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REVIEW

The use of the multi-model ensemble in probabilistic climate projections

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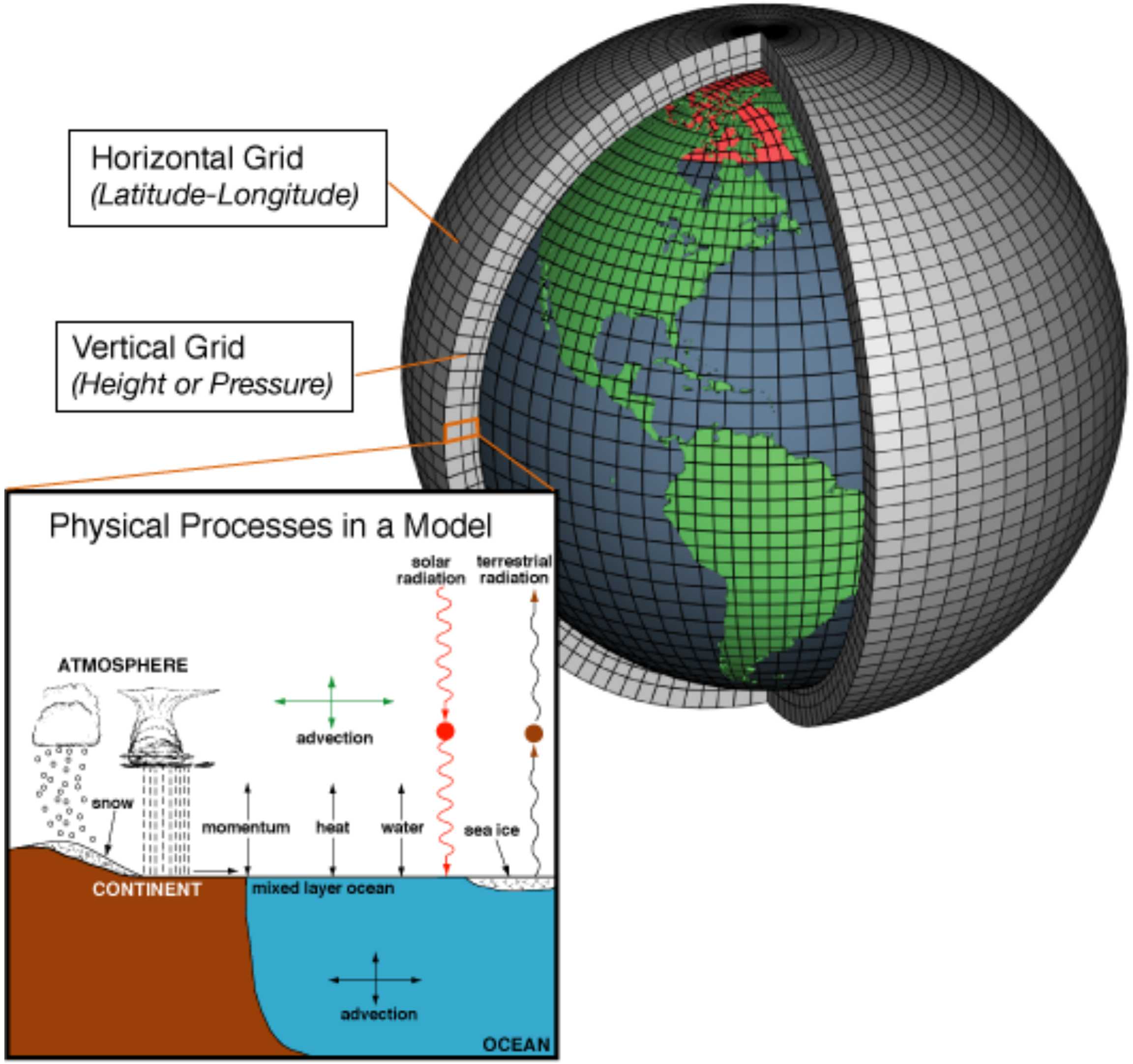
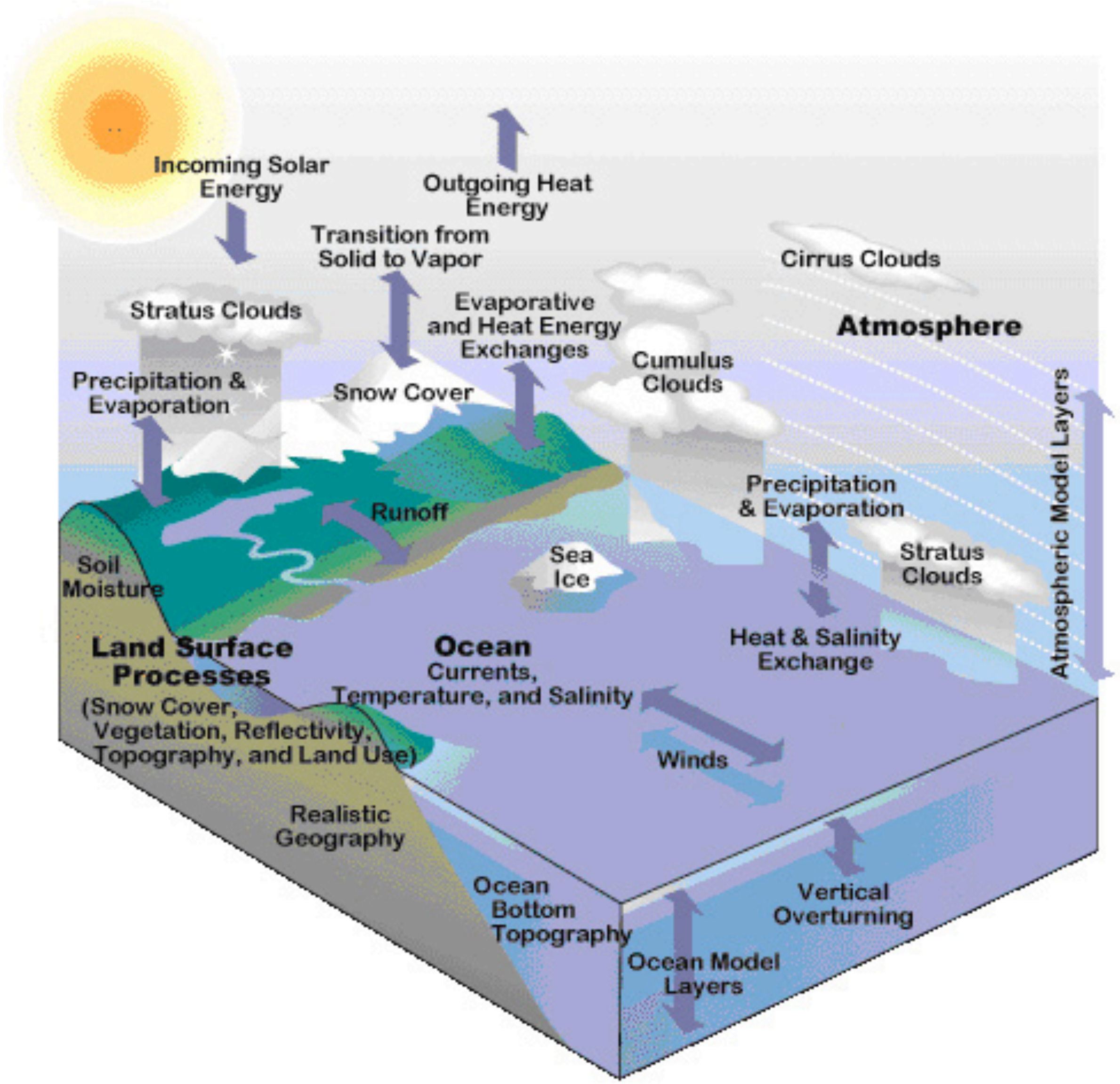
Climate Models

