Exascale Applications in Climate Science

William D. Collins

UC Berkeley and LBL

Berkeley, California

Major contributor:

David Bader

UC Berkeley and LBL

Berkeley, California

Model Development and Integrated Assessment

Goal: **Enhance climate models as scientific, prediction, and decision-support tools.**

Metric: **Quantify, attribute, and reduce significant sources of error to improve simulation accuracy**

Goals of the workshop

- **Review and identify the critical scientific challenges at the frontiers of climate change science and prioritize them in terms of decadal or annual timelines.**

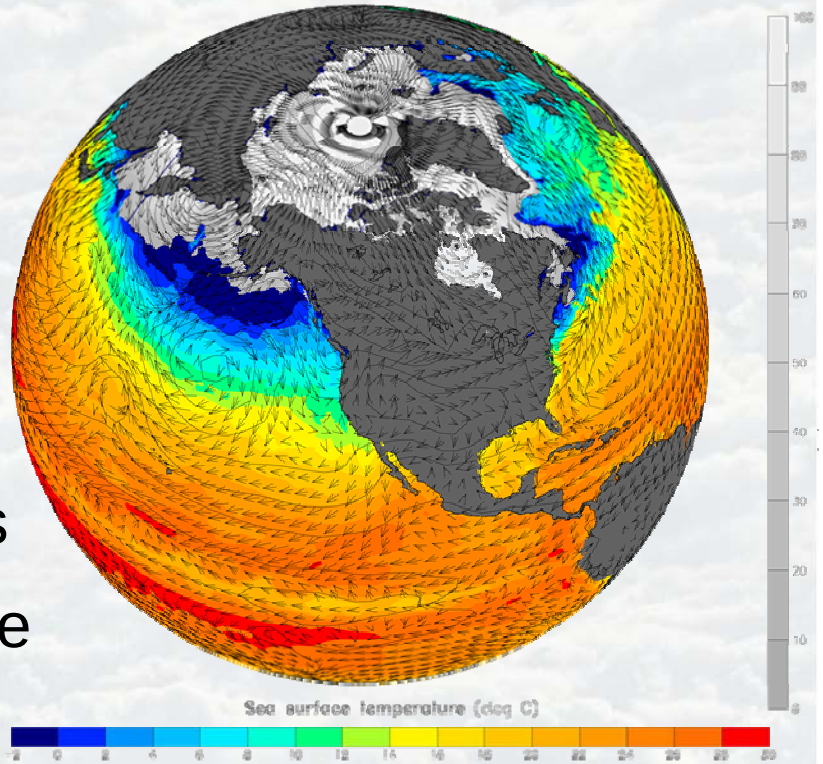
- **Identify those challenges where high end computing at the extreme scales is critical for climate change science success within the next two decades.**

- *Engage international scientific leaders in a discussion of the opportunities they might have to shape the nature of extreme scale scientific computing. e.g. we hope to involve some participants of the World Climate Summit held in 2008.*

- *Provide the high performance computing community with an opportunity to understand the potential future needs of the climate change research community and its clients.*

Topics of the workshop

- Underlying scientific and computational challenges
- Research and development to address these challenges
- Prospective scientific outcomes
- Potential new computational developments and techniques
- Potential impact on climate science
- Timeline for these impacts



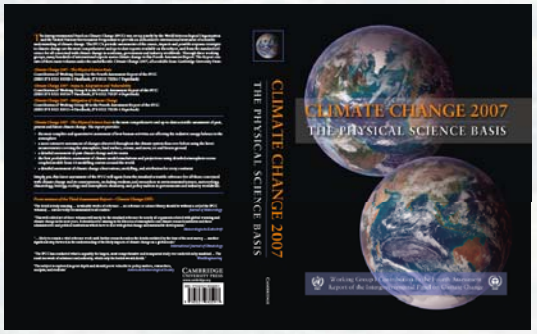
Time periods for science and computation

Three time periods under consideration:

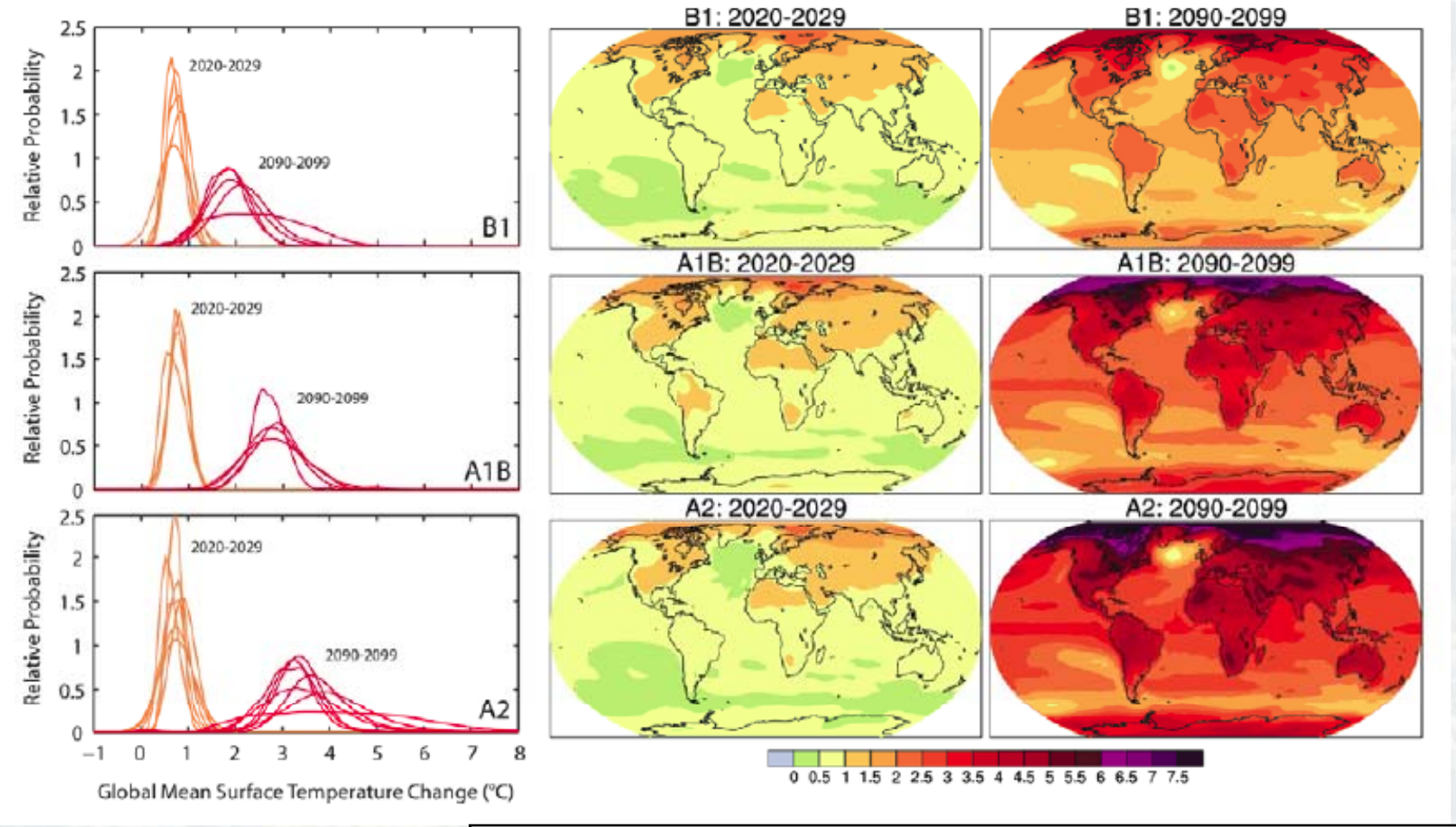
- **2009-2015:** *the next IPCC assessment (AR5)*
- **2015-2020:** *the sixth IPCC assessment (AR6)?*
- **2025 and beyond**

