Extreme Climate Change:

Scaling Laws and Scale Invariance

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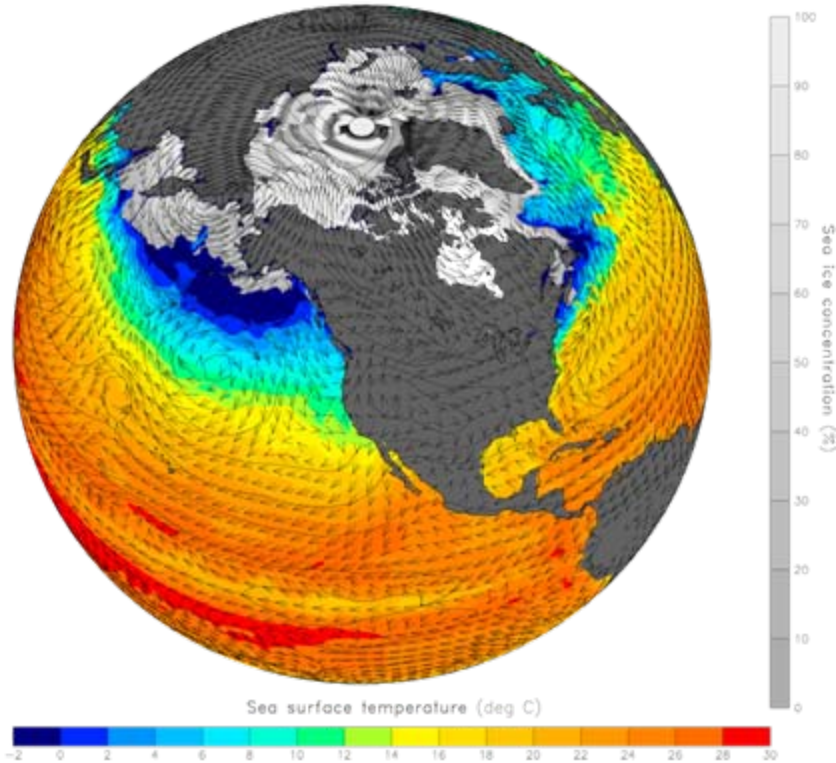
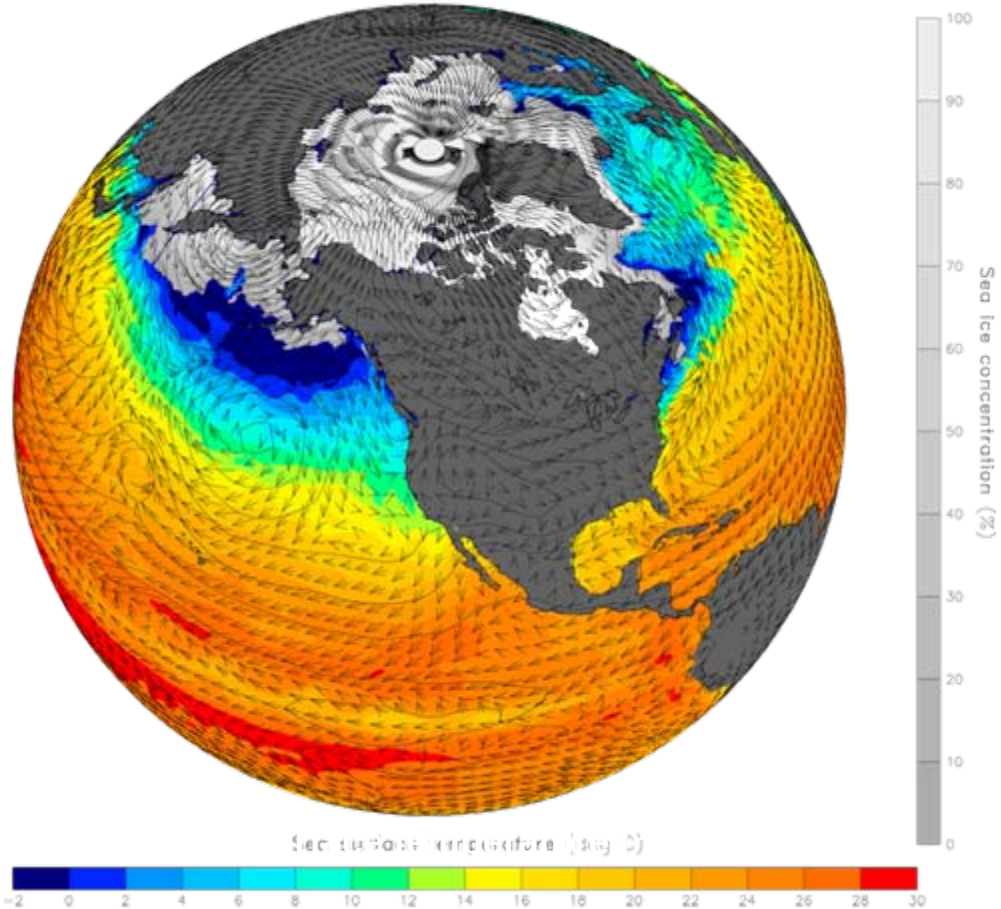
Topics

- Application of climate models for mean climate change
- Directions for model development
- Application of climate models for climate extremes
- Changes with resolution in mean and extreme rainfall
- Implications for future work



What is a climate model?

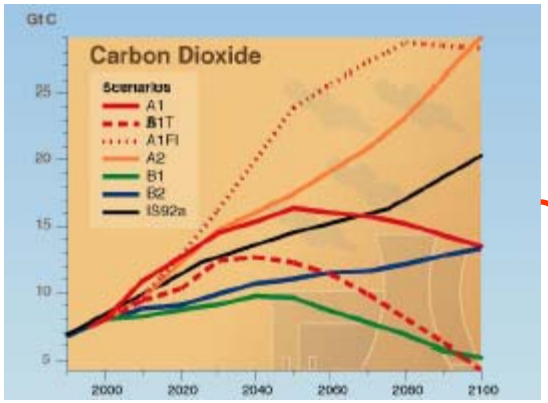


- Synthesis of climate theory & data
- Tool for predicting the future
- Tool for understanding the past
- Numerical “parallel Earth”