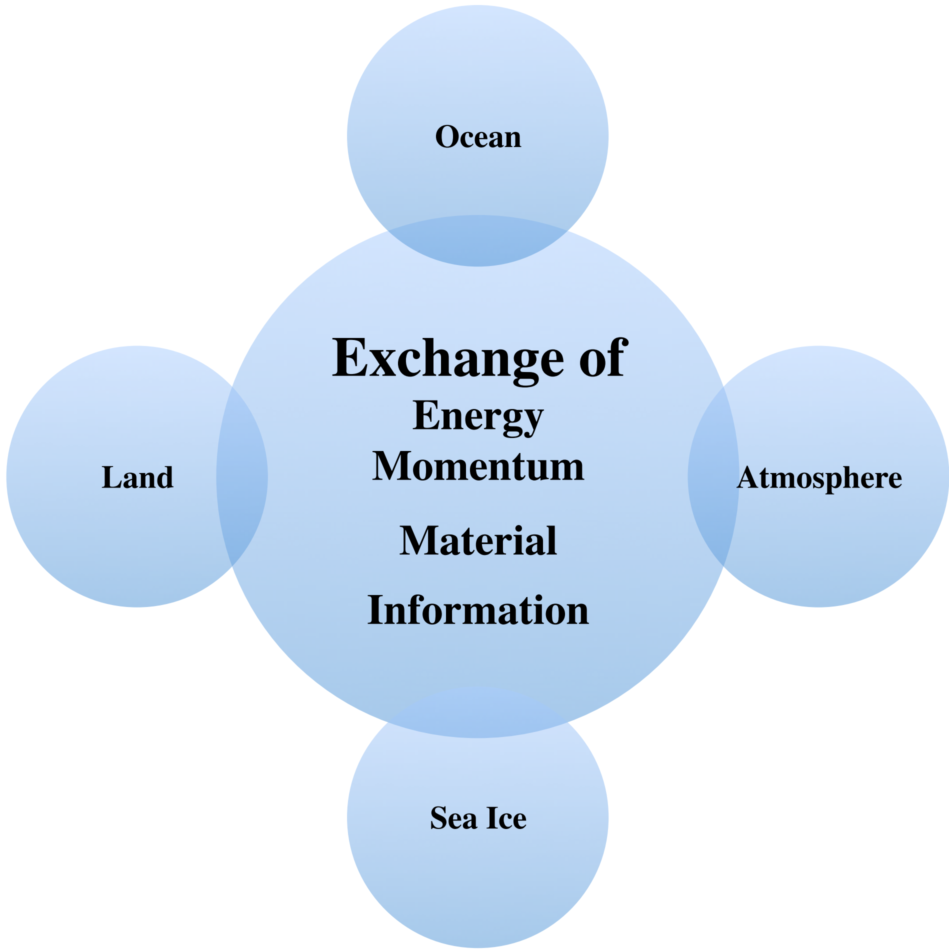
- Atmosphere-Ocean Generation Circulation Models (AOGCMs)
- 4 major subcomponents
  - Ocean
  - Atmosphere
  - Sea Ice
  - Land



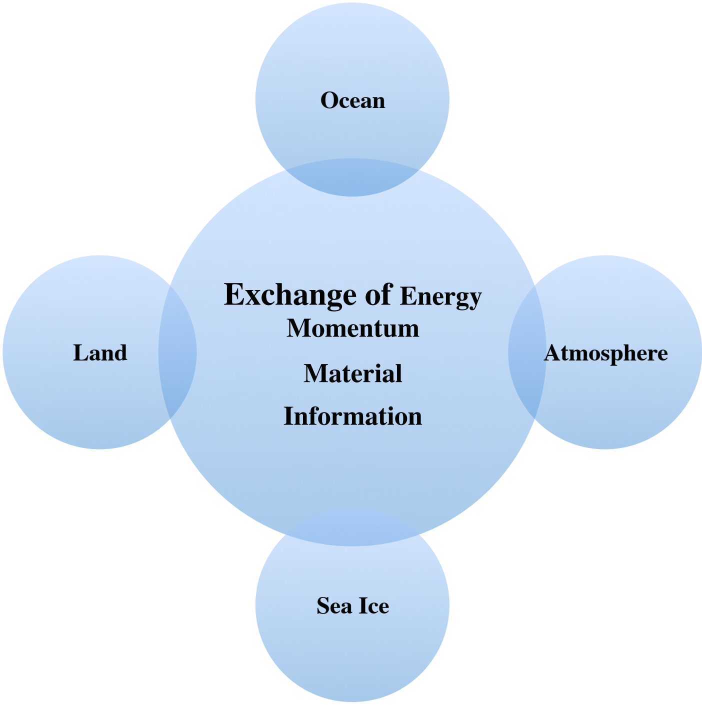


- Community Climate System Model (CCSM v3)
- 3 x 10^{12} calculations for single earth day simulation.
- National Center for Atmospheric Research supercomputer cluster

