Computational and Informational Technology Rate Limiters to the Advancement of Climate Change Science

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Climate Science Subcommittee

Charged on 15 August 2007

Constituted on 10 September 2007

James Hack, NCAR (Co-chair)
Eugene Bierly, AGU (Co-chair)
Dave Bader, LLNL
Phil Colella , LBL
William Collins , LBL
John Drake, ORNL
Ian Foster, ANL
Brian Gross, GFDL
Philip Jones , LANL
Edward Sarachik, Univ of Washington
Dean Williams, LLNL

Teleconference in early October

Subcommittee meeting at AGU on October 16-17 2007

ASCAC-BERAC Subcommittee Panel Meeting

- Ground rules?
  - we need to interpret charge broadly
  - we cannot solve the world’s climate problems
  - need to converge on a few key points
    - focused on DOE’s strengths, opportunities for leverage
    - stay away from institutional issues as much as possible
  - goal is relatively short balanced response
    - point to upcoming NRC (and other) reports

Bottlenecks to progress in climate modeling investments by ASCR and BER

Well balanced?

ASCR- facilities/infrastructure investments		BER- Basic science/observational/modeling investments
Computational solutions	↔	Computational requirements
Software solutions	↔	Software needs
Algorithm/applied math sol'ns	↔	Algorithm needs (e.g.,efficiency)
Data management solutions	↔	Data management needs
Networking solutions	↔	Networking needs
Collaboration technology	↔	Collaboration technology needs
Adequate investments here to ensure progress?? ⇒	{	Investments in basic knowledge Investments in observations Investments in modeling techniques

Global Mean Surface Temperature Anomalies

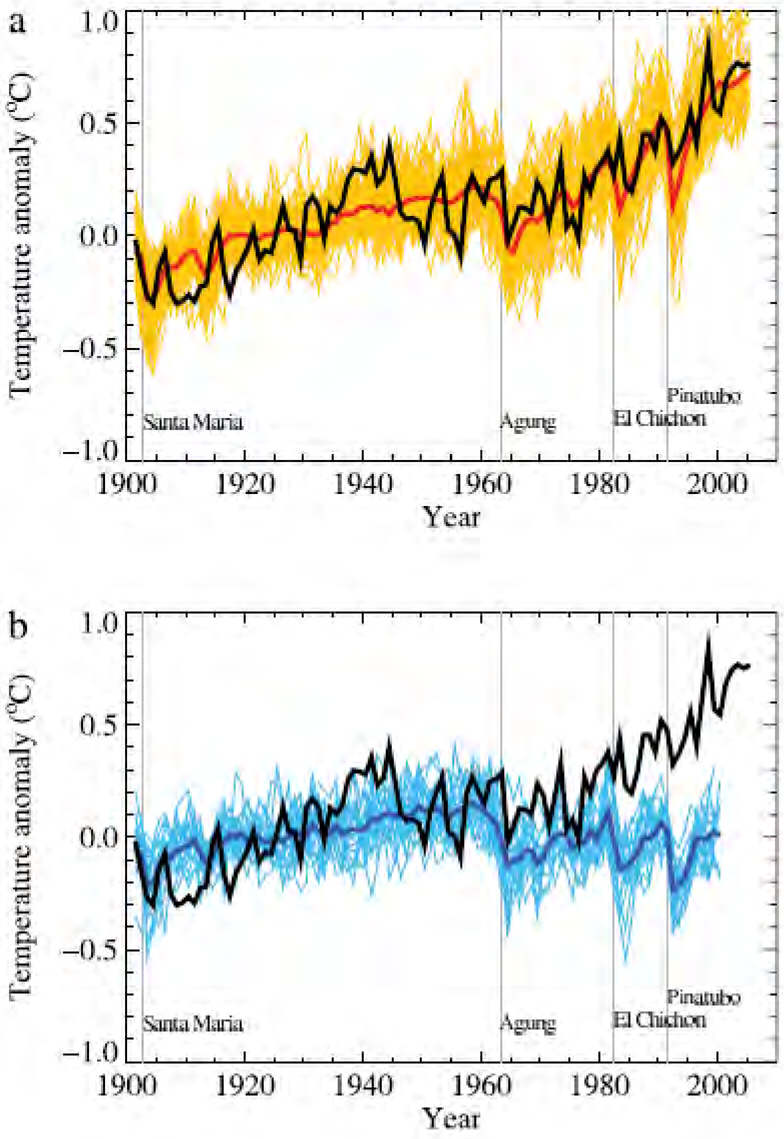
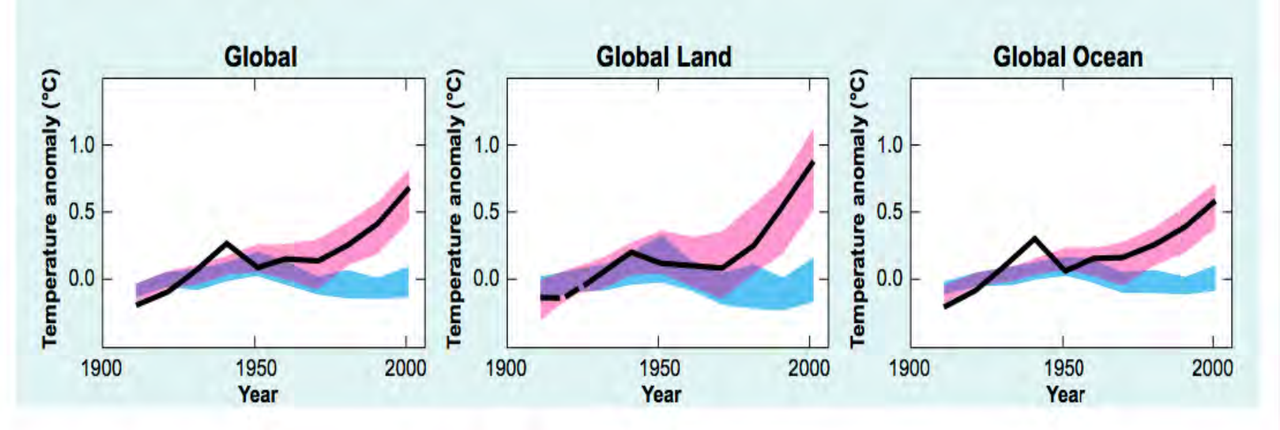


Figure TS.23. (a) Global mean surface temperature anomalies relative to the period 1901 to 1950, as observed (black line) and as obtained from simulations with both anthropogenic and natural forcings. The thick red curve shows the multi-model ensemble mean and the thin lighter red curves show the individual simulations. Vertical grey lines indicate the timing of major volcanic events. (b) As in (a), except that the simulated global mean temperature anomalies are for natural forcings only. The thick blue curve shows the multi-model ensemble mean and the thin lighter blue curves show individual simulations. Each simulation was sampled so that coverage corresponds to that of the observations. {Figure 9.5}