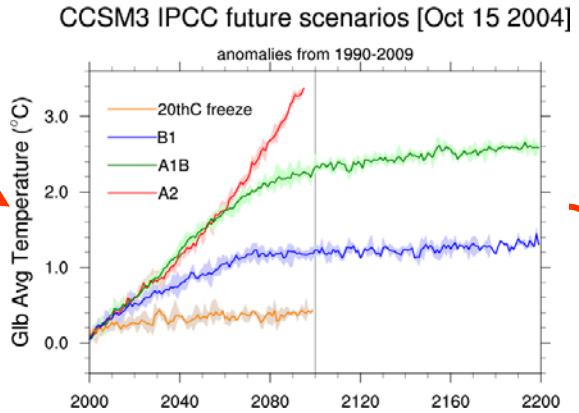
NERSC’s Supercomputer Franklin

Climate Simulations for IPCC Assessments

IPCC Emissions Scenarios



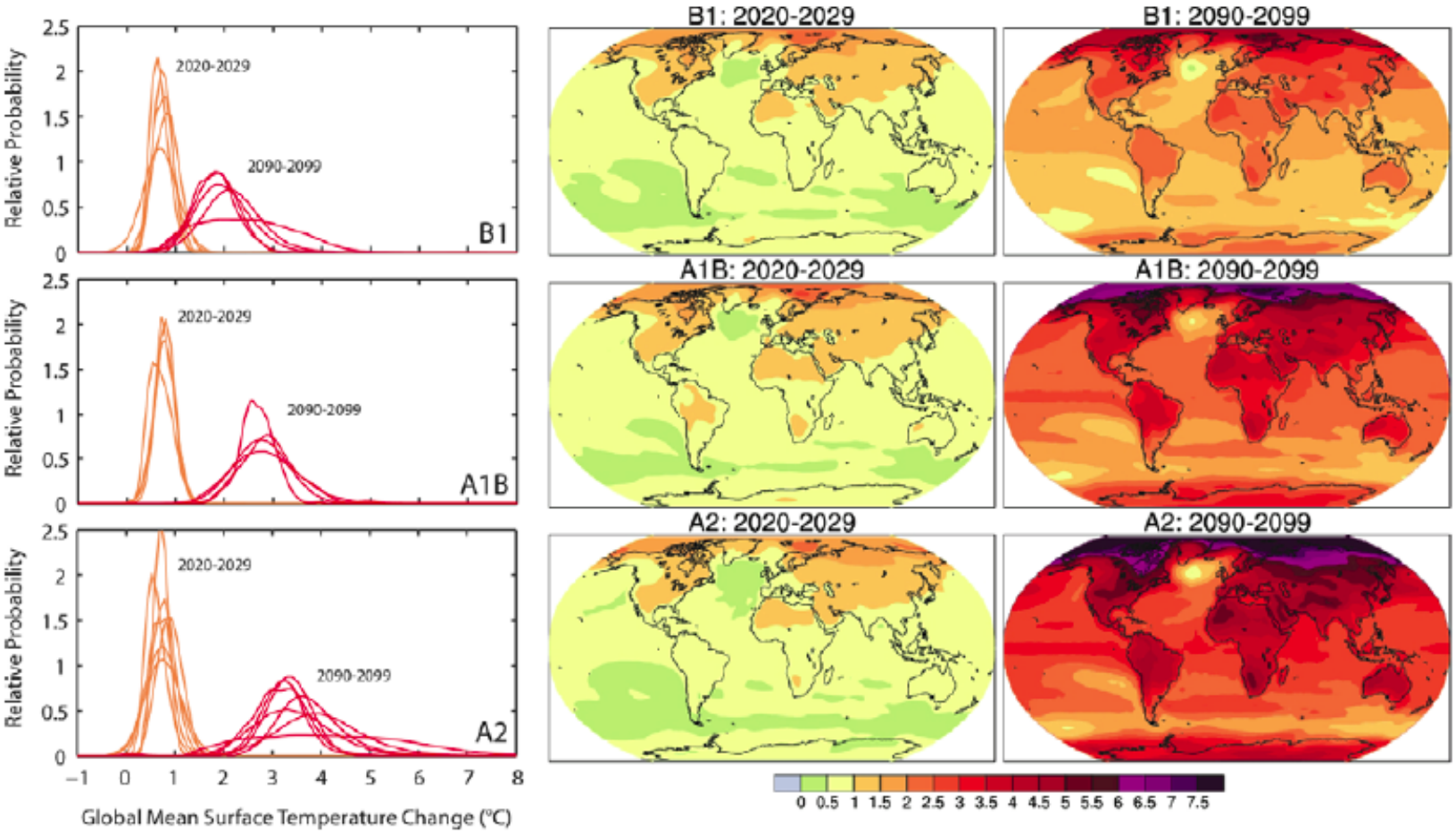
Climate Change Simulations



IPCC 4th Assessment

2007

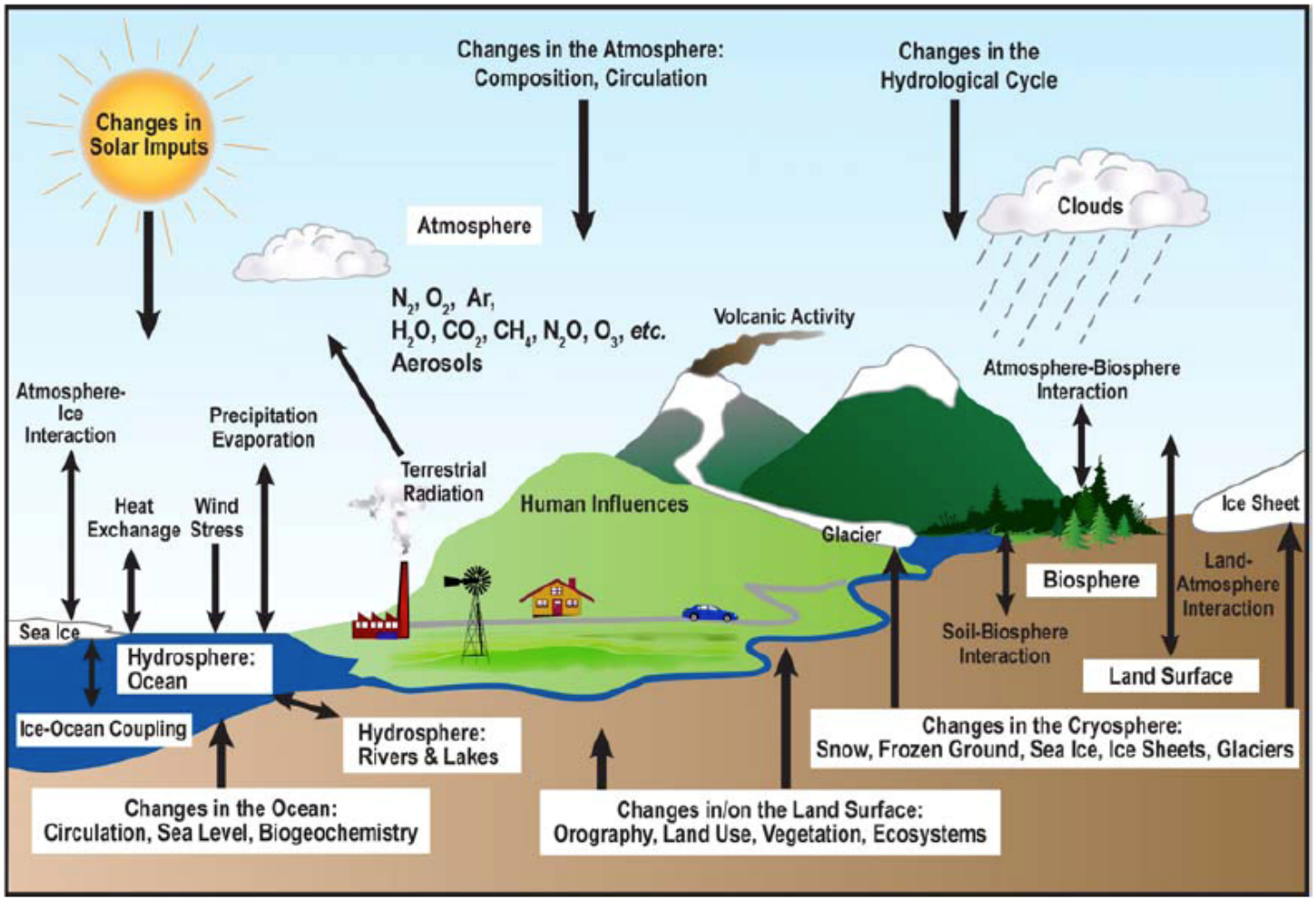
Projection of regional temperatures



IPCC AR4, 2007

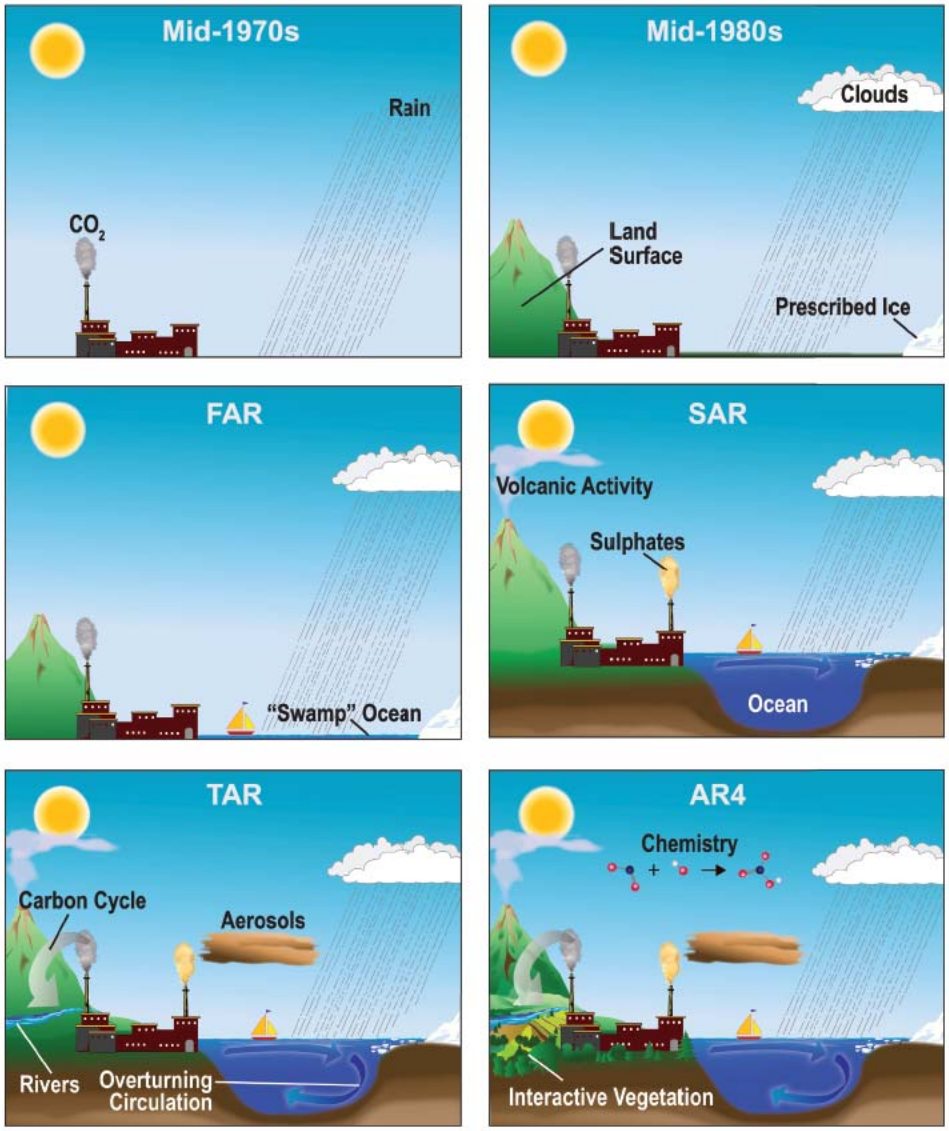
- Roughly 2/3 of warming by 2030 is from historical changes.
- Warming by 2030 exceeds 20th C natural variability by >2x.