Complex System



Complex System



- Nonlinear
- Feedback

  Logistic Map $x_{n+1} = rx_n(1 - x_n)$

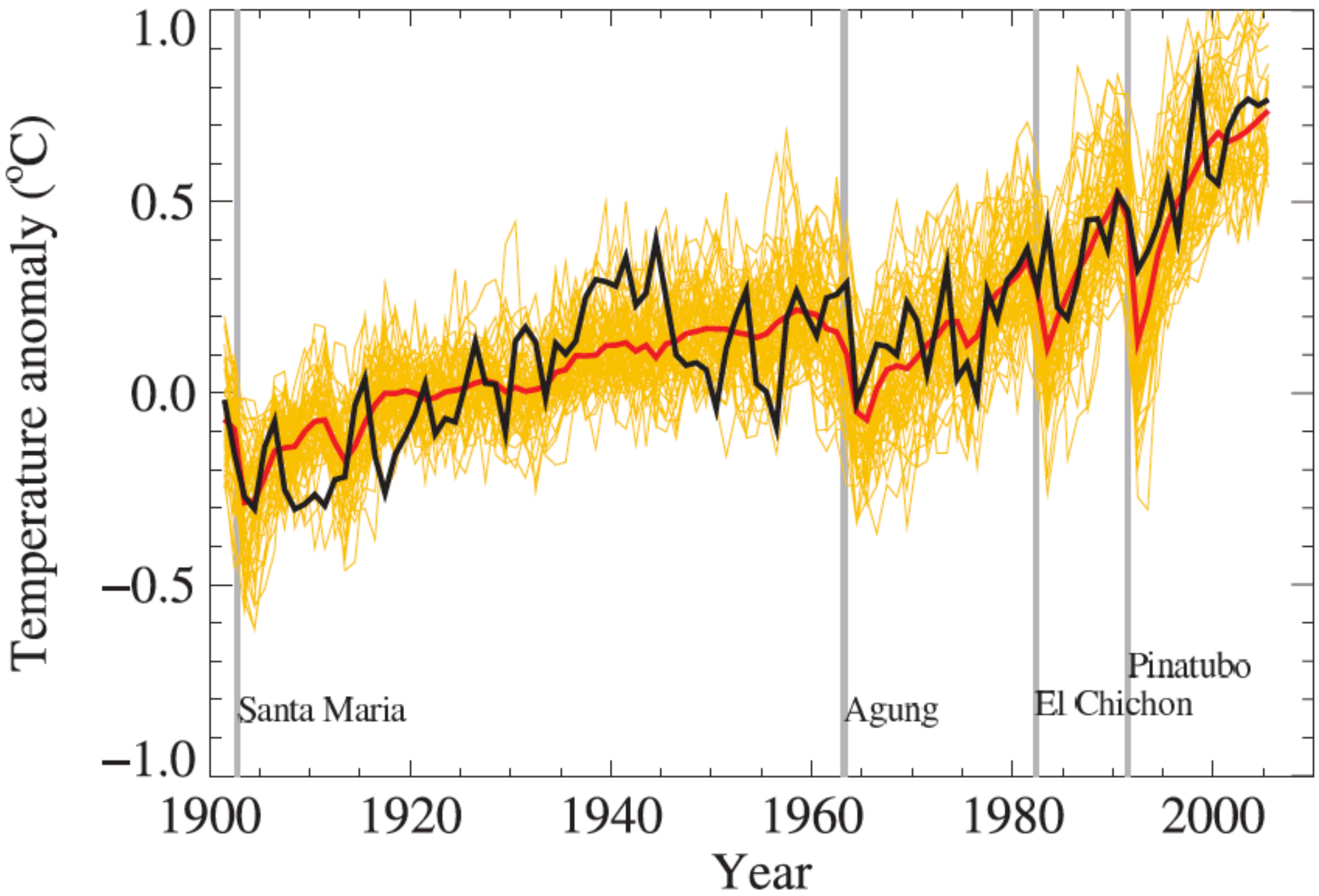
  nonlinear, no feedback, chaotic
- Interdependent sub-components or sub-systems
- Micro and macro-states
- Spontaneous ordering
- Emergence
- Memory
- *"Complexity starts when causality breaks down"**

- Ladyman, J.; Lambert, J.; Wiesner, K. What Is a Complex System? *Eur. J. Philos. Sci*. **2013**, *3*, 33–67
- Schmidt, G. A. The Physics of Climate Modeling. *Phys. Today* **2007**, *60*, 72–73.