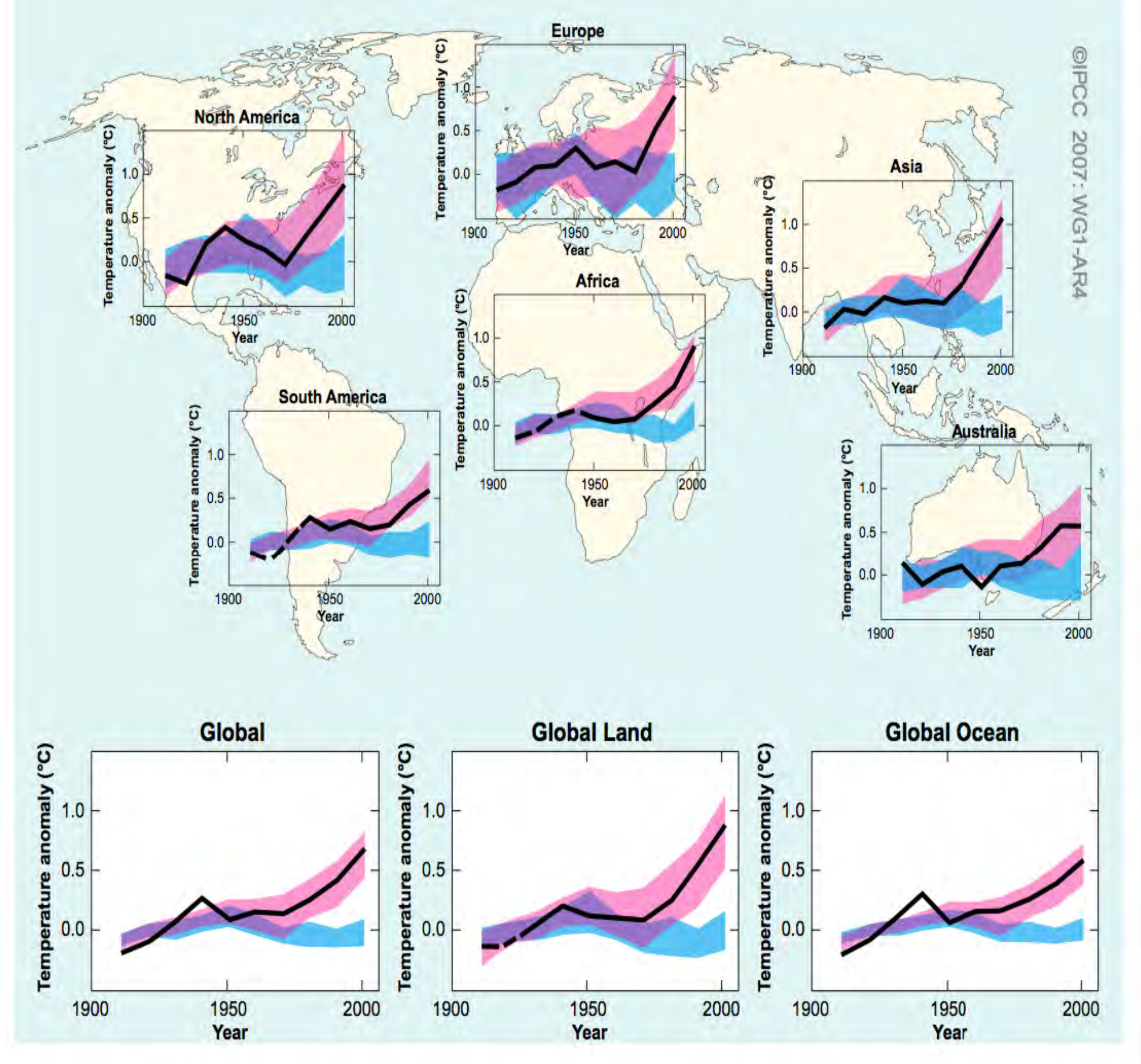
Summary for Policymakers (IPCC AR4)

Global and Continental Temperature Change



Summary for Policymakers (IPCC AR4)