Two+ emerging classes of science applications:

- *Low resolution, long timescale*: **global change**
- *High resolution, short timescale*: **regional change**



Projection of regional temperatures



IPCC AR4, 2007

- Roughly 2/3 of warming by 2030 is from historical changes.
- Challenges for 2030: Regional adaptation, global mitigation

Interactions between science and applications

- **Application challenge:**
  How will the physical/chemical/biogeochemical system change, and how will these changes affect society and the ecology?

- **Beyond IPCC – new partners in climate applications:**
  - *Resource management agencies*
  - *Public and private-sector decision makers*

- **Scientific and computational implications:**
  - *Will applications drive computing toward capacity instead of capability?*
  - *Integration of forcing agent formation and evolution is key for mitigation.*
  - *Integration of drivers from energy technology is key for policy formation.*

Role of uncertainty

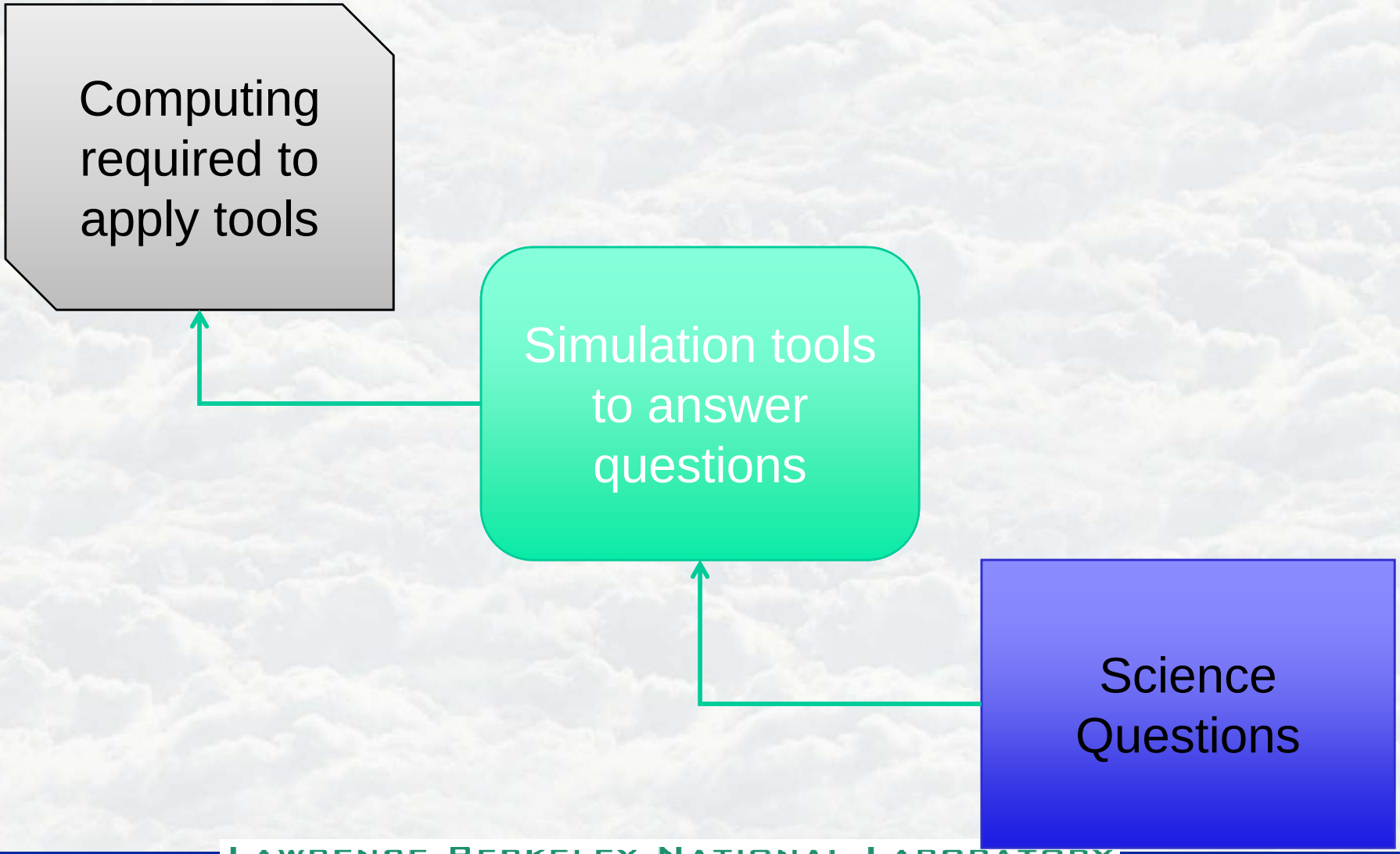
- **Quantification of uncertainty: Is this our goal?**

- **Risk quantification – Should our goal instead be "actuarial tables" of climate risk?**

- **Model verification framework –**
  —*Models are tuned or informed by data.*
  —*This is complicated by data gaps.*

- **Need for new model evaluation frameworks:**
  —*Formal theory of model adjustment relative to data.*
  —*Formal theory of perturbed physics ensembles.*

Science to exascale translation



List of Priority Research Directions

- How do the carbon, methane, and nitrogen cycles interact with climate change?
- How will local and regional water, ice, and clouds change with global warming?
- How will the distribution of weather events, particularly extreme events, that determine regional climate change with global warming?
- What is the future sea level and ocean circulation?