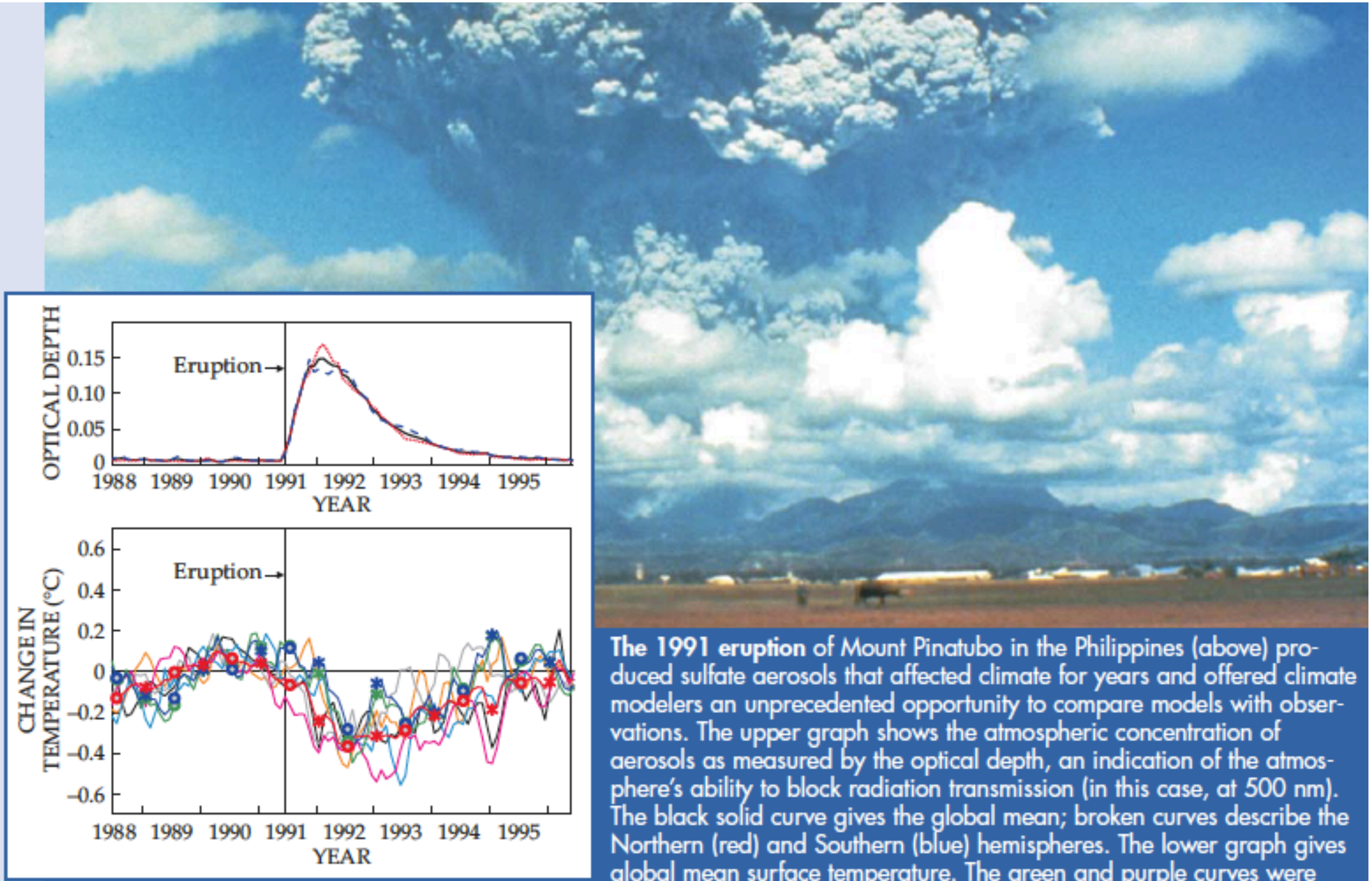
Model Parameters / Variables

- Atmospheric Temperature
- Precipitation
- Pressure
- Wind velocity
- Humidity
- Vertical Profiles
- Ocean Temperature
- Ocean Salinity
- Ocean Circulation
- Sea Ice Distribution
- Vegetation

FAQ 8.1, Figure 1. *Global mean near-surface temperatures over the 20th century from observations (black) and as obtained from 58 simulations produced by 14 different climate models driven by both natural and human-caused factors that influence climate (yellow). The mean of all these runs is also shown (thick red line). Temperature anomalies are shown relative to the 1901 to 1950 mean. Vertical grey lines indicate the timing of major volcanic eruptions. (Figure adapted from Chapter 9, Figure 9.5. Refer to corresponding caption for further details.)*



- Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi and K.E. Taylor, 2007: Cilmate Models and Their Evaluation. In: Climate Change **2007**: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate



The 1991 eruption of Mount Pinatubo in the Philippines (above) produced sulfate aerosols that affected climate for years and offered climate modelers an unprecedented opportunity to compare models with observations. The upper graph shows the atmospheric concentration of aerosols as measured by the optical depth, an indication of the atmosphere's ability to block radiation transmission (in this case, at 500 nm). The black solid curve gives the global mean; broken curves describe the Northern (red) and Southern (blue) hemispheres. The lower graph gives global mean surface temperature. The green and purple curves were generated from two somewhat different observational data sets. The red curve gives the average of five runs simulated by the GISS ModelE GCM. Circles indicate June–August; asterisks, December–February. (Photograph by Dave Harlow, courtesy of the US Geological Survey; graphs adapted from J. Hansen et al., http://arxiv.org/abs/physics/0610109.)

- Schmidt, G. A. The Physics of Climate Modeling. *Phys. Today* **2007**, *60*, 72–73.

Goals of Climate Modeling

- Better representations of physical processes ("simulations-for-understanding")
- Better representations of the future climate ("simulations-for-decision-support")

Thompson, Erica and Smith, Leonard A. (2014) The hawkmoth effect. In: LSE Research Festival 2014, 8 May 2014, The London School of Economics, London, UK. (Unpublished)

Review

The use of the multi-model ensemble in probabilistic climate projections

By Claudia Tebaldi[1,*] and Reto Knutti[2]

- 1987 – Human population reaches 5 billion
- 1988 – Intergovernmental Panel on Climate Change (IPCC) formed
- 1990 – IPCC AR1 – Temperature rises 0.3 – 0.6 degrees in last hundred years. Human emissions in addition to natural causes global warming.
- 1995 – IPCC AR2 – “discernable human influence” on Earth’s climate
- 1997 – Kyoto Protocol – Developed nations to reduce emissions by 5% by 2008-2012
- 1999 – Human population reaches 6 billion
- 2001 – IPCC AR3 – “new and stronger evidence” – Human greenhouse emissions main contributor
- 2007 – IPCC AR4 – > 90% likely that modern day climate change results from human intervention

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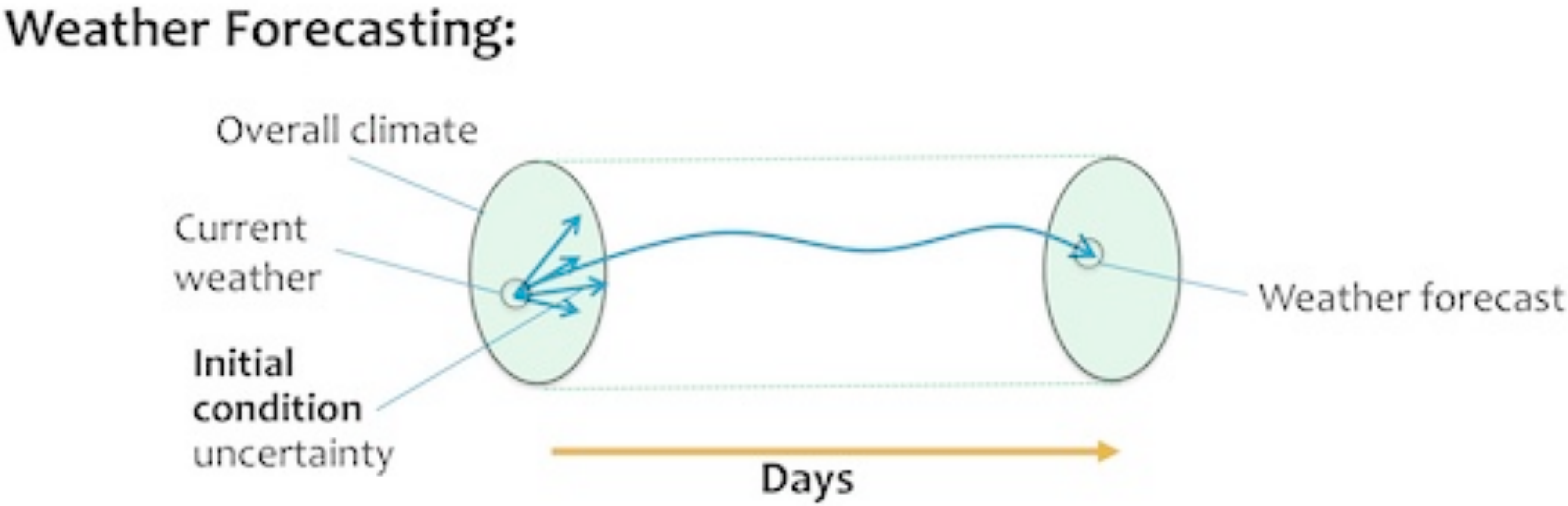