Global and Continental Temperature Change

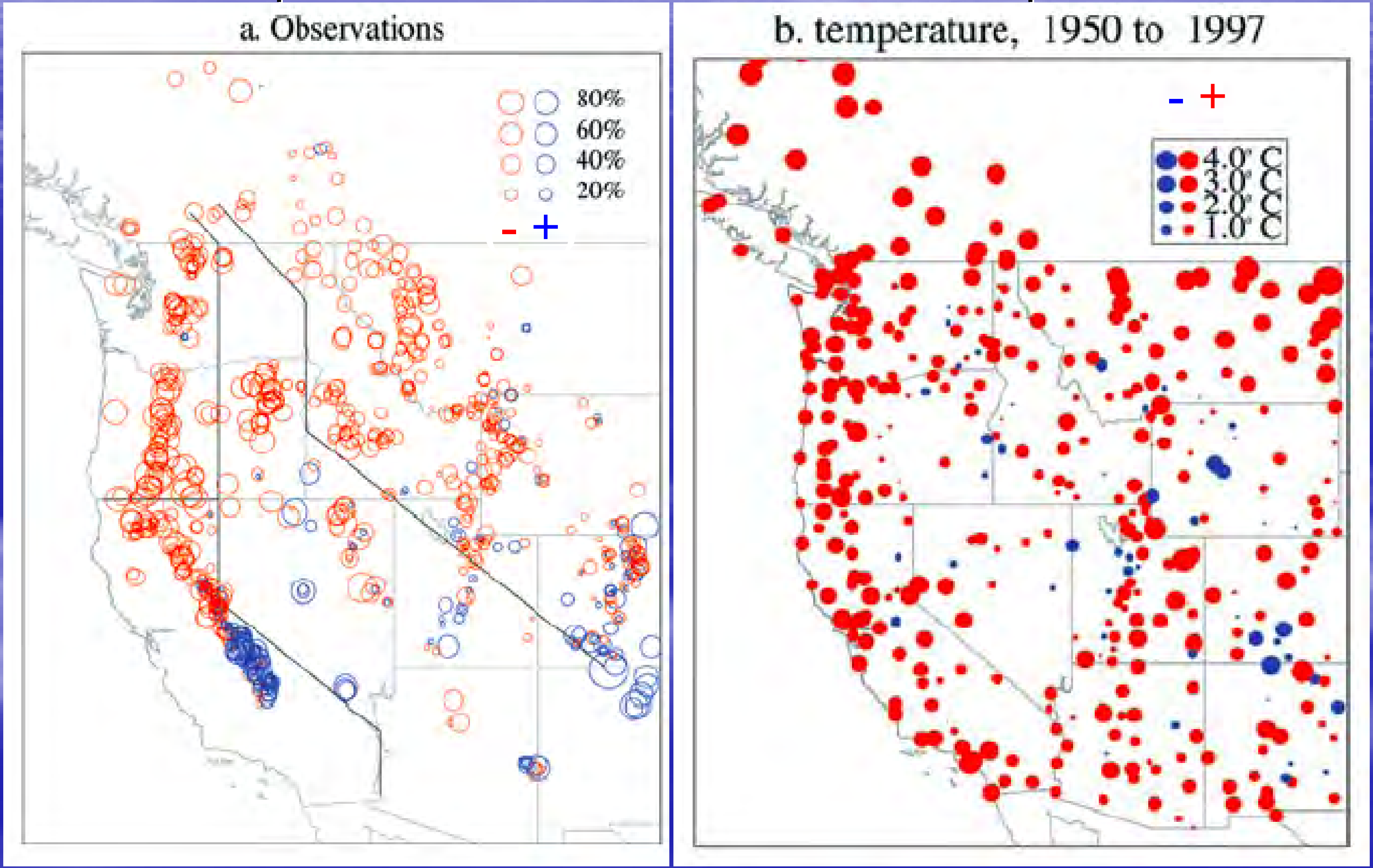


Regional Impacts of Climate Change

Observed Change 1950-1997

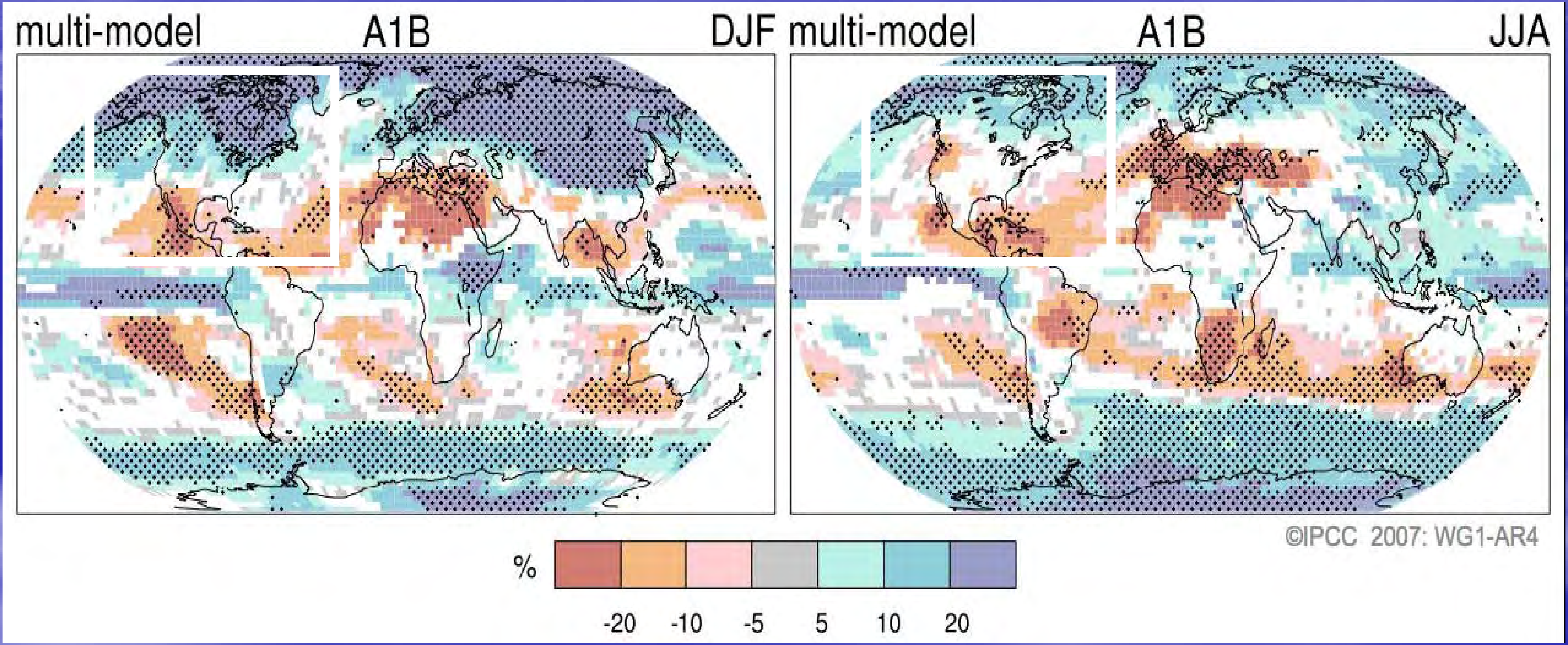
Snowpack

Temperature



Mote et al 2005

Regional Climate Change

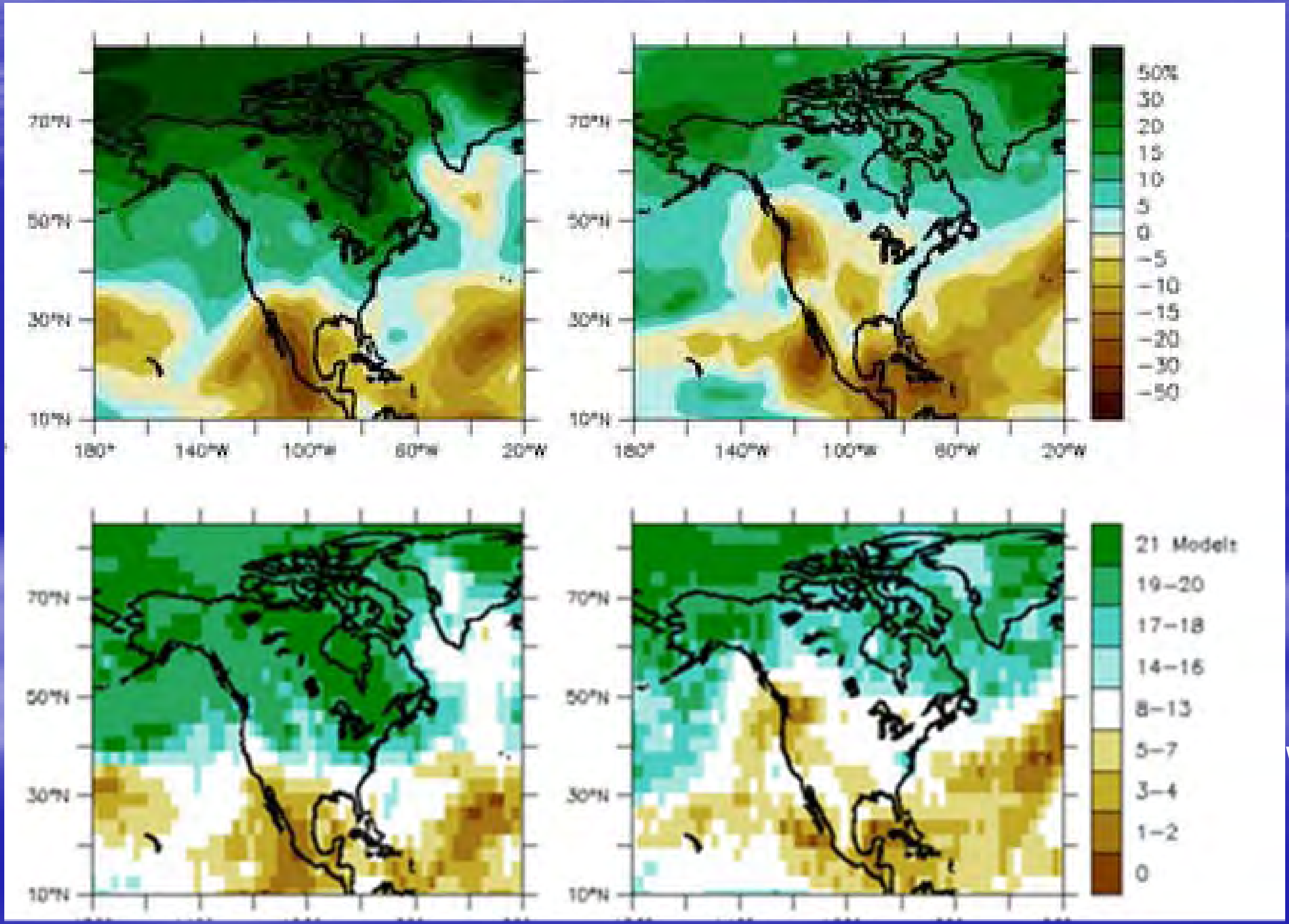


©IPCC 2007: WG1-AR4

Regional Climate Change

2080-2099 (A1B) - 1980-1999

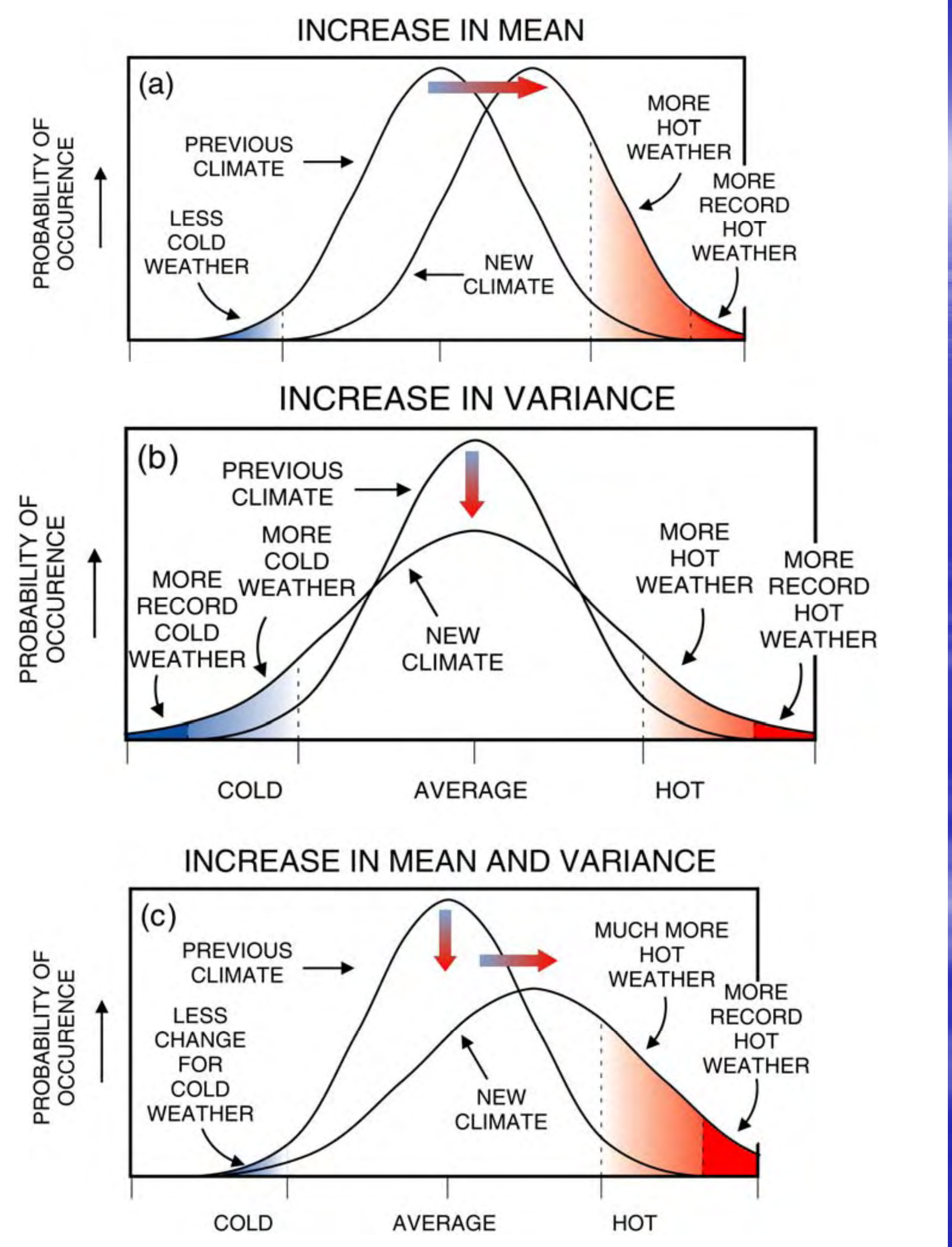
DJF **JJA**



Precipitation (%)

# of Models with ΔP > 0

Climate change and its manifestation in terms of weather (climate extremes)



Extreme Events
Storms, Floods, Droughts, Cyclones

- More frequent droughts and periods of intense precipitation
- Direct loss of life and injury
- Indirect effects
