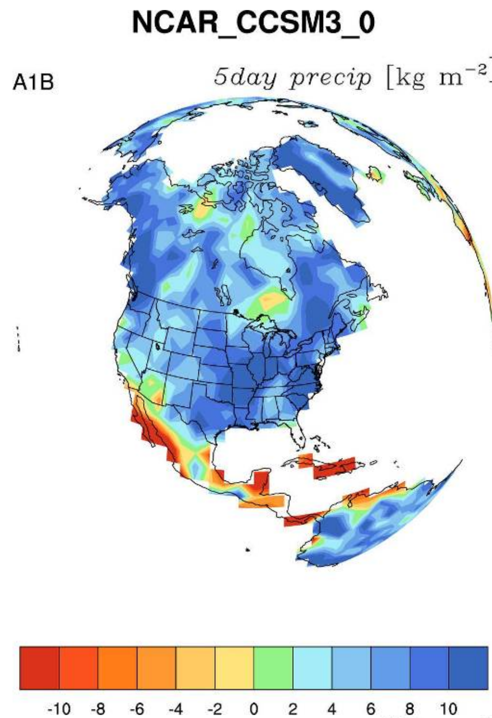
Unprecedented coordinated climate change experiments from 16 groups (11 countries) and 23 models collected at PCMDI (over 31 terabytes of model data), openly available, accessed by over 1200 scientists; over 200 papers

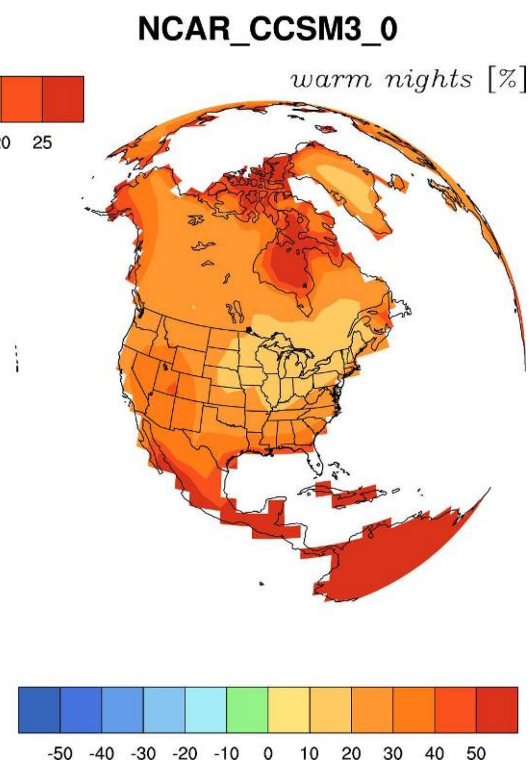
Committed warming averages 0.1°C per decade for the first two decades of the 21st century; across all scenarios, the average warming is 0.2°C per decade for that time period (recent observed trend 0.2°C per decade)

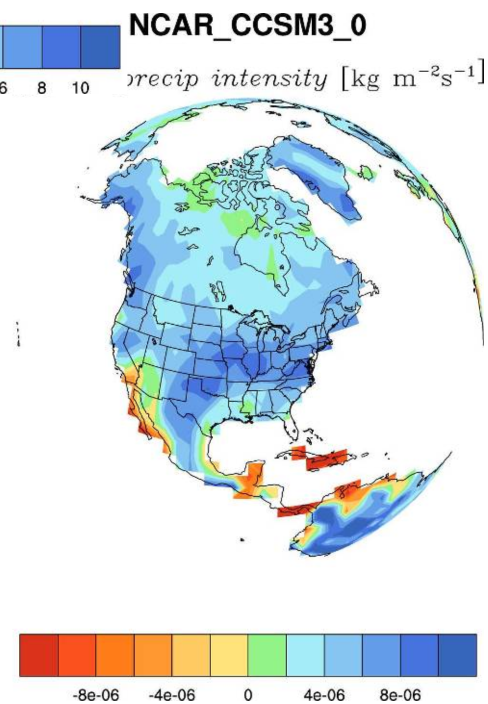


Figures based on Tebaldi et al. 2006: *Climatic Change*, Going to the extremes; An intercomparison of model-simulated historical and future changes in extreme events, http://www.cgd.ucar.edu/ccr/publications/tebaldi-extremes.html









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The Breakthrough 2007 IPCC Fourth Assessment Report

The IPCC AR4 findings are stronger and clearer than any previous report.

Working Group 1 (The physical basis of climate change)

- Warming is unequivocal
- "Very likely" that most of the late 20th century warming is due to human emissions.

Working Group 2 (Climate change impacts, adaptation and vulnerability)

- Large-scale changes in food and water availability
- Dramatic changes in ecosystems
- Increases in flood hazards and extreme weather

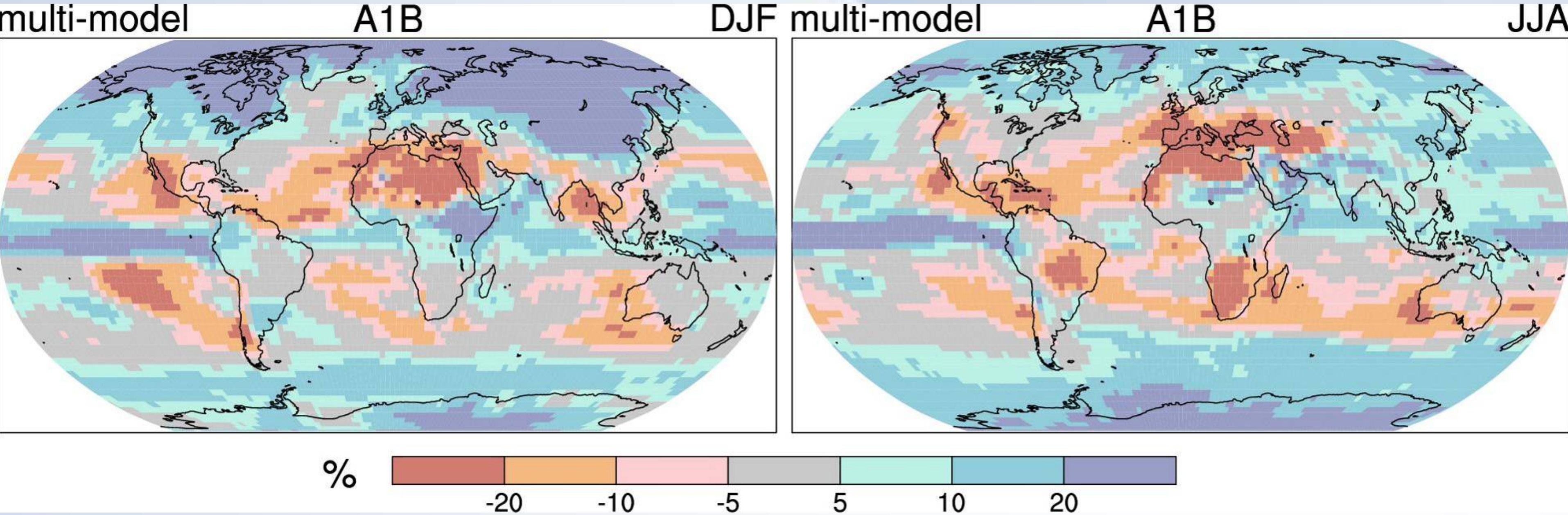
Working Group 3 (Mitigation of climate change)

- Some devastating effects of climate change can be avoided through quick action
- Existing technologies can balance climate risks with economic competitiveness.

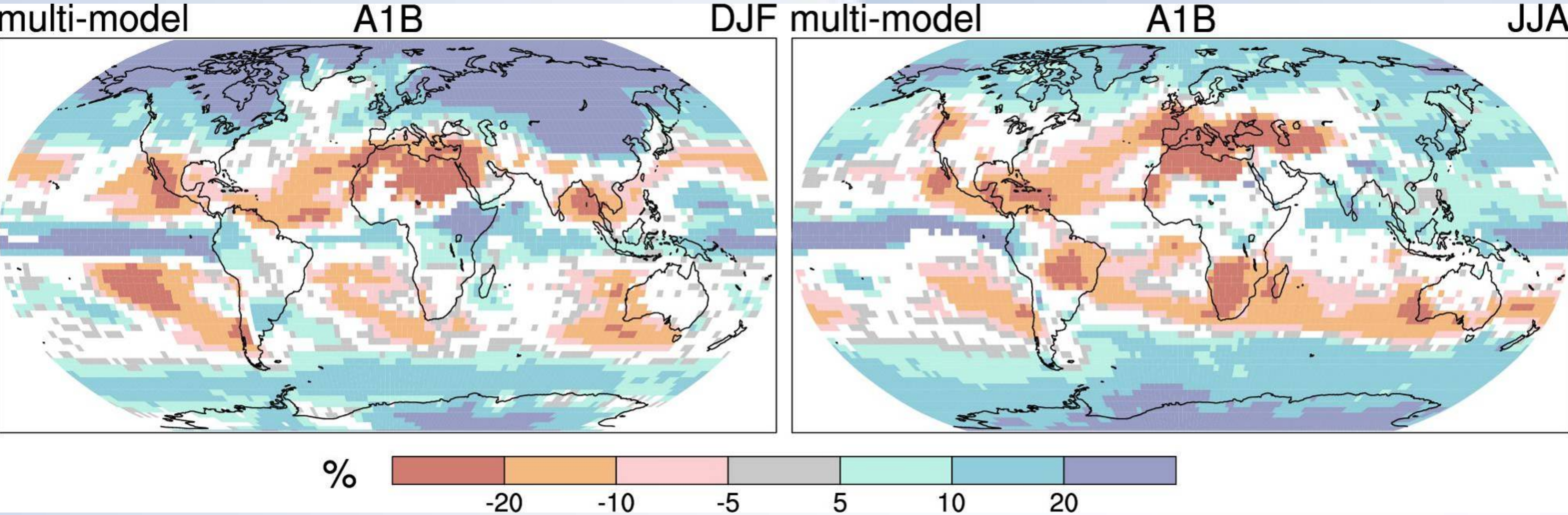
Conclusion: The strength & clarity of the AR4 conclusions due to:

- Better observations,
- Models, and
- HPC.

The strong NSF/DOE partnership was critical to our success.



Multi-model average precipitation % change, medium scenario (A1B), representing seasonal precipitation regimes, total differences 2090-99 minus 1980-99



White areas are where less than two thirds of the models agree in the sign of the change

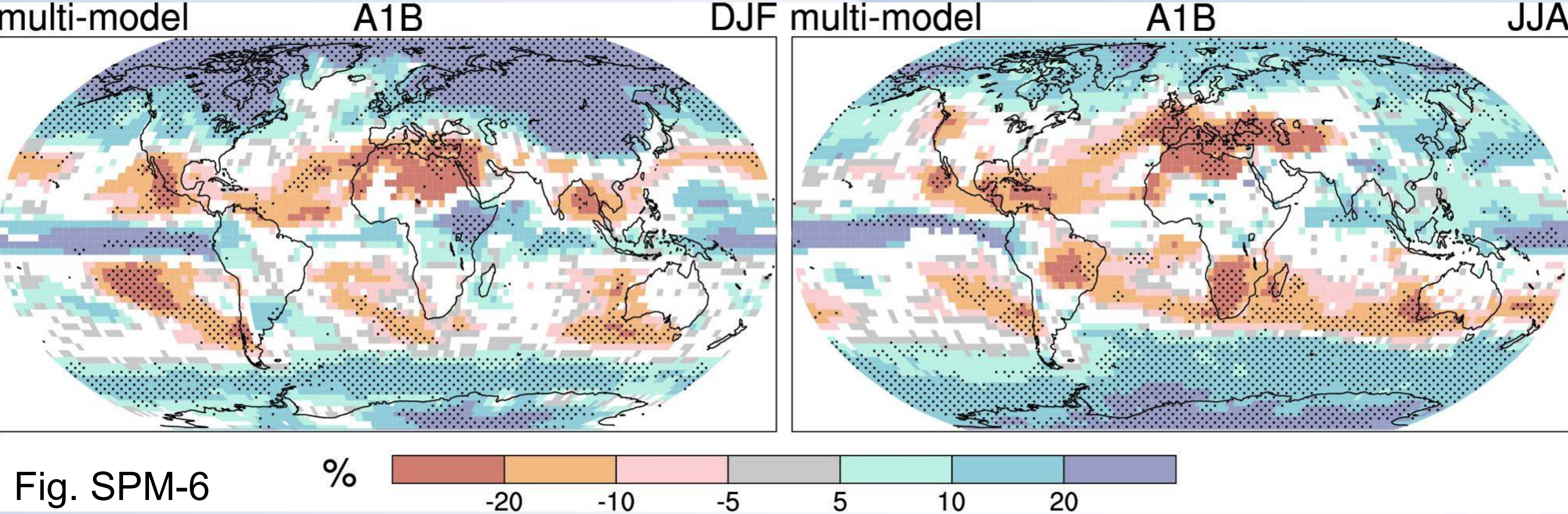


Fig. SPM-6

Stippled areas are where more than 90% of the models agree in the sign of the change

Precipitation increases very likely in high latitudes

Decreases likely in most subtropical land regions

This continues the observed patterns in recent trends

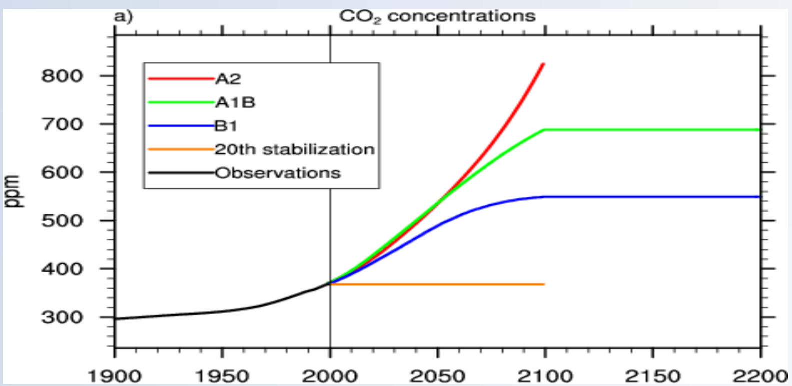
Climate Change Epochs

Before | IPCC AR4 | After

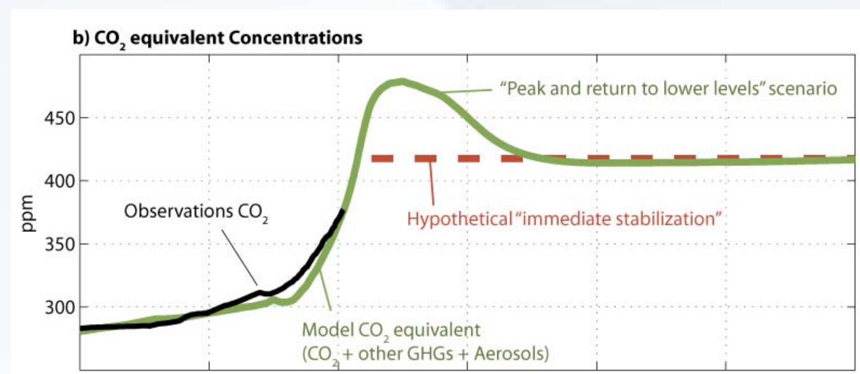
Attribute sources of historical warming

Project range of possible non-mitigated future warming from SRES scenarios

Quantify Climate Change Commitment



- Project adaptation needs under various mitigation scenarios
- Time-evolving regional climate change on short and long-term timeframes
- Quantify carbon cycle feedbacks



Conclusion: With the wide public acceptance of the IPCC AR4 findings, the climate science community is now facing the new challenge of quantifying time evolving regional climate change that human societies will have to adapt to under several possible mitigation scenarios, as well as addressing the size of carbon cycle feedbacks with more comprehensive Earth System Models

Earth System Grid has transformed CCSM data services

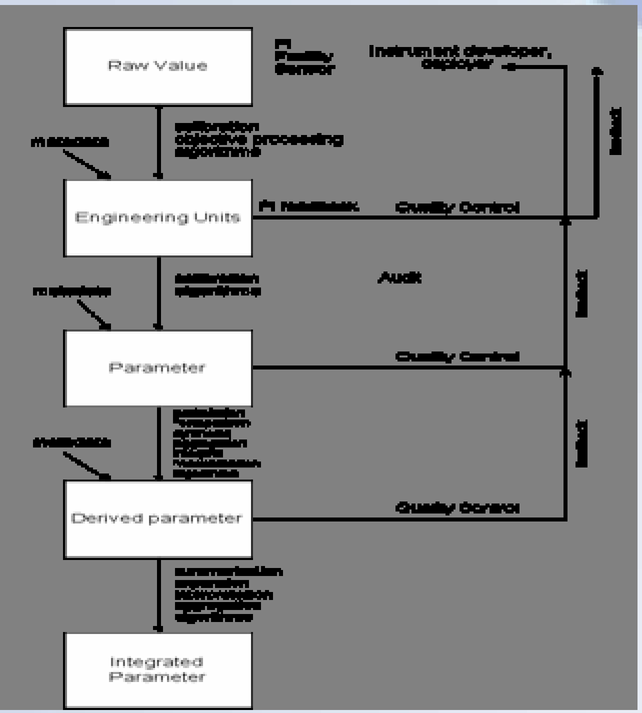
“Lets our Scientists do Science”

- **CCSM3.0 Release (2004)**
  - **Source Code, Input data and Documentation**
  - **So easy that it was almost an afterthought.**
- **IPCC AR4 (2005-present)**
  - **Distributed data services through PCMDI and NCAR**
  - **Delivered the model data for the IPCC AR 4 (WG 1)**
  - **Changed the World**
- **Ongoing CCWG Research**

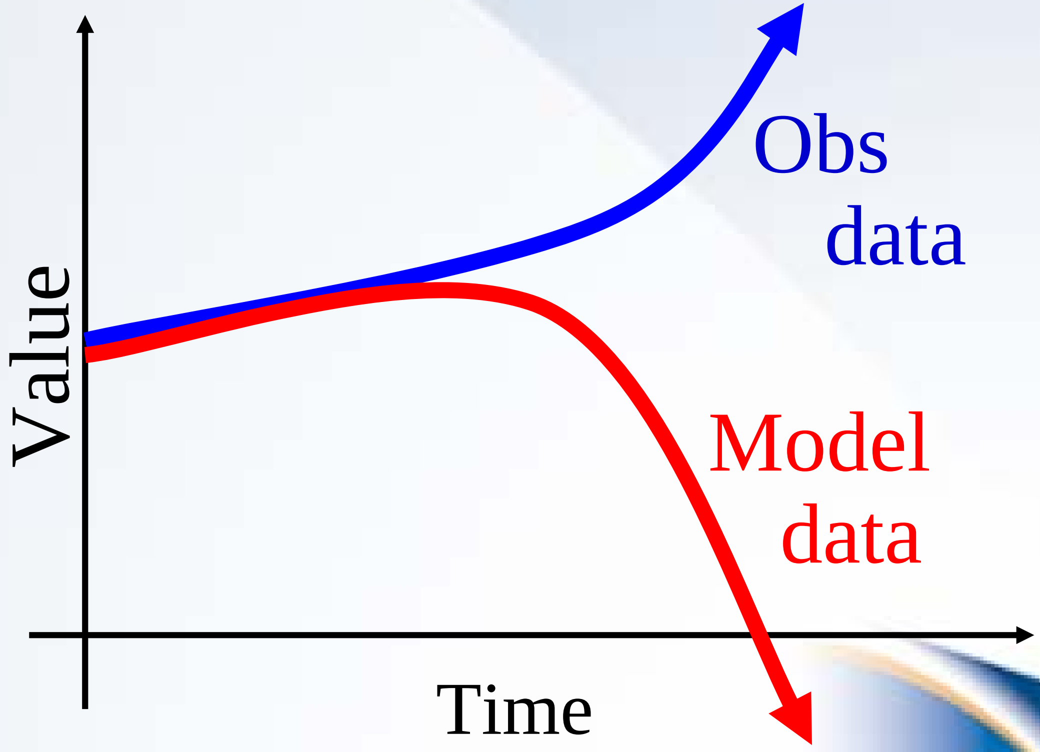
ESG data services have been a huge win for us…

- **Promoted use of data/metadata standards & richer metadata**
- **Much cheaper, easier and effective**
- **Allows us to reach huge new research/app communities (GIS)**

Lessons Learned



1. Observational data is very similar to model data



2. Observational data is very different from model data

Lessons Learned

3. Don’t let scientists build their data management and distribution systems on their own!

…but don’t let the CS folks do it alone, either

Building robust, useful data systems requires close collaboration between the two communities!