Computational tools for ocean prediction

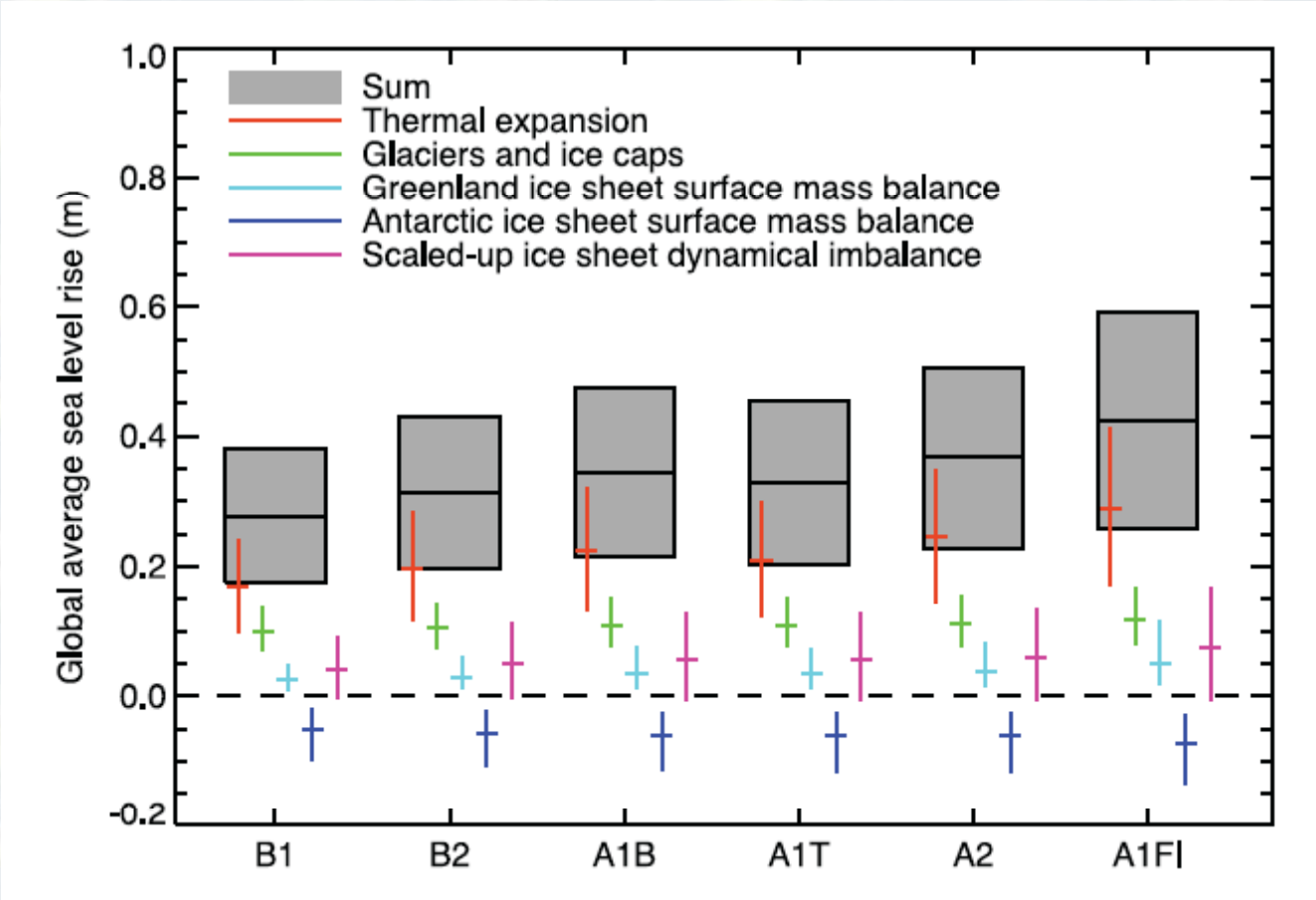
- *What is the future of sea level and ocean circulation?*

  —**Multiscale models of both ice sheets and ocean/ice interaction.**

  —**Models for deep water formation – ultra high resolution.**

  —**Fully dynamic models of land ice for sea level rise.**

Uncertainties in sea level rise



- Global sea level in 21st century may be underestimated by a factor of 3.

Computational tools for local hydrological cycle

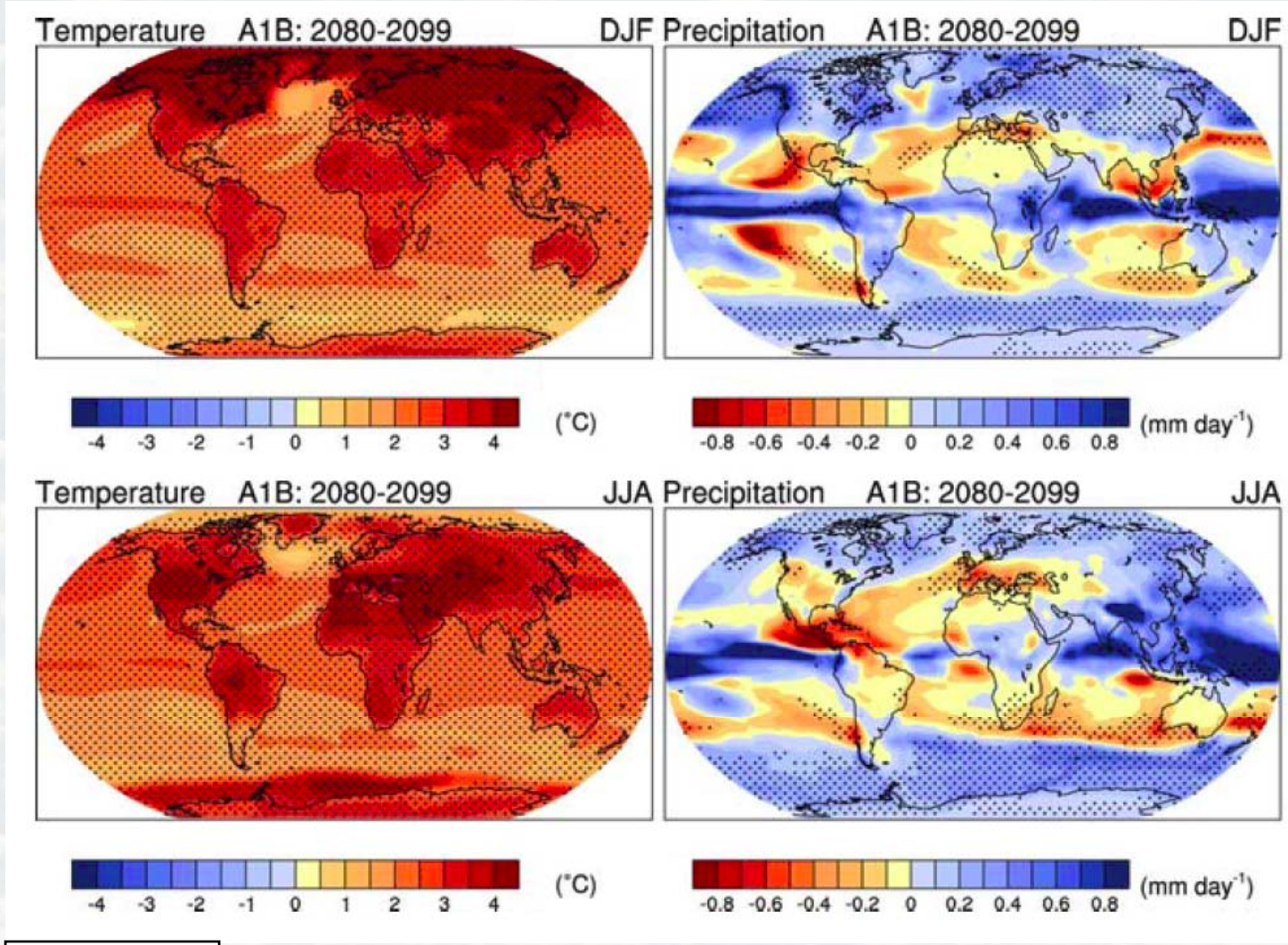
- *How will local and regional water, ice, and clouds change with global warming?*

