Climate/Earth System Projections and their Uncertainties - An Overview

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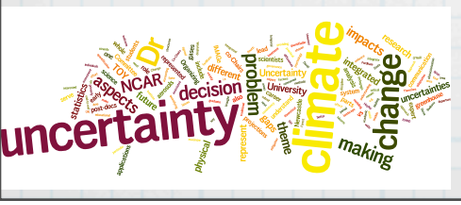
Pennsylvania State University

Uncertainty in Climate Change Research: An Integrated Approach

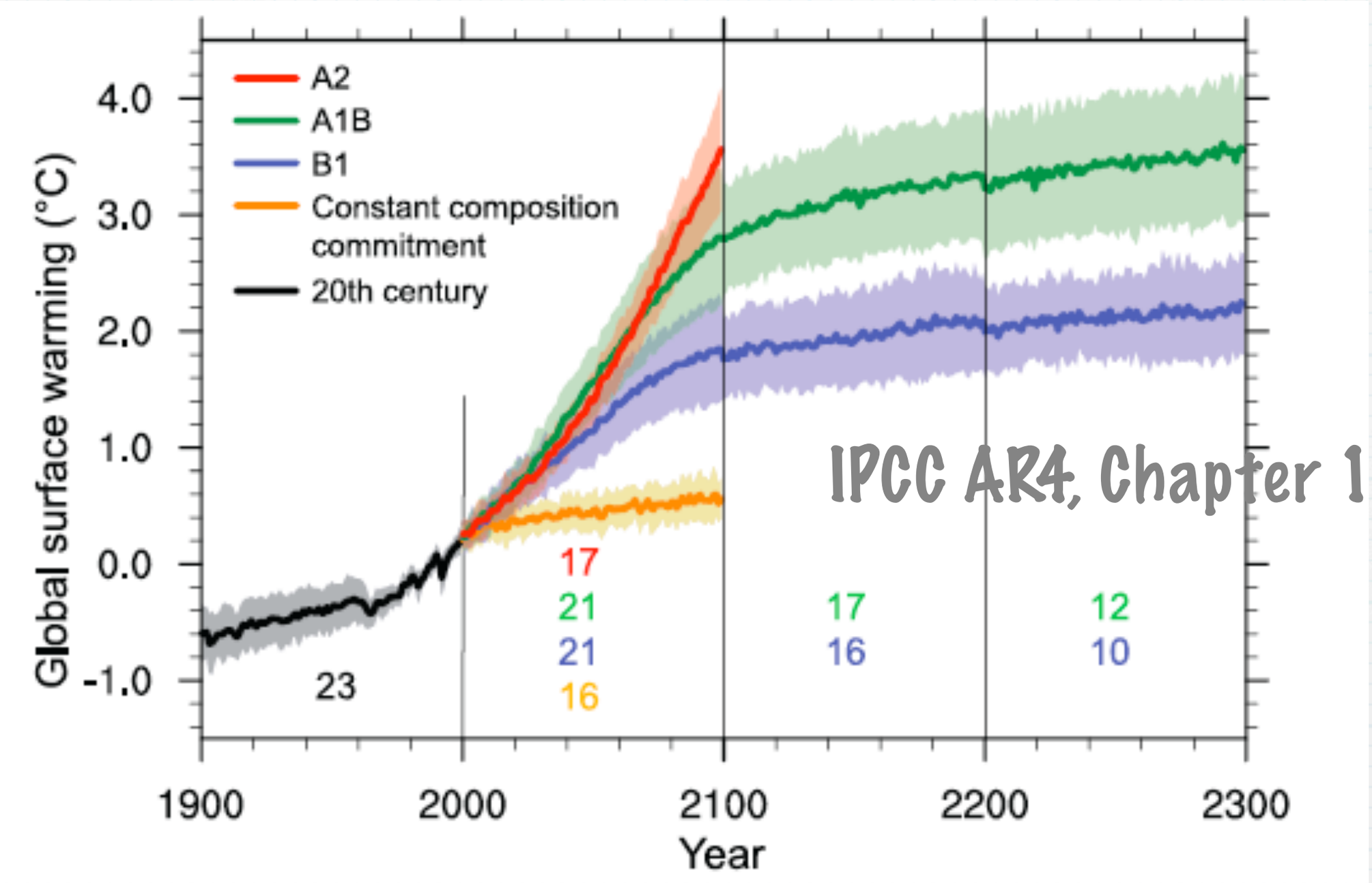
NCAR TOY Workshop
2012 August 6-17



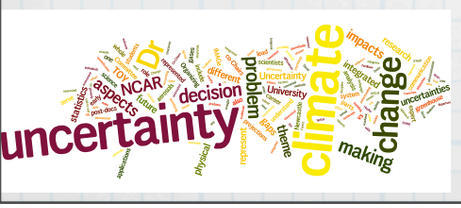
Day 2 - Climate Talk outline

* Sources of uncertainty in climate predictions
* Intro to climate model hierarchy
* Climate System Response
* Characterizing Model uncertainty
* Segue to climate science talks

What drives uncertainty?