Lessons Learned

4. Effective Data Distribution Systems Require Sustained Investment

Home Grown Data Systems

- Initially Cheap
- $$$ in long term
- Limited Scale

Institutional Data Portal

- Modest Investment
- Agile and Right-sized for Many Projects
- Institutional Scale

Earth System Grid

- Large Investment
- Infrastructure for Large Projects
- Spans Institutions

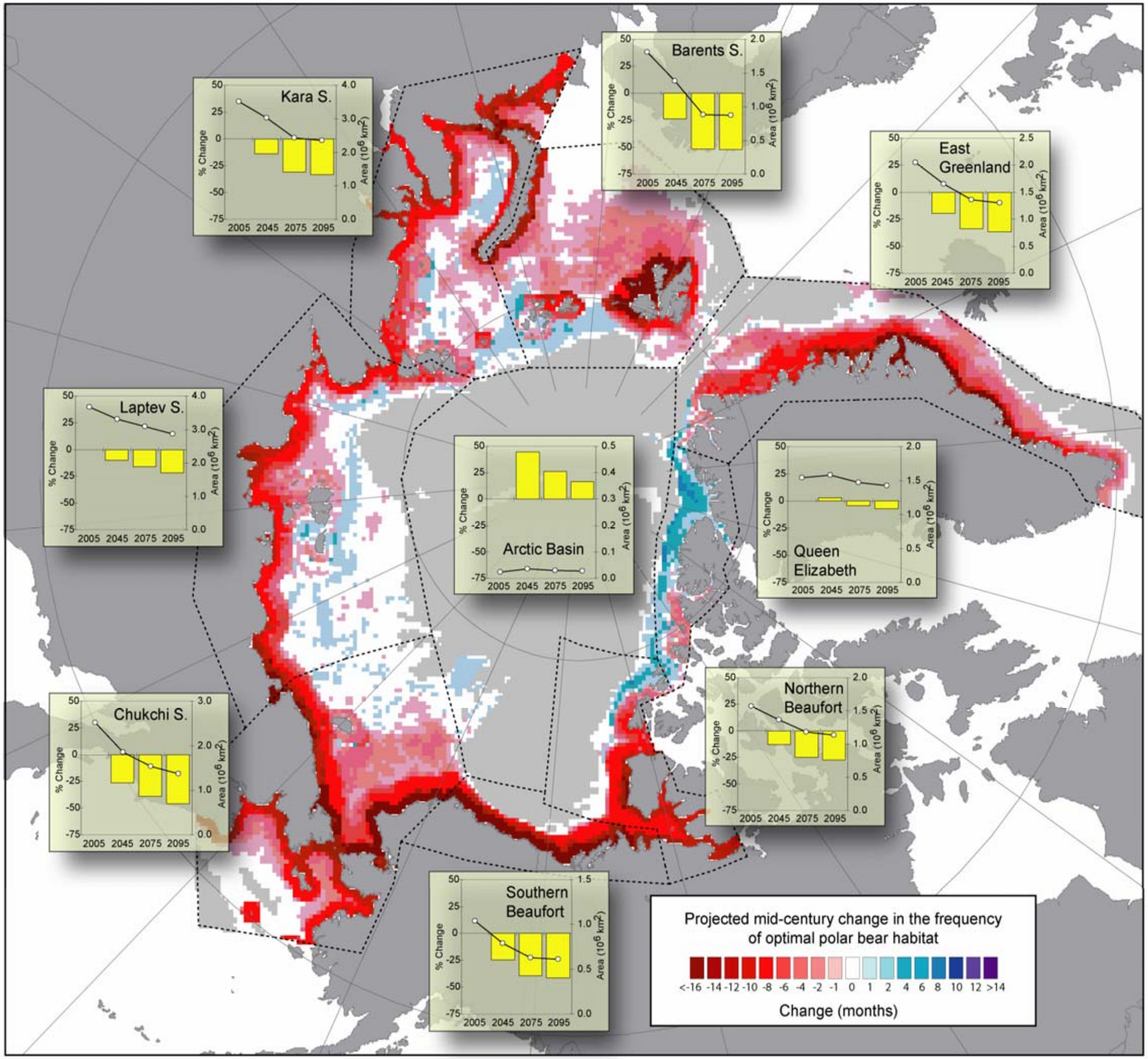
USGS
science for a changing world

Briefing on Results:

USGS Science Strategy to Support U.S. Fish & Wildlife Service Polar Bear Listing Decision: *a 6 month effort*

U.S. Department of the Interior
U.S. Geological Survey

Habitat Change Projection: 2001-2010 to 2041-2050

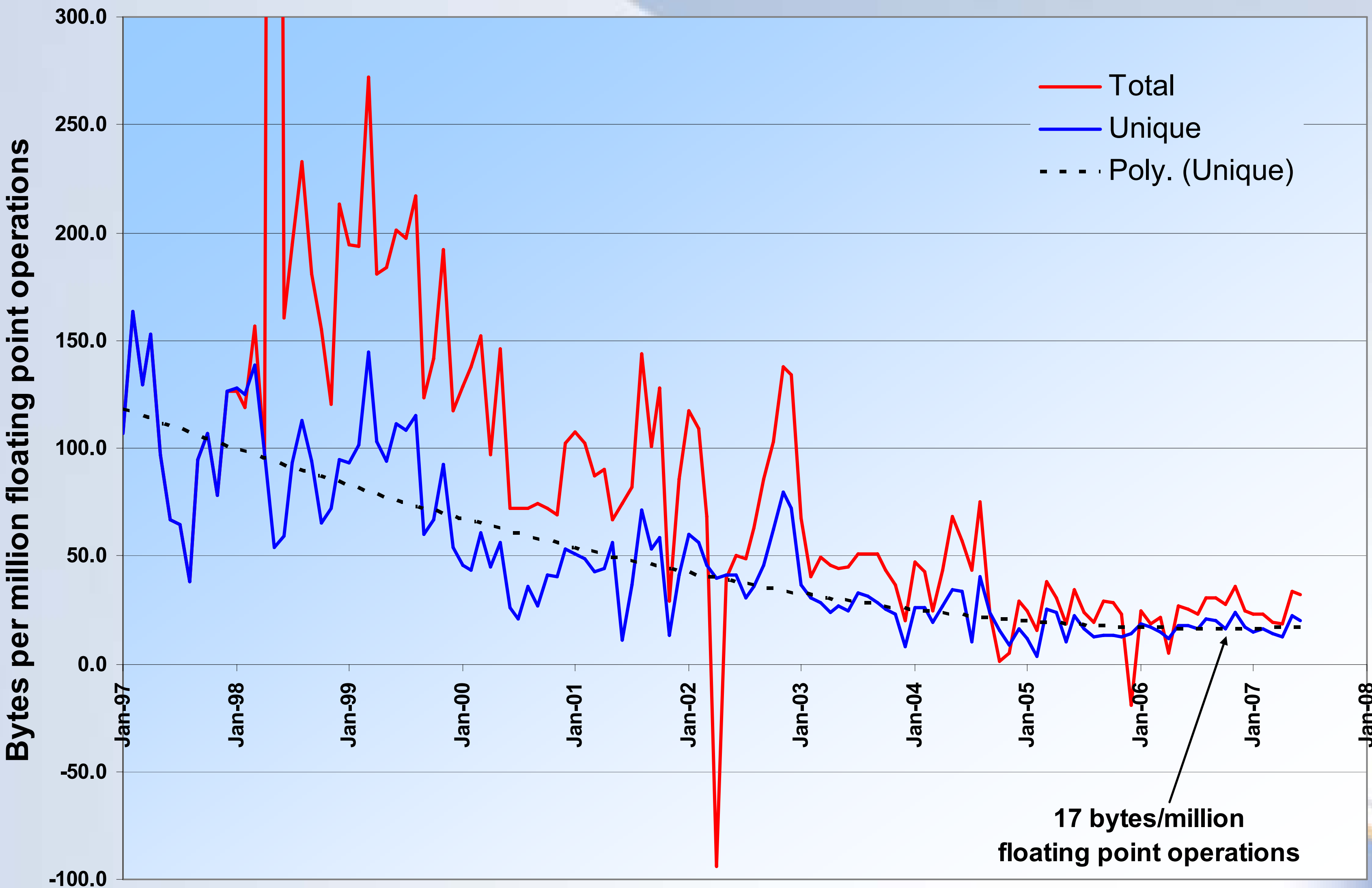


IPCC/CMIP4 Models

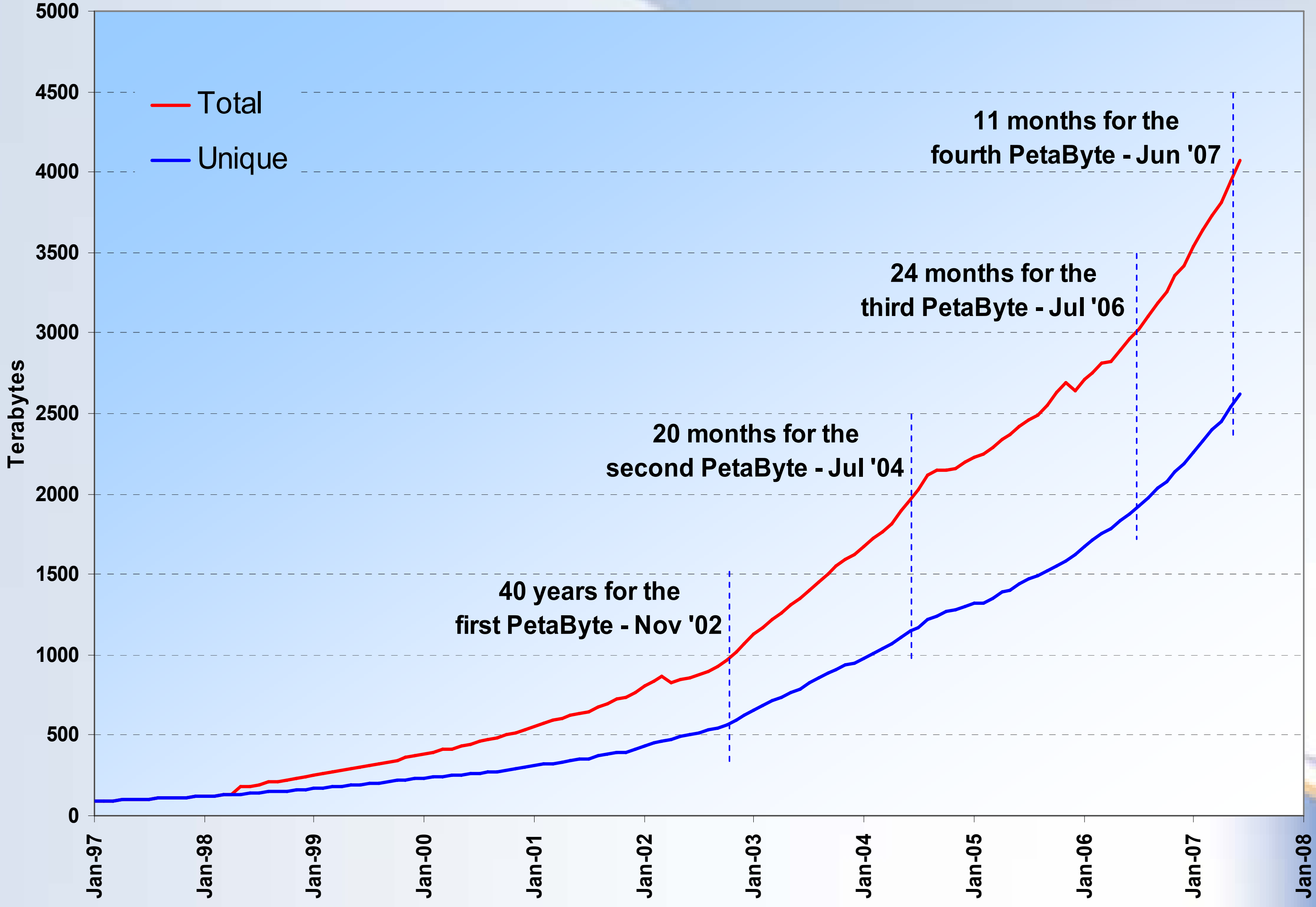
1 bccr_bcm2_0
2 cccma_cgcm3_1
3 cccma_cgcm3_1_t63
4 cnrm_cm3
5 csiro_mk3_0
6 gfdl_cm2_0
7 gfdl_cm2_1
8 giss_aom
9 giss_model_e_r
10 iap_fgoals1_0_g
11 inmcm3_0
12 ipsl_cm4
13 miroc3_2_hires
14 miroc3_2_medres
15 miub_echo_g
16 mpi_echam5
17 mri_cgcm2_3_2a
18 ncar_ccsm3_0
19 ukmo_hadcm3
20 ukmo_hadgem1

USGS Report: Durner et al. (2007)

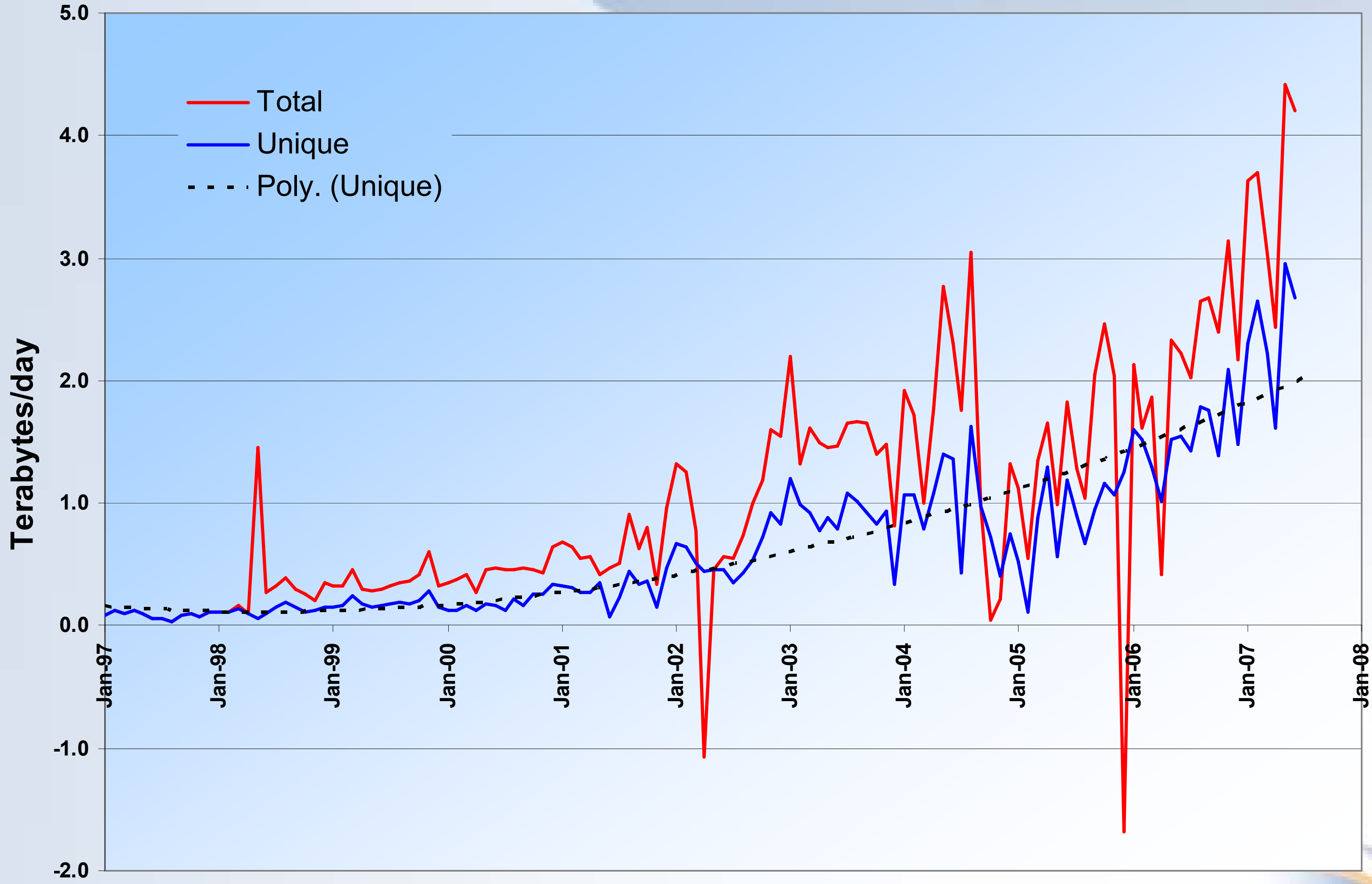
MSS Growth vs. Sustained Computing (The Good News)



Total MSS Data Holdings
(The Bad News)



MSS Net Growth Rate (Even Worse News)



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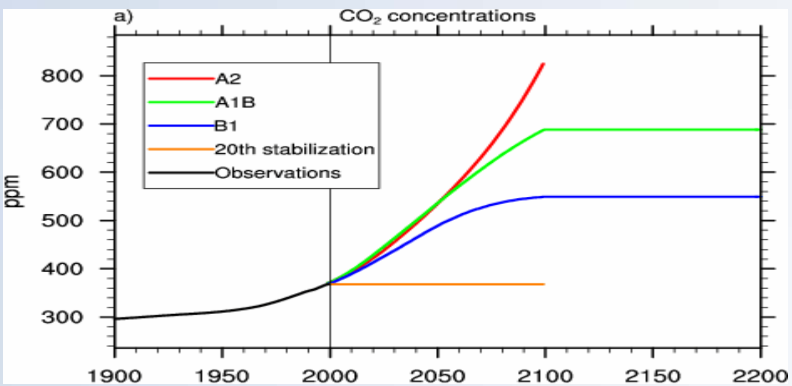

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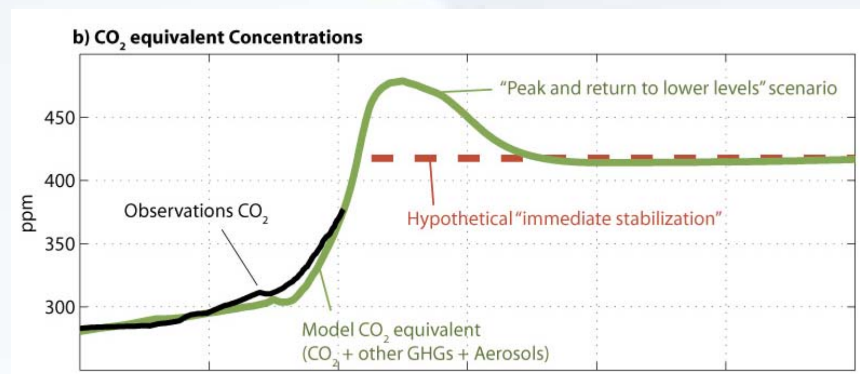

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DOE CCRD Directions

- Less emphasis on climate change detection and attribution
- More emphasis on decision support for policy makers
  - provide decision-makers with scientific information on "acceptable" target levels for stabilizing atmospheric CO_2
  - possible adaptation and mitigation strategies for the resulting climates before or after stabilization.

"Long Term Measure" for DOE Climate Change Research

Deliver improved scientific data and models about the potential response of the Earth's climate and terrestrial biosphere to increased greenhouse gas levels for policy makers to determine safe levels of greenhouse gases in the atmosphere.

Imperative post IPCC: Improved climate/earth system models for regional prediction.

• What does a 2^{o} C rise imply in terms of regional change and impacts?

Where to place century-scale hydroelectric investments in an evolving climate?

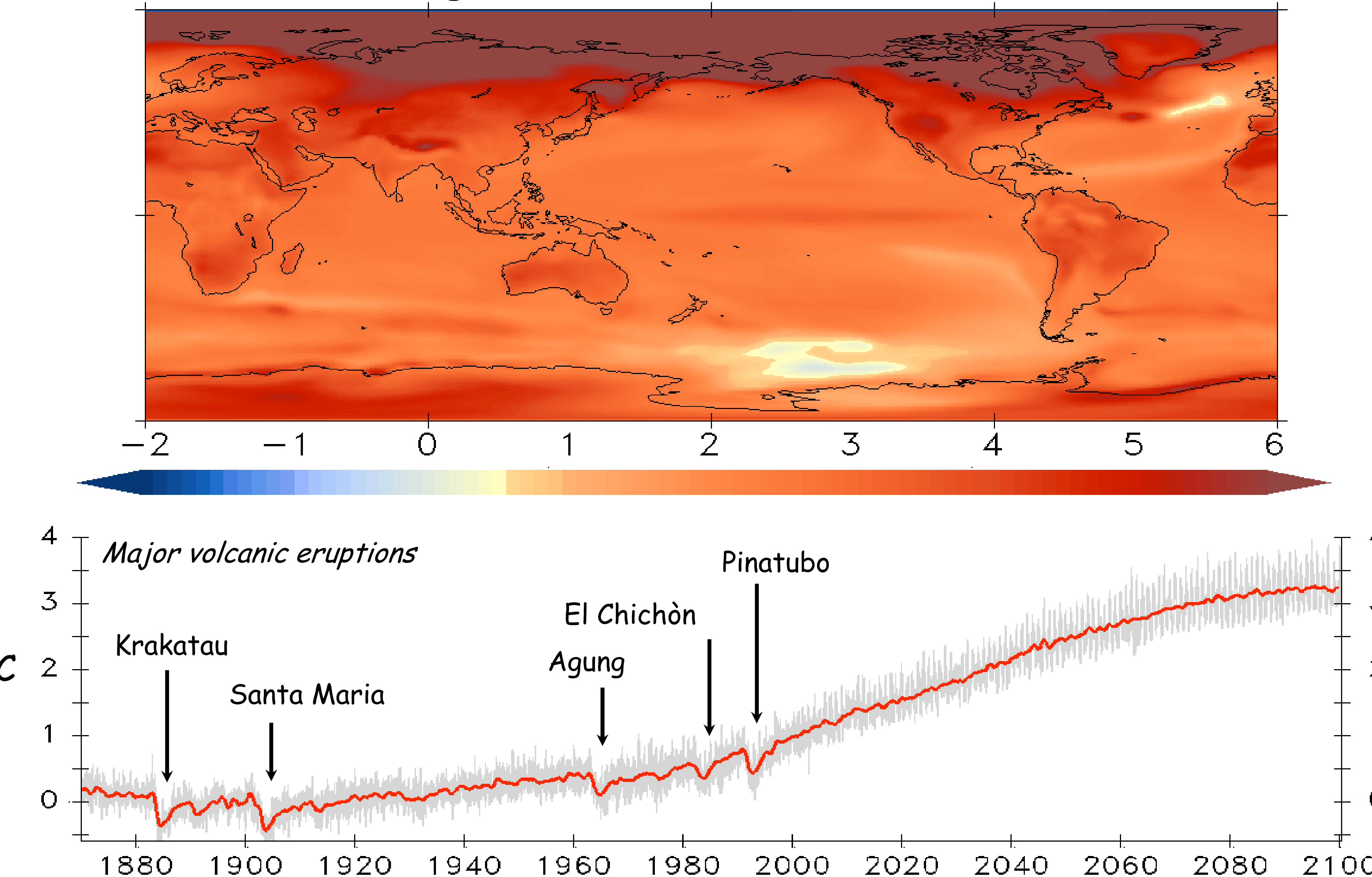
Geoengineering strategies

- Space mirrors, (Wood, Angel)
- High Altitude Sulfur injections
- Seeding stratocumulus clouds to brighten clouds
- Sequestration of CO_2
- Iron Fertilization, ...