Climate processes and components

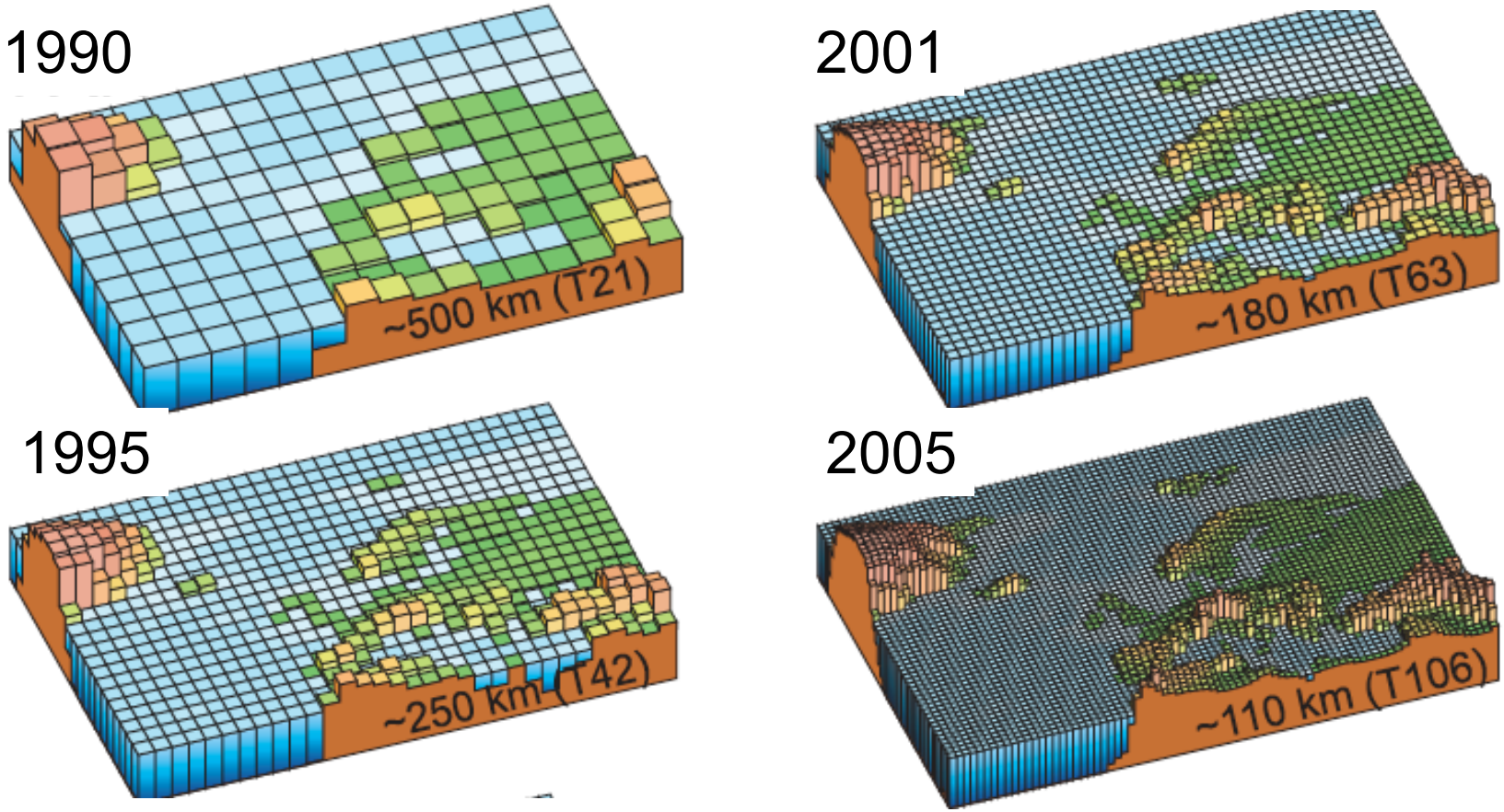


IPCC AR4, 2007

Evolution of processes in climate models



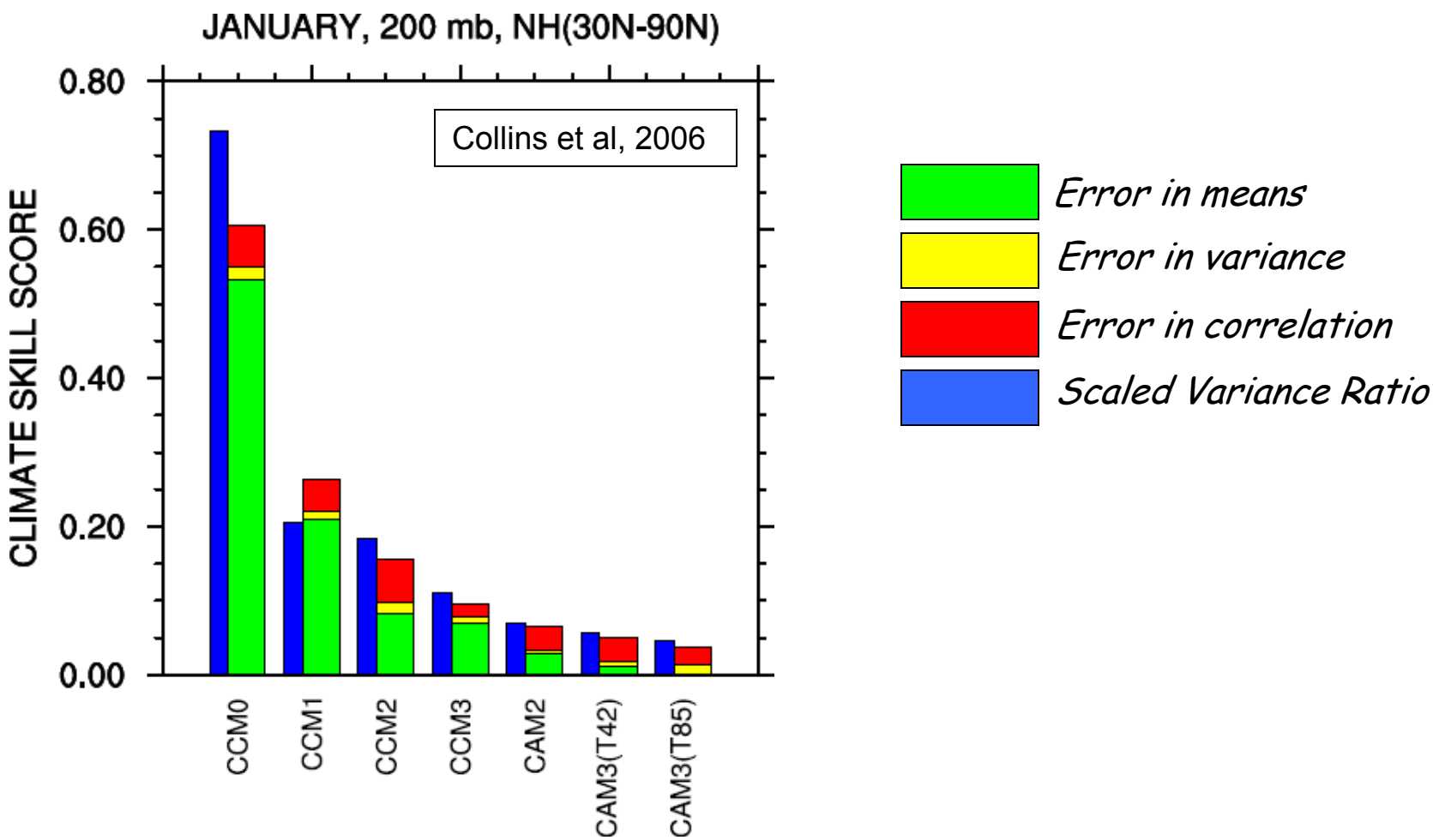
Resolution of climate models



IPCC AR4, 2007

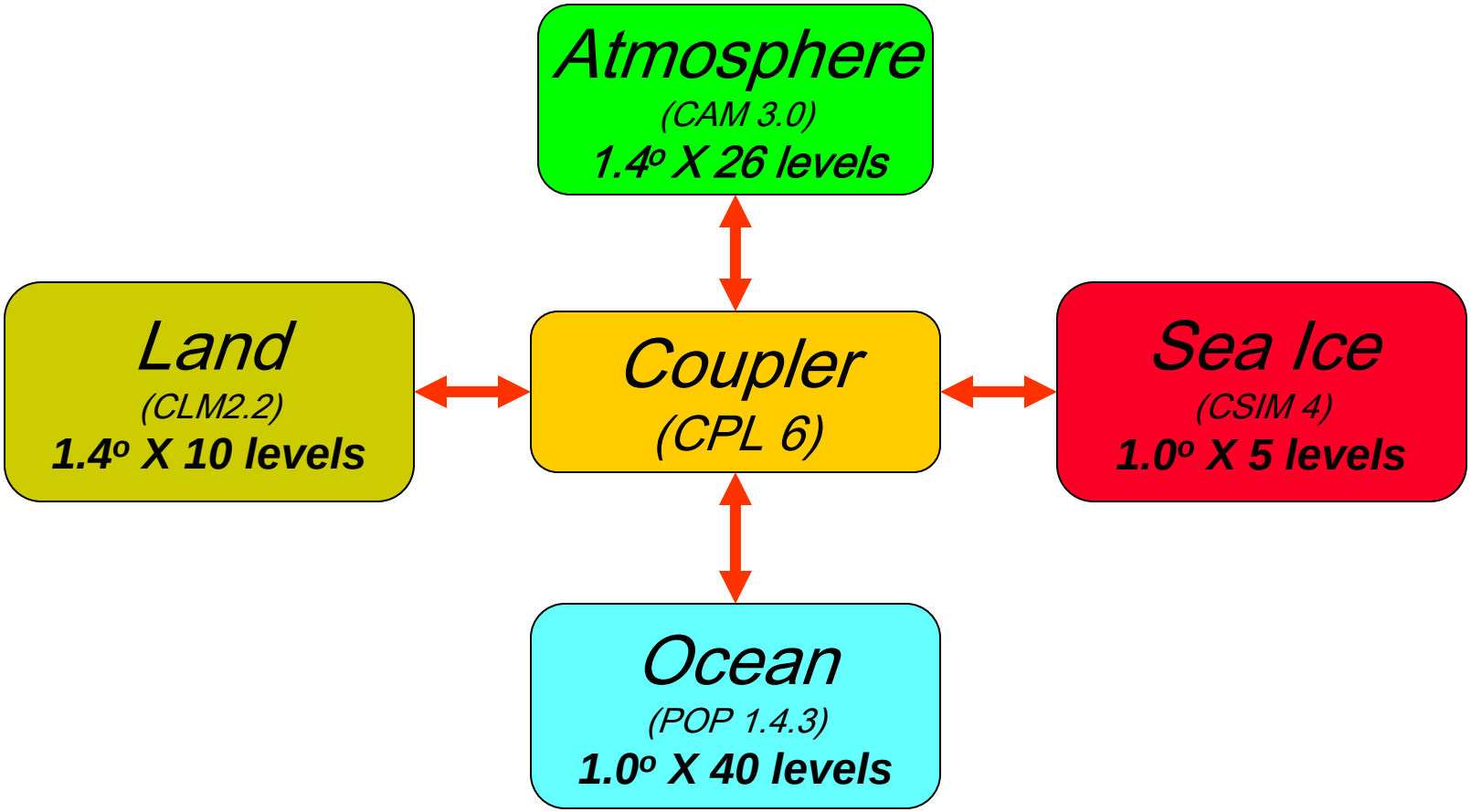
- Resolution has increased by a factor of 5.
- Are the model(s) converging with increased resolution?

Fidelity of atmospheric winds vs. resolution



- The resolution of Community Model has increased by a factor of ~6.
- The fidelity of its simulated winds has improved by a factor of ~20.

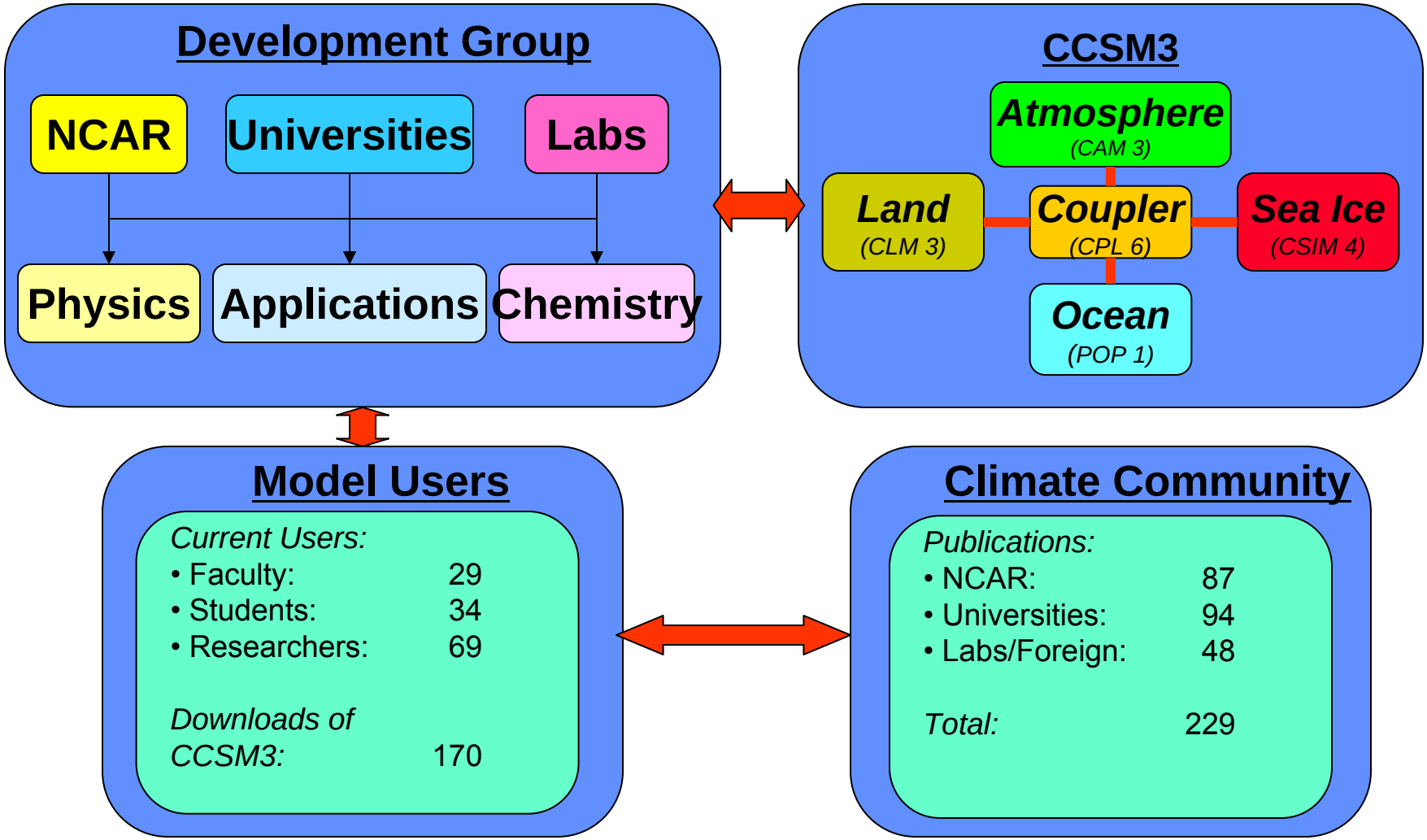
The Community Climate System Model CCSM3



http://www.ccsm.ucar.edu

Collins et al, 2006

The Modeling Community



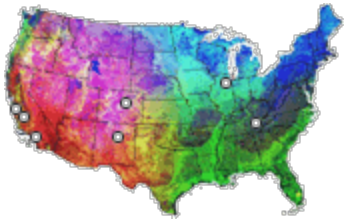
Modern Climate Model Implementations

Computational requirements of CCSM3:

- **~1 quadrillion operations/simulated year**
- *Rate of simulation:* **3.5 sim. years/day**
- *Output:* **10 GB/simulated year**
- *Data volume for IPCC:* **~100 TB**
- *Development effort:* **~1 person-century**

Distribution of CCSM3 Simulations

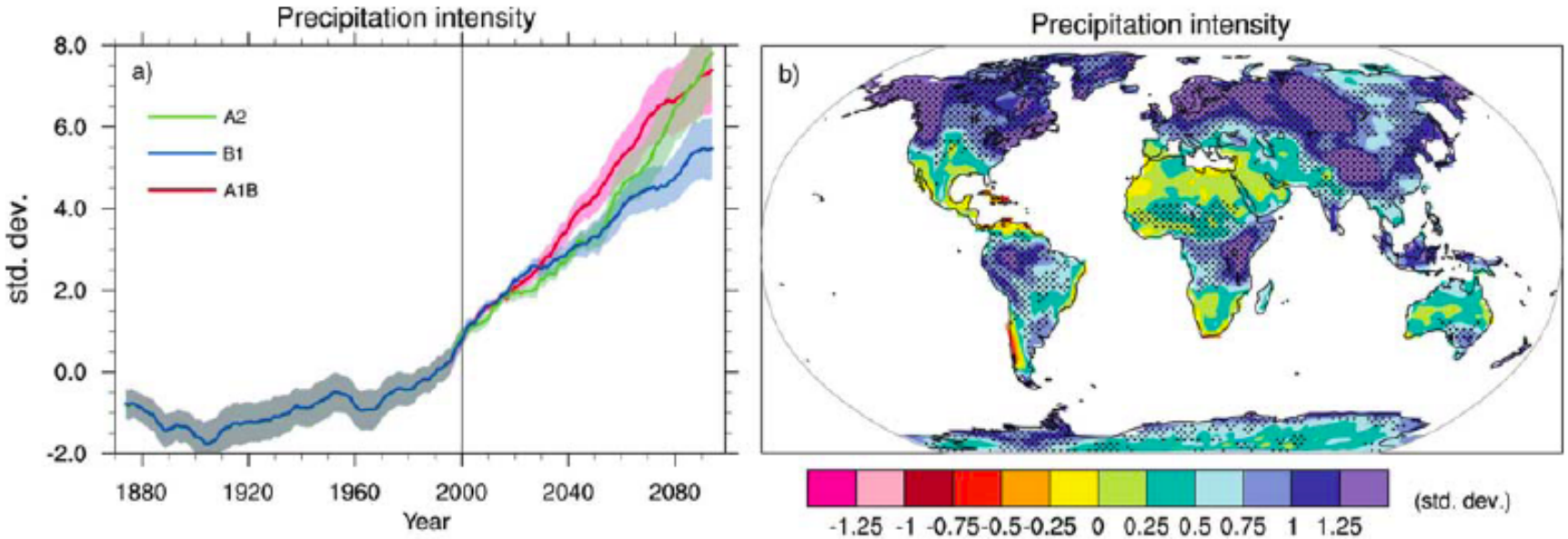
- **Central site: Earth System Grid**
  - —*DOE project to integrate major centers for supercomputing and analysis*



- **CCSM3 output available:**
  - —*Current contents:* *All code, input, and output*
  - —*Model simulations:* *10,000 years of ensembles*
  - —*Data volume:* *110 TB*

- **Access point: https://www.earthsystemgrid.org/**
- **Global access: PCMDI at LLNL**

Climate impacts: precipitation intensity

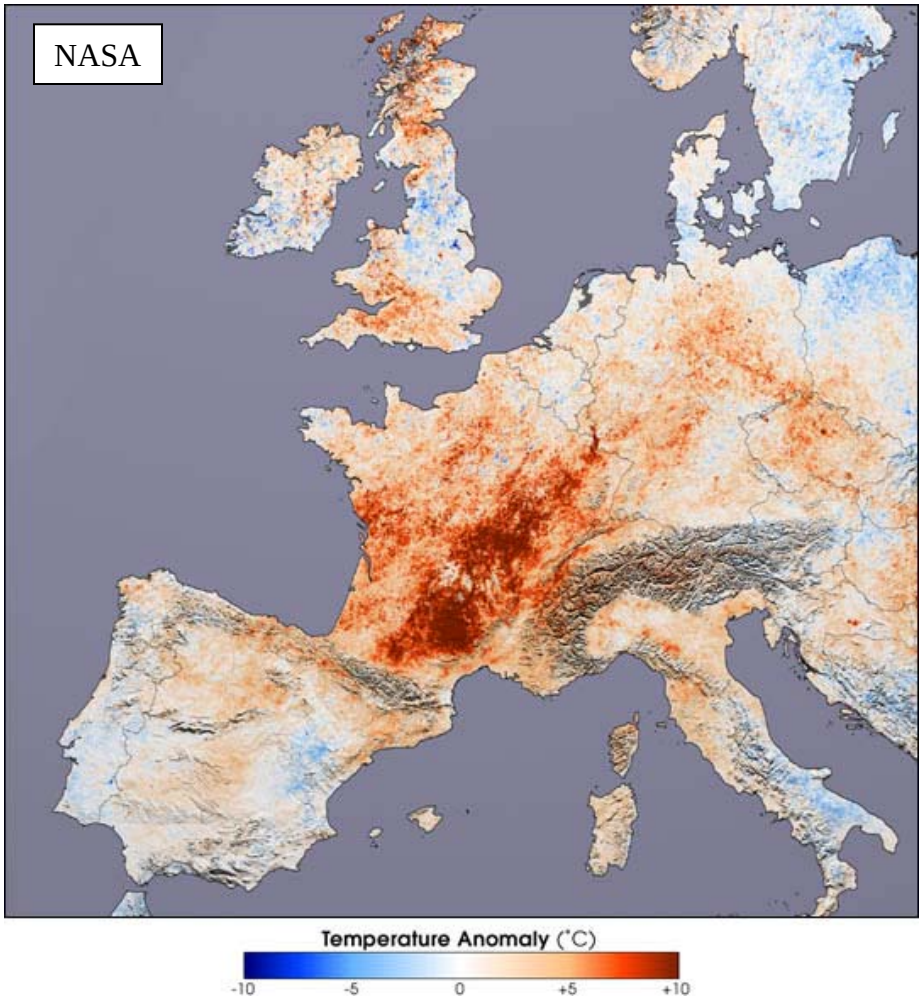


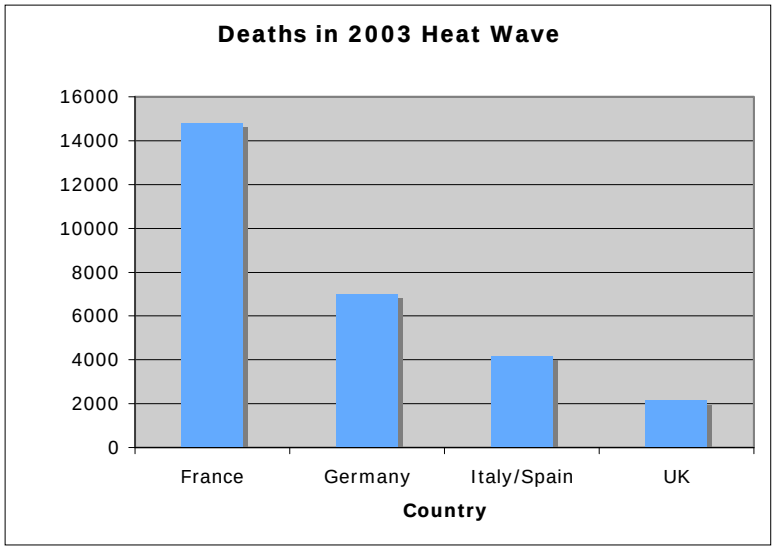
IPCC AR4, 2007

- Precipitation intensity is annual rainfall divided by the number of wet days.
- Precipitation intensity increases significantly at higher latitudes by 2100.