  —**Traditional global models at 10 to 25 km will be important for resolving topography, could improve the jets and moisture transport.**

  —**Near-term tool: global cloud resolving model.**

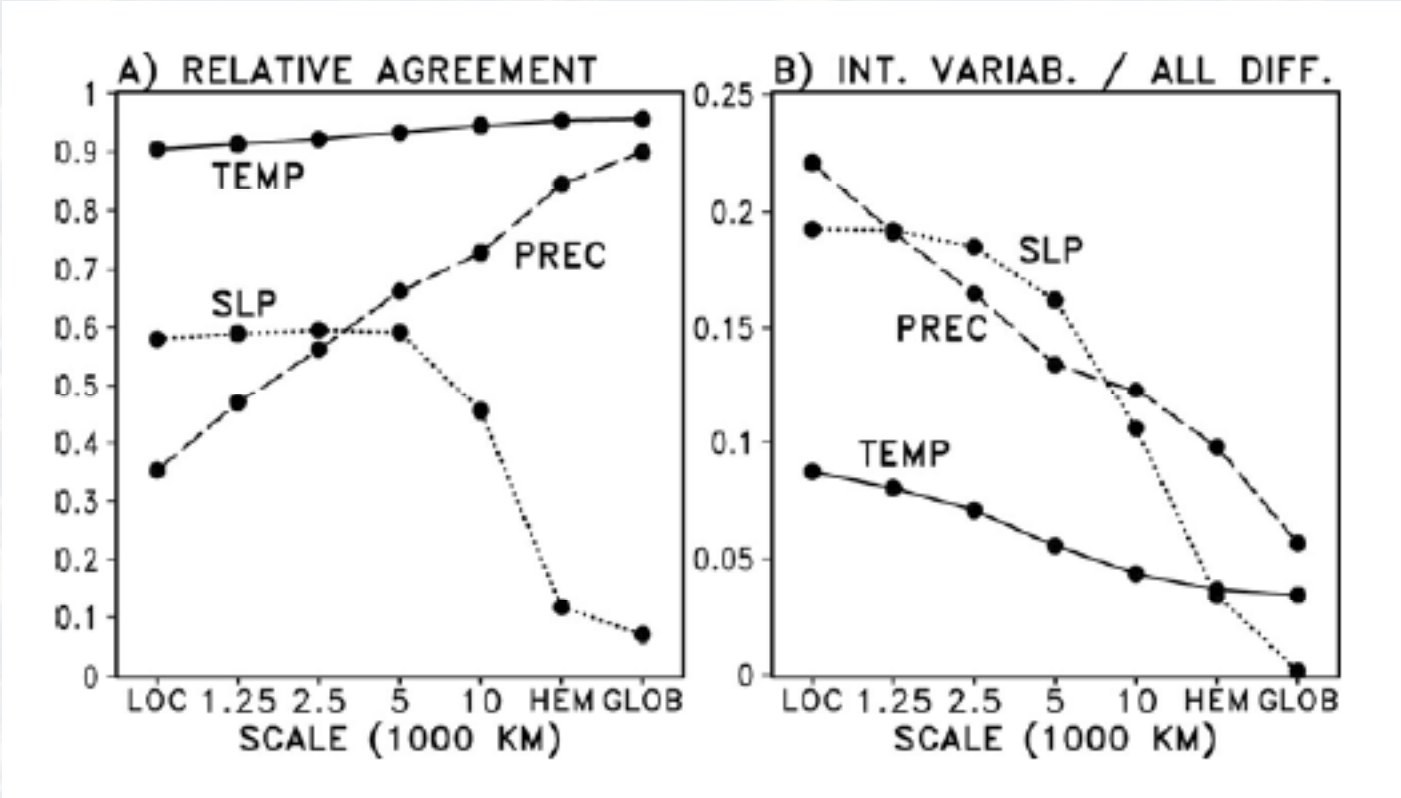
  —**Tool will address: What are the critical cloud controls? What is the importance of the motions between cloud resolving and LES scales?**