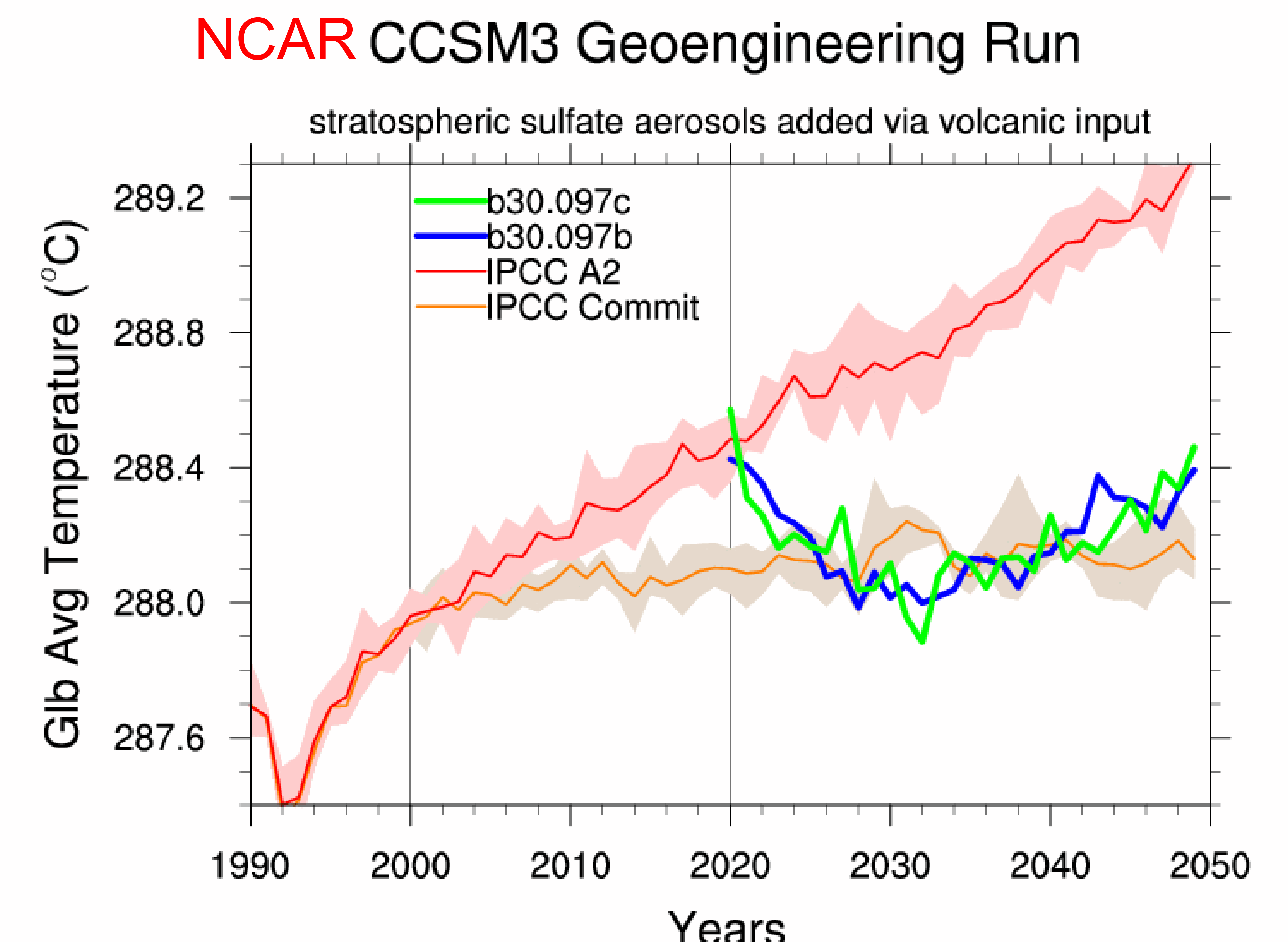
We are not proposing that geo-engineering be carried out! We are proposing that the implications should be carefully explored.

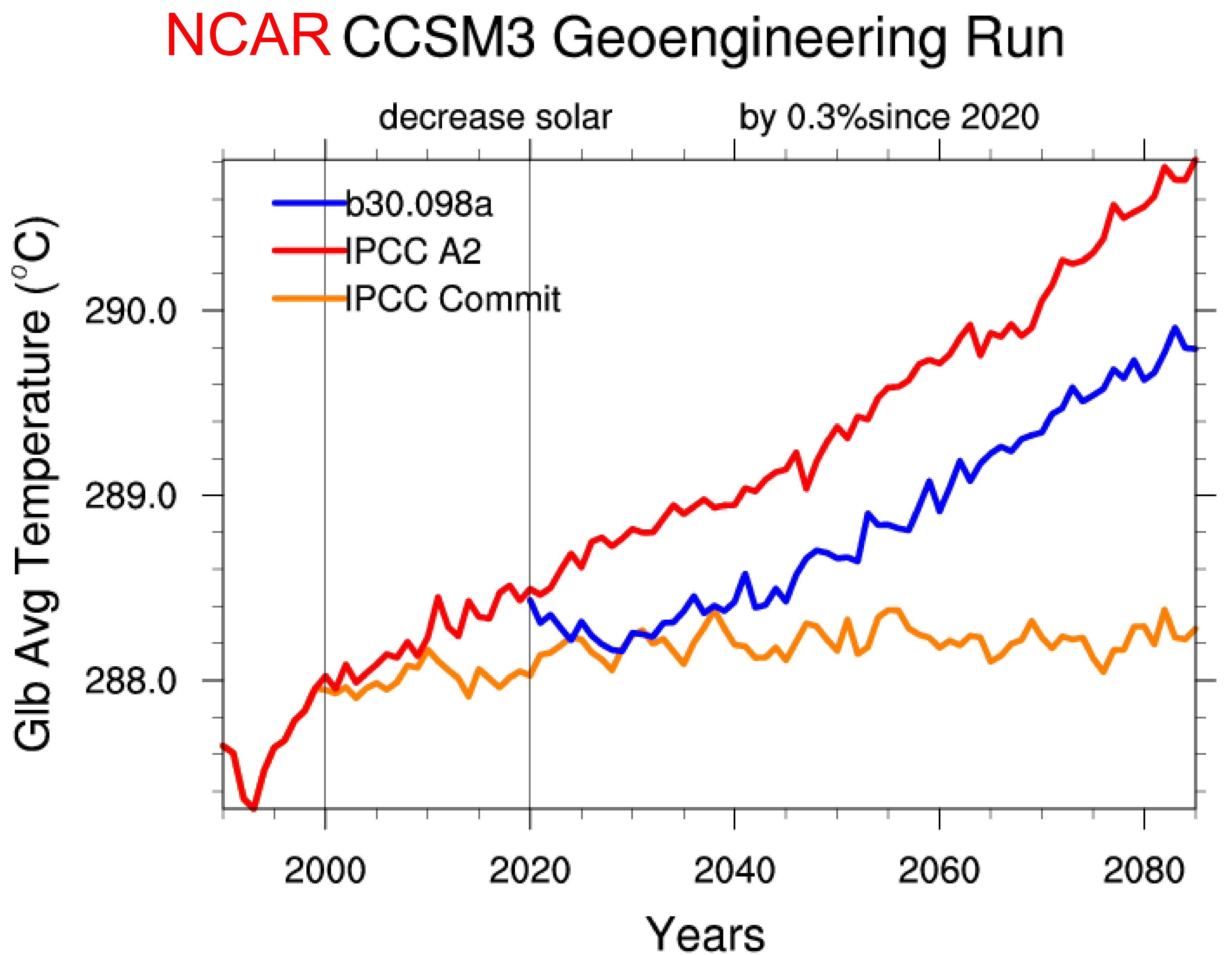
Phil Rasch NCAR

A1B °C change relative to 1870-1899 baseline



Global average surface temperature (relative to 1870-1899 mean)


NCAR CCSM3 Geoengineering Run
stratospheric sulfate aerosols added via volcanic input
b30.097c
b30.097b
IPCC A2
IPCC Commit
289.2
288.8
288.4
288.0
287.6
Glb Avg Temperature (°C)
1990
2000
2010
2020
2030
2040
2050
Years


NCAR CCSM3 Geoengineering Run
decrease solar
by 0.3%since 2020
b30.098a
IPCC A2
IPCC Commit
290.0
289.0
288.0
Glb Avg Temperature (°C)
2000
2020
2040
2060
2080
Years

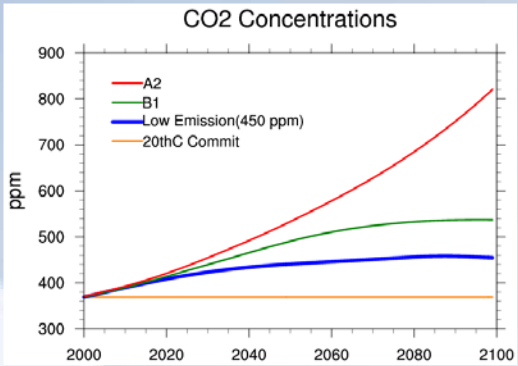
Low Emission Future Scenarios

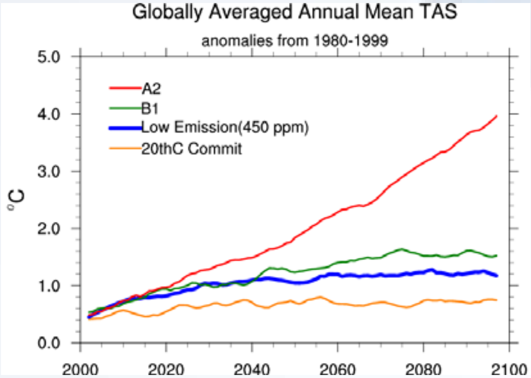
Goal: 2°C Δ Global Sfc Air Temperature from Pre-industrial to 2100

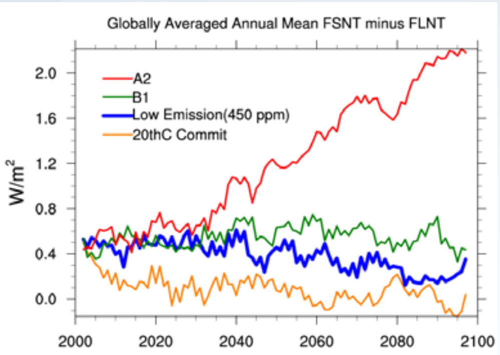
Integrated Assessment Model: PNNL MiniCAM
Input: Goal + Energy,Economics,Land Use,etc
Output: Emissions from 14 regions

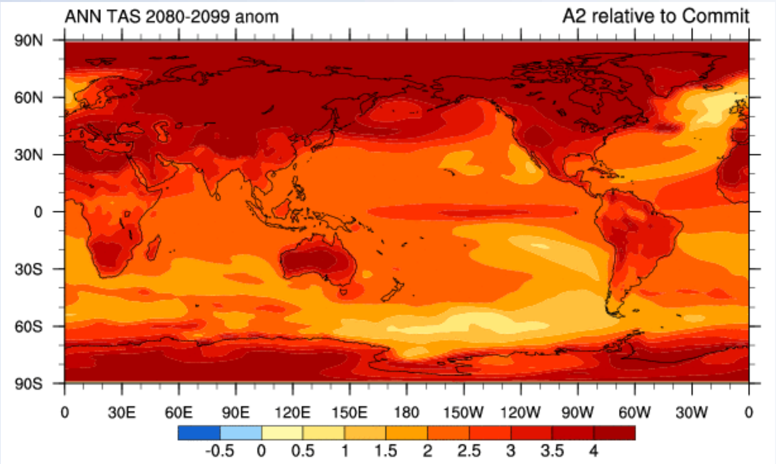
Climate Scenario Generator: NCAR MAGICC
Input: Emissions from MiniCAM
Output: GHG Concentrations

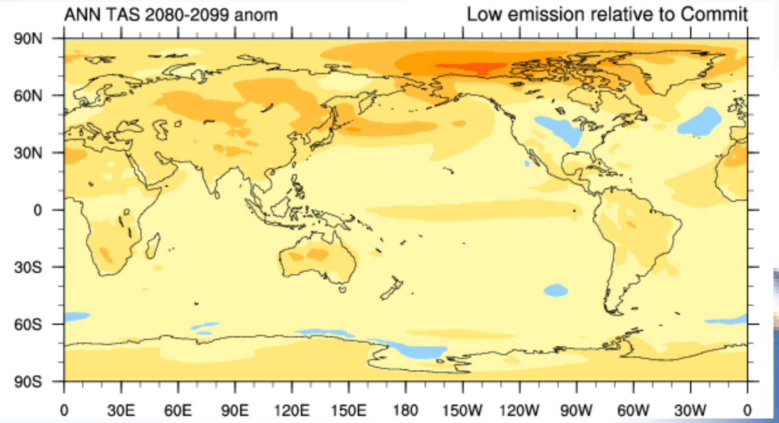
Coupled Climate System Model: CCSM3
Input: GHG Concentrations from MAGICC
Output: Climate Projections from 2006 to 2100





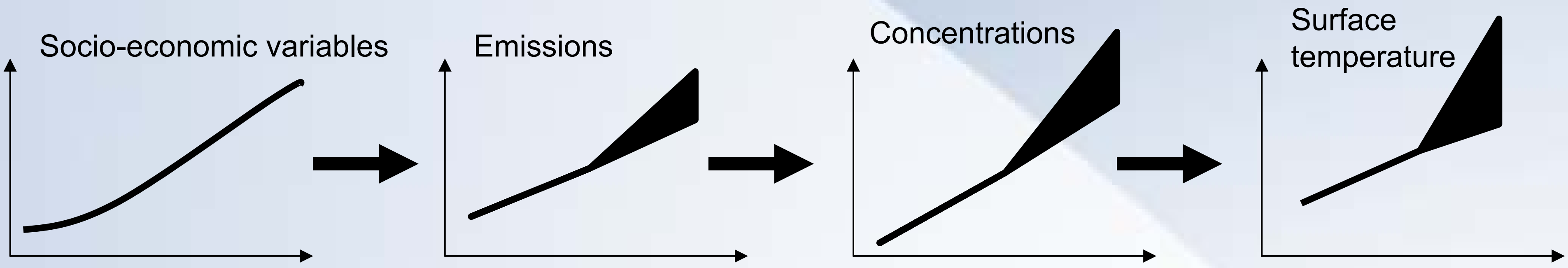




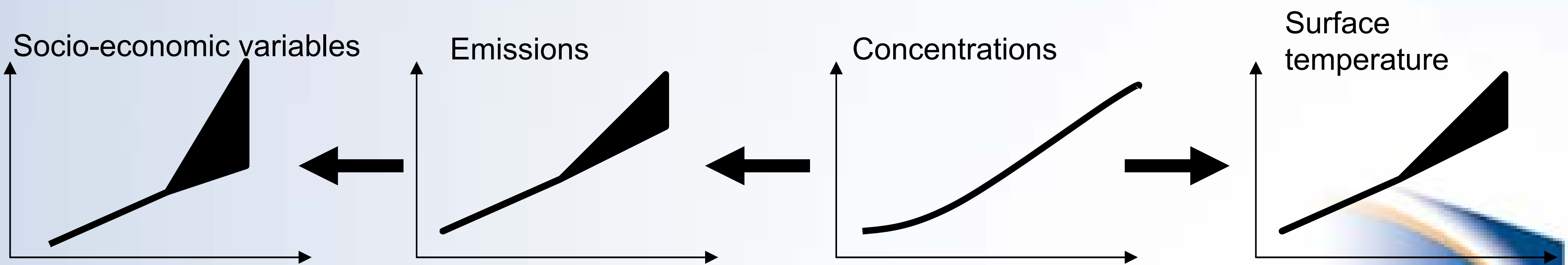


21st Century Experiments:
Long term (to 2100 and beyond))

- Forward approach: uncertainties build up; start with socioeconomic variables



- Reverse approach: uncertainties go both ways; start with stabilization scenario concentrations, work back to emissions and socio-economic conditions



	2007–2008	2008–2010	2010–2012	2012–2014
	2007 2008	2009 2010	2011 2012	2013 2014
	Preparatory phase	PHASE 1	PHASE 2	PHASE 3
ESM		Earth system modelling using CECPs	Earth system modelling using new scenarios	Earth system modelling using new scenarios
IAM	Selection and delivery of Community Emissions and Concentration Pathways (CECPs)	Development of *new* demographic, socio-economic, land use, technology and emissions scenarios	Development of *new fully integrated* demographic, socio-economic, land use, technology and emissions scenarios	Development of *new fully integrated* demographic, socio-economic, land use, technology and emissions scenarios
IAV	Assist in selecting CECPs Initiate discussion on IAV organisation Begin search for funding partners	Establish IAV steering group Identify contact institution Create regional nodes Inform IAV community Plan public IAV repository	Format scenario information Identify "marker" scenarios Develop tools and guidance Develop regional storylines Fix baselines/base case Establish IAV repository Register for repository Carry out IAV studies Hold periodic workshops Report initial results Meta-analysis of IAV results	Evaluate, inter-compare, synthesize and report results Initiate new or continue ongoing IAV studies

POSSIBLE IPCC FIFTH ASSESSMENT

Jerry Meehl, NCAR

Two classes of models to address two time frames and two sets of science questions:

1. Near-Term (2005-2030)

higher resolution (perhaps 0.2°), no carbon cycle, some chemistry and aerosols, single scenario, science question: e.g. regional extremes

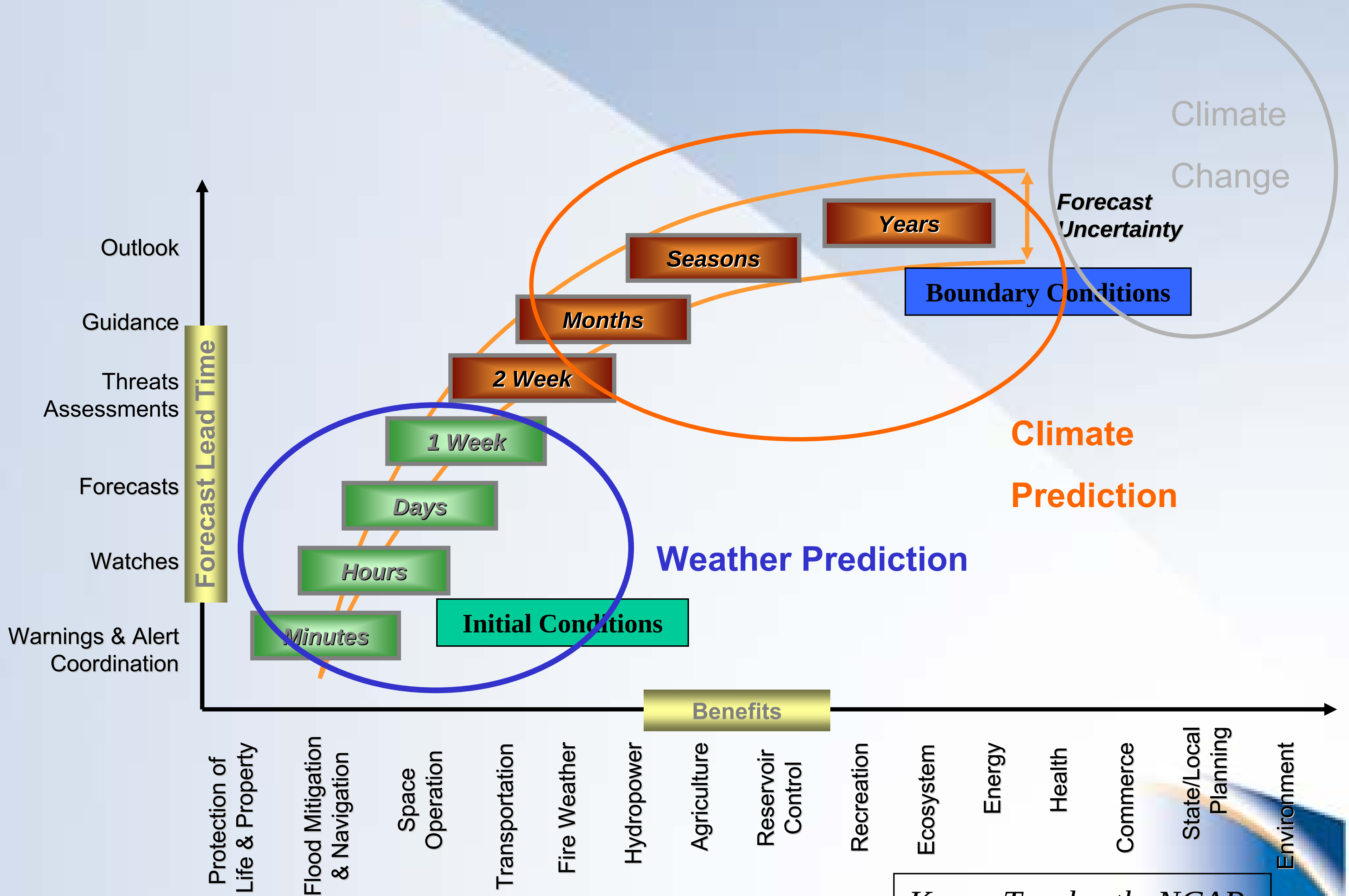
2. Longer term (to 2100 and beyond)

lower resolution (roughly 1.5°), carbon cycle, specified or simple chemistry and aerosols, benchmark stabilization concentration scenarios