Climate extremes: 2003 European heat wave

August 2003 temperature anomalies



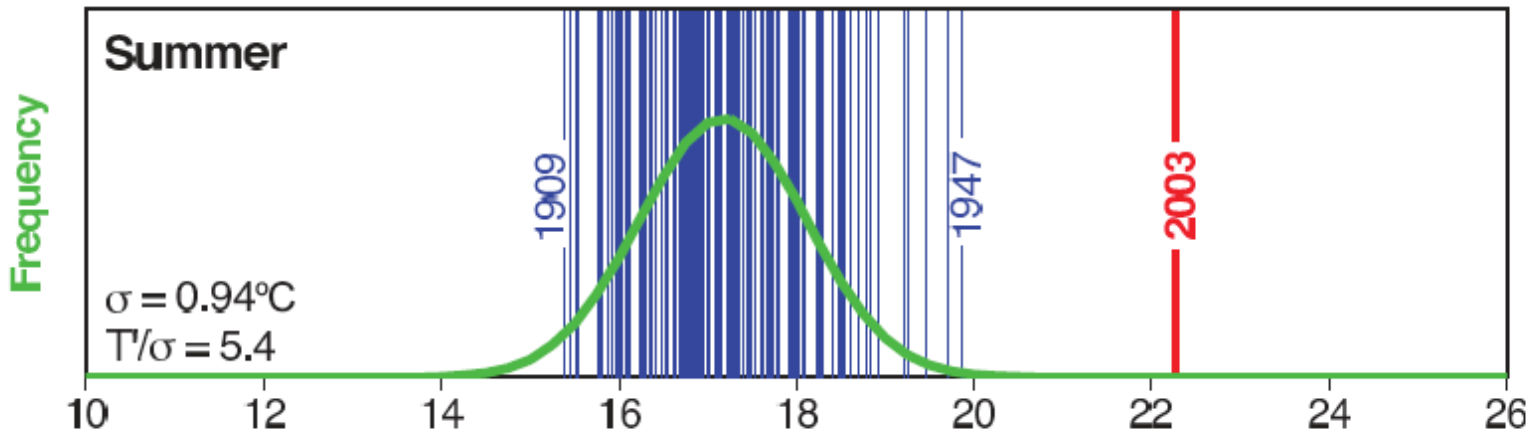


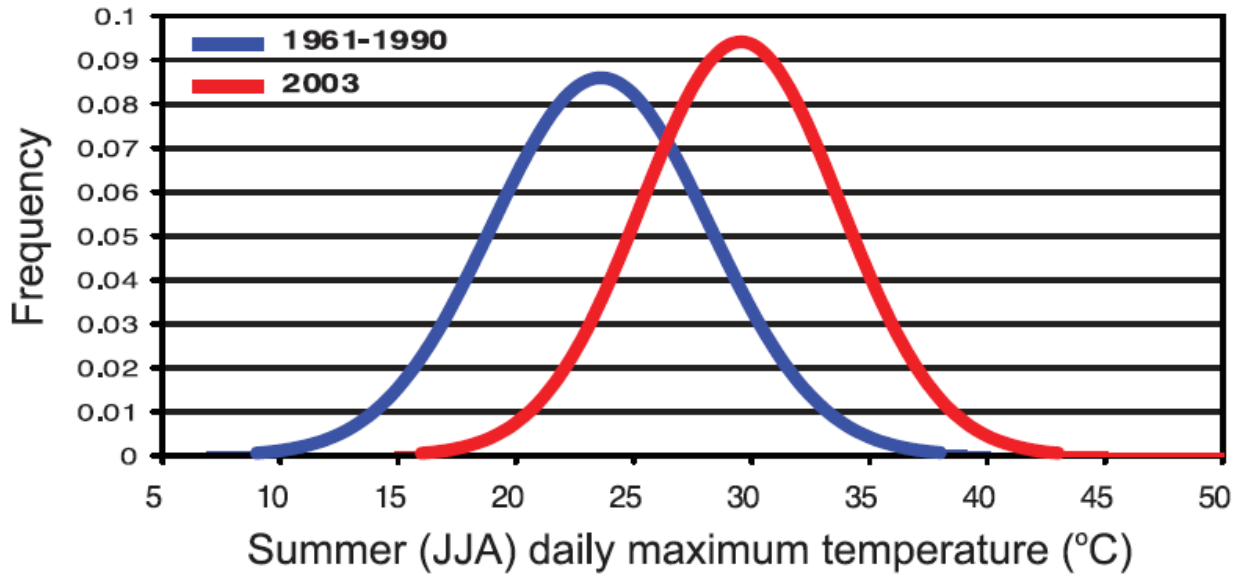
Key vulnerabilities of industry, settlements and society are most often related to:

- climate phenomena that exceed thresholds for adaptation, related to the rate and magnitude of climate change, particularly extreme weather events and/or abrupt climate change
- limited access to resources (financial, human, institutional) to cope, rooted in issues of development context

An “extreme” is an usual climate state

Monthly average August 2003 temperatures

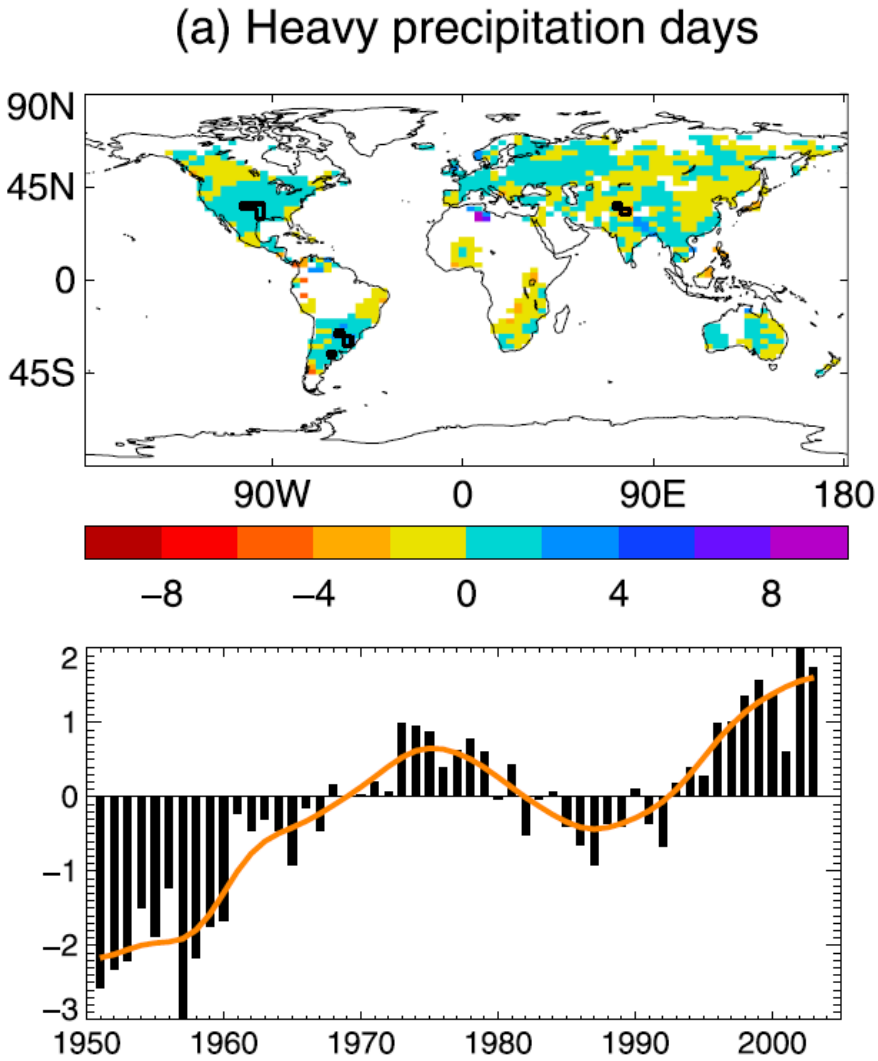




IPCC AR4, 2007

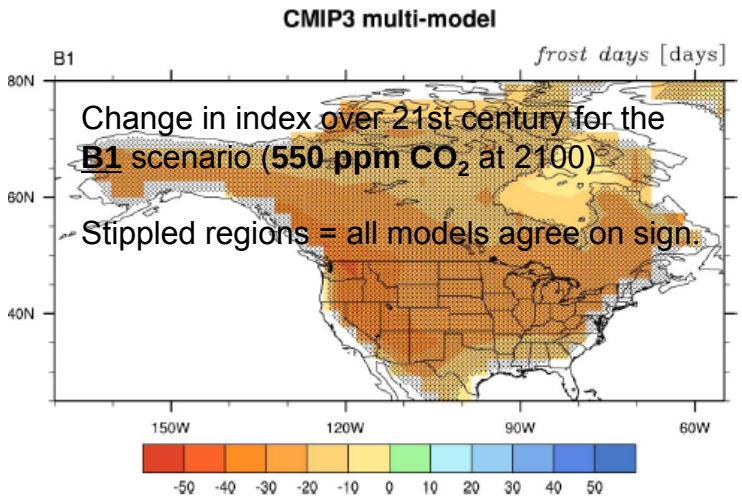
Are extreme events likely to change?

- There is an increased risk of more frequent and longer-lasting heat waves.
- Growing season length has been projected to increase as climate warms.
- Climate models project increased summer dryness and winter wetness in most parts of the northern middle and high latitudes.
- Precipitation will tend to be concentrated into more intense events, with longer periods of little precipitation in between.



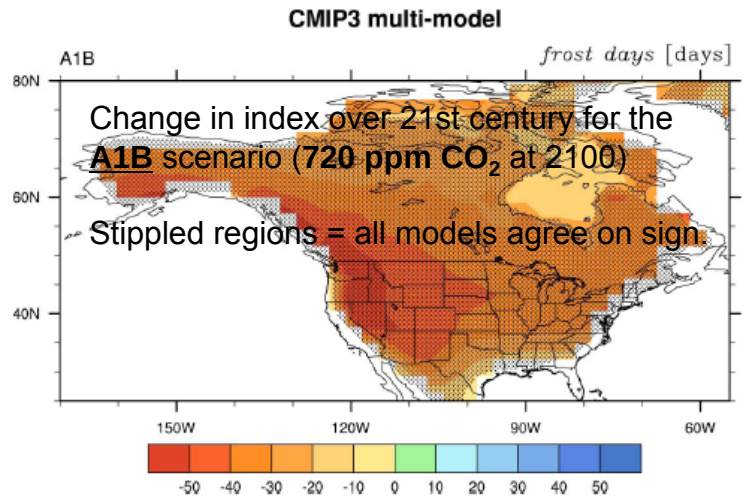
Alexander et al, 2006

Climate extreme indices for North America



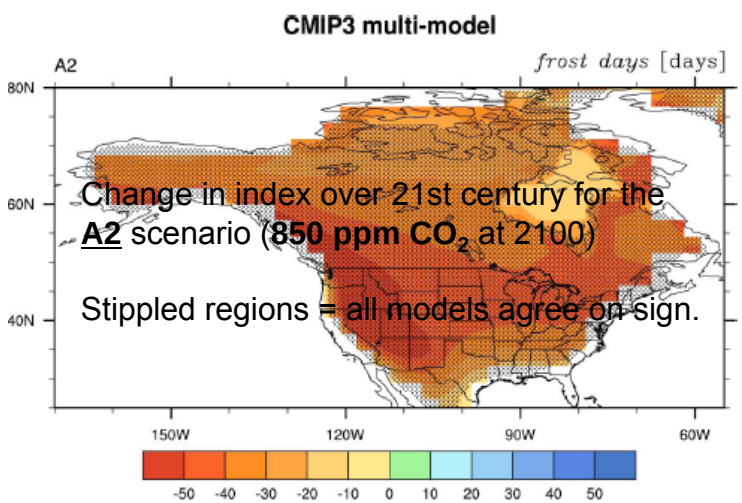
Change in index over 21st century for the **B1** scenario (**550 ppm CO_2** at 2100)

Stippled regions = all models agree on sign.