  - Loss of shelter
  - Population displacement
  - Contamination of water supplies
  - Loss of food production
  - Increased risk of infectious disease epidemics (diarrhoeal and respiratory)
  - Damage to infrastructure for provision of health services

Improving Climate Models

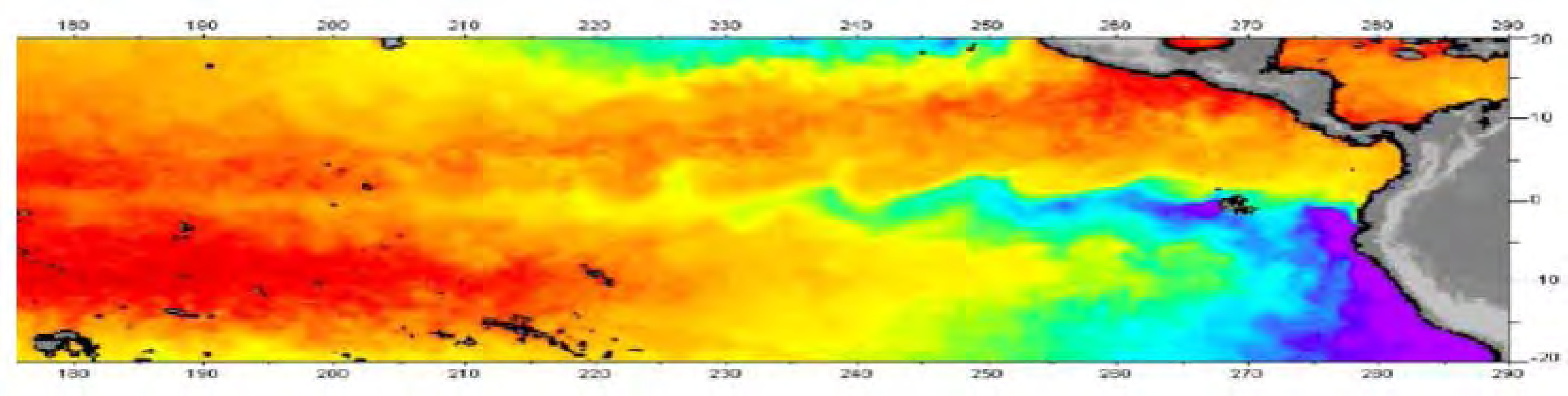
Effect of Systematic Errors

- **Efforts to reduce systematic errors crucial – biases affect both a model’s climate sensitivity and also utility as a predictive tool**

- **Approaches: (1) improve existing physical parameterizations**
  (2) more accurate incorporation of phenomena

- **A working hypothesis is that the internal dynamics of the system are more accurately represented at higher resolution**