IPCC AR4, Chapter 10

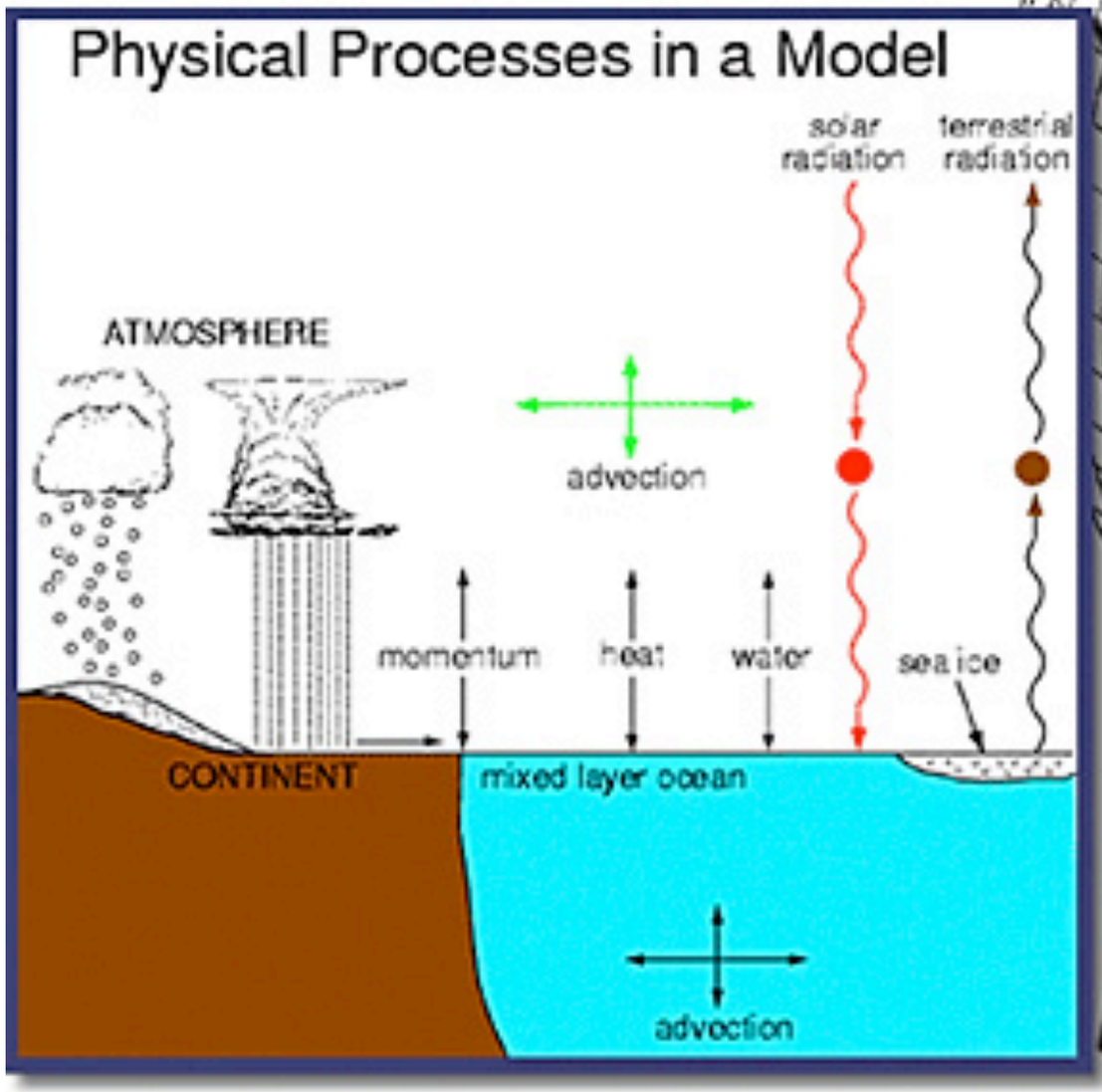


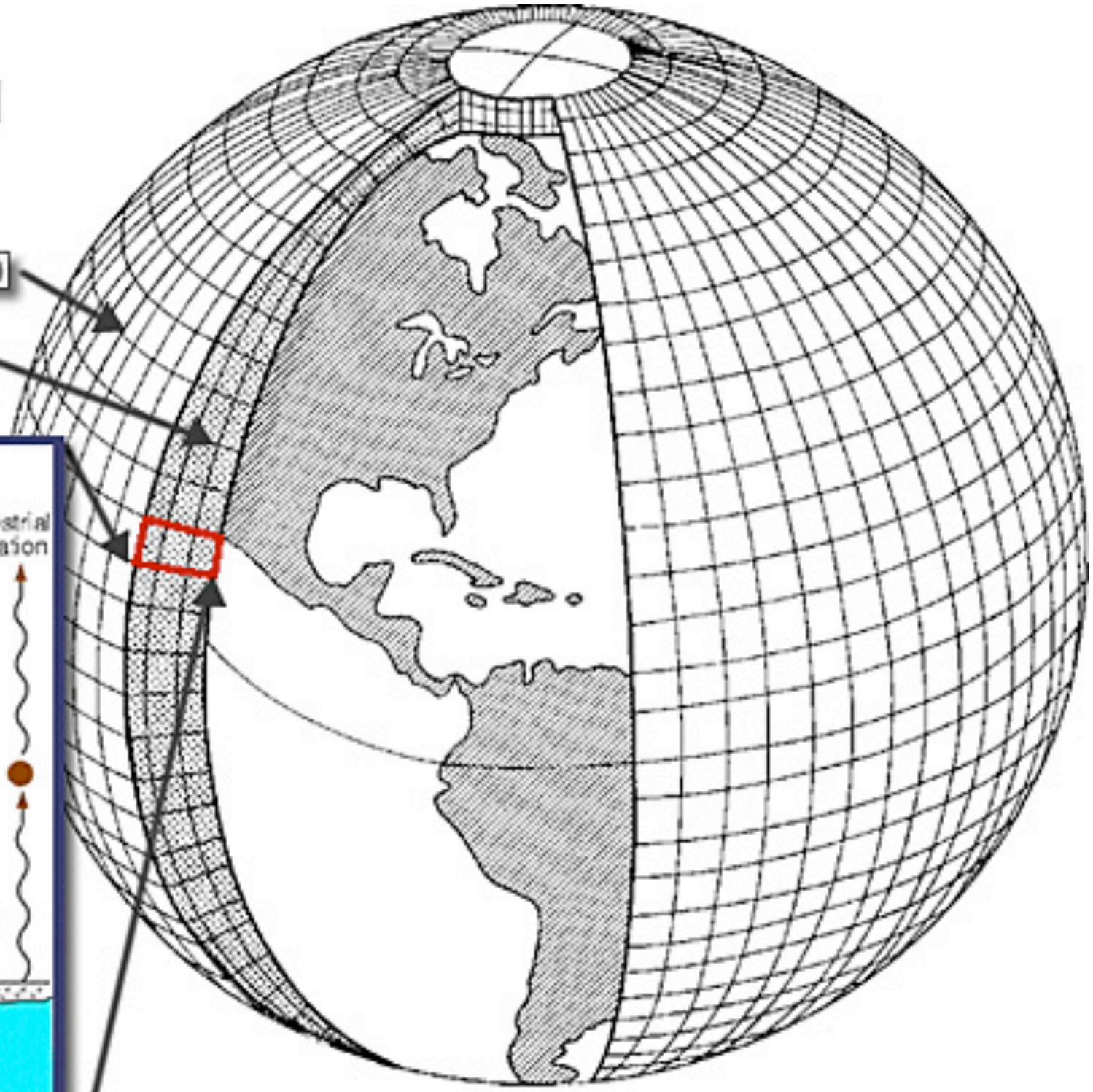
Uncertainty from combination of: Model response and forcings

Schematic for Global Atmospheric Model

Horizontal Grid (latitude - longitude)

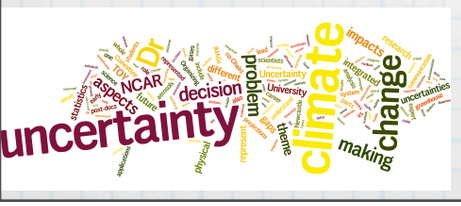
Vertical Grid (height or pressure)