Low confidence in impact on rainfall



IPCC AR4, 2007

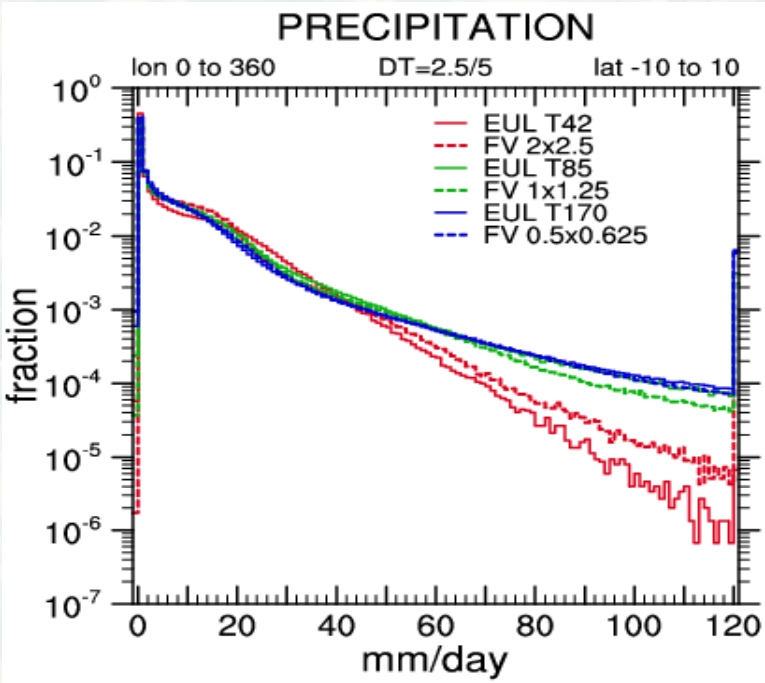
Predictive confidence vs. resolution

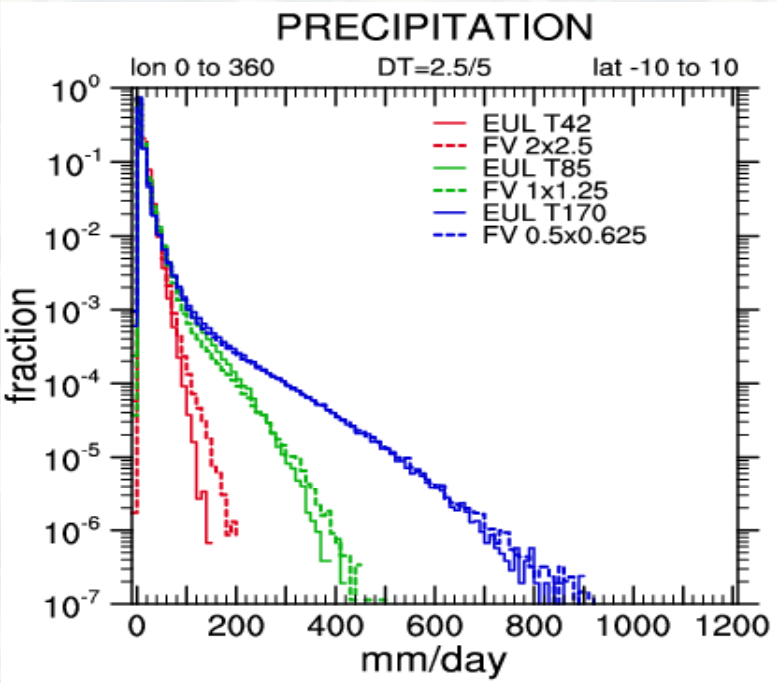


IPCC AR4, 2007

- Consistency among simulated rainfall **decreases** at **smaller** scales.
- Internal variability in simulated rainfall **increases** at **smaller** scales.

Precipitation extremes vs. resolution





Williamson, 2007

- Do the extreme rainfall rates converge with increasing resolution?
- **Not for CCSM:** The rates do not converge for higher resolution.

Computational tools for GHG and nutrient cycles

- *How do the carbon, methane, and nitrogen cycles interact with climate change?*

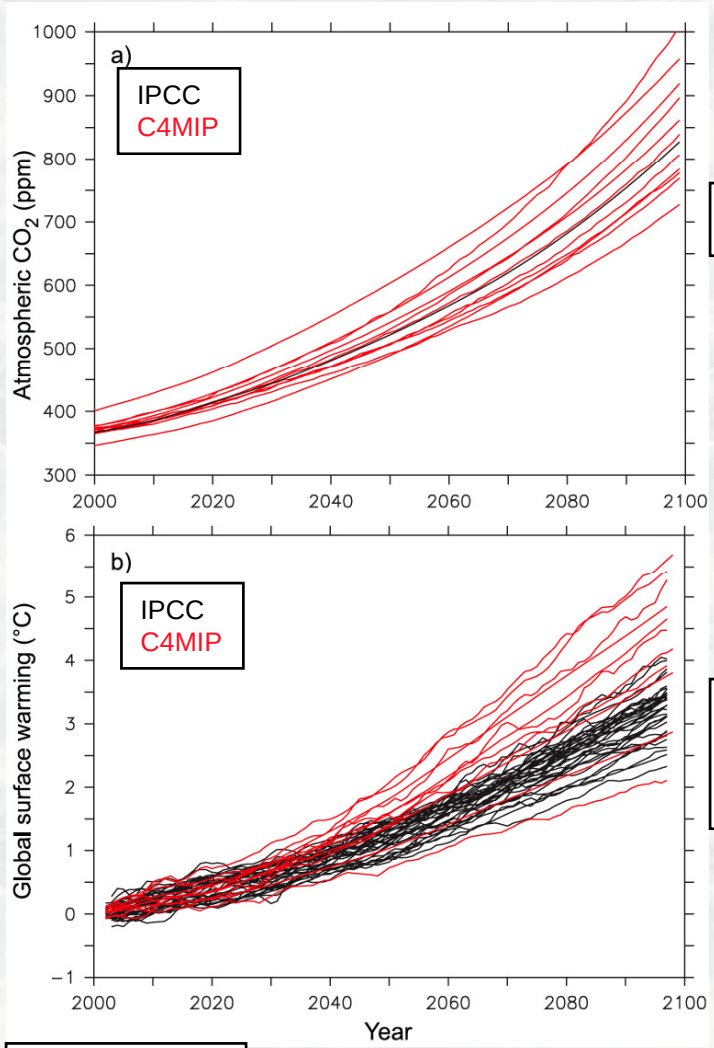
  —**Process models of fire.**

  —**Process models of dust.**

  —**Modeling the coastal zone:**
  Biological models for the ocean sea floor is critical.