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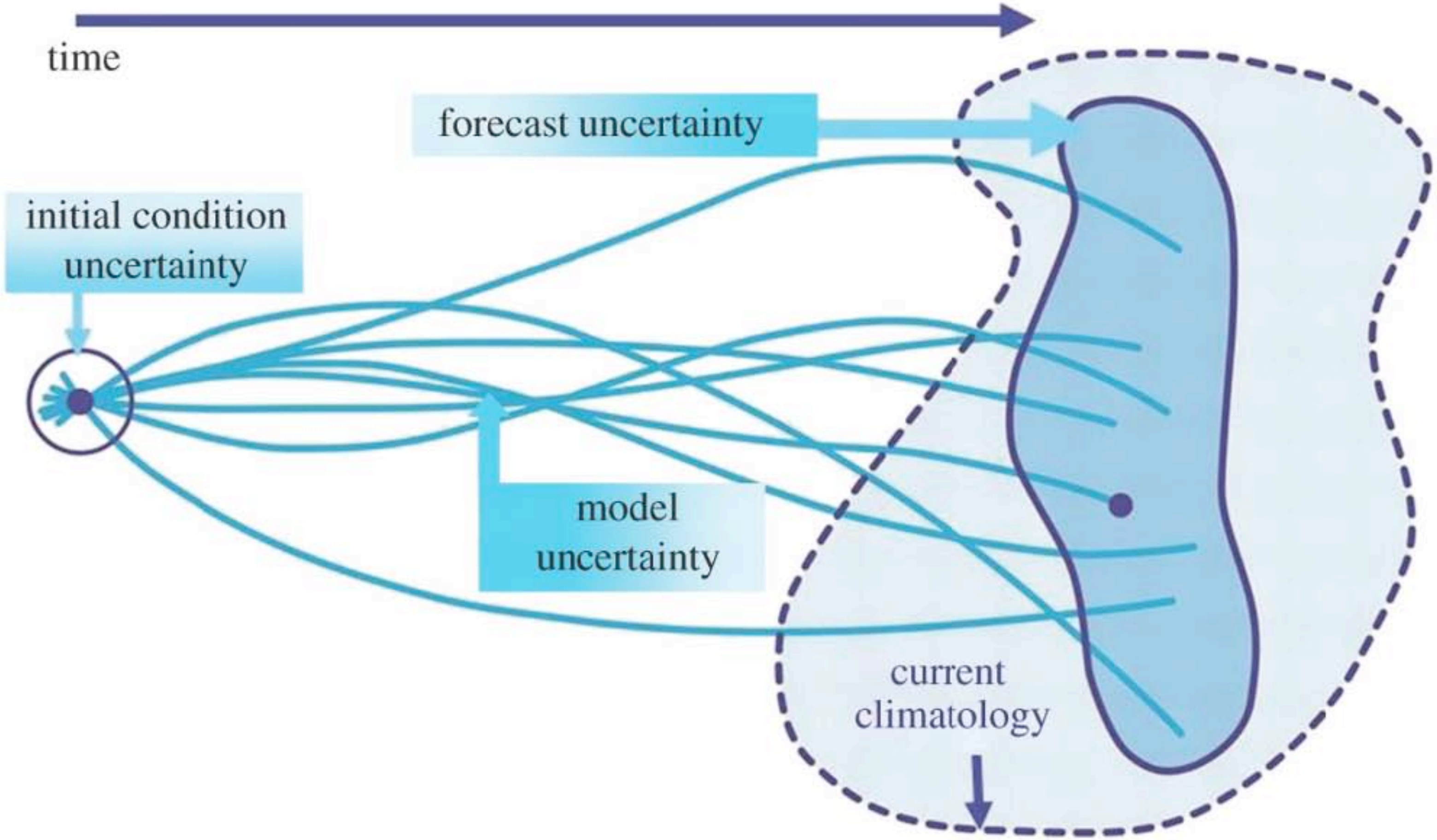


Slingo, J.; Palmer, T. Uncertainty in Weather and Climate Prediction. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2011**, *369*, 4751–4767.