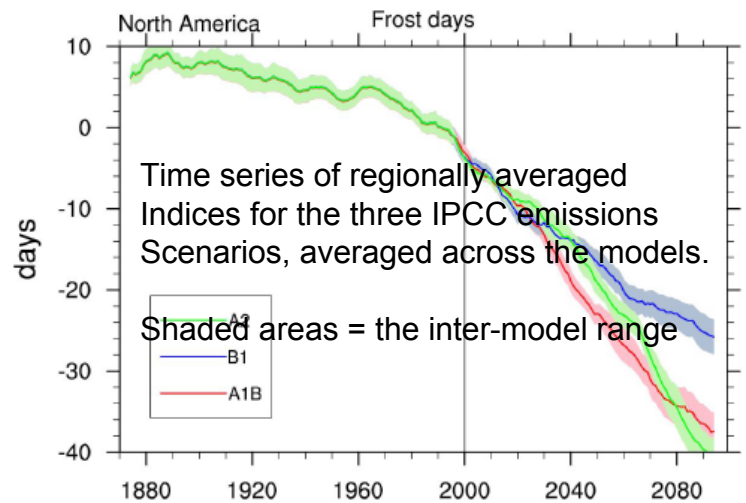
Change in index over 21st century for the **A1B** scenario (**720 ppm CO_2** at 2100)

Stippled regions = all models agree on sign.



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

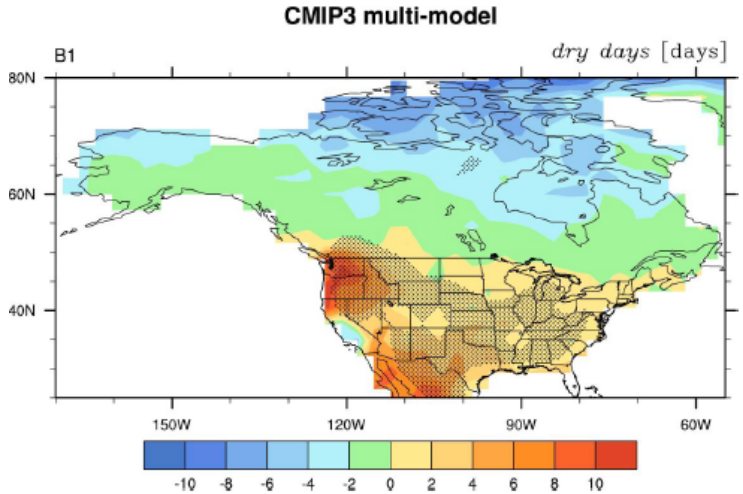
Stippled regions = all models agree on sign.

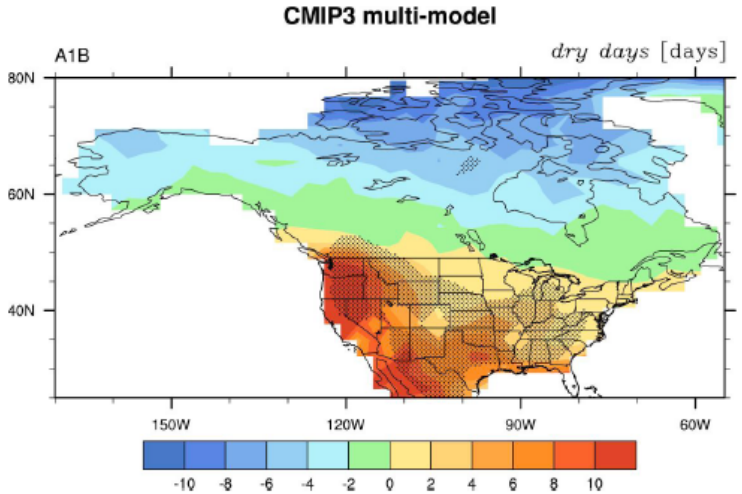


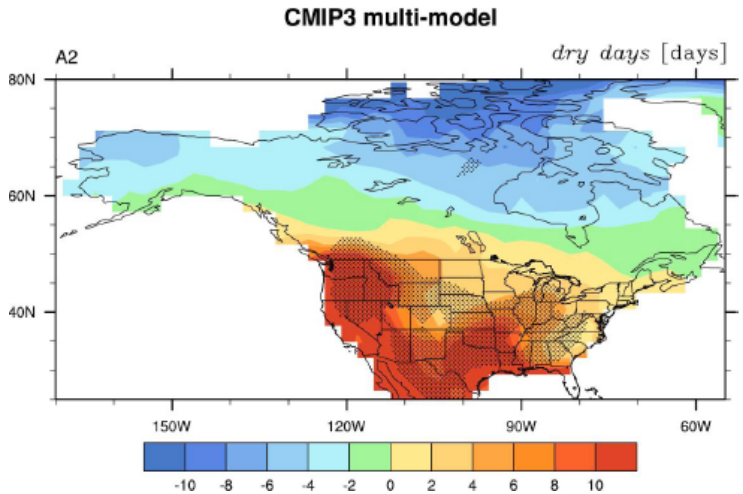
Time series of regionally averaged Indices for the three IPCC emissions Scenarios, averaged across the models.