  —**Modeling biogeochemical cycles at the level of single organisms: Data from metagenomic analyses.**

Effects of carbon-cycle feedbacks

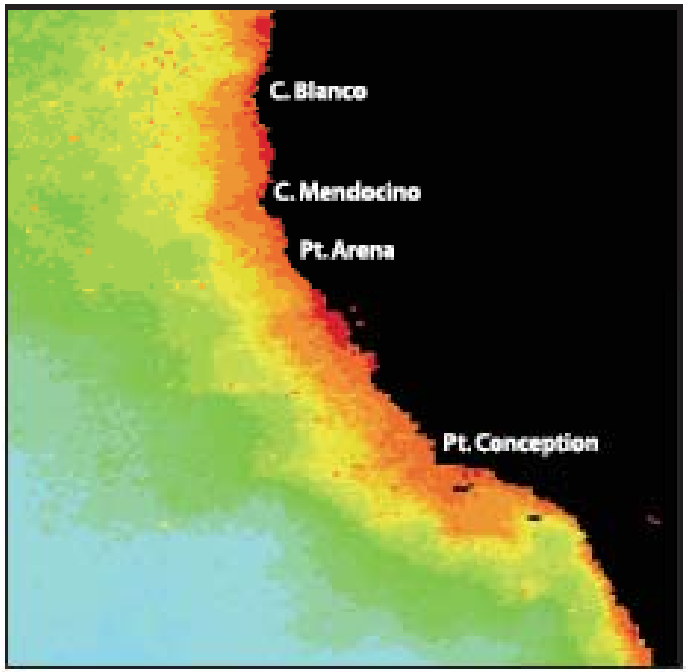


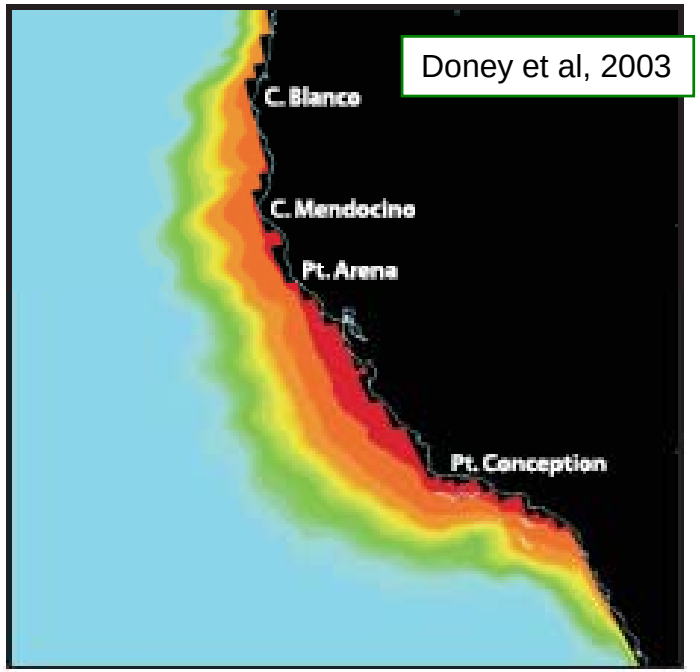
IPCC AR4, 2007

- Carbon cycle has positive feedback on CO_2.

- The feedback increases surface temperatures.
- It increases range of uncertainty.

Grand challenges in ocean biogeochemistry





Doney et al, 2003

Fig. 9.16. Annual mean chlorophyll for the California Current coastal region from SeaWiFs and the UCLA regional coastal ecosystem model ROMS (James McWilliams, pers. comm.)

- Biogeochemistry in coastal zones.
- Interactions of ocean fronts and eddies with ocean ecosystems.
- Treatment of the ocean carbon cycle at the organism level.

Computational tools for climate extremes

- *How will the distribution of weather events, particularly extreme events, that determine regional climate change with global warming?*

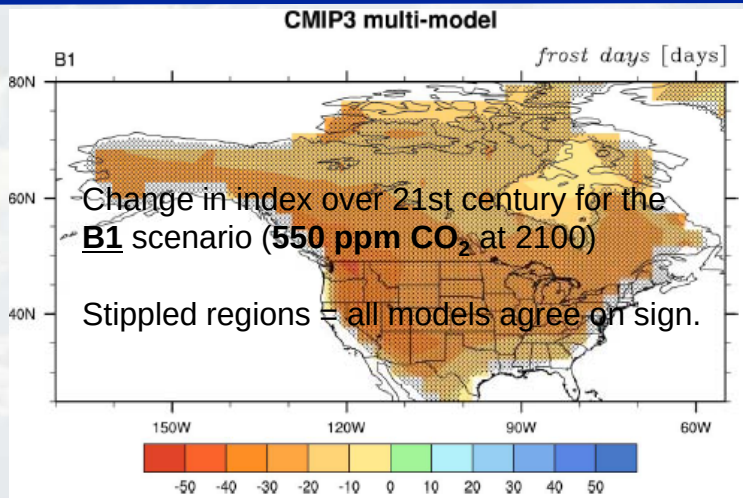
  —**Hierarchical multiscale models.**

  —**Unified modeling framework / seamless prediction?**

  —**Capability for big ensembles or long-term integrations.**

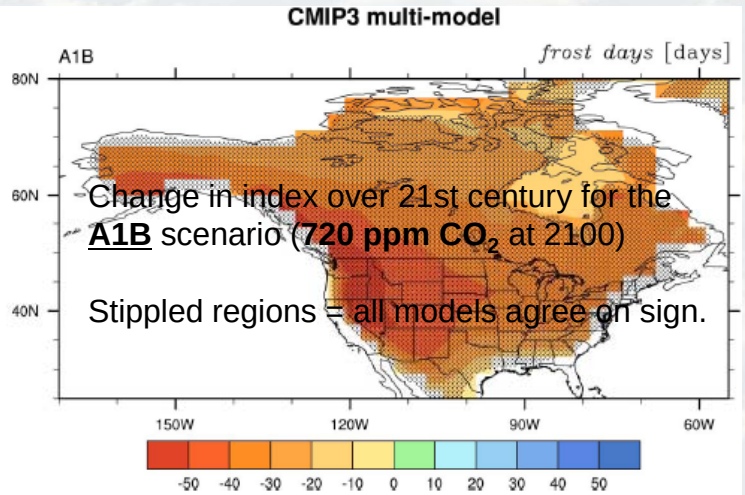
  —**How is parameterized physics connected with prediction of extreme events?**

Extremes: Climate index maps & series



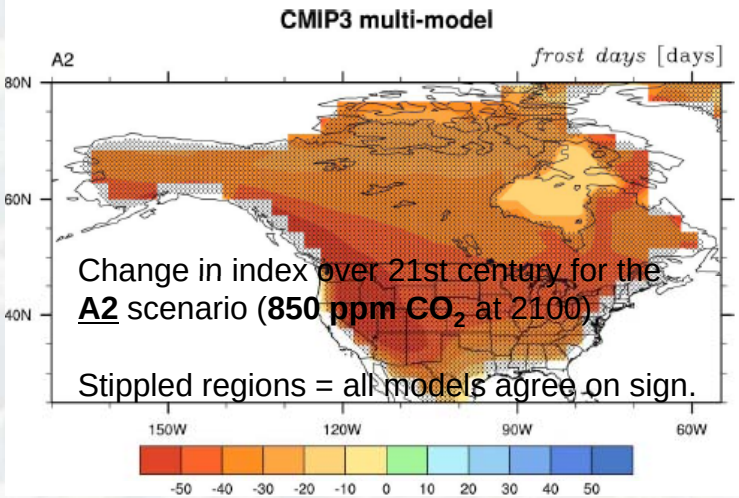
Change in index over 21st century for the **B1** scenario (**550 ppm CO_2** at 2100)

Stippled regions = all models agree on sign.