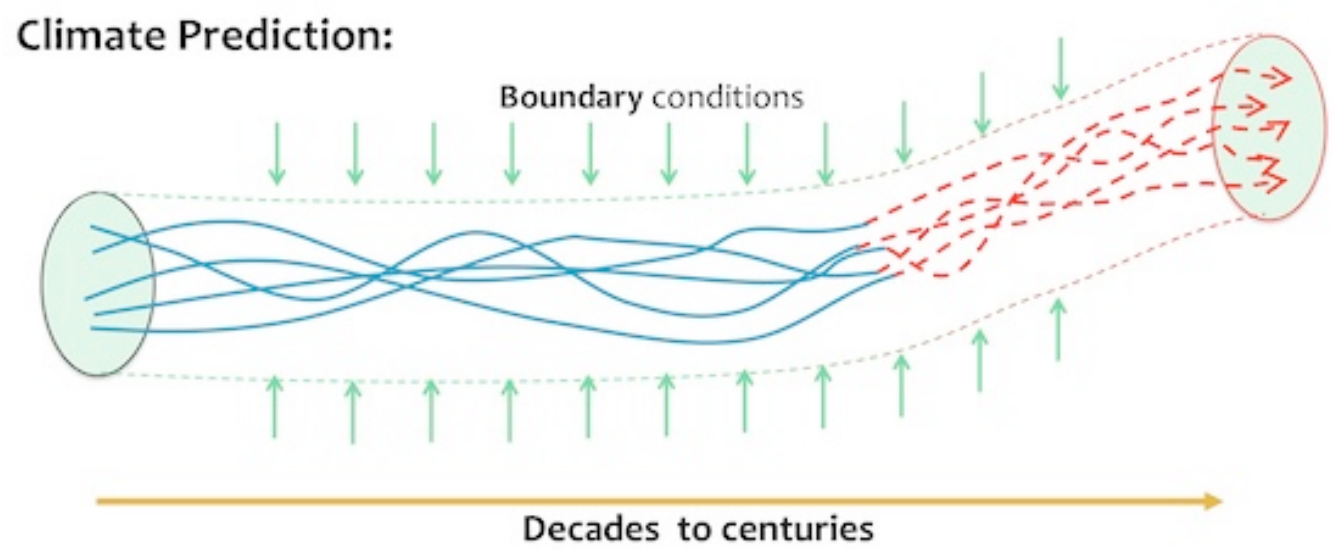
Sources of Uncertainty

1. Initial Conditions
2. Boundary Conditions
3. Parameter Uncertainty $x_{n+1} = ax_n^3 + bx_n$

   Numerical Uncertainty (grid resolution, truncation, Numerical method)

1. Model or Structural Uncertainty

$$x_{n+1} = ax_n^{2.5} + bx_n \text{ or } x_{n+1} = ax_n^{(2.5+\sin(x_n))} + bx_n + c\sin(x_n)$$



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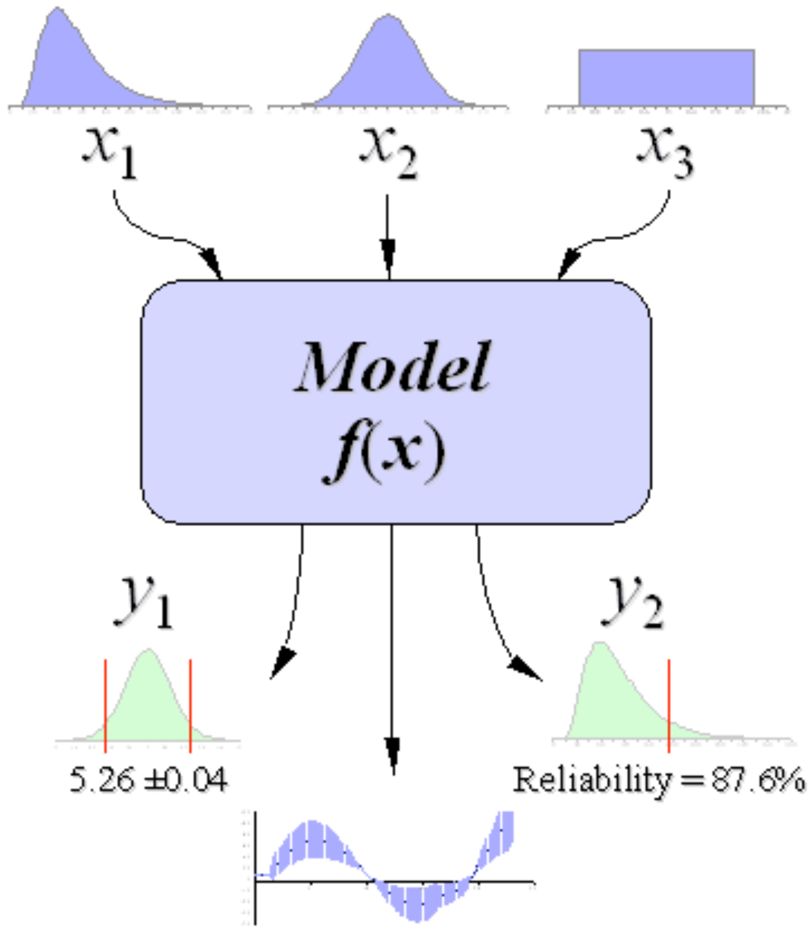
Parametric uncertainties

- Particle Physics Ensemble (PPE) methods
  - Parameter variation to explore the parameter space
  - Multi-parameter perturbations
  - Simple but exhaustive
  - Successfully employed in a variety of climate models and scenarios



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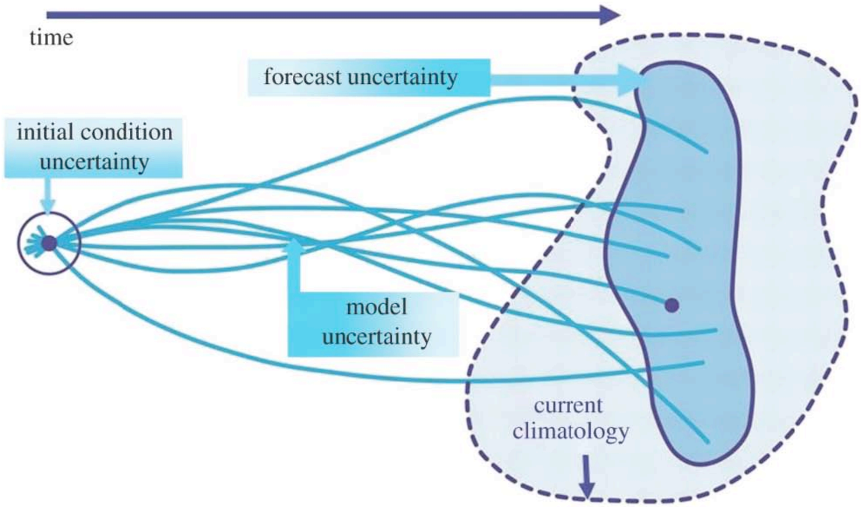
Multi-model ensembles

- Set of model simulations using structurally different models.
- *"increases skill, reliability and consistency of model forecasts"*
- Diagnosis, validation and intercomparison of results/ predictions from different models



Equilibrium climate sensitivity is defined as the global mean temperature response of an atmospheric climate model run with a simple (slab) ocean to a doubling of CO_2. It is now believed that the most likely value for climate sensitivity is around 3.0°C.