Science question: e.g. feedbacks

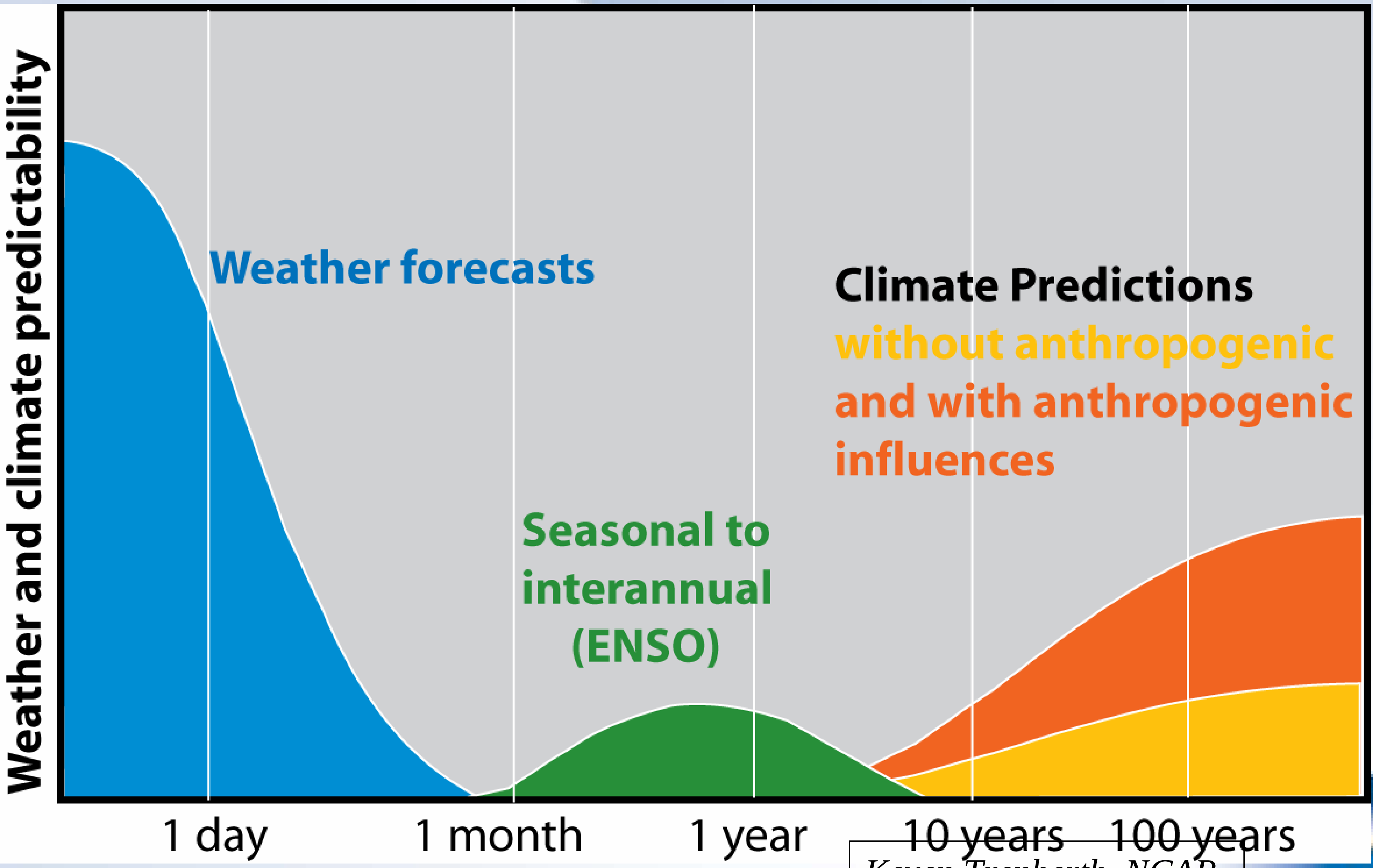
Jerry Meehl, NCAR

Seamless Suite of Forecasts



Keven Trenberth, NCAR

Predictability of weather and climate



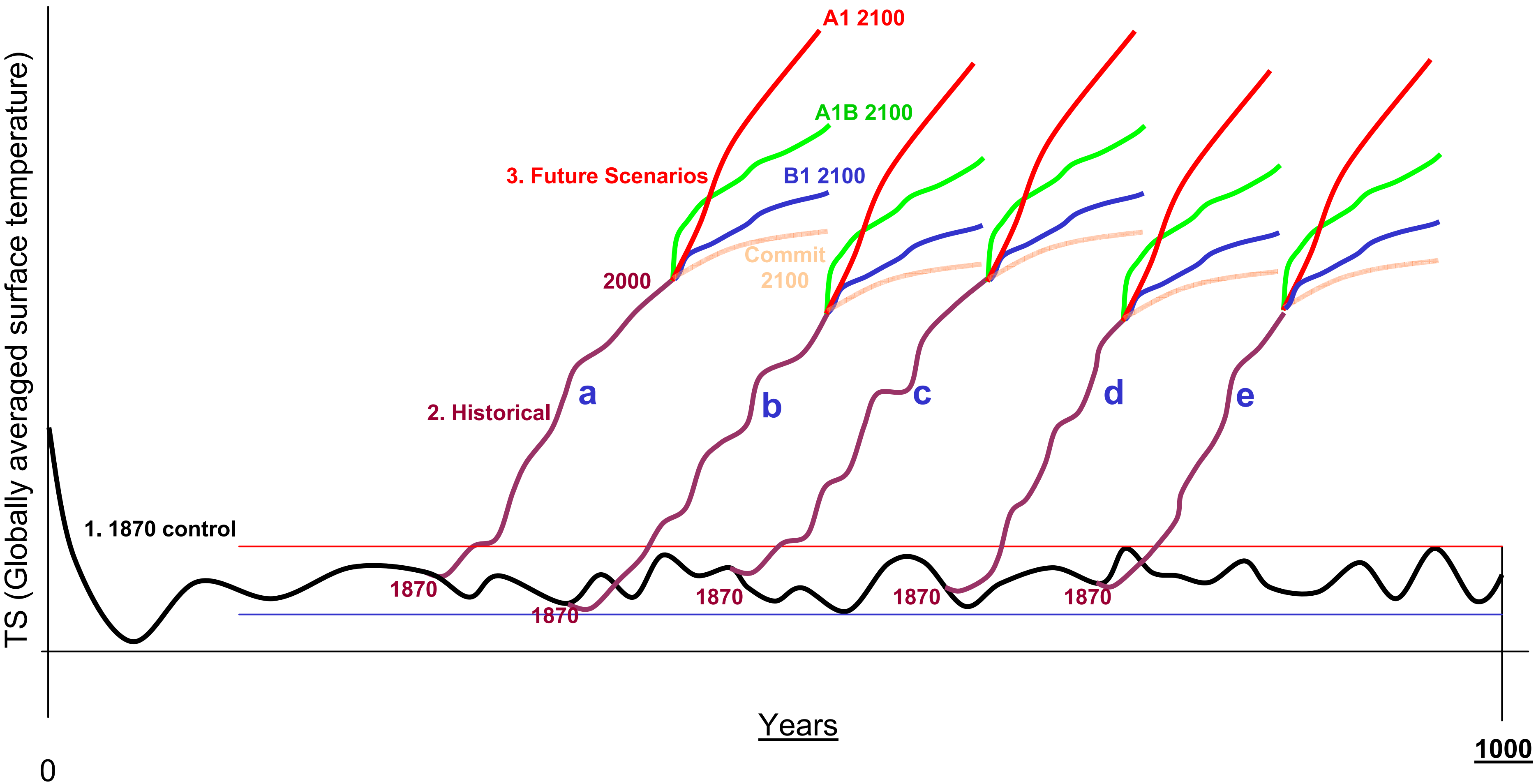
Keven Trenberth, NCAR

Probablistic Climate Simulations

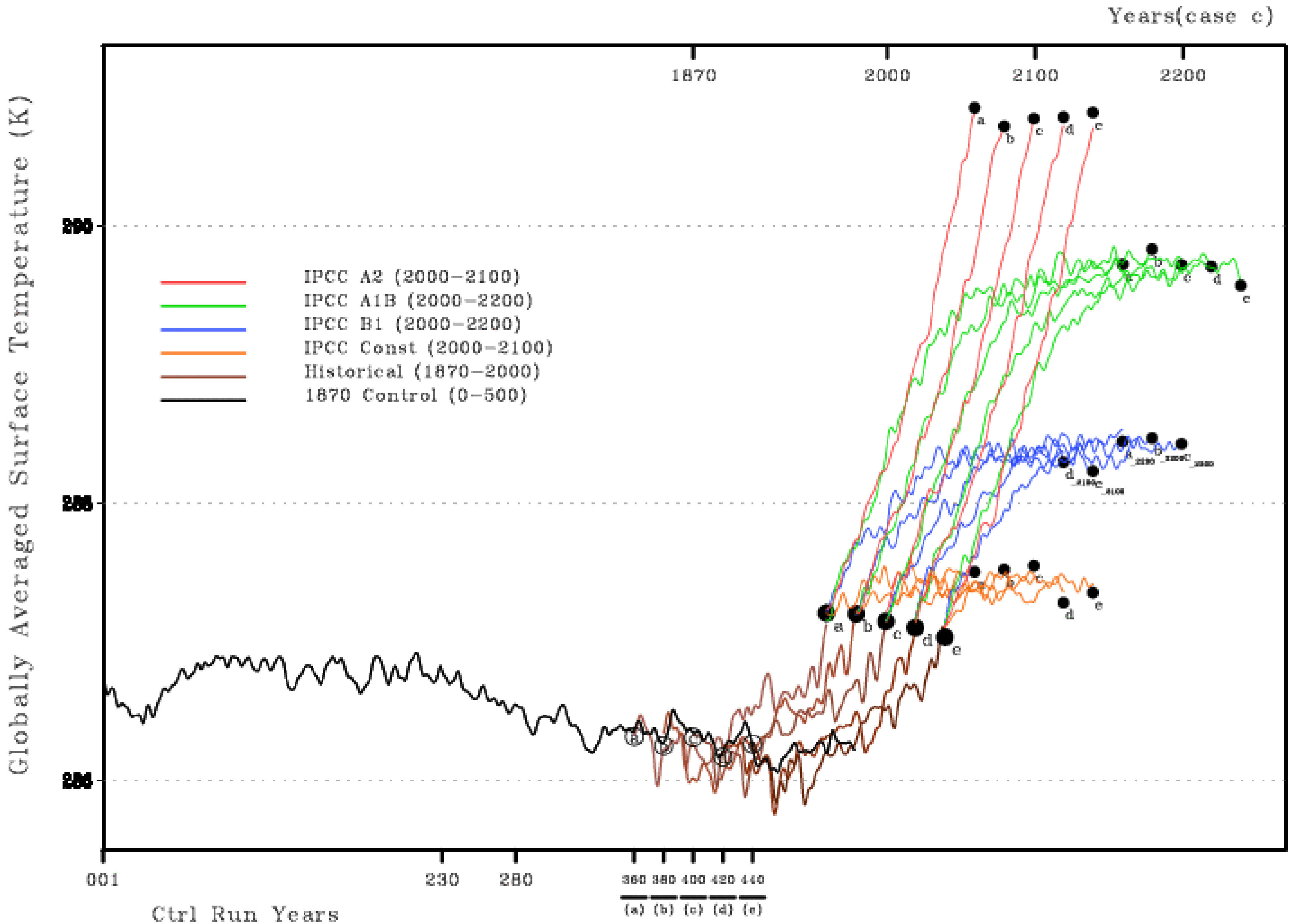
Stage 1. 1870 control run: 1000 years with constant 1870 forcing: Solar, GHG, Volcanic Sulfate, O3

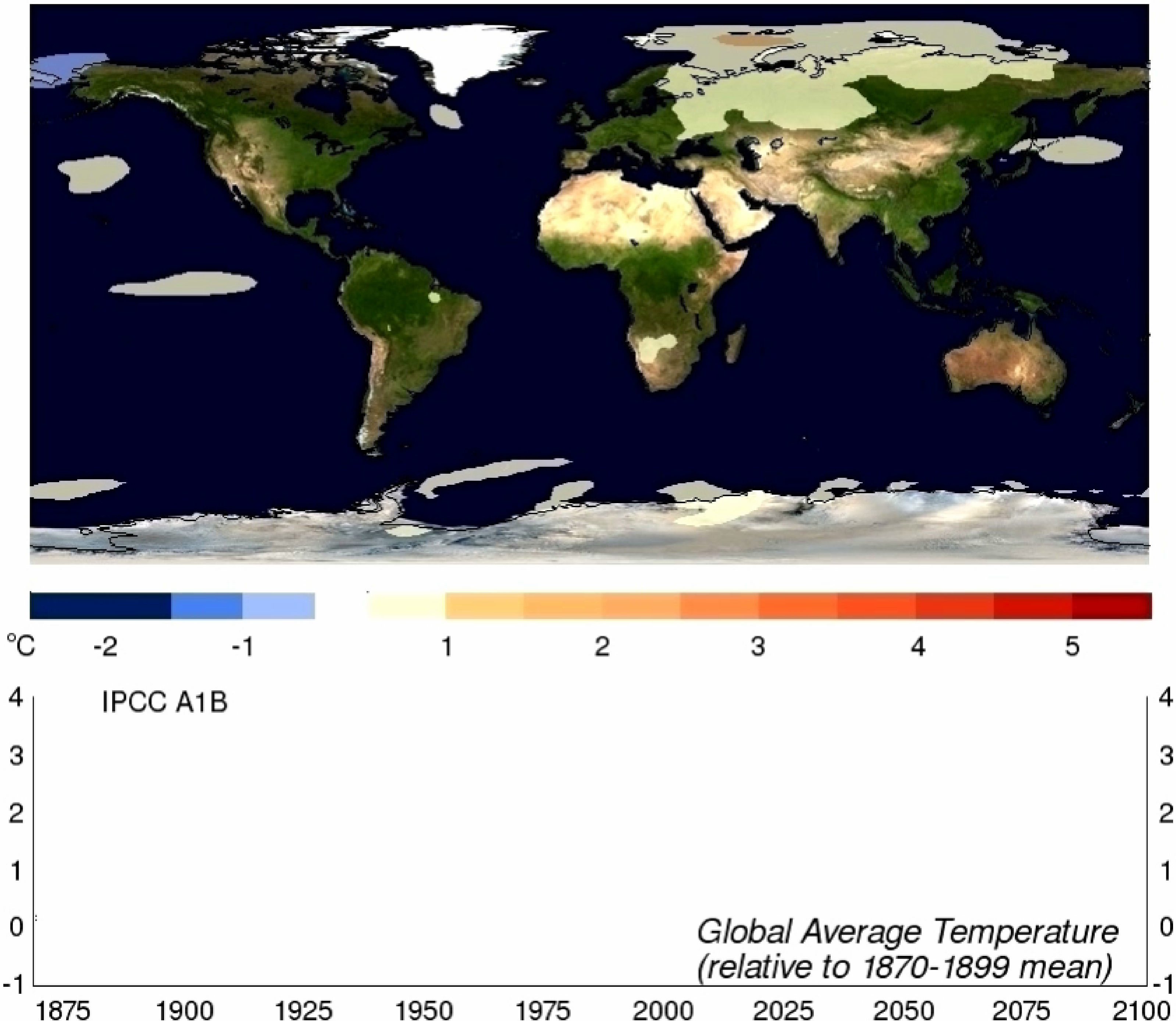
Stage 2. Historical: 1870-2000 run using time-evolving, observed, Solar, GHG, Volcanoes, O3

Stage 3. Future Scenarios: 4 2000-2100 IPCC Scenarios from end of historical run



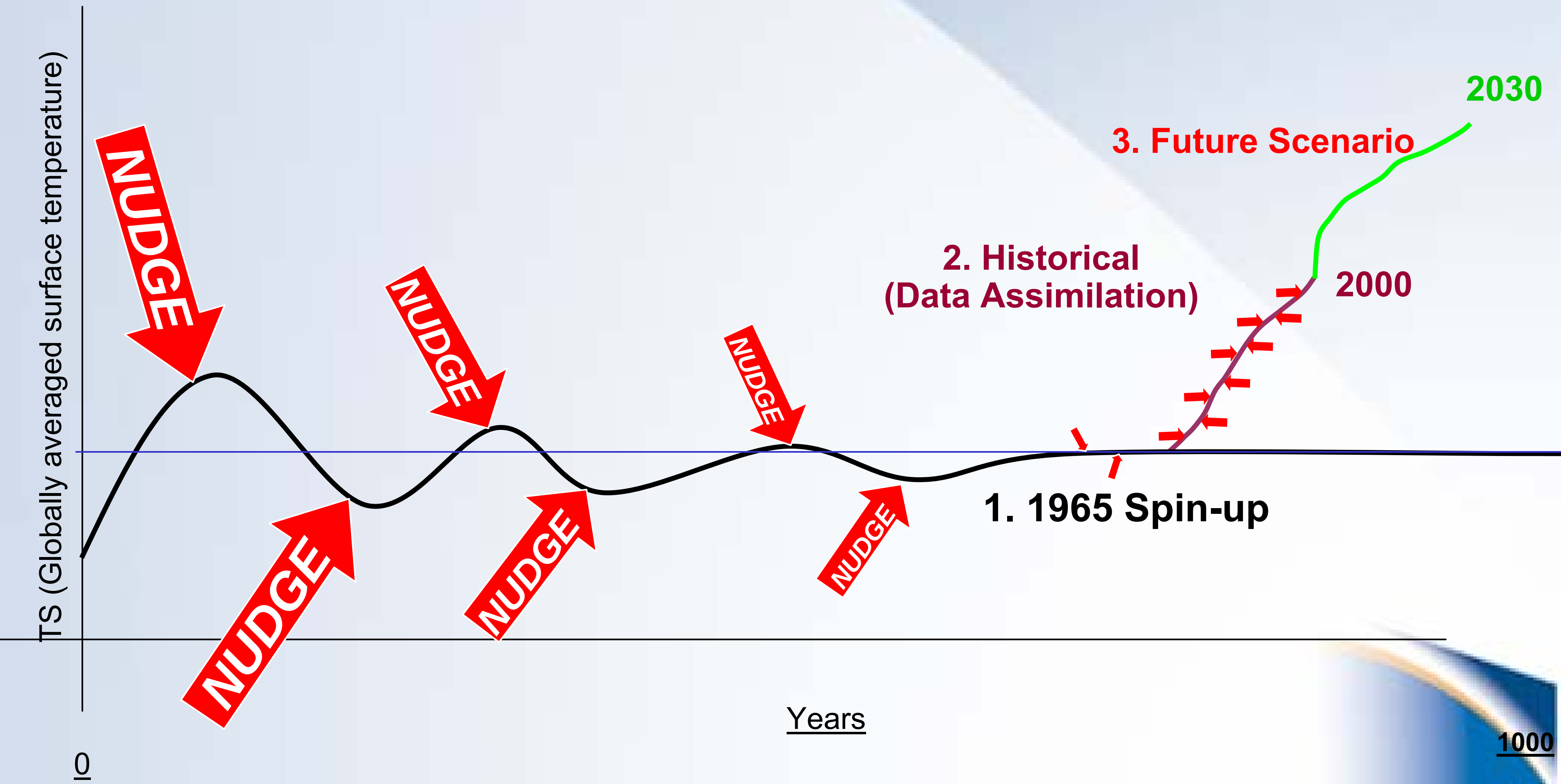
CCSM3 IPCC RUNS





°C -2 -1 1 2 3 4 5
IPCC A1B
Global Average Temperature
(relative to 1870-1899 mean)
4 3 2 1 0 -1
1875 1900 1925 1950 1975 2000 2025 2050 2075 2100

Deterministic Climate Prediction



Earth Observations in Climate Models

Probabilistic Climate Simulations:

- Model Verification,
  - ERBE, SHEBA, GRACE,
  - New: Life and biogeochemistry
  - Globally, regionally, and pointwise.
  - Annual, monthly, daily, instantaneous
- Atmospheric Boundary Conditions
  - Solar, GHG, Sulfates, O_3, dust

Deterministic Climate Predictions:

- Same requirements as Probabilistic plus
- Initial Conditions & Assimilation (
  - Atmospheric initial state not that important (will follow ocean)
    - Detailed atmospheric composition and annual cycle
  - Ocean: 4-D T (tropics) and S (high-lats) most important
    - Argo (2KM depth) global float array big improvement
  - Sea-ice: Have extent, need thickness
  - Land: Water (Snow, Soil, River) and Vegetation (LAI/Land cover)