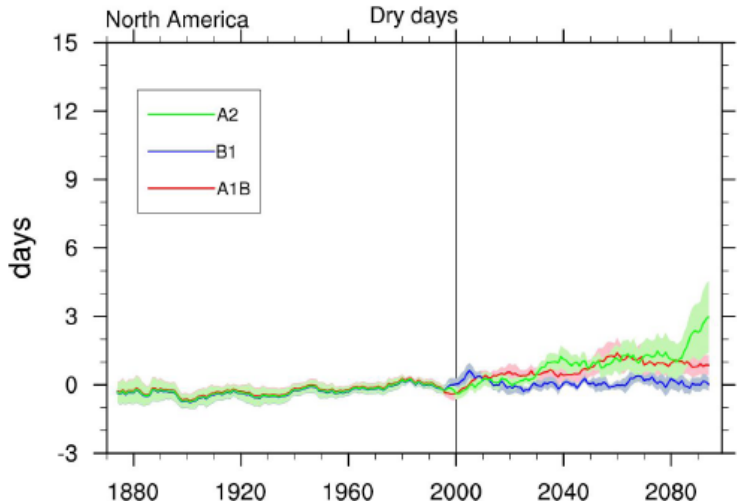
Shaded areas = the inter-model range

Maximum number of dry days

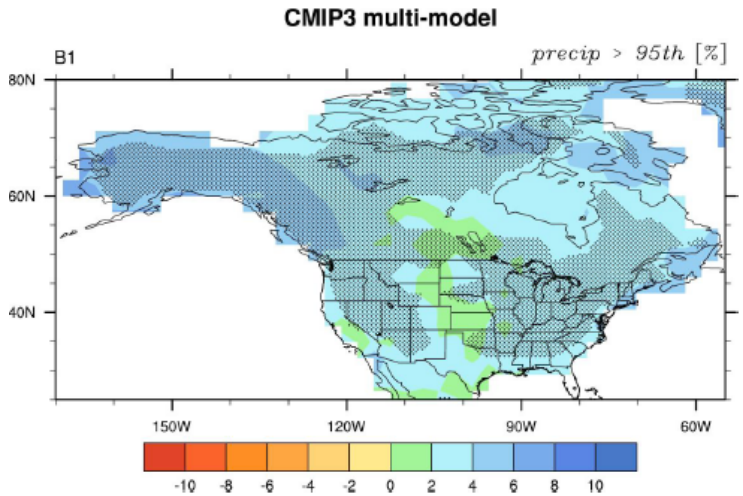


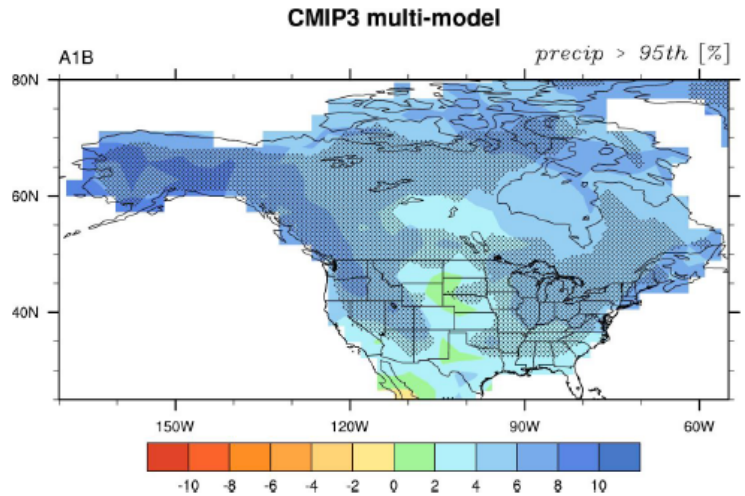


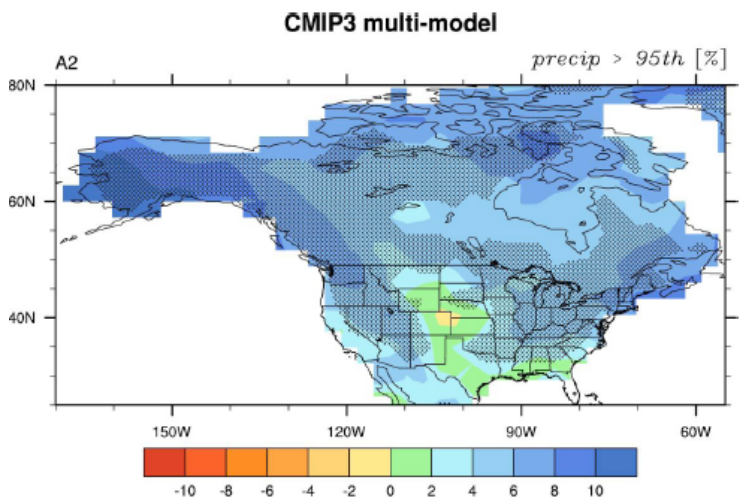


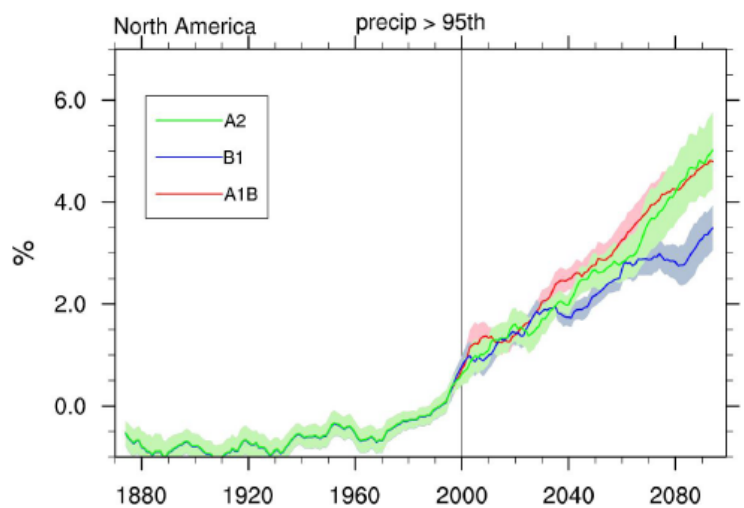


Precipitation fraction > 95th percentile

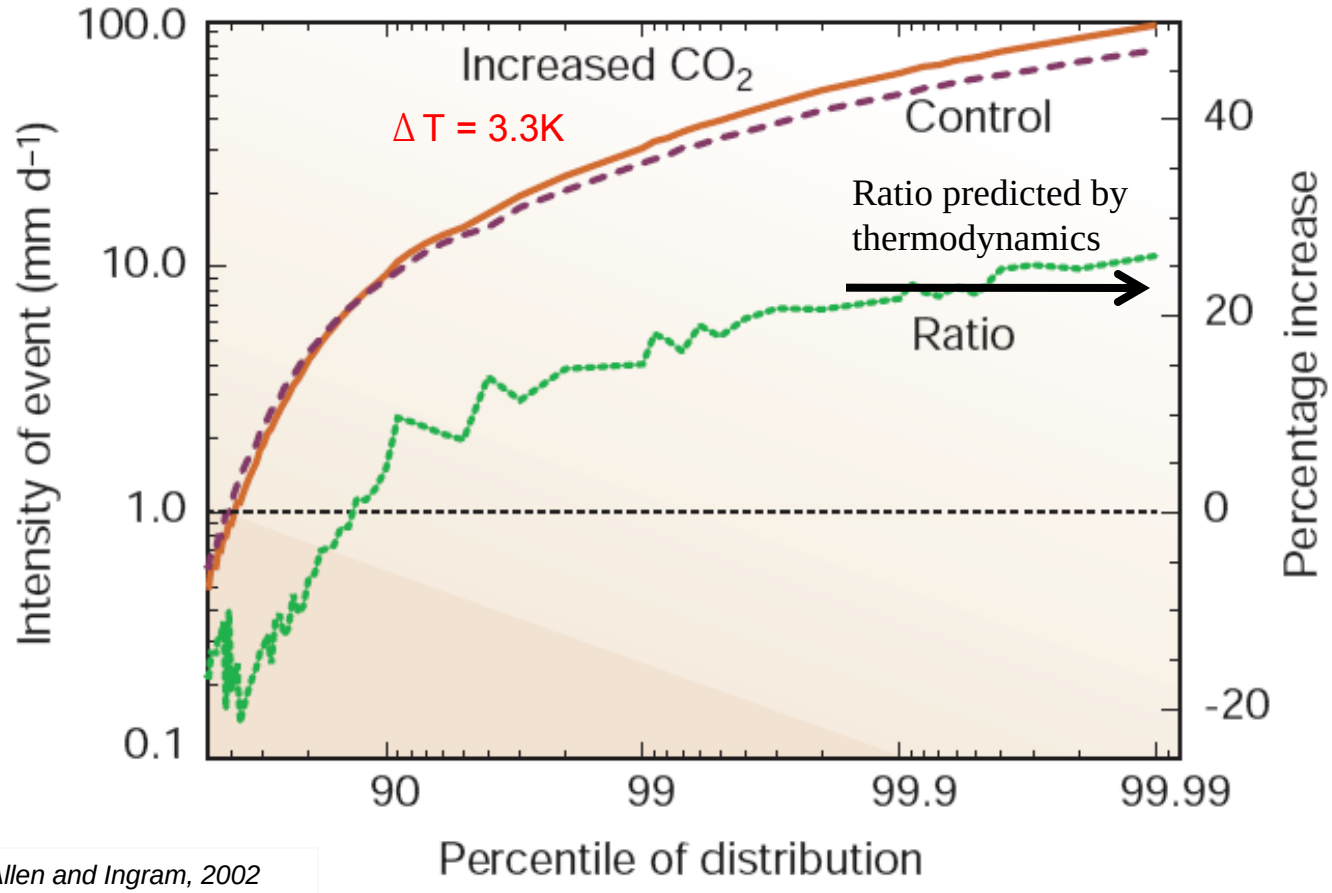








Precipitation extremes and thermodynamics

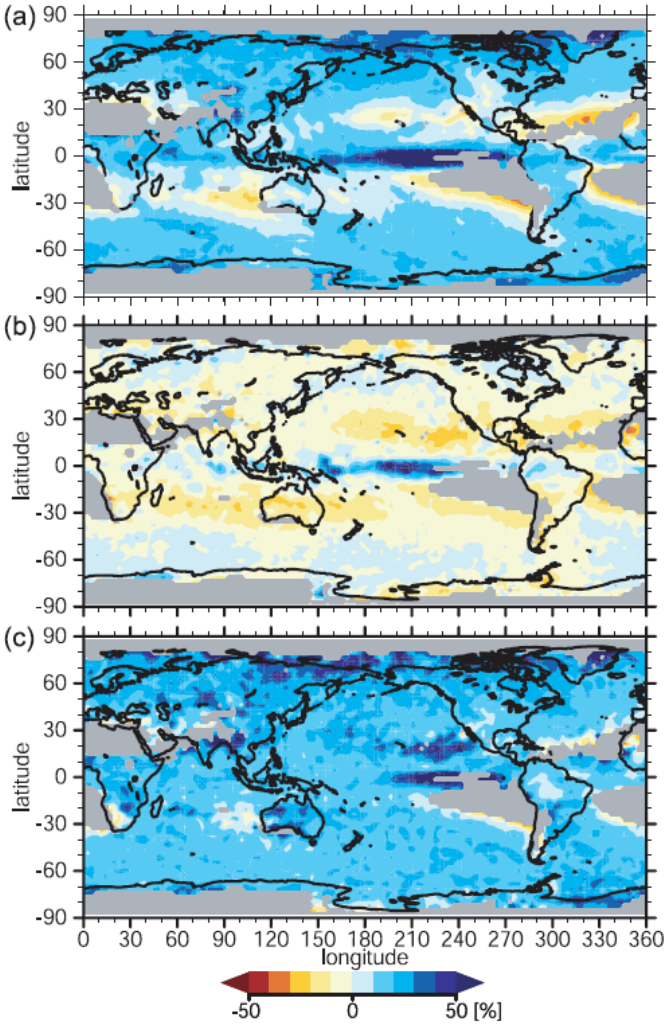


Allen and Ingram, 2002

- Increases in most extreme precipitation are set by higher saturation humidities.
- Saturation humidities are set by the Clausius-Clapeyron thermodynamic law.

Extreme precipitation change: 2000 to 2100

- **Other analyses also suggest that thermodynamics governs the increase in most extreme rainfall.**
- **Could other factors be important?**
- **What sets the increased duration in dry periods?**