Resolving tropical instability waves



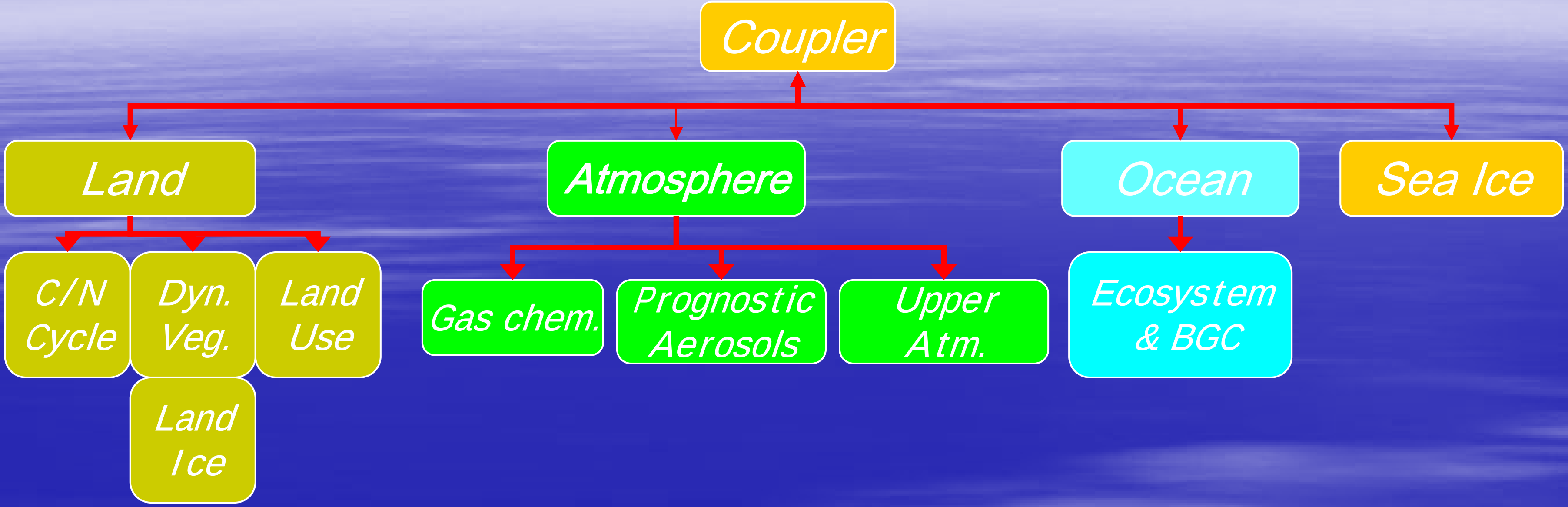
Improving Climate Models

Upscaling Research

- **Basic requirement: the research community needs to gain considerable experience running models in climate mode with mesoscale processes resolved, together with theoretical and diagnostic efforts, to:**
  - ✓ **improve understanding of multiscale interactions in the coupled system**
  - ✓ **identify those of greatest importance and those that require more data to understand**
  - ✓ **document their upscaling effects on climate**
  - ✓ **identify those processes that can be parameterized, and those that cannot**

NCAR

CCSM: Evolution toward an ESM



Coupler

Land

Atmosphere

Ocean

Sea Ice

C/N Cycle

Dyn. Veg.

Land Use

Land Ice

Gas chem.

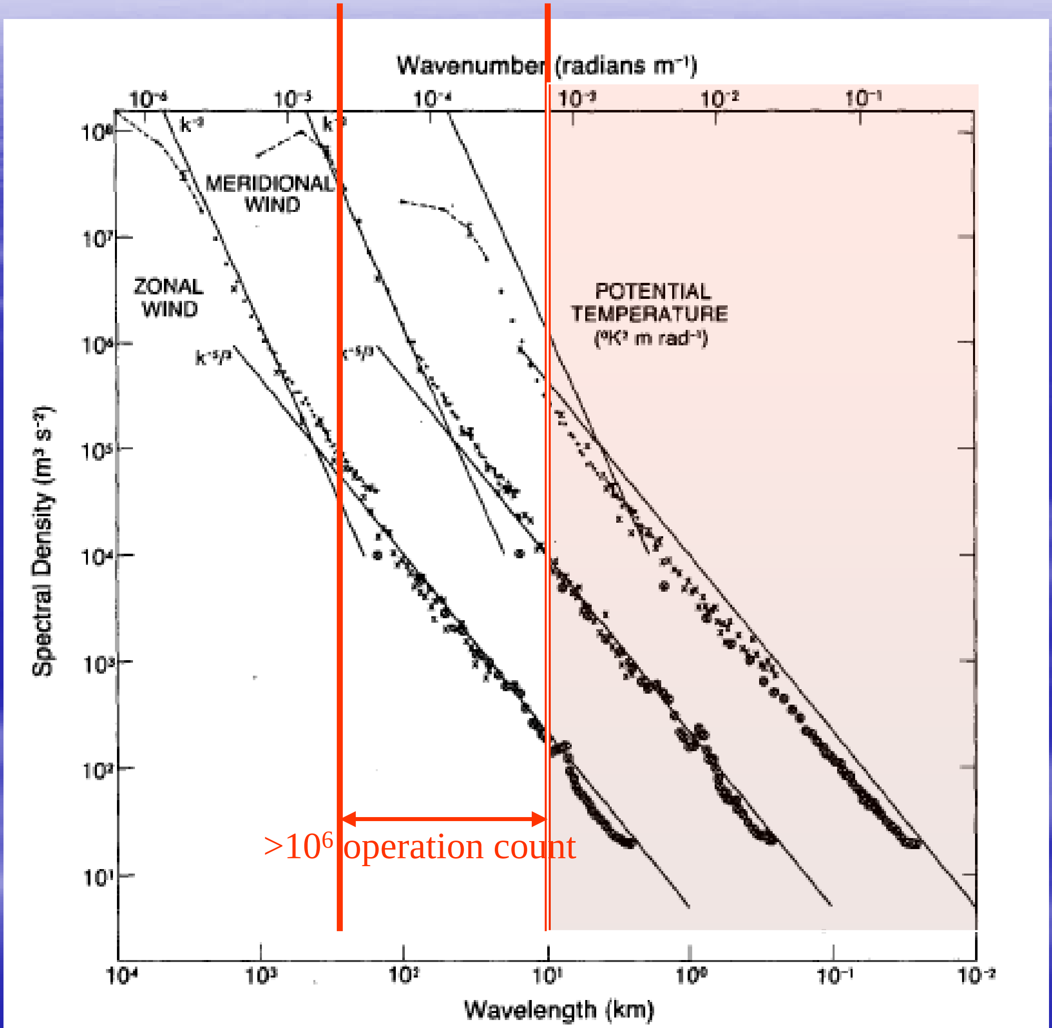
Prognostic Aerosols

Upper Atm.

Ecosystem & BGC

- Coupled climate-chemistry model in the next 2-3 years
  - Terrestrial and oceanic biogeochemical models
  - Ocean ecosystem and terrestrial C/N models
  - Ability to simulate interactions of aerosols with water and biogeochemical cycles
- Explore and understand importance of upper atmospheric process
- Land use and land cover change