Long Adjustment Time

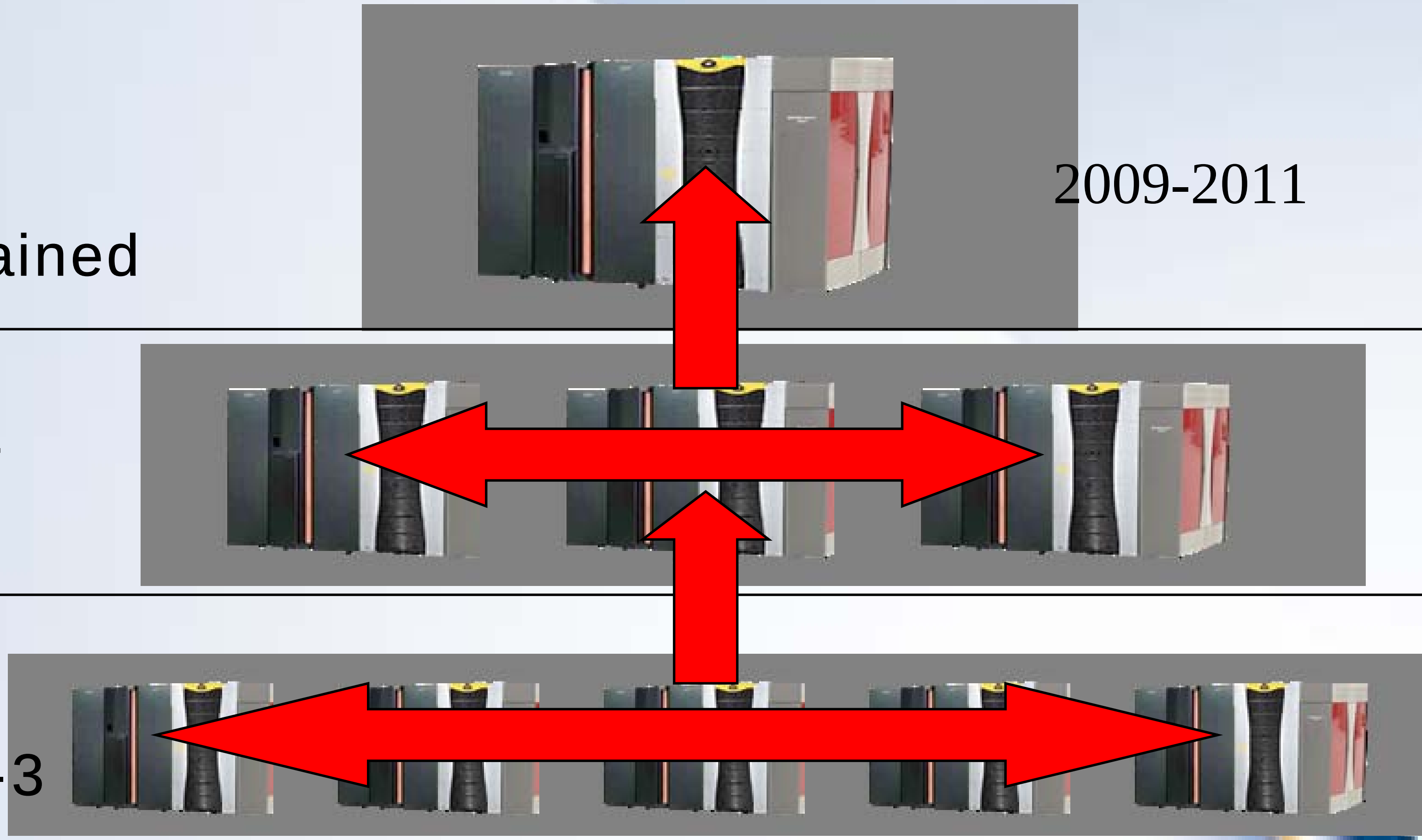
NSF Cyberinfrastructure General Purpose Platforms

Track-1
1Pf sustained

2009-2011

Track-2
100 Tf

Track-3

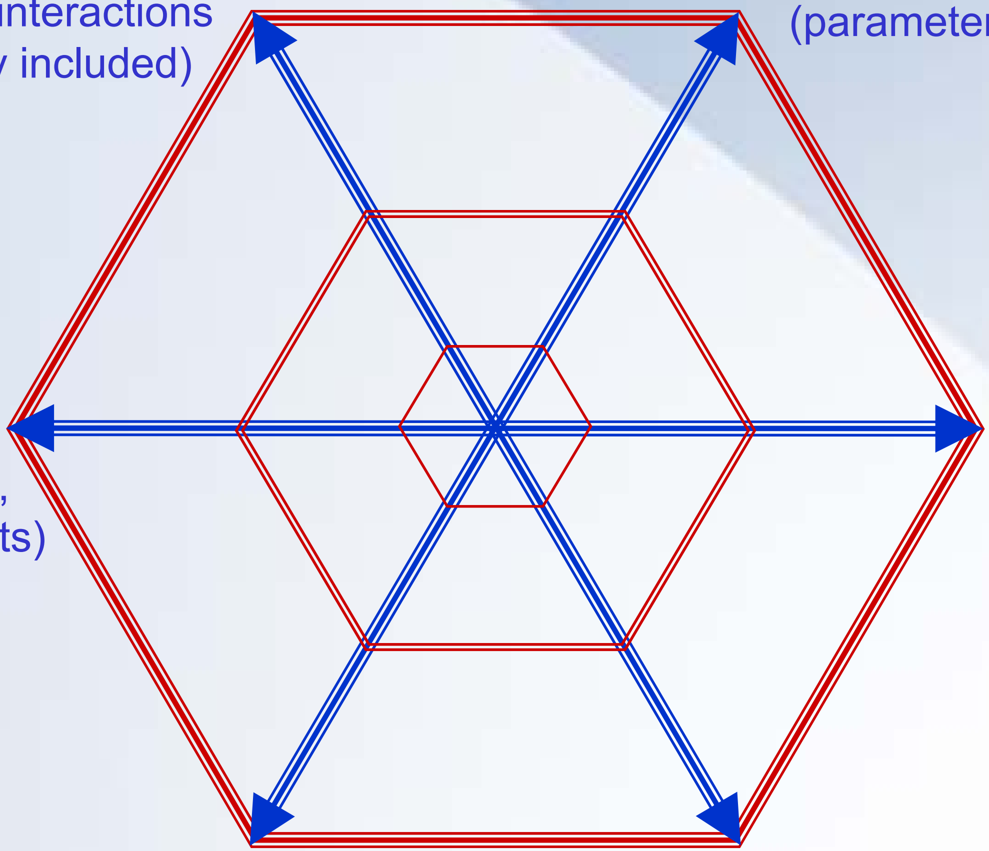


Petascale Climate Simulations

- Topic 1. Across scale modeling: simulation of the 21st century climate with a coupled atmosphere-ocean model at 0.1 degree resolution (eddy resolving in the ocean). For specific time periods of the integration, shorter-time simulations with higher spatial resolution: 1 km with a nonhydrostatic global atmospheric model and 100 m resolution in a nested regional model. Emphasis will be put the explicit representation of moist turbulence, convection and hydrological cycle.

- Topic 2. Interactions between atmospheric layers and response of the atmosphere to solar variability. Simulations of the atmospheric response to 10-15 solar cycles derived by a high-resolution version of WACCM (with explicit simulation of the QBO) coupled to an ocean model.

HPC dimensions of Climate Prediction



New Science
(new processes/interactions not previously included)

Better Science
(parameterization → explicit model)

Spatial Resolution
(simulate finer details, regions & transients)

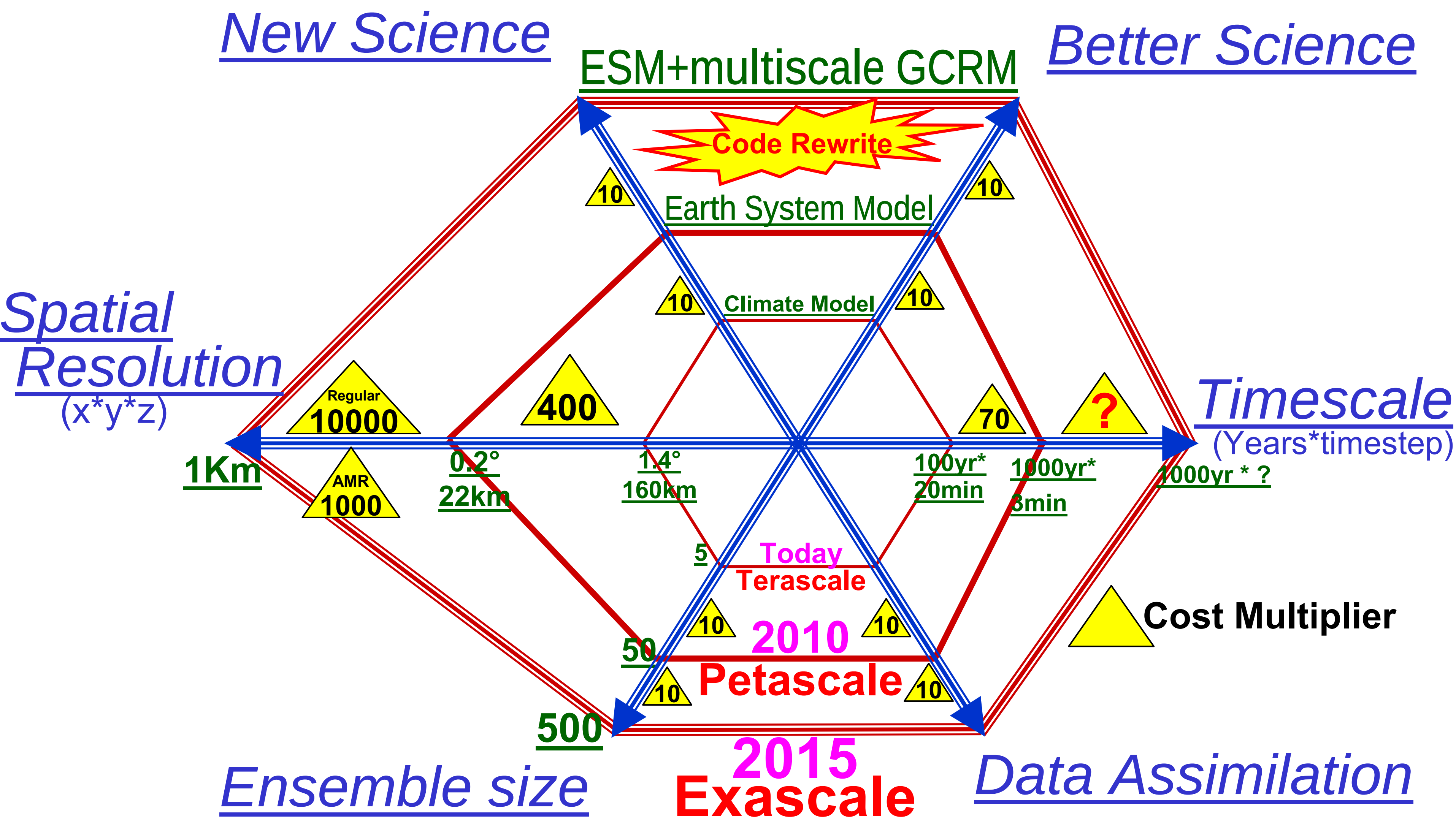
Timescale
(Length of simulations * time step)

Ensemble size
(quantify statistical properties of simulation)

Data Assimilation
(decadal prediction/ initial value forecasts)

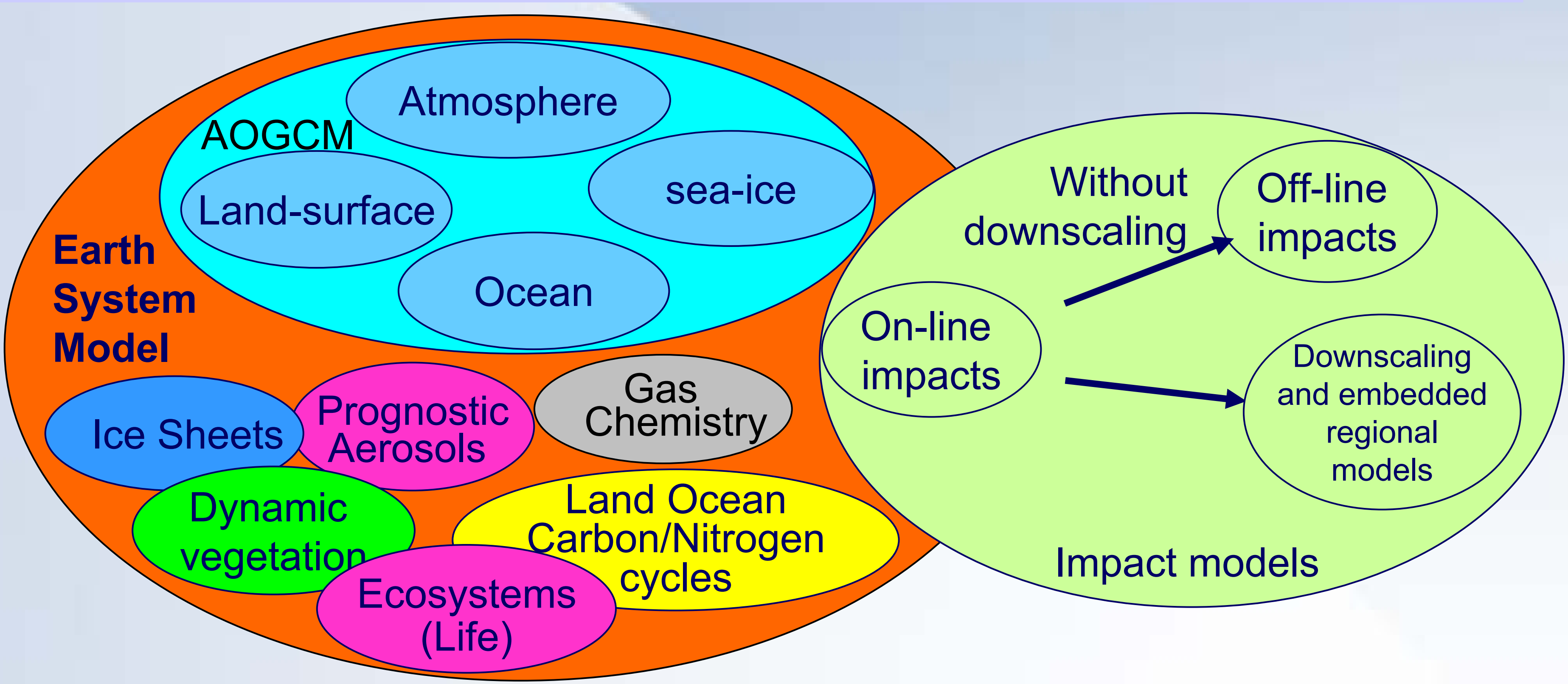
Lawrence Buja (NCAR) / Tim Palmer (ECMWF)

HPC dimensions of Climate Prediction

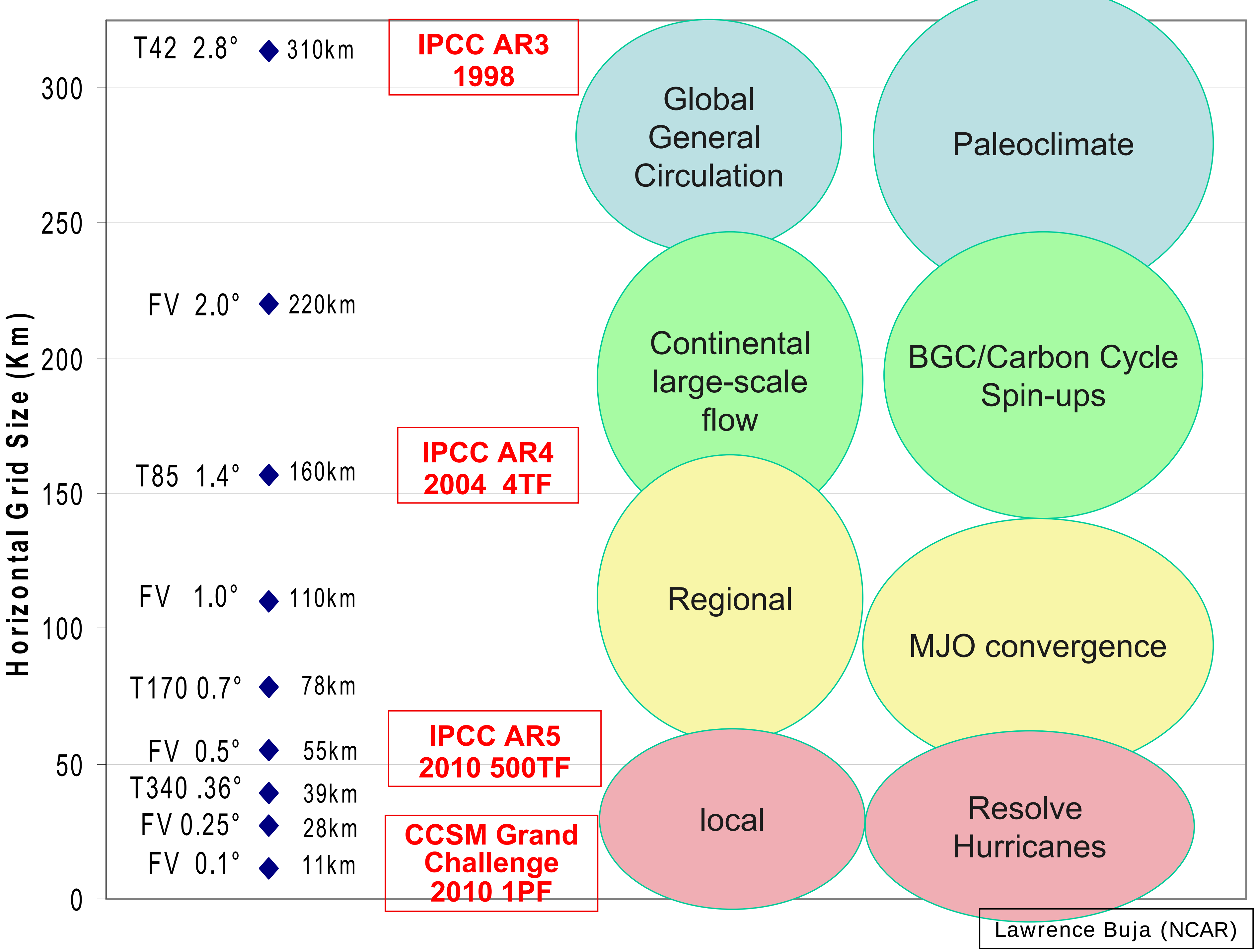


Lawrence Buja (NCAR)

From ESMs To Impacts

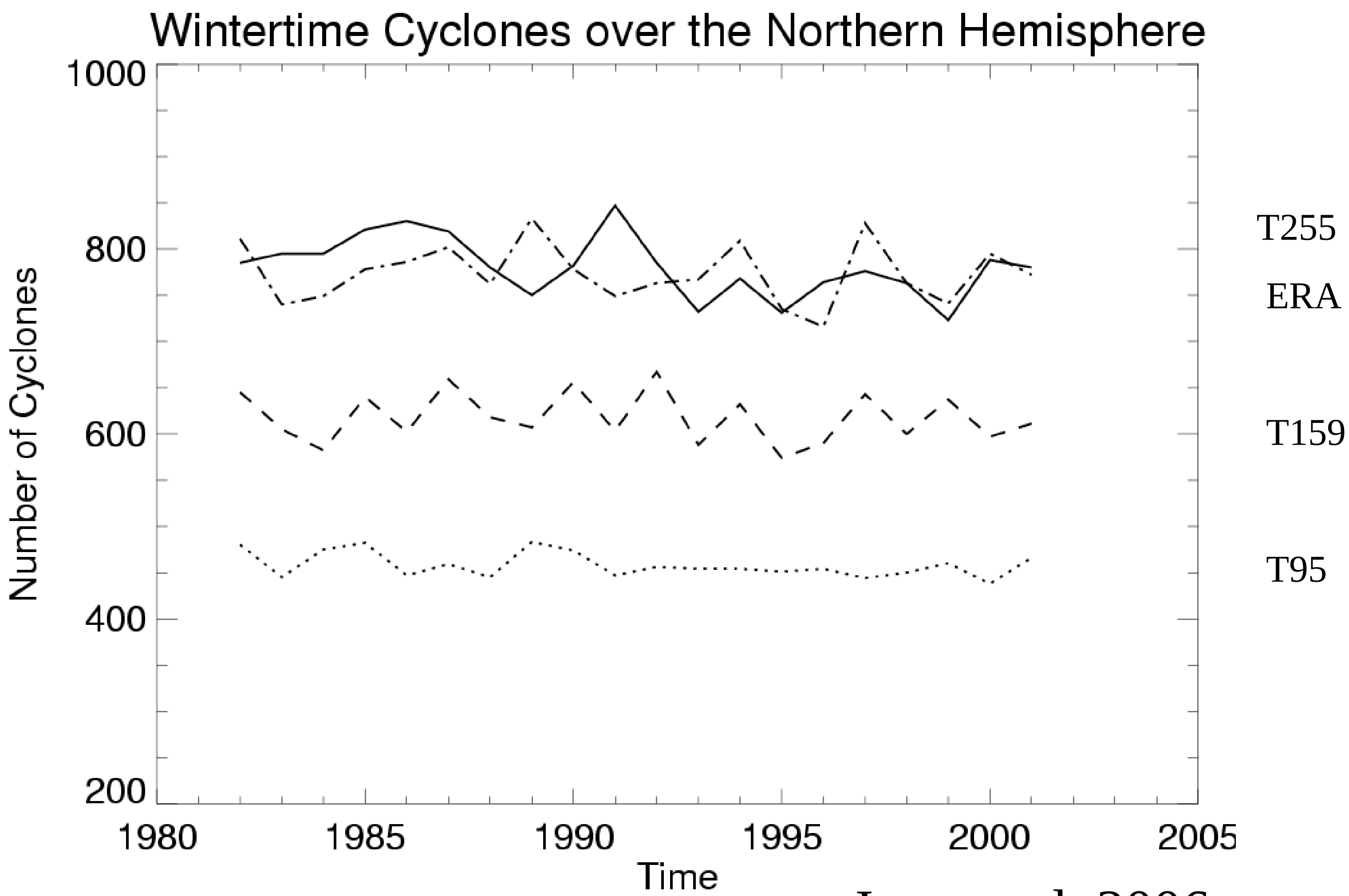


Schematic of an AOGCM (oval at upper left) and Earth System model (in orange oval) and various types of impact models (right).