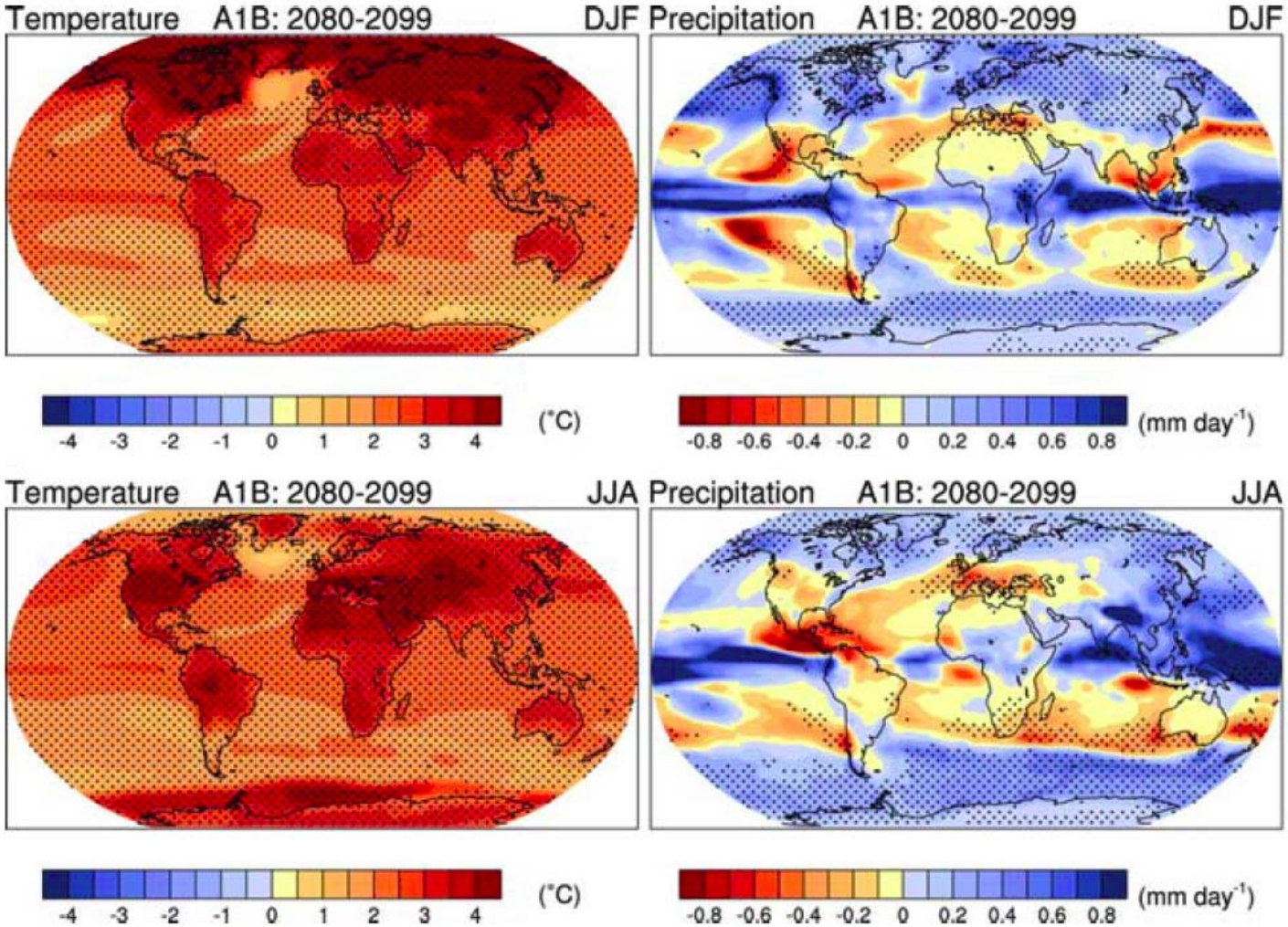
Total increase in 99% rainfall

Increase from dynamics

Increase from thermodynamics

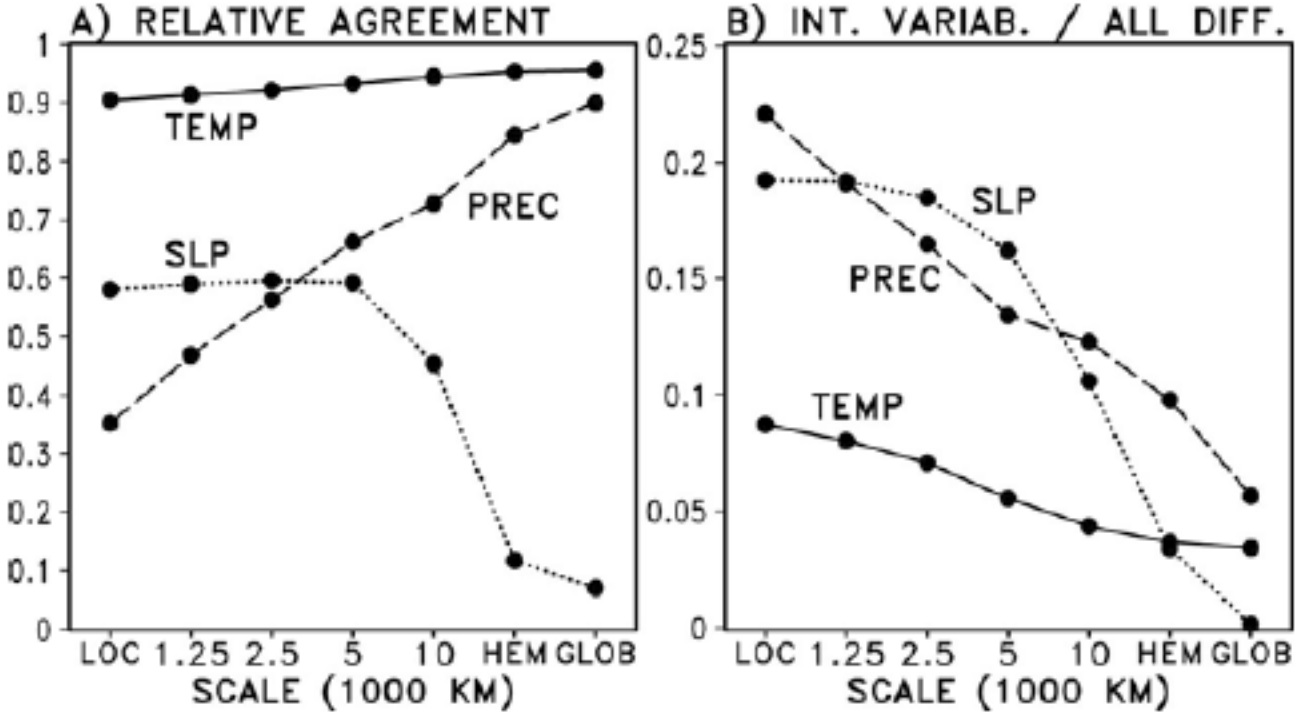
Emori and Brown, 2005

Low confidence in impact on rainfall



IPCC AR4, 2007

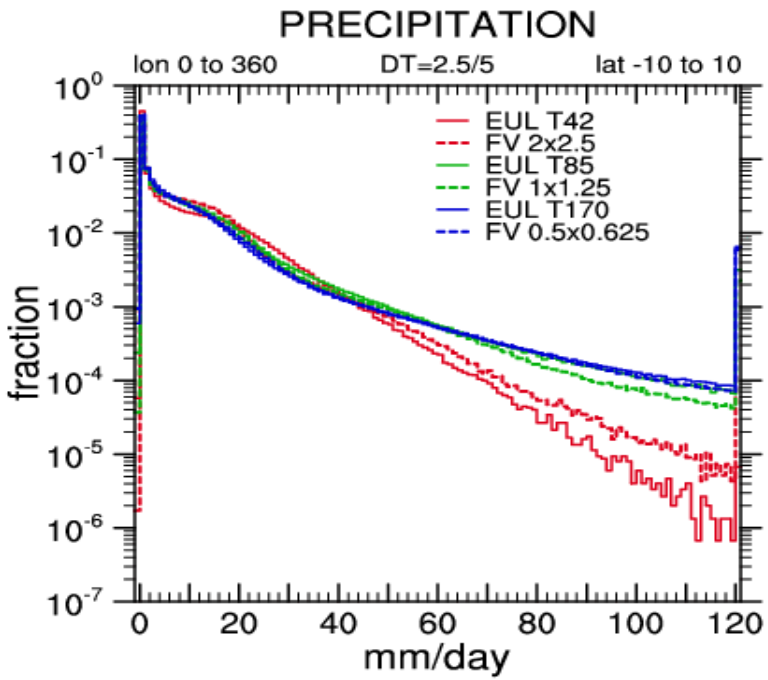
Predictive confidence vs. resolution

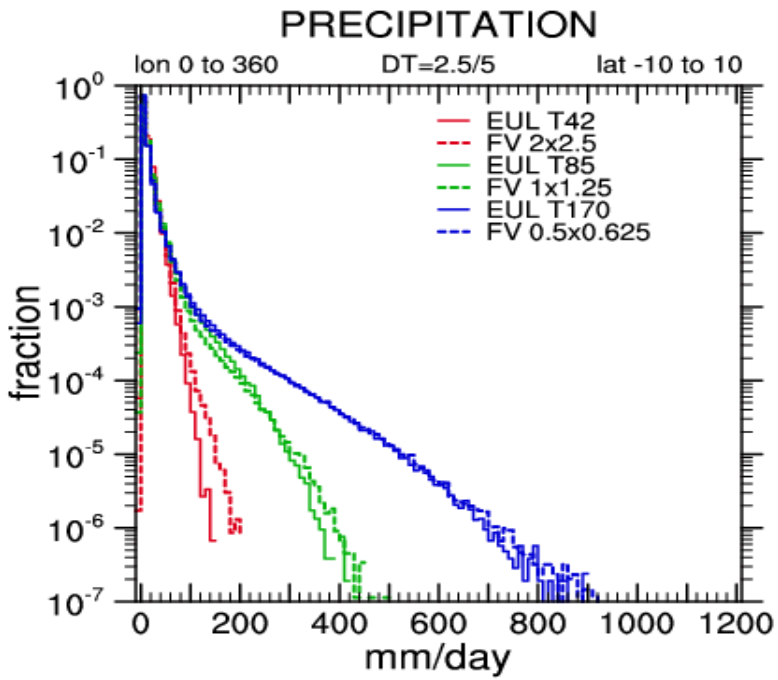


IPCC AR4, 2007

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

Precipitation extremes vs. resolution

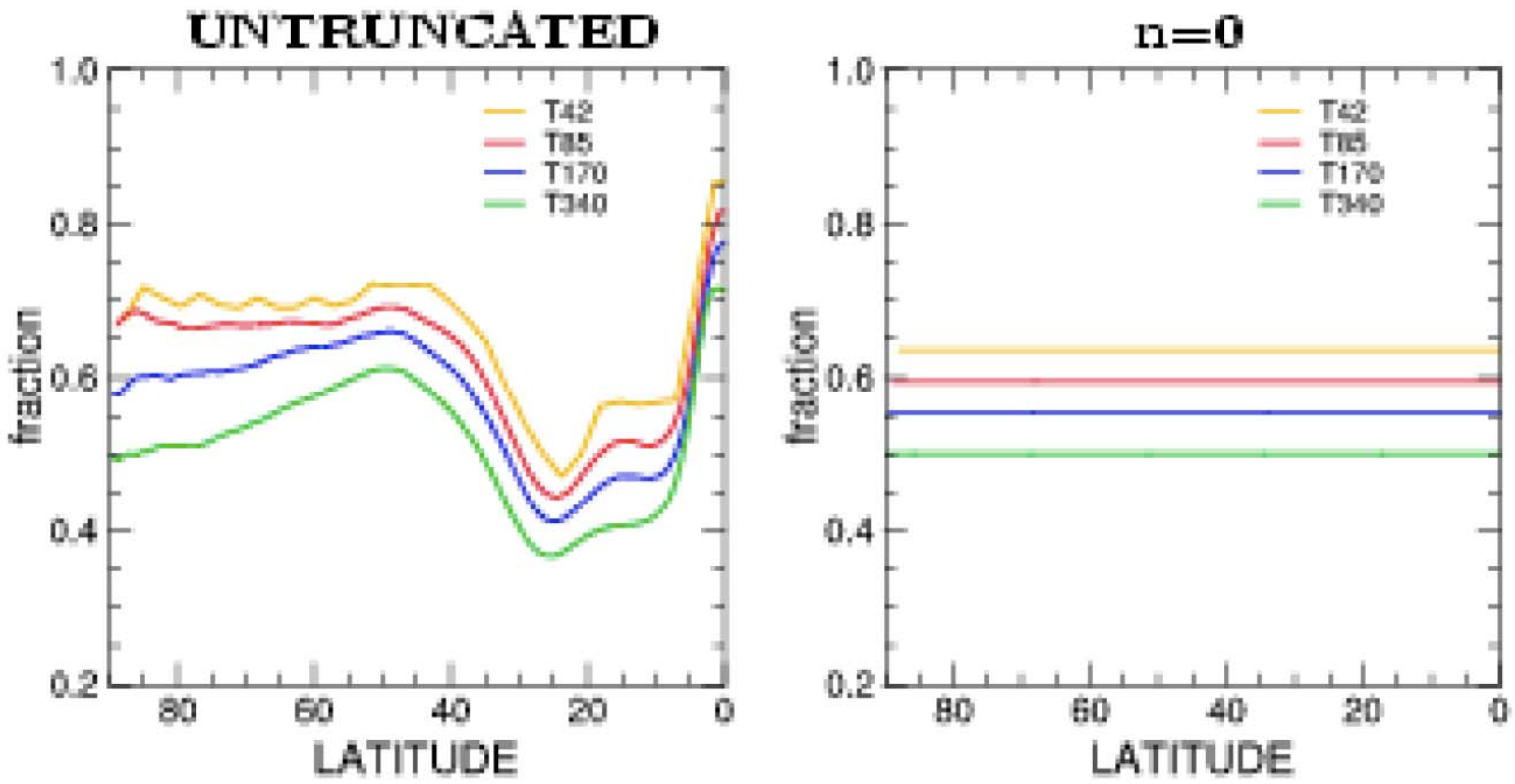




Williamson, 2007

- Do the extreme rainfall rates converge with increasing resolution?
- **NO**? The rates do not converge for higher spatio-temporal resolution.

Changes in cloud amount vs. resolution



Williamson, 2007

- Do cloud properties and amounts converge with increasing resolution?
- **NO**? Cloud amounts show no sign of convergence (in at least 1 model).

Future research in climate extremes

- **What factors govern higher frequency of dry spells?**
- **What factors govern concurrence of extremes, e.g. dry spells and heat waves?**
- **Are projected extremes robust?**
  - *Errors in model mean state*
  - *Errors in model physics*
  - *Resolution convergence*
- **GCMs were designed for means, not extremes.**
- **We need GCMs designed for resolution independence and convergence at small scales.**

Conclusions

- **Climate change prediction will increasingly focus on regional effects and unusual weather.**
- **The focus on extreme climate change will require identification of highly intermittent phenomena.**
- **These predictions require models that converge with increasing spatial and temporal resolution.**
- **Climate models need physics that obeys the scale invariance of the real atmosphere.**