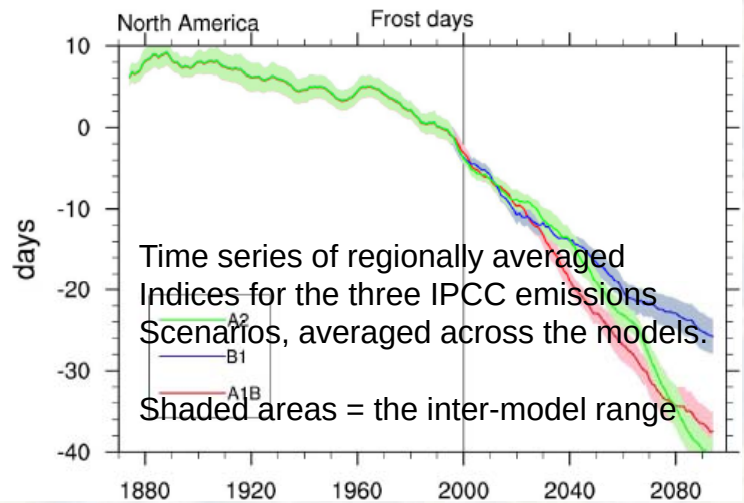
Change in index over 21st century for the **A1B** scenario (**720 ppm CO_2** at 2100)

Stippled regions = all models agree on sign.



Change in index over 21st century for the **A2** scenario (**850 ppm CO_2** at 2100)

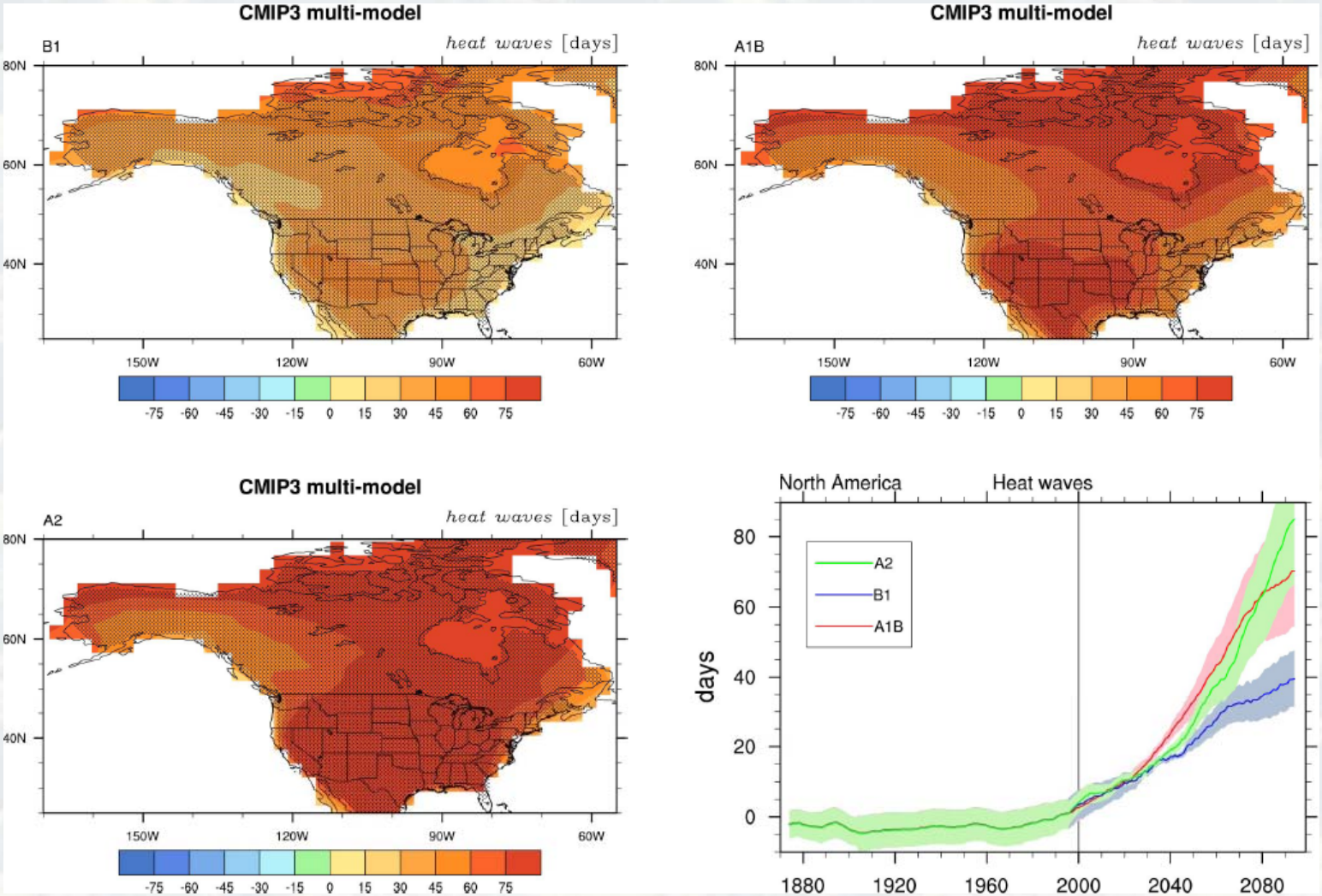
Stippled regions = all models agree on sign.