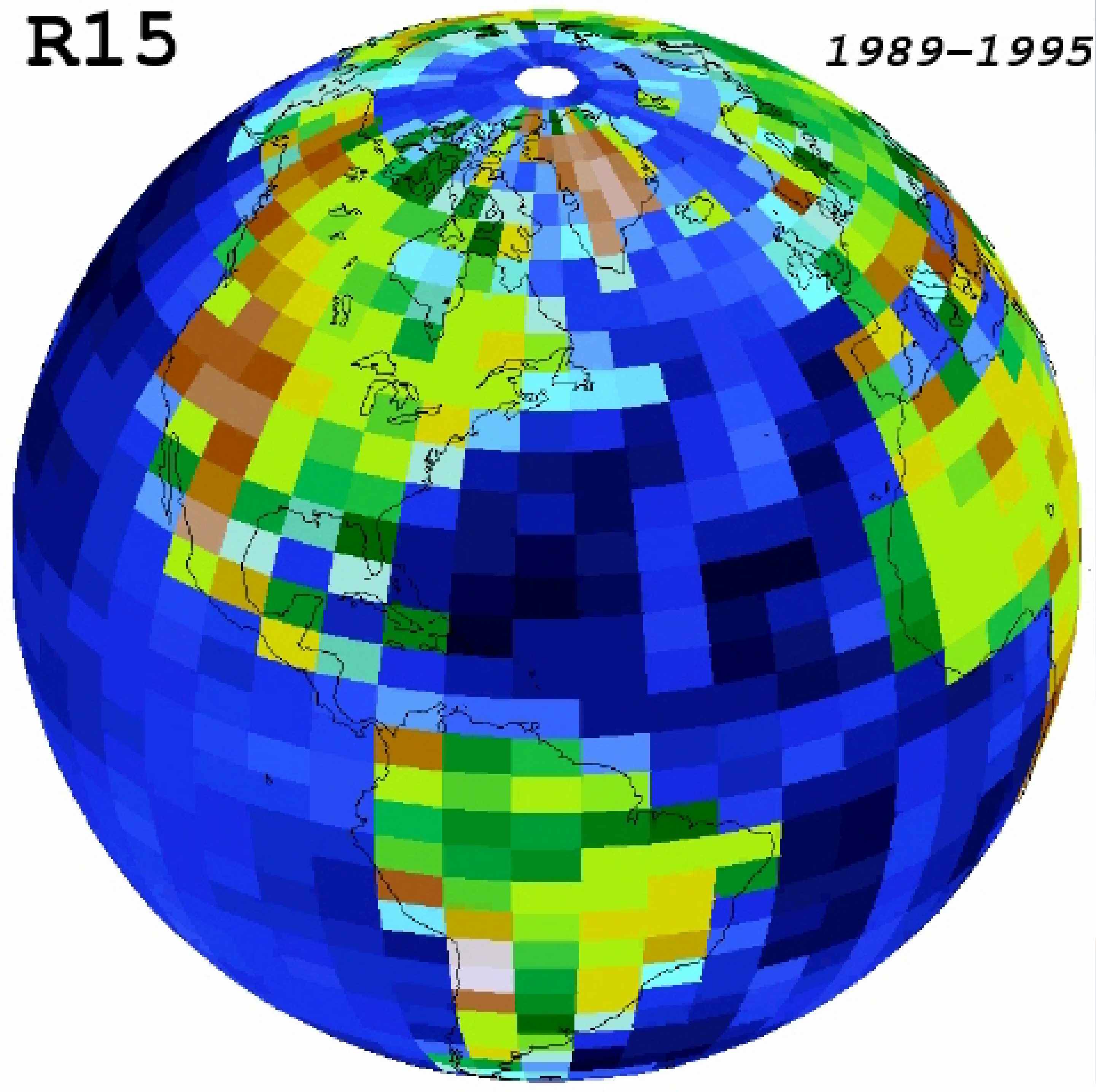


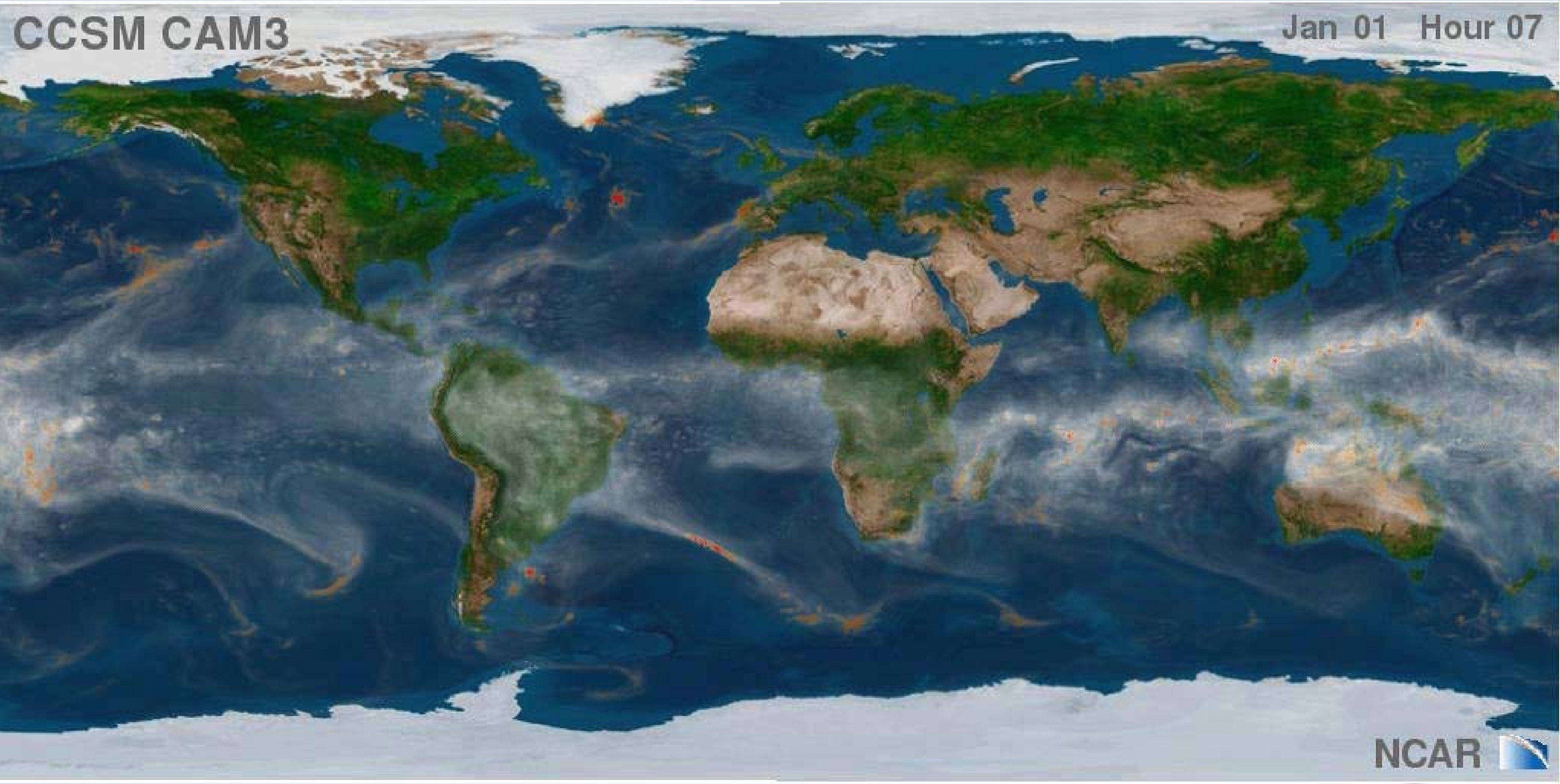
Horizontal Grid Size (Km)
300
250
200
150
100
50
0
T42 2.8° 310km
FV 2.0° 220km
T85 1.4° 160km
FV 1.0° 110km
T170 0.7° 78km
FV 0.5° 55km
T340 .36° 39km
FV 0.25° 28km
FV 0.1° 11km
IPCC AR3 1998
IPCC AR4 2004 4TF
IPCC AR5 2010 500TF
CCSM Grand Challenge 2010 1PF
Global General Circulation
Paleoclimate
Continental large-scale flow
BGC/Carbon Cycle Spin-ups
Regional
MJO convergence
local
Resolve Hurricanes
Lawrence Buja (NCAR)

Number of Northern Hemisphere Cyclones



Jung et al. 2006

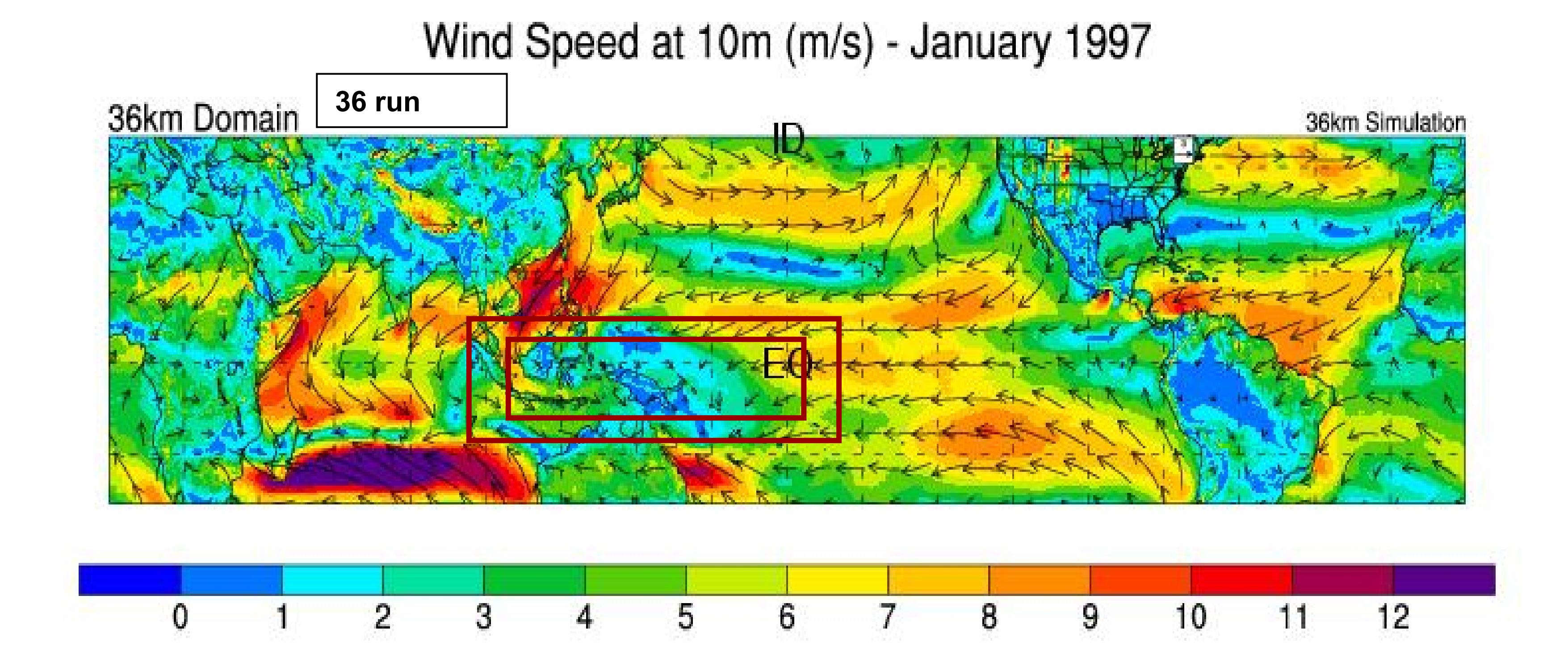

R15
1989–1995

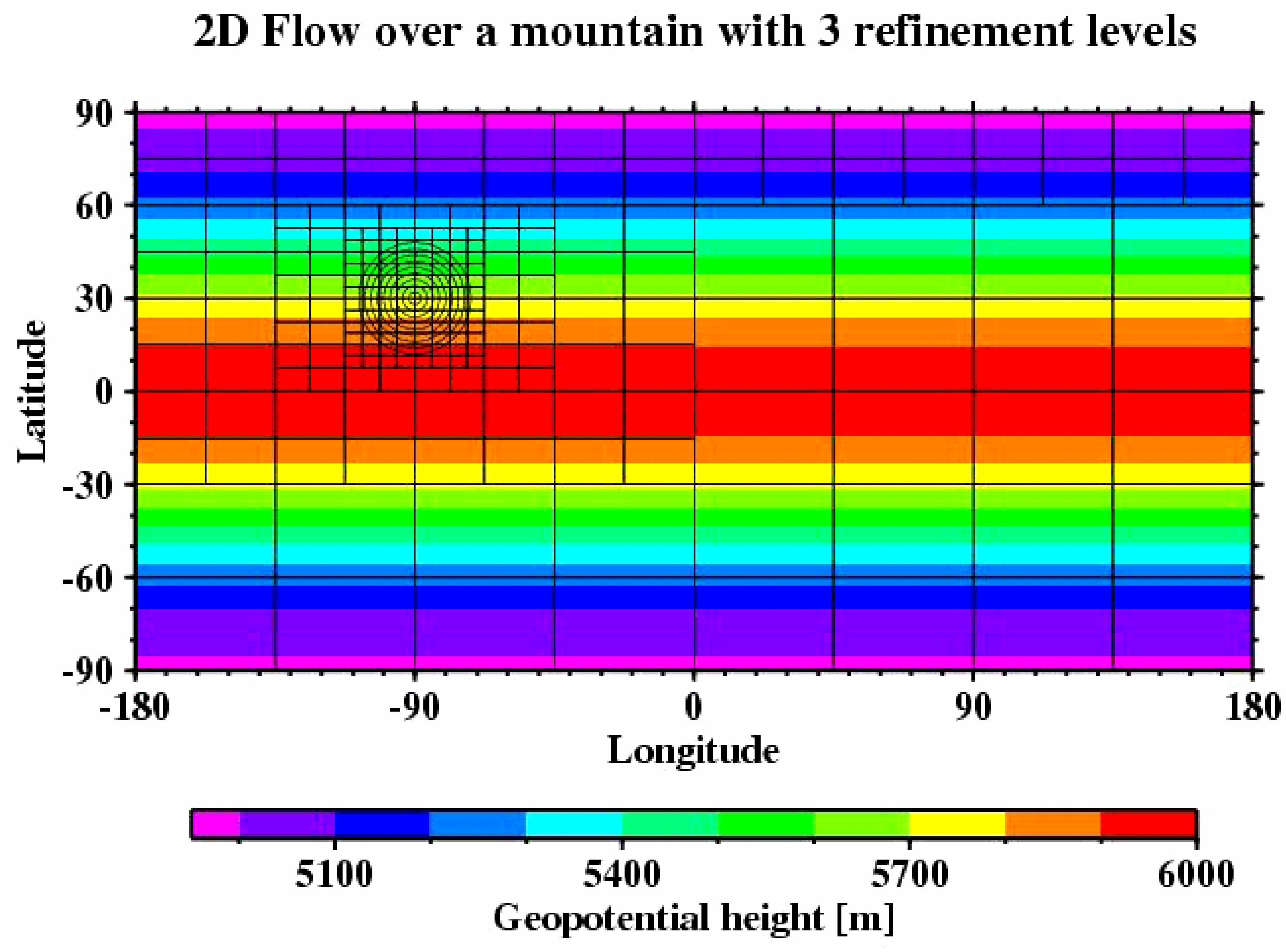

CCSM CAM3
Jan 01 Hour 07
NCAR

Nested Regional Climate Model

Joint initiative: MMM, CGD and PNL:

- ***First Step: Downscaling for US climate forecasting;***
- ***Second Step: Tropical Channel Model with 2-way nested high-resolution grids to investigate development and role of tropical modes and scale interactions;***
- ***Next Step: Fully nested within CAM and CCSM in 2-way interactive mode.***





2D Flow over a mountain with 3 refinement levels
90
60
30
0
-30
-60
-90
Latitude
-180
-90
0
90
180
Longitude
5100
5400
5700
6000
Geopotential height [m]

Community Climate System Model (CCSM)

Current Configuration

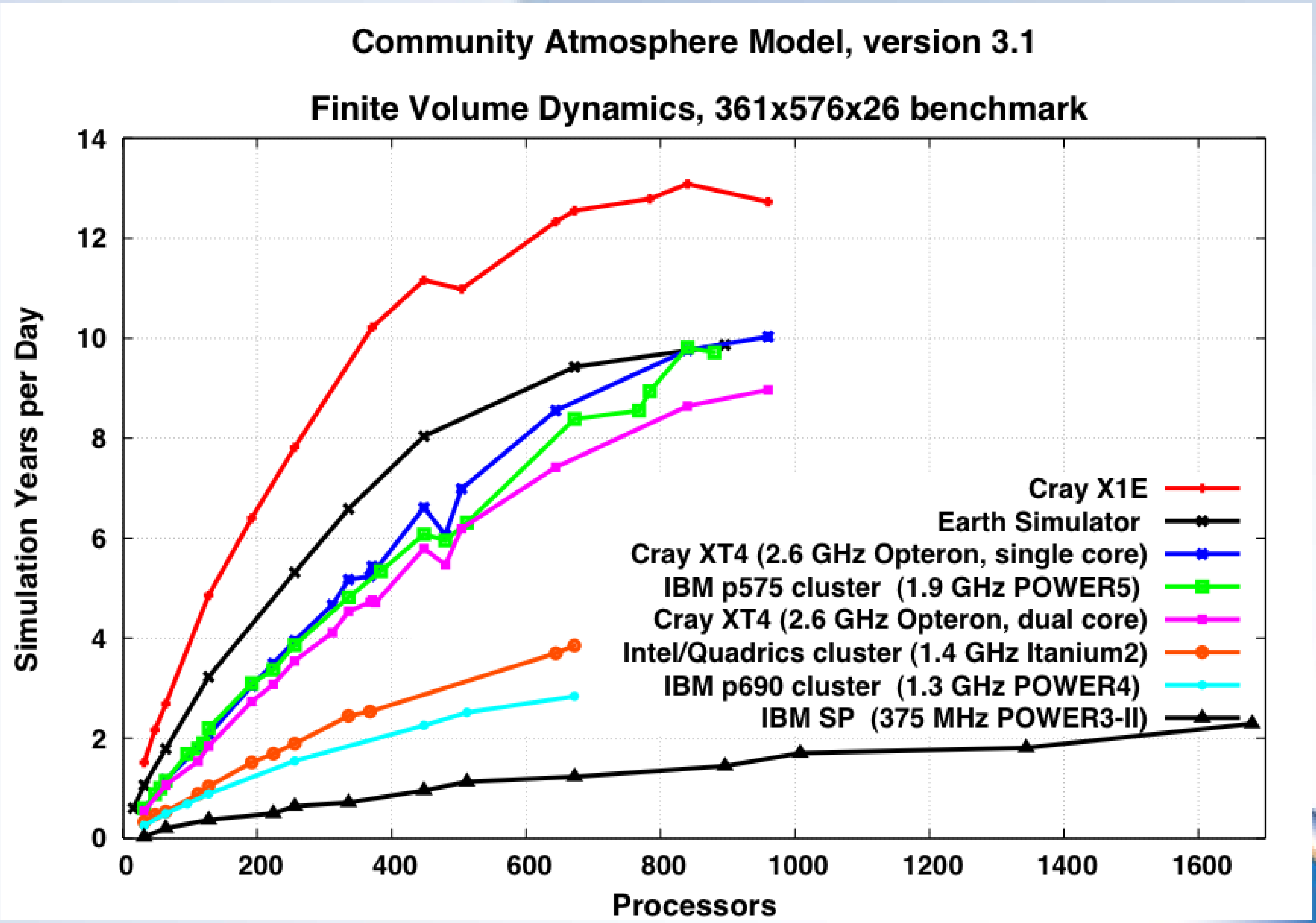
- Hub and spoke design with single or multiple executables
- Exchange boundary information through coupler
- Each code quite large: 60-200k lines per code
- Need 5 simulated years/day --> Must run at “low” resolution
- Standard configuration run at scaling sweetspot of O(200) processors

Petascale Configuration

- Single executable at ~5 years wall-clock day
- Targeting 10K - 120K processors per simulation
  - CAM @ 0.25° (30 km, L66)
  - POP @ 0.1° Demonstrated 8.5 years/day on 28K Bluegene
  - Sea-Ice @ 0.1° Demonstrated 42 years/day on 32K Bluegene
  - Land @ 0.1°
  - Cpl