Atmospheric Motion Spectra



$>10^6$ operation count

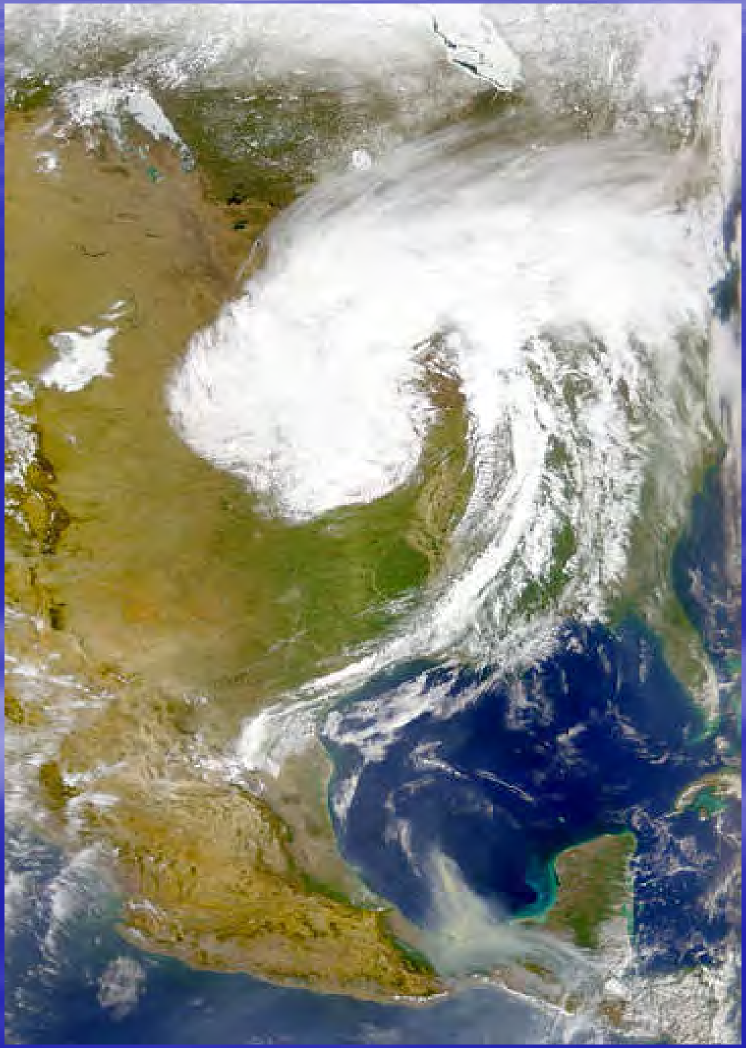
FIG. 3. Variance power spectra of wind and potential temperature near the tropopause from GASP aircraft data. The spectra for meridional wind and temperature are shifted one and two decades to the right, respectively; lines with slopes −3 and −5/3 are entered at the same relative coordinates for each variable for comparison.

Nastrom and Gage (1985)