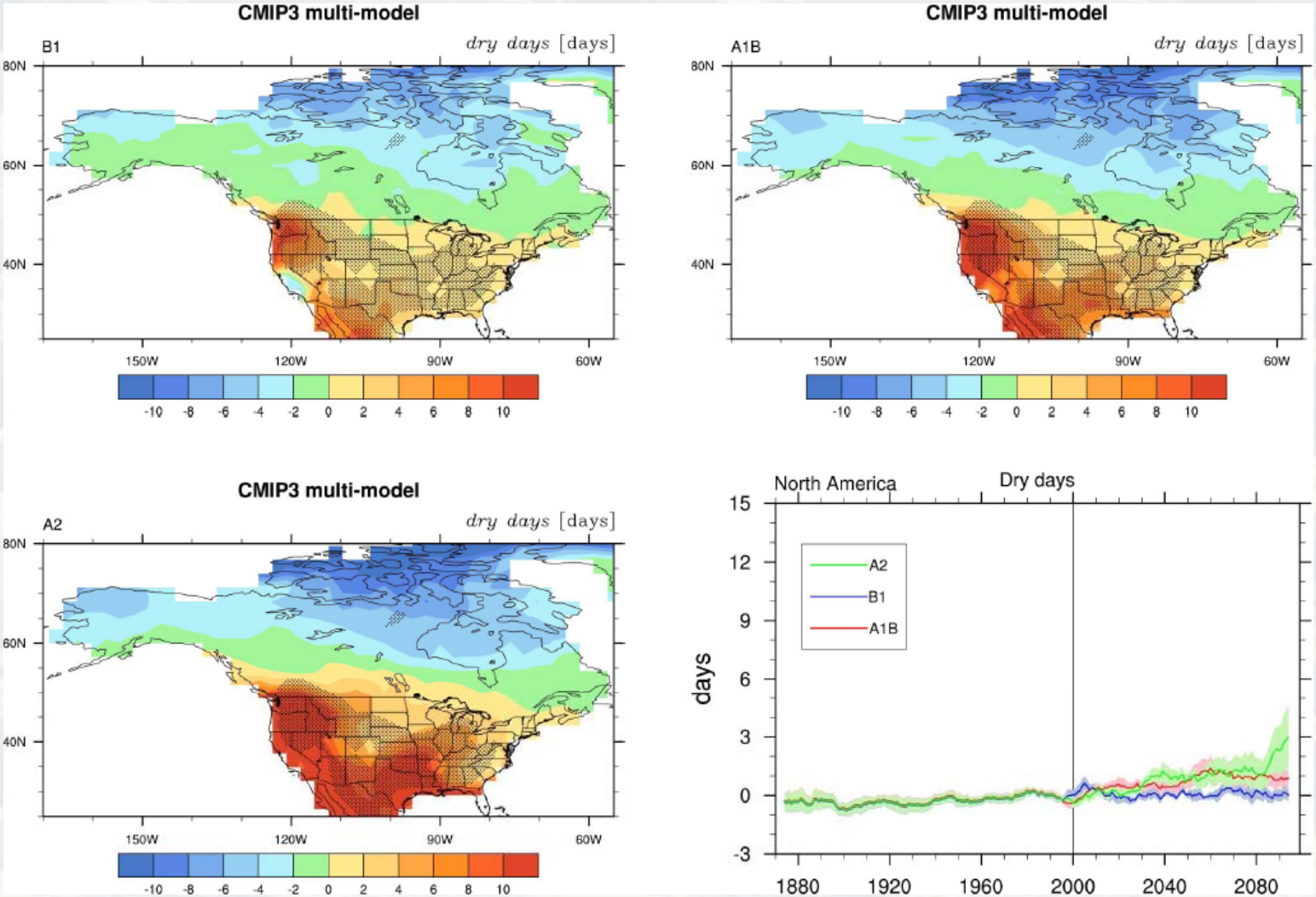
Time series of regionally averaged Indices for the three IPCC emissions Scenarios, averaged across the models.

Shaded areas = the inter-model range

Change in heat wave duration



Change in maximum number of dry days



Local and regional changes in water, ice, and clouds

Scientific and computational challenges

What are the critical cloud controls on climate?

What is the importance of motions and particle-scale processes that are still unresolved?

Potential scientific impact

These models will enable rapid progress in a wide variety of climate science issues (where clouds play an important role).

These models will bridge scales from weather to climate for the first time.

Summary of research direction

Development of global cloud resolving models and their application.

Potential impact on climate change sciences

These models will ultimately improve our ability to project changes in regional water cycles, a critical element of integrated assessment (Timescale: 5-10 years)

Cloud resolving models will be used to improve traditional climate models used for climate projection. (Timescale: 2-5 years)

Quantify impacts of water resources on energy production and use. (Timescale: 5-10 yrs)

What is the future sea level and ocean circulation?

Scientific and computational challenges

What are the importance processes governing ice sheet melt?

How do we more accurately represent important vertical mixing in the ocean?

How do mixing eddies and surface forcing combine to affect the stability and variability of the Meridional Overturning Circulation.

Potential scientific impact

These models will quantify the rate of future sea level rise.

These models will improve quantification of ocean heat uptake and exchange of carbon dioxide.

Summary of research direction

•Multiscale models of both ice sheets and ocean/ice interaction.

•Models for ocean circulation at truly eddy-resolving resolution.

•Fully dynamic models of land ice for sea level rise.

Potential impact on climate change sciences

These models will provide more robust estimates of sea level rise and its impact on coastal communities and energy infrastructure (Timescale: 5-10 years)
These models will quantify the risk of abrupt changes in ocean circulation (Timescale: ditto)

How do the carbon, methane, and nitrogen cycles interact with climate change?

Scientific and computational challenges

What are the natural methane and nitrogen cycles, and how are they being altered by climate change?

What is the strength of the global carbon sink, and how will it change?

Potential scientific impact

Understand the carbon cycle over the Holocene.

Understand the significant roles of life forms and cycles in the carbon cycle.

Understand the significant roles of human-driven and natural disturbance on the carbon and nitrogen cycles.

Summary of research direction

- Modeling the coastal zone
- Modeling BGC cycles that capture ecosystem demography and its temporal evolution.
- Process models of land-surface disturbance.
- Anthropogenic forcing of the natural cycles.
- Process models of natural BGC nutrients.

Potential impact on climate change sciences

Quantify impacts of land use change and on weather and climate driven by biofuel and other energy production and use (Timescale: 5-10 years)
Assessing related geo-engineering measures (Timescale: 10-15 years)

How will extreme weather and climate events change?

Scientific and computational challenges

•Massive ensembles and long-term integrations are required to quantify extreme events.

• Tools for analyzing high frequency, high resolution data on climate timescales.

• What governs the statistics of weather, in particular extreme weather?

Potential scientific impact

Role of tropical cyclones in climate.

Understand the frequency, duration, intensity and spatial distribution of droughts, deluges, and heat waves.

Understand the processes behind long-distance interactions of weather and climate

Summary of research direction

•Hierarchical multiscale models.

•Unified weather and climate prediction framework

•How are specific physical processes connected with prediction of extreme events?

Potential impact on climate change sciences

How will changes in weather extremes affect environmental security and societal stability?

How will the frequency and intensity of disruptive extreme events evolve with global warming?

Open issues

- Role of assimilation in our model development.
- Science and application drivers: short vs. long-term
- Implications for computing: capacity vs. capability
- Which driver(s) are primary: Energy, human dimensions?
- Impact focus vs. mitigation focus.
- How do we address model development and IA in a single framework?
- Rather than uncertainty reduction, focus on uncertainty quantification & risk reduction.