CAM Performance

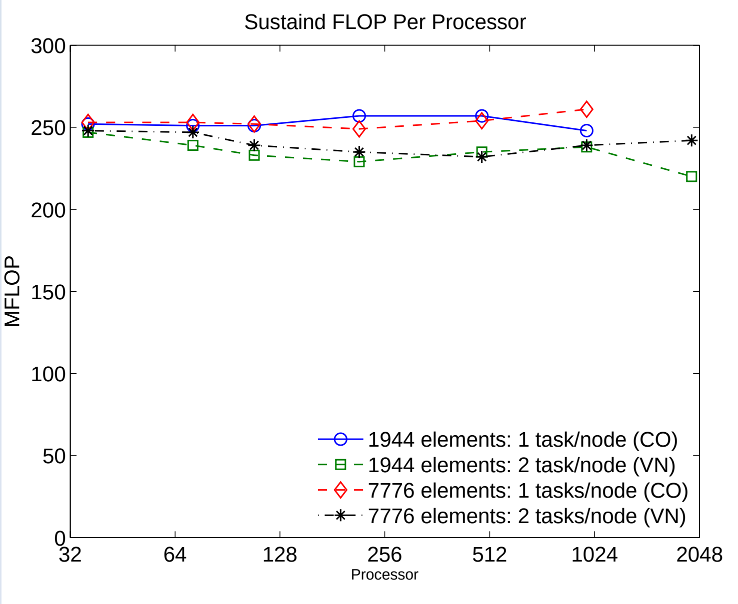
(Pat Worley, ORNL)

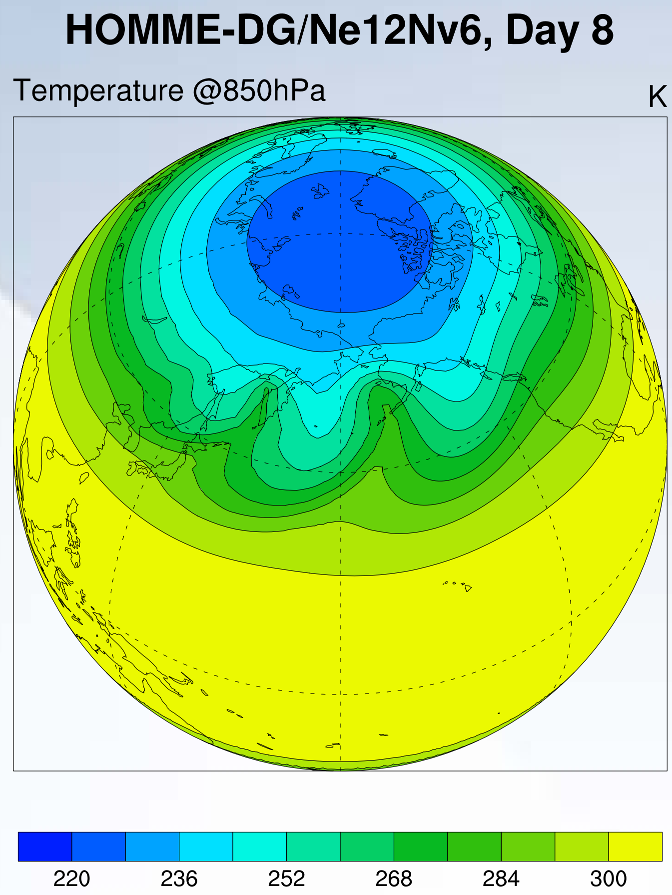


High-Order Method Modeling Environment (HOMME)

Ram Nair, Henry Tufo

The High-Order Method Modeling Environment (HOMME) is a framework to investigate using high-order element based methods to build conservative and accurate atmospheric general circulation models (AGCMs). Currently, HOMME employs the discontinuous Galerkin and spectral element methods on a cubed-sphere tiled with quadrilateral elements to solve the primitive equations, and has been shown to scale to O(10K) processors of a Cray XT 3/4 and O(32K) processors of an IBM Blue Gene/L.

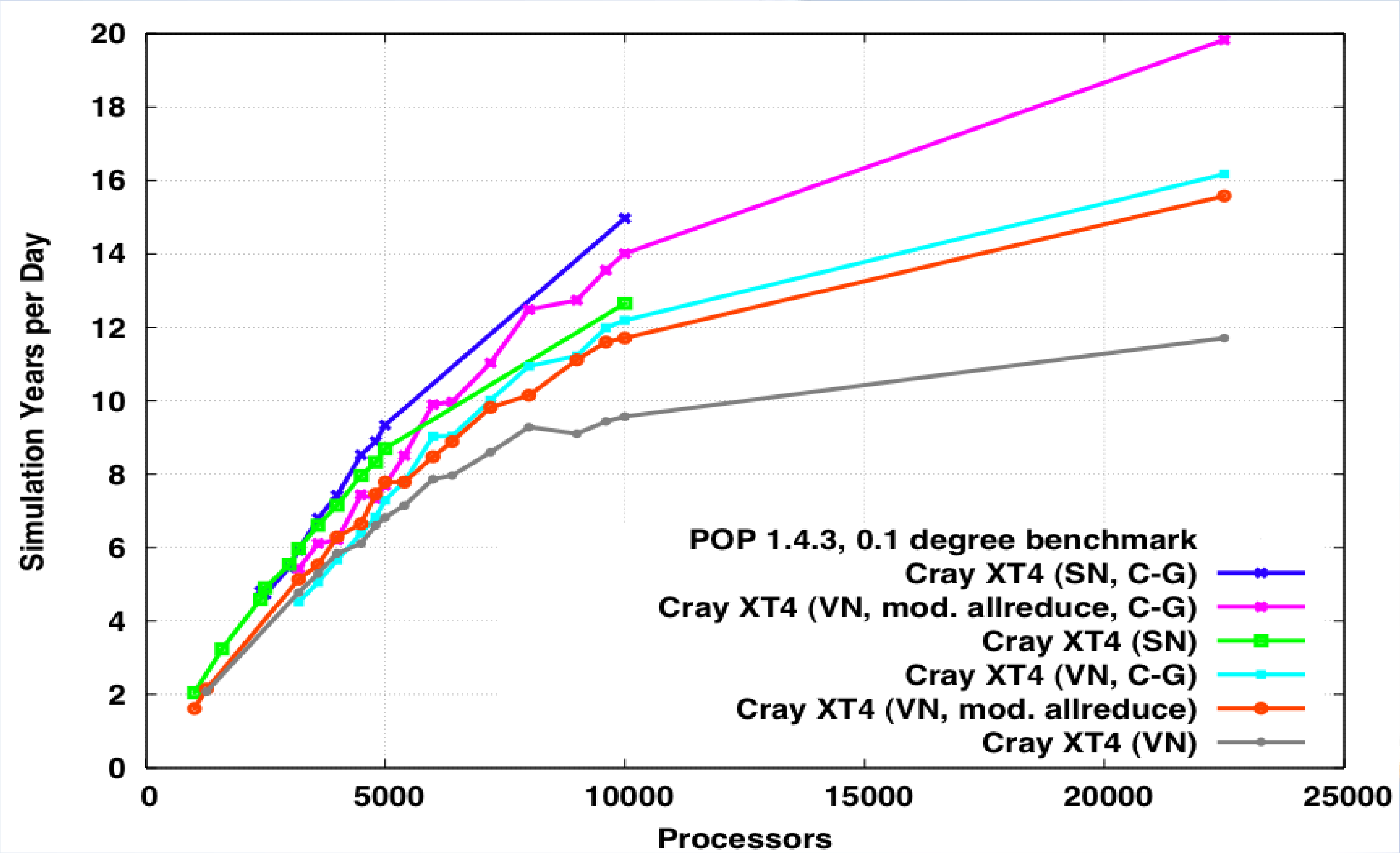




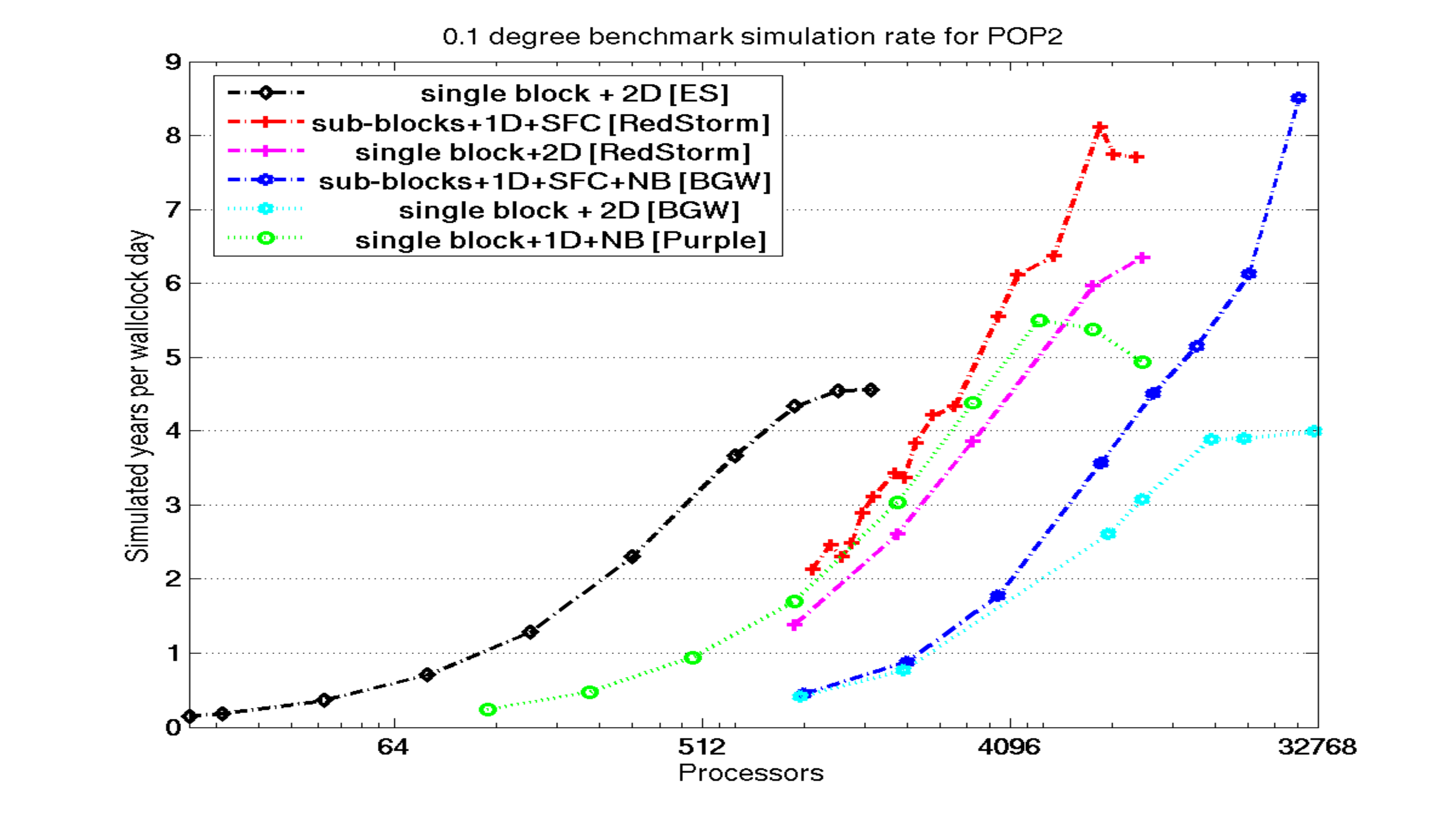
The primary objective of the HOMME project is to provide the atmospheric science community a framework for building the next generation of AGCMs based on high-order numerical methods that efficiently scale to hundreds-of-thousands of processors, achieve scientifically useful integration rates, provide monotonic and mass conserving transport of multiple species, and can be easily coupled to community physics packages.

POP Performance

(Pat Worley, ORNL)

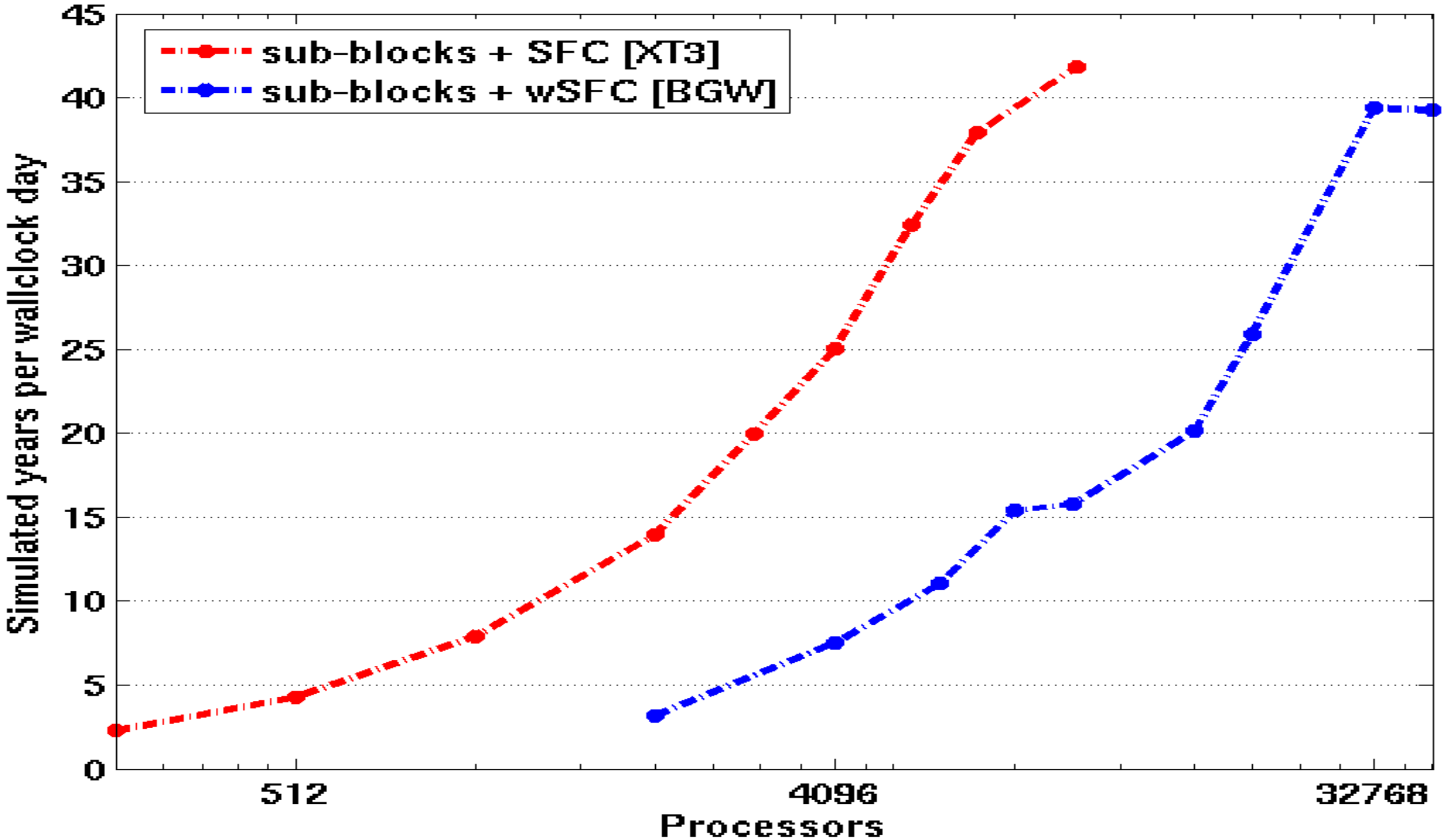


POP 0.1° benchmark



Courtesy of J. Dennis, Y. Yoshida, M. Taylor, P. Worley

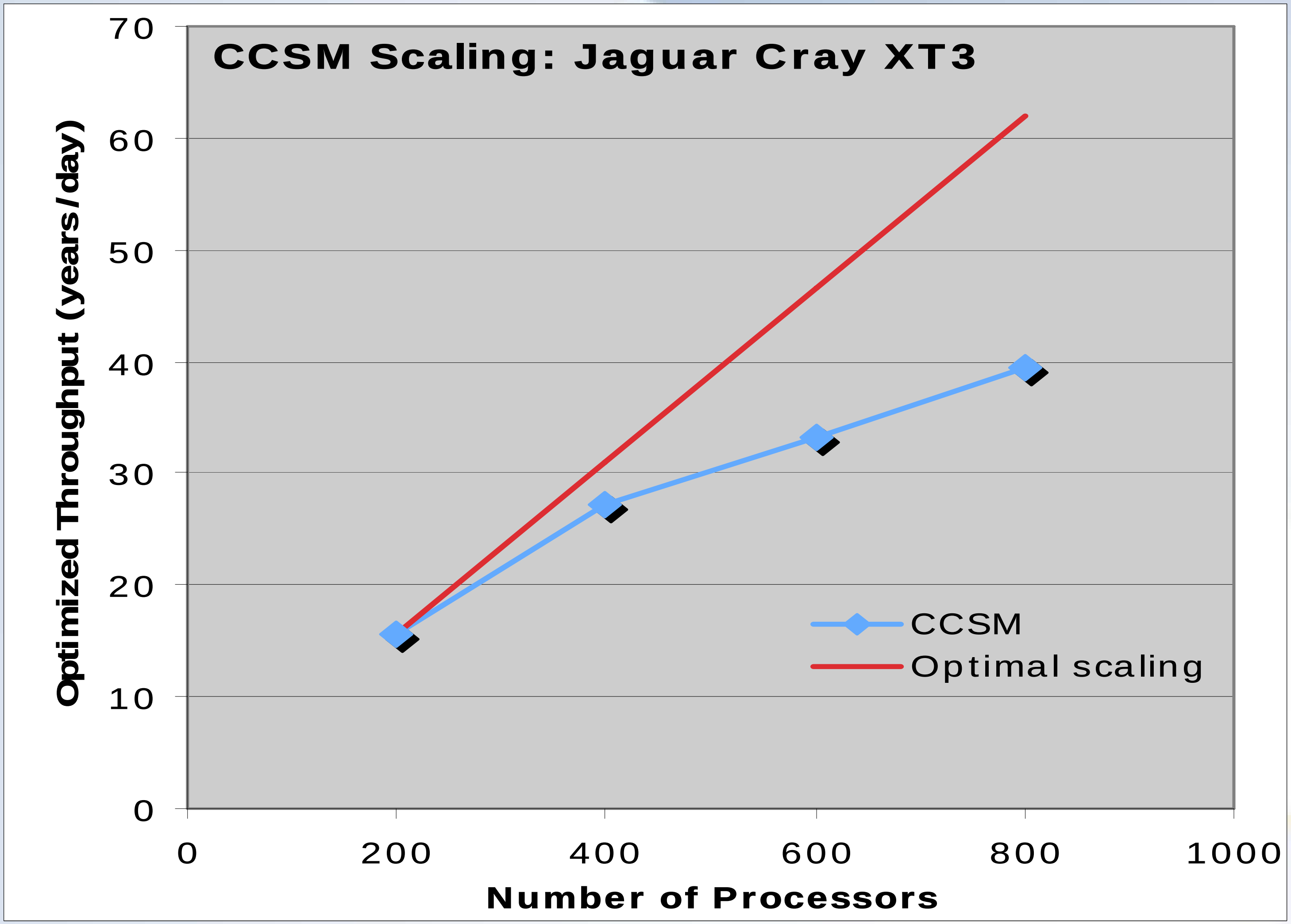
CICE4 @ 0.1°



Courtesy of John Dennis

CCSM Performance

(Jon Wolfe, NCAR)



HPC Directions

Finally heading toward "massively" parallel capabilities in our models.

- We will be running high resolution (global 1/10 degree) on 10s of thousands of processors.
- That means improving both performance and memory scaling. Of late, most of our effort has been dealing with memory scaling because machines like IBM bluegene are limited to 256 Mb to 1Gb of memory per processor. ,
- I believe a lot of the scaling success is resulting from the fact that hardware is becoming better balanced. 5 years ago, we had fast processors and less capable memory and communication systems on supercomputers. In the last 5 years, the processor speed increases have slowed, but the memory and communication system performance has been catching up, in a relative sense.
- At 1/10 degree, we might be able to have 1 global array declared at any one time. This has forced us to seriously recode various parts of the model that are usually ignored, like initialization and I/O.

We are beginning to truly require a parallel I/O capability.

- In terms of scaling, we are working on improving the scaling capabilities of models like CAM by improving decomposition strategies and reducing communication cost.

The first petascale machines will look like IBM-BG / Cray-XT4.