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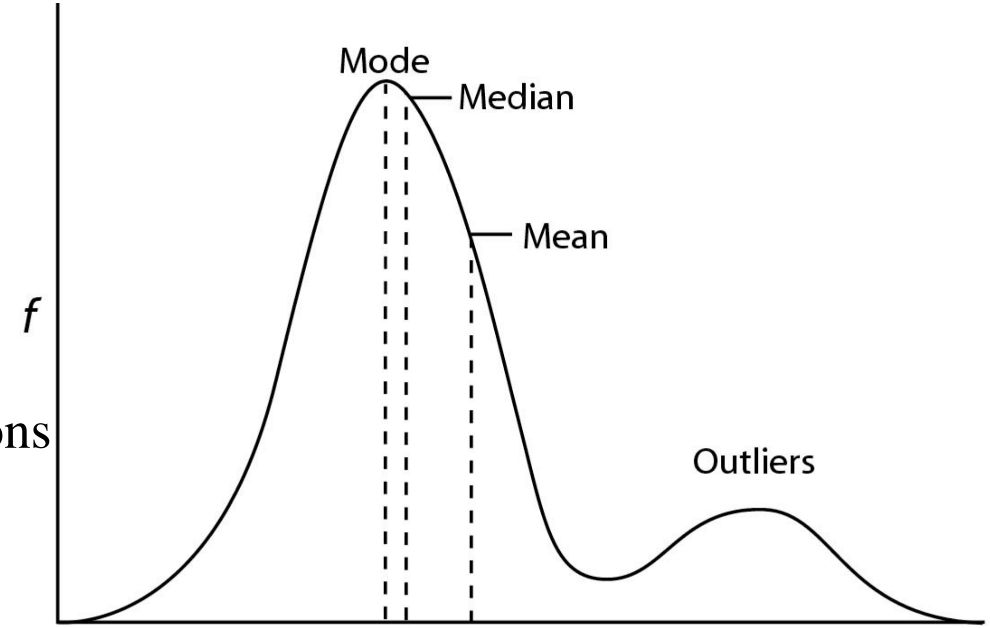
Inter-comparison of Models

- Weighted averaging or Bayesian methods
  - Model performance in replicating current climate and inter-model agreement in projections of future change is used.
  - Reliability Ensemble Average (REA):

$$R_i = [(R_{B,i})^m \times (R_{D,i})^n]^{[1/(m\times n)]} = \left\{ \left[\frac{\epsilon_T}{|B_{T,i}|} \right]^m \times \left[\frac{\epsilon_T}{|D_{T,i}|} \right]^n \right\}^{[1/(m\times n)]}$$

$$\widetilde{\Delta T} = \frac{\sum_i R_i \Delta T_i}{\sum_i R_i}$$

Median over mean for populations with outliers



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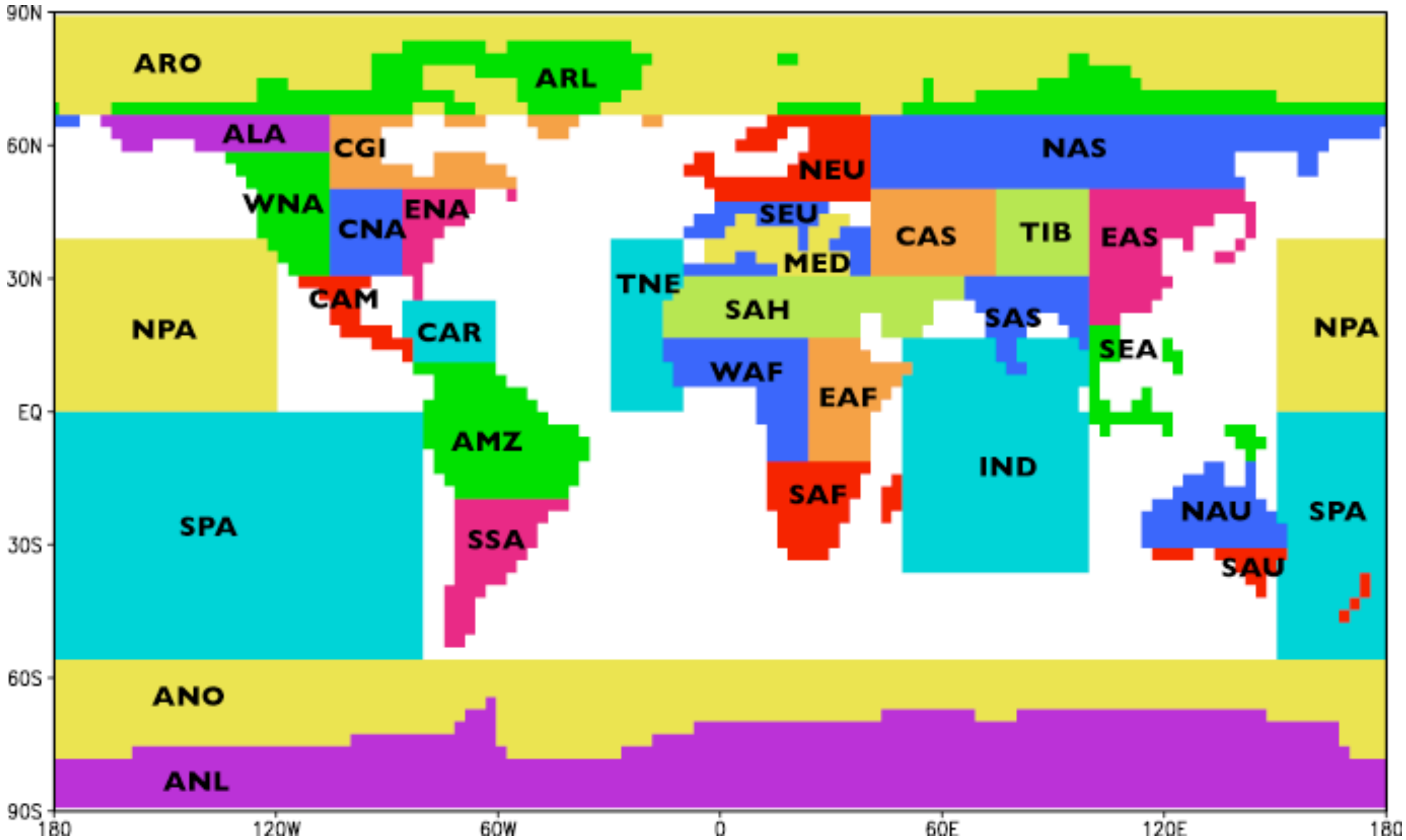
Inter-comparison of Models