Atmospheric Energy Transport

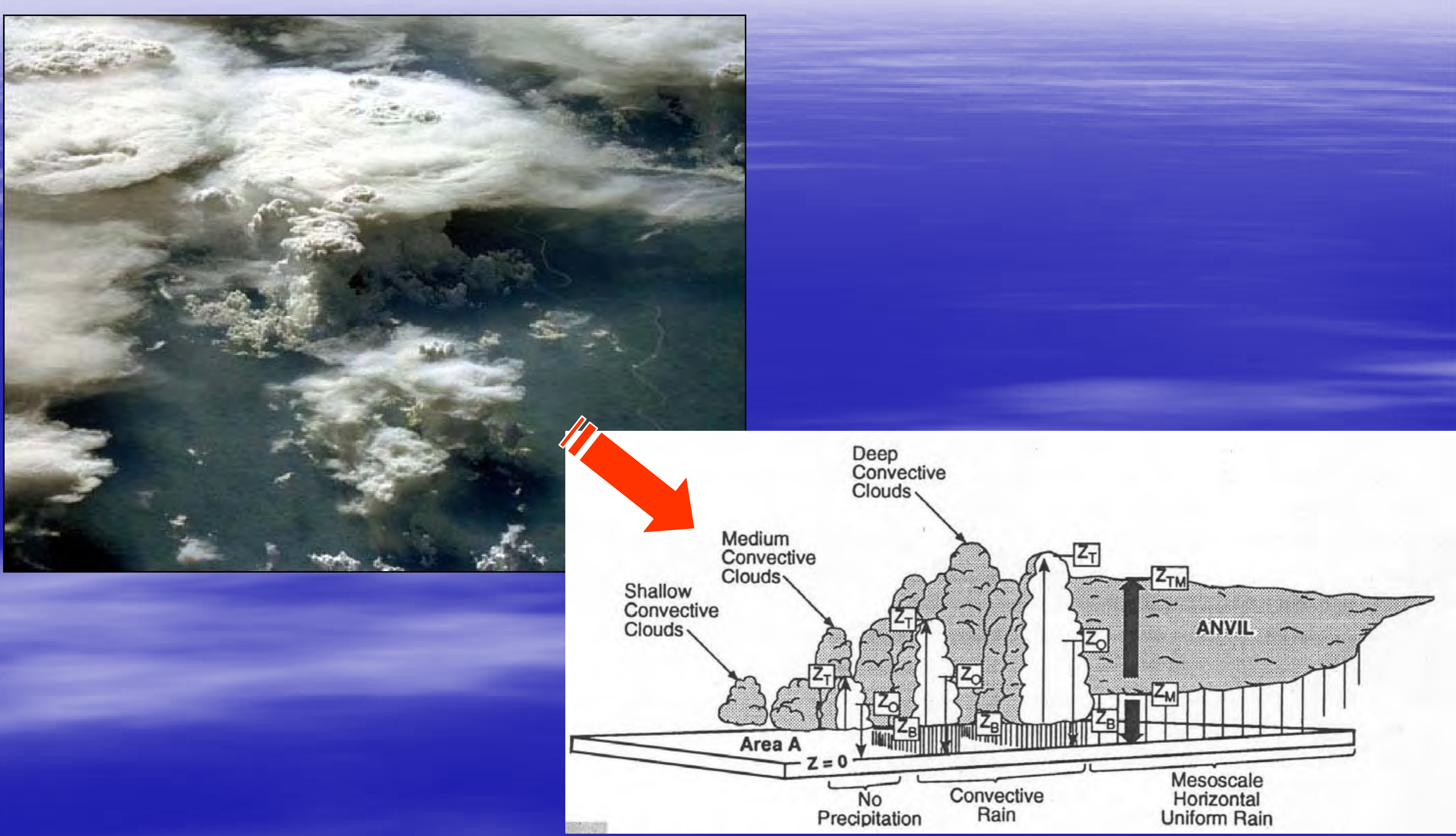
Synoptic-scale mechanisms

extratropical storms

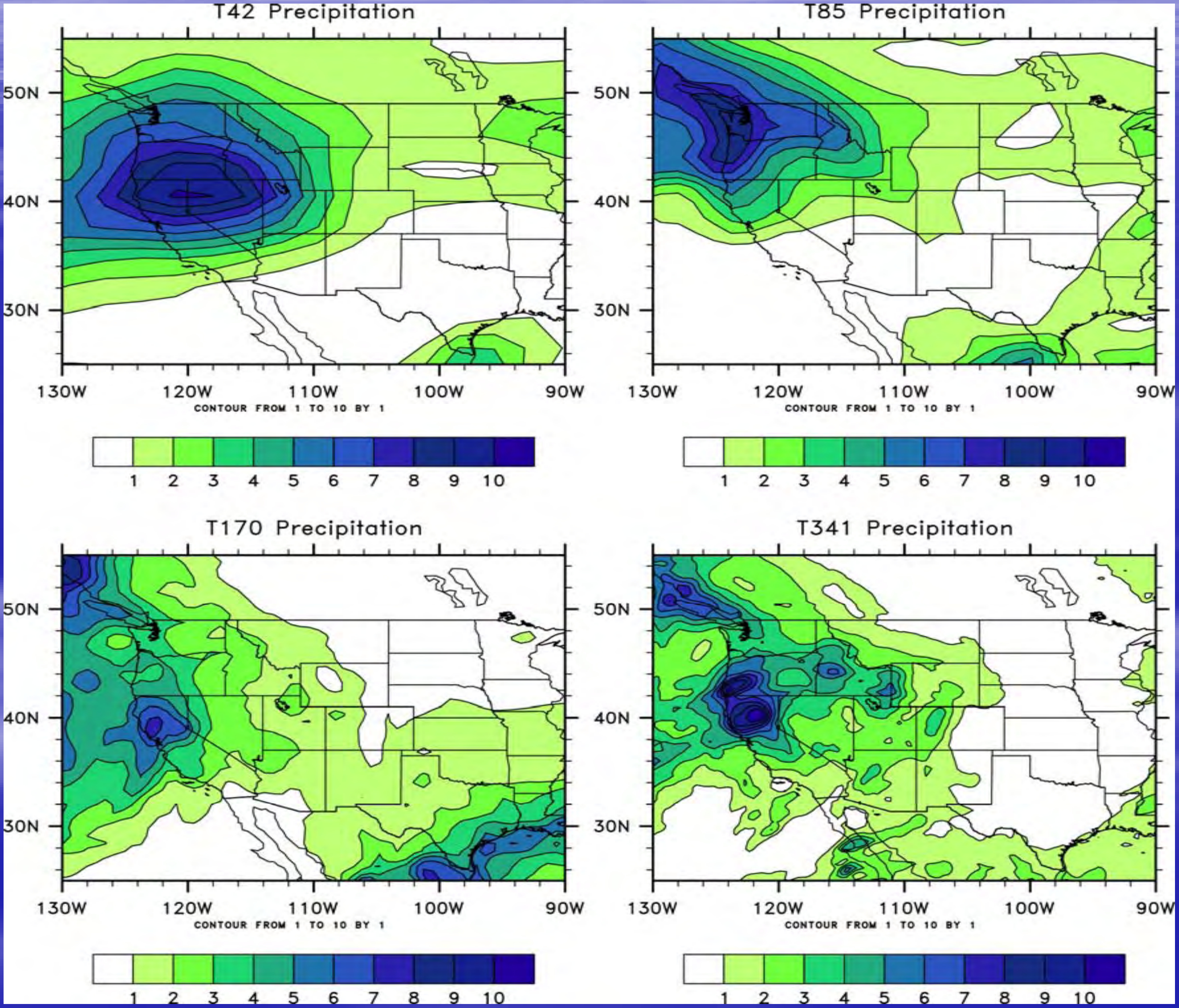


http://www.earth.nasa.gov

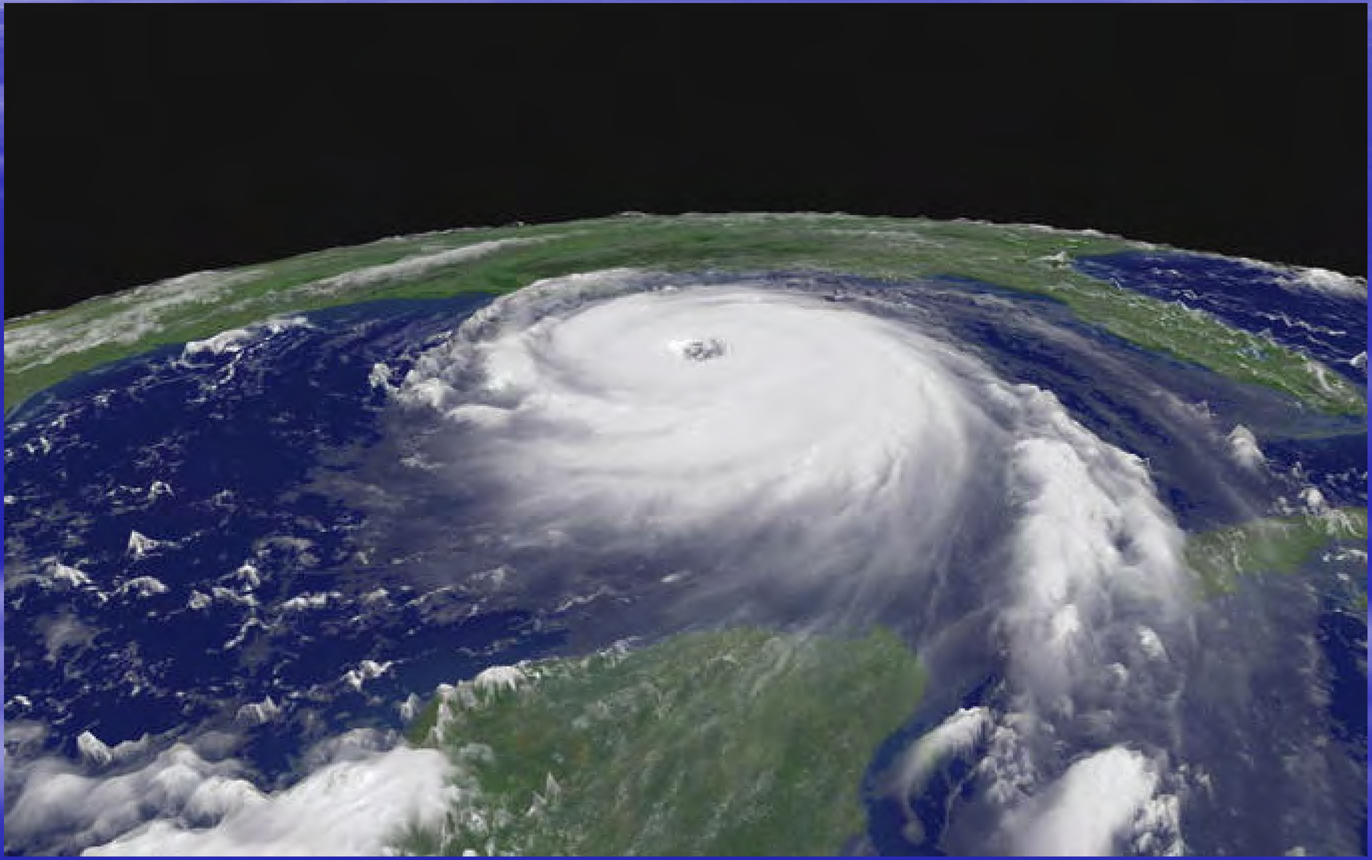
Process Models and Parameterization



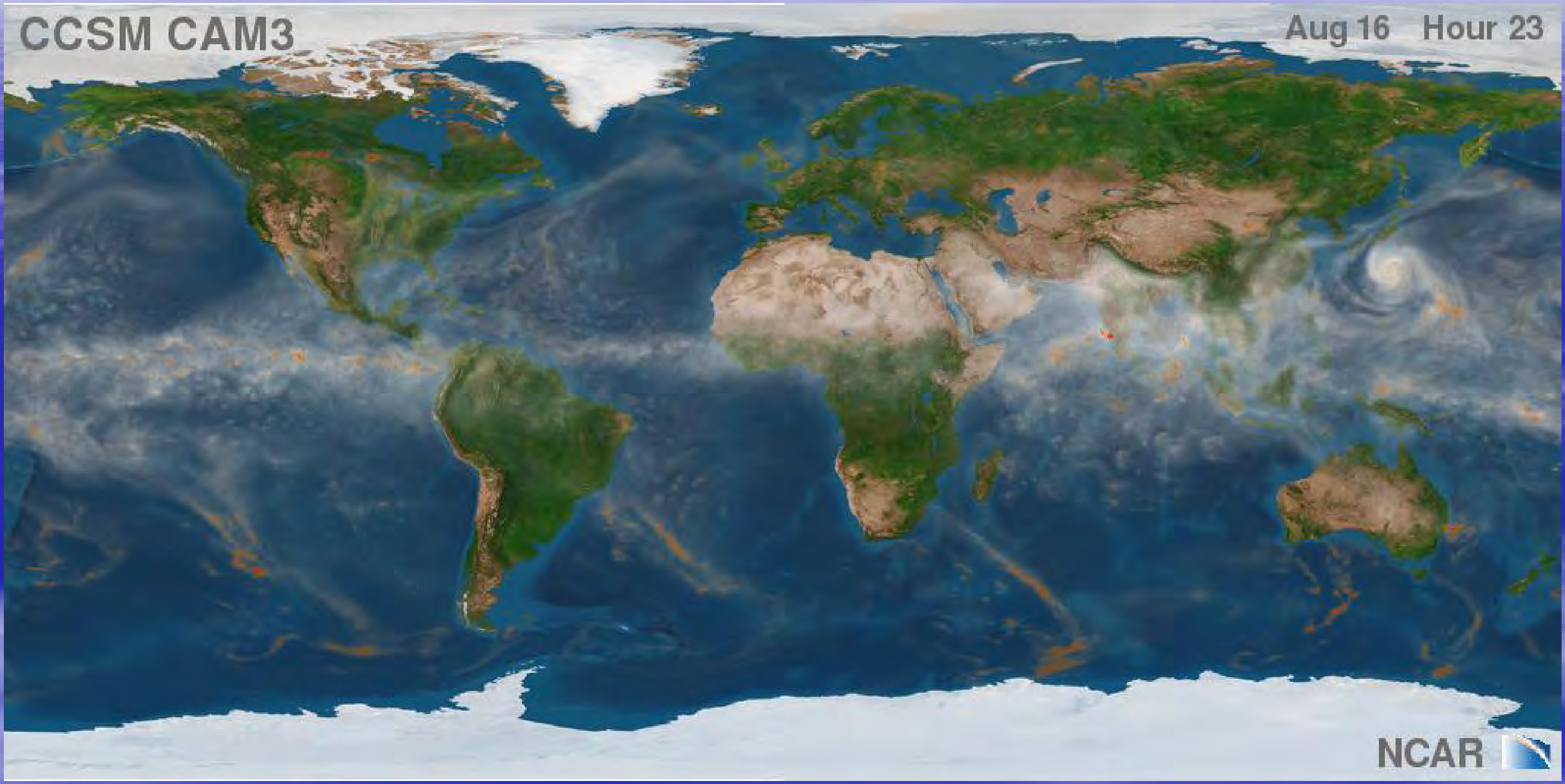
Precipitation rate as function of horizontal resolution



Capturing Primary Phenomenological Scales of Motion in Global Models



High Resolution Climate Simulation



Column Integrated Water Vapor

Science Opportunities

- Decadal prediction on regional scales
  - Accuracy in global models
- Climate extremes (heat waves, drought, floods, synoptic events, etc.)
- Climate variability (low frequency variability)
- Water cycle, particularly in the tropics
  - Potential impacts on biofuels
  - Interactions of the water cycle on mitigation and adaptation strategy
  - Amplifier on carbon cycle response to global warming
- Human induced impacts on carbon cycle
  - Half impacts are taken up by the system (will that change?)
  - How will climate change affect the carbon cycle?
- Sea level rise
  - Melting of the Greenland and Antarctic ice sheets
- Abrupt climate change

Rate limiters

- Decadal prediction
  - Ocean assimilation
    - Ingesting observations
    - Applied mathematics
    - Rapid exploration of design space
    - Computationally intensive
      - Ensembles, Resolution Assimilation methodology (4-D VAR, ensemble Kalman filters)
  - Atmospheric resolution
    - Explicit representation of important phenomenology (~100km feature size)
    - Need to revisit parameterization techniques and assumptions
      - e.g., statistical equilibrium assumptions questionable
    - Challenge to simultaneously & accurately represent climate and weather
    - Can't necessarily rely on NWP experience for vision of path forward

Rate limiters

- Climate Extremes
  - Ability to capture higher-order moments of climate
    - Heat waves, growing season, drought, floods, synoptic events, etc
  - Baseline resolutions need to be higher
  - Demands on data storage, management, scaling of analysis tools, human resources
  - Questions about relationships of extreme events to large scale climate variability

Rate limiters

- Climate variability (low frequency variability)
  - Separating signal from noise (signals emerging from unforced variability)
    - Stationarity of climate statistics
  - Observationally limited
    - length of instrumented record
  - Limited by basic scientific knowledge
    - process understanding
  - Carbon cycle
  - Dynamic vegetation cycles (succession)
  - Scale interaction questions (wide dynamic range in time/space scales)

Think of multiscale math program as opportunity

Models

- Carbon cycle
- Forcing terms that represent multiscale nature of problem
  - e.g., water cycle
- Need for evaluation infrastructure (accelerate prototyping process)
  - Test cases
  - Data for evaluation
  - Staged increases in complexity
  - Modularized functionality
- Time to start with a clean piece of paper?
  - Well managed end-to-end multi-faceted enterprise
- Questions about reward structure for development activities