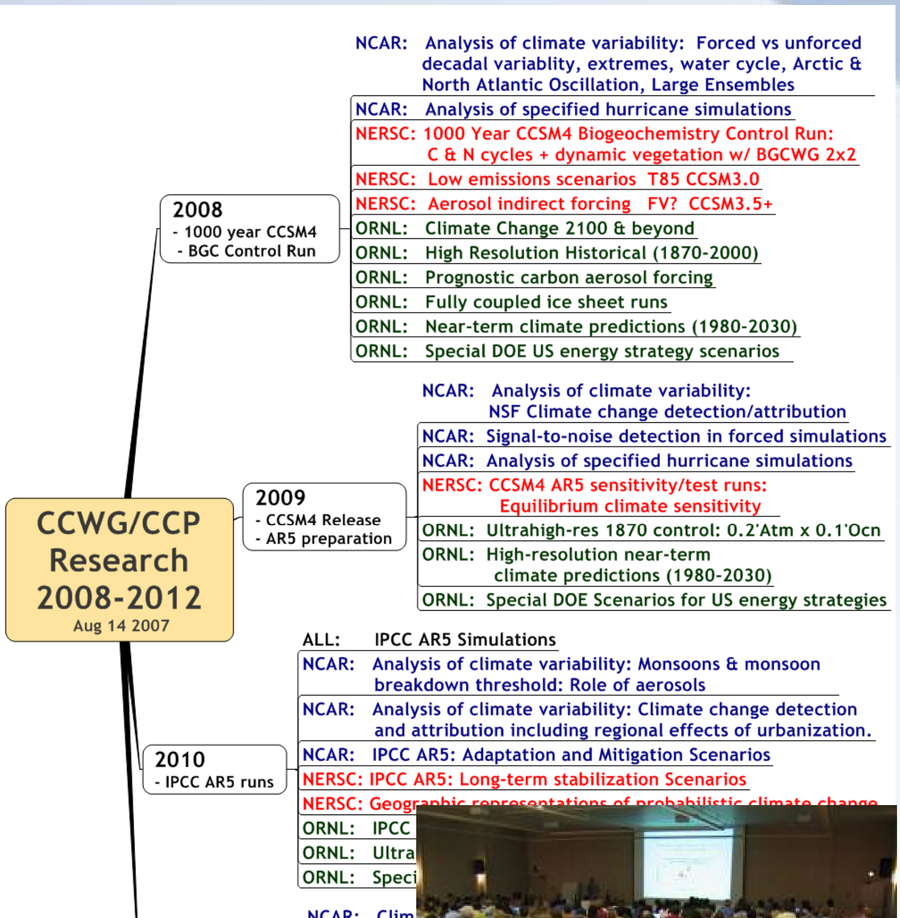
- We are migrating CCSM to a more flexible coupling strategy, focusing on single executable (instead of multiple executable) and on the ability to run models sequentially, concurrently, or a combination of the two in order to optimize performance for a given configuration. This will give us an important capability to both improve model performance and also use the hardware resources better.
- This effort is really focused on the technical ability to run higher resolution on 10s of thousands of processors. That capability will then allow the science to have a chance to evolve at these resolution, and it will also benefit our moderate resolution runs by improving our scaling capabilities.

Moving to the Petascale

- **Scientific goals:**
  - Seamless downscaling, integrated weather and climate modeling
  - Earth system modeling at eddy-resolving scale
  - Climate "snap shots" at cloud resolving scale
- **Computing:**
  - We must move to MPP with >10K processing elements (PEs) soon.
  - Systems now have 5-30K PEs, seeing success porting to these platforms.
- **Challenges:**
  - Skilled personnel for code development on these platforms
  - Scalable numerics and analysis techniques
  - Robust and fault-tolerant communication frameworks
  - HPC platforms can be very fragile
- **Common issues for all component models:**
  - Parallel IO
  - Eliminate all serial code
  - Memory usage

- **Petascale box ≠ Petascale science**

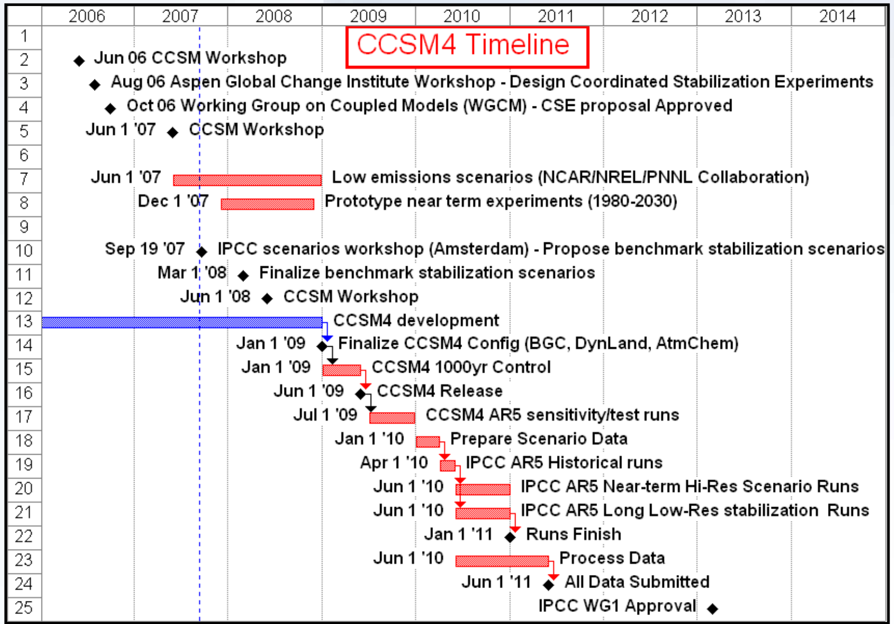
Future Plans



The current model development timeline anticipates CCSM4 in 2009 in time to participate in the next set of internationally coordinated mitigation scenario experiments in 2010-2011

short term climate change: 30-year climate predictions at higher resolution and a single scenario
long term climate change: 300-year climate change simulations at medium resolution and carbon cycle for benchmark mitigation scenarios

A next-generation Earth System Model will also be under development during this time period.



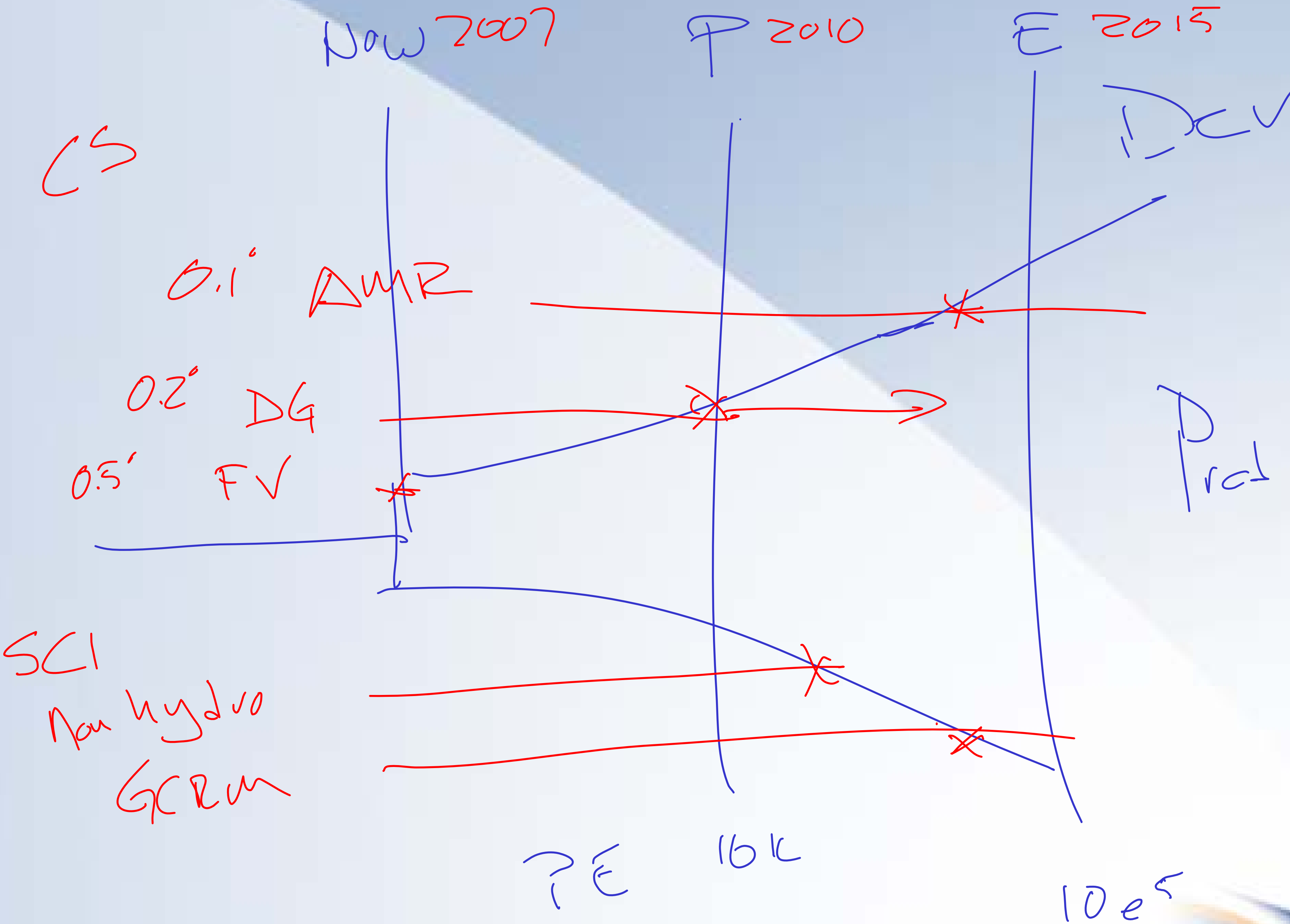
The overarching goal is to ensure that CCSM plays a substantial and credible leadership role in climate change science, and makes substantial contributions to national and international coordinated climate change experiments and assessments

Final Thoughts on Future Directions/Needs

1. More computationally parallel versions of CCSM that can run efficiently on new generation parallel supercomputer systems
2. We are beginning to experience a Data Tsunami"
3. Balanced Systems" (HPC+DataStorage+Portal) needed.
4. Talented people are the limiting resource
5. Continued DOE/NSF interagency collaboration essential.

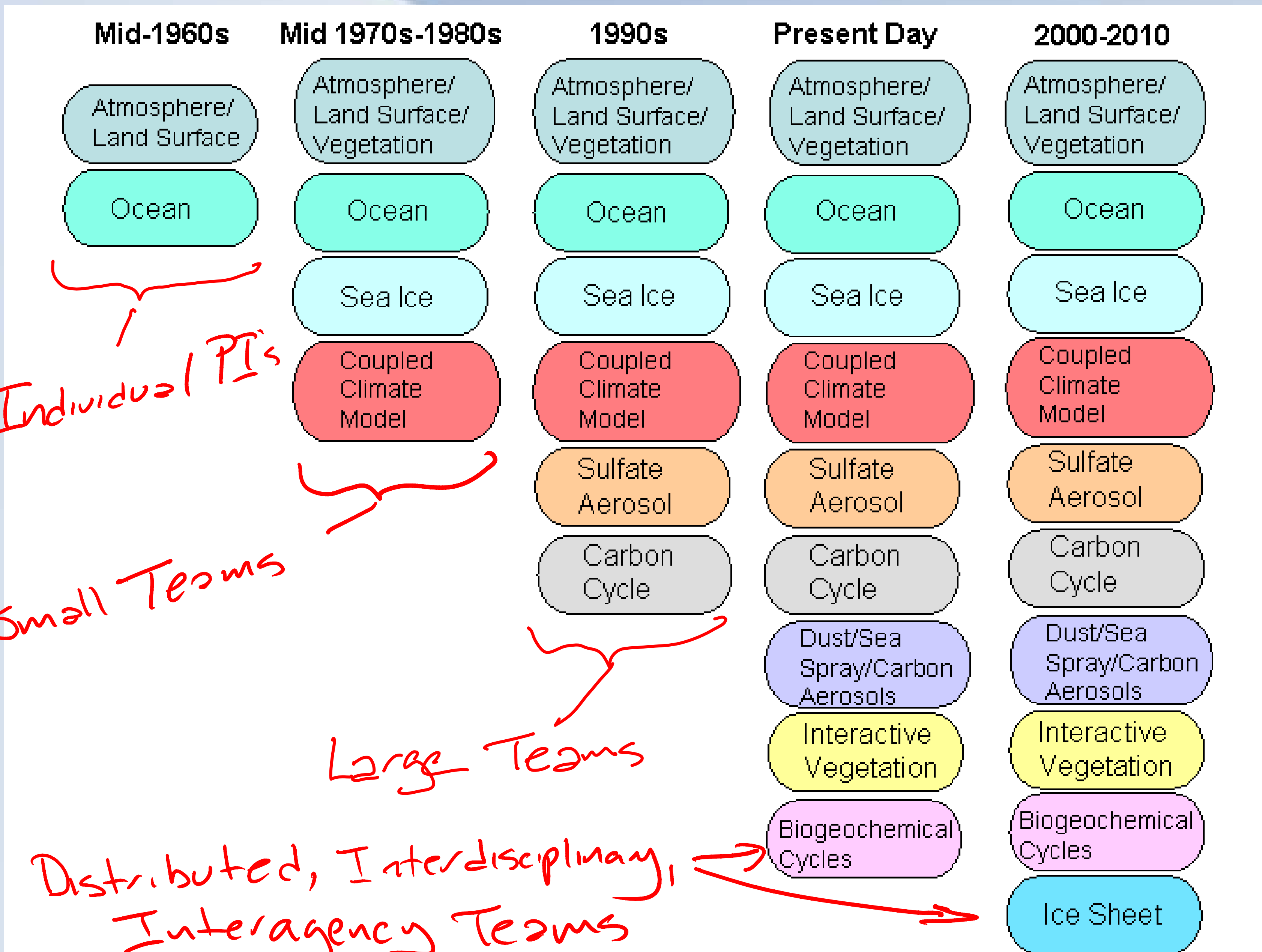
6. We need versions of CCSM that have less biases and capture ENSO and other natural variability more realistically
7. High Resolution versions that resolve hurricanes, cyclones and ocean eddies -> Global Cloud Resolving Models
8. Moderate Resolution Version that have carbon, nitrogen and related chemical/biogeochemical cycles
9. Better treatment of aerosol effects (direct and indirect):
   sulfate, carbon, and dust

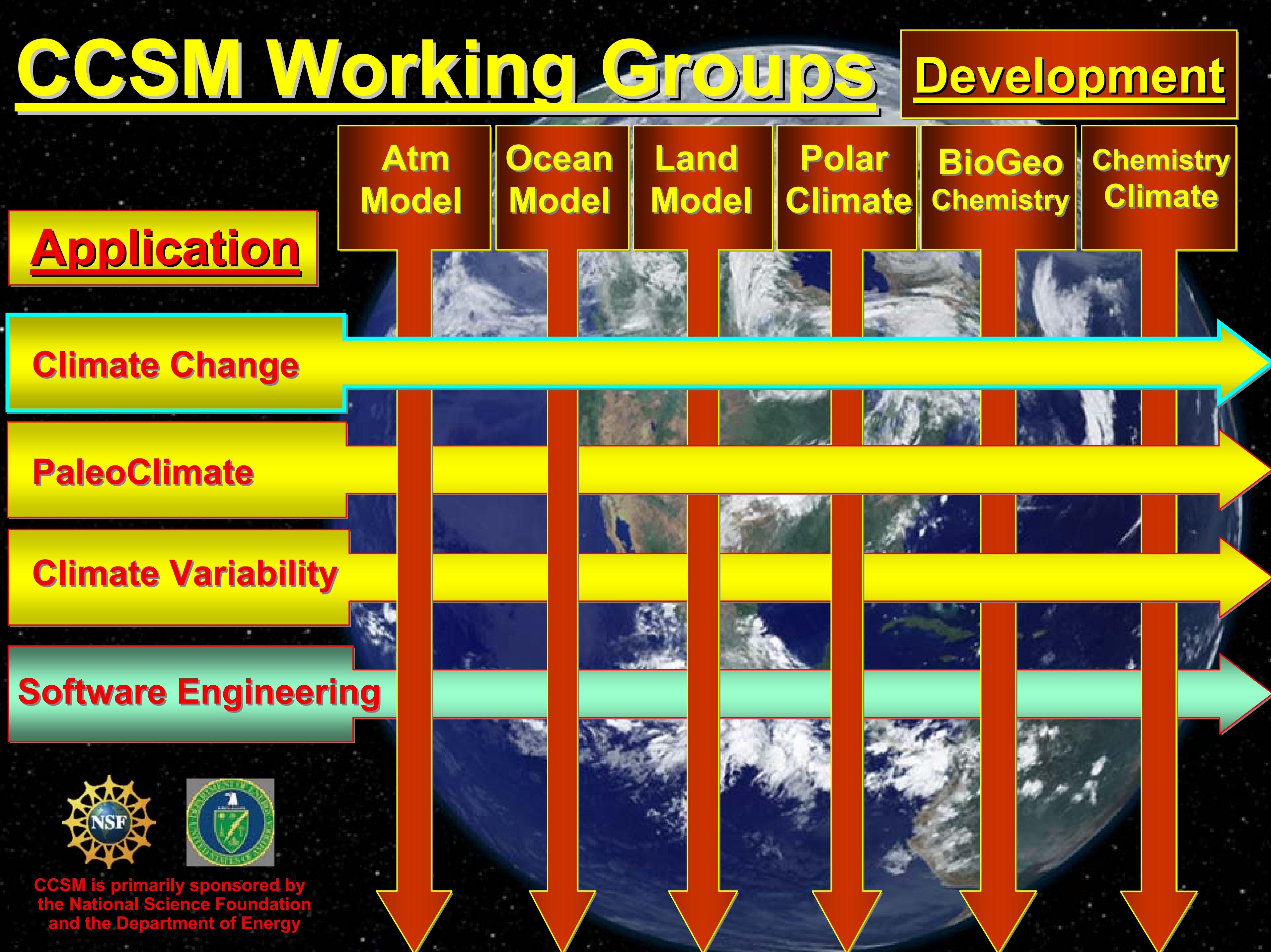
Thanks!   Any Questions?

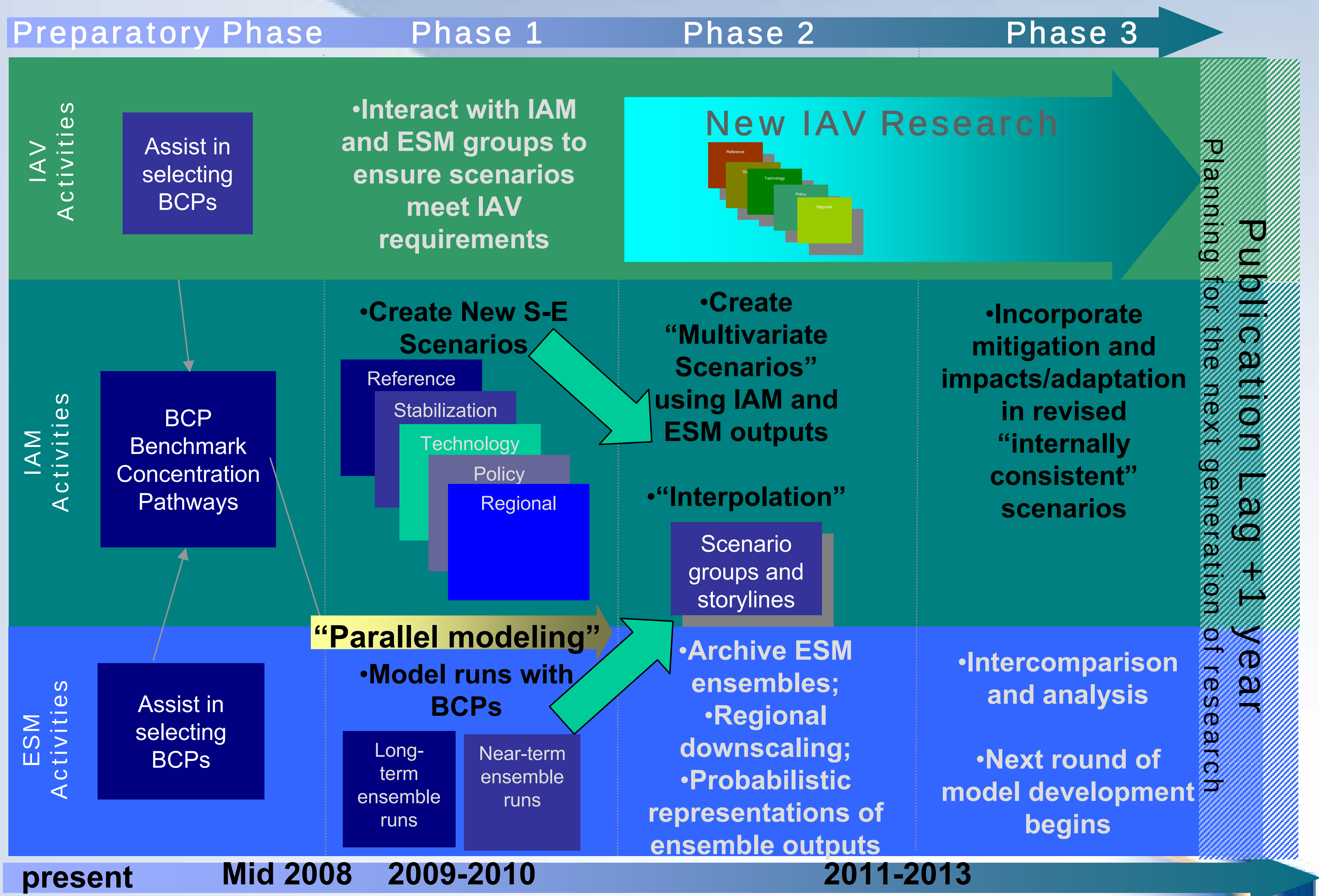


Now 2007
P 2010
E 2015
DCV
CS
0.1°
AMR
0.2°
DG
0.5°
FV
Prod
SCI
Non hydro
GCRM
PE
16K
10e5

Timeline of Climate Model Development




CCSM Working Groups
Development
Atm Model
Ocean Model
Land Model
Polar Climate
BioGeo Chemistry
Chemistry Climate
Application
Climate Change
PaleoClimate
Climate Variability
Software Engineering
NSF
CCSM is primarily sponsored by the National Science Foundation and the Department of Energy



Jerry Meehl, NCAR