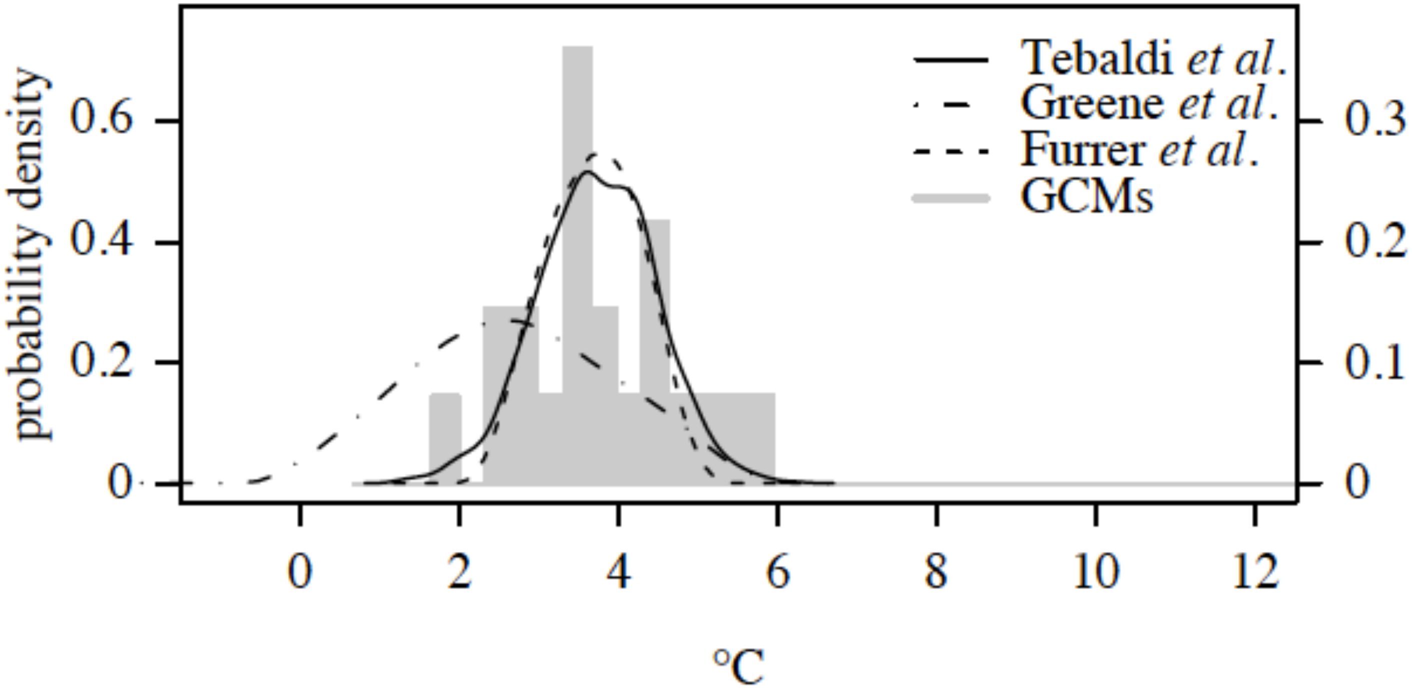
- IPCC uses multi-model projections for long-term climate change with unweighted multi-model means.
- IPCC AR3 (2001) – two models discarded because of extreme estimates of warming!
- Quantifying distance in 'model space' is formally difficult

IPCC World Regions



Model Comparison

- Predicted temperature rise in winter in 2100
- WNA (Western North America) region estimates
- SRES A1B scenario (Balance of fossil intensive and fossil-free energy sources)



Challenges in using Model-model Ensembles

(a) Metrics, skill and lack of verification

- Emission scenario as a boundary condition – uncertainty
- *"simulating the past, and present correctly does not guarantee that the models will be correct in the future"*
- Is a model that performed extremely well in every past/present scenario case, more likely to be correct in the future?
- *"The crux lies in defining a metric for model performance which might be relevant for predicting future climate, but must be based on observations from the past or present. There is no unique way of doing that"*

Challenges in using Model-model Ensembles

- *"The choice of a metric to weight model for future projections is therefore pragmatic, subjective and often also influenced by what can be observed with sufficient accuracy."*
- Choice of (multi-)metrics and ranking of model performance
  - Atmospheric temperature, precipitation, pressure, ocean temperature, etc
  - Models evaluation for both the mean and the trends over a time period.

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Challenges in using Model-model Ensembles

(b) Model dependence and mean bias

- Question of model independency and improved performance by averaging.
- *"There might also be 'unknown unknowns', i.e. misrepresentations of processes, missing processes or uncertainties in processes that we are not aware of."*
- *"The current generation of models cannot be considered to be fully independent, nor are the models distributed around the true representation of the climate system. Therefore, in the absence of new knowledge about the processes and a substantial increase in computational resources to correctly resolve or parametrize them, our confidence in models should not increase unboundedly, and thus our uncertainty should not continue to decrease when the number of models increases."*

Challenges in using Model-model Ensembles

(c) The ensemble of opportunity

- Human decisions – subjectivity and non-scientific aspects involved in modeling – computational resources and funding
- Recent studies using simpler models have generated larger climate sensitivities upto 6 degrees or more.

Challenges in using Model-model Ensembles

(d) Model Tuning and Evaluation

- Circular reasoning – using same datasets to tune and evaluate models.
- *“Agreement with observations can be spurious, and can arise from a cancelling of errors, not necessarily guaranteeing that processes are correctly simulated.”*
- *“It remains to be shown that an automating tuning approach can produce model solutions substantially better than those produced by experts making choices on the parameters based on their experience and understanding of the processes.”*
- Observation uncertainties – lack of data in certain spatio-temporal segments and using models to *observe*’
- Missing sub-components of model. New models have larger sub-components

Conclusions

- Need for quantitative metrics for propagation into impact, mitigation and management models.
- Need for multi-performance metrics
- Concerted international efforts on model development

- *"Given the often non-rational and unpredictable behaviour of humans, their decisions and the difficulty in describing human behaviour and economics in models, the perfect climate forecast (as opposed to a projection that is conditional on the scenario) is a goal that will probably be impossible due to the uncertainties in emission scenarios and the feedback loops involving the agents that the forecast is directed towards. Nonetheless, a comprehensive picture of the uncertainty in climate projections remain a key goal to aim for, and we should welcome the opportunity of taking advantage of independent resources and minds at work on it, by intelligently combining their – always different to some degree – results."*

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Future Directions

- Propagation into impact models
- Propagation into policy & decision making