- Validation
- Verification tests

Algorithms

- Scalable isotropic dynamical cores
  - dynamic load balancing capabilities
- Alternative vertical discretizations
- Implicit or large time step discretizations
- Robust grid remapping algorithms
- Assimilation methodologies
  - Ocean, carbon cycle, …
  - adjoints, ensemble Kalman filters, …
- Need to address multiscale science
  - Variable resolution refinements
  - Uniform high-resolution
- Error estimation techniques
- Multiscale data compression (e.g., wavelet techniques)

Production Quality Software

- High-performance parallel I/O standard
- Future programming models
  - MPI/OpenMP replacements
  - Methodologies and tools required to exploit highly parallel architectures
    - performance analysis tools
    - libraries
  - Tools for refactoring application codes
  - Language improvements
- Componentization
  - verification; unit testing, …
- Scalable and distributed analysis software
- Math and application frameworks
- Benefits to partnerships in development of software environment
  - DOE needs to exercise more control of the broader activity
  - Substantial investment in software for current and future machines a priority

Facilities

- Capacity at the order 1000 processor level is inadequate
  - Availability of machines and allocation strategies
- Data management, migration and analysis
  - Suitable storage hierarchy, bandwidth, support for workflow and analysis
  - Provision for dealing with both model and observationally generated data
- Allocation process (INCITE) may be suboptimal
  - Programmatic deliverables subject to 2nd proposal process
  - Improved partnership between OASCR and other offices in SC
- Future requirements will increase both capacity & capability requirements
  - Some of these scientific initiatives are ready to exploit enhanced resources
- Resource allocation
  - Optimally managing facility for production, high-throughput debug, and analysis work
- Priority to evolve toward stable operating environment
  - Facilitate environment for scientific productivity

Summary and Preliminary Recommendations

1. Strategically invest in collaborations on the development of algorithms and scalable software supporting climate change science to reduce or eliminate rate limiters

2. Continue to invest in leadership class computational facilities, data storage facilities, analysis environments, and collaborative tools and technologies, and carefully coordinate these resources to support climate research productivity across the DOE and the broader national and international efforts,

3. Focus the scientific effort to pursue robust predictive capability of lower-probability/higher-risk impacts, including climate extremes and abrupt climate change

4. Develop computational and theoretical foundations for new modes of climate simulation, including ensemble short-range forecasts and Earth system assimilation.

5. Develop a strong scientific understanding of leading-order uncertainties in the carbon cycle, in particular how the efficiency of natural carbon sinks will change with our changing climate.