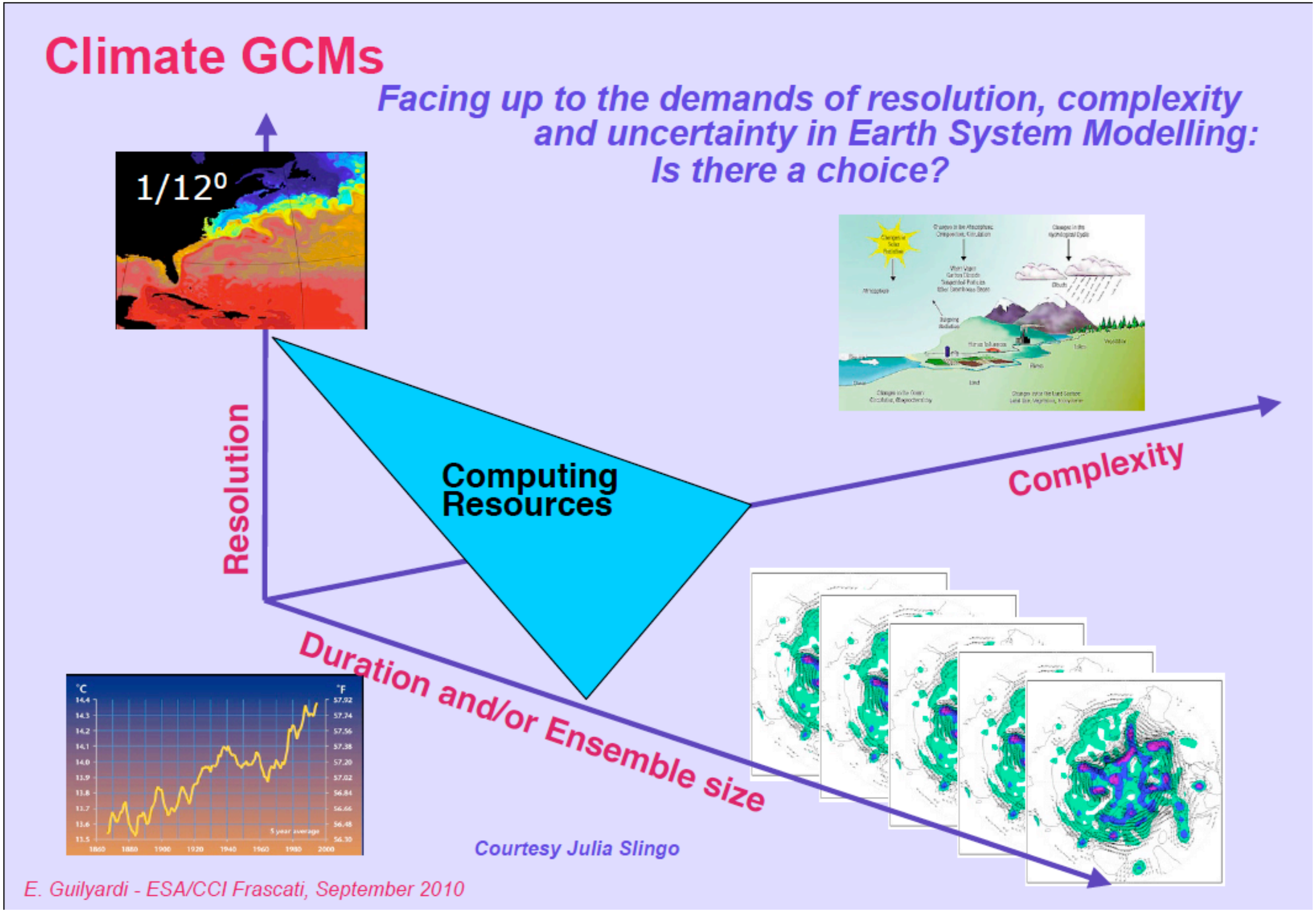


Sources of Uncertainty in Climate Projections

- Structural & Parametric uncertainty
- Forcing, Response, Internal Variability
- Response time-scales, spatial-scales
- How to quantify Uncertainties
  - Forward sensitivity runs
  - Inverse estimates of parameters



What limits our ability to understand uncertainty in models?



Courtesy of Julia Slingo (via Eric Guilyardi)

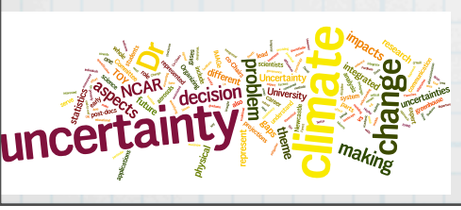
Climate Model Hierarchy

* Simplest model = Energy Balance Model
* EMIC = Earth-system model of Intermediate Complexity
* Most complex = Earth System Model

* Climate Models are designed for specific purposes and uncertainty analysis is not often one of them.

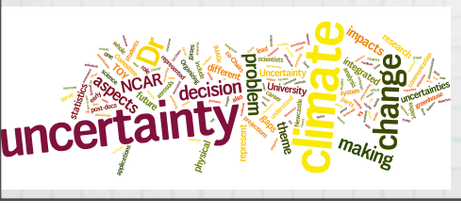
Model Complexity: Components

* Atmosphere/Ocean/Land/Ice = Atmosphere-Ocean General Circulation Model := AOGCM
* Add: Atmospheric Chemistry, Carbon-cycle, Vegetation = Earth System Model = ESM
* Add Human/Societal dimension = Integrated Earth System Model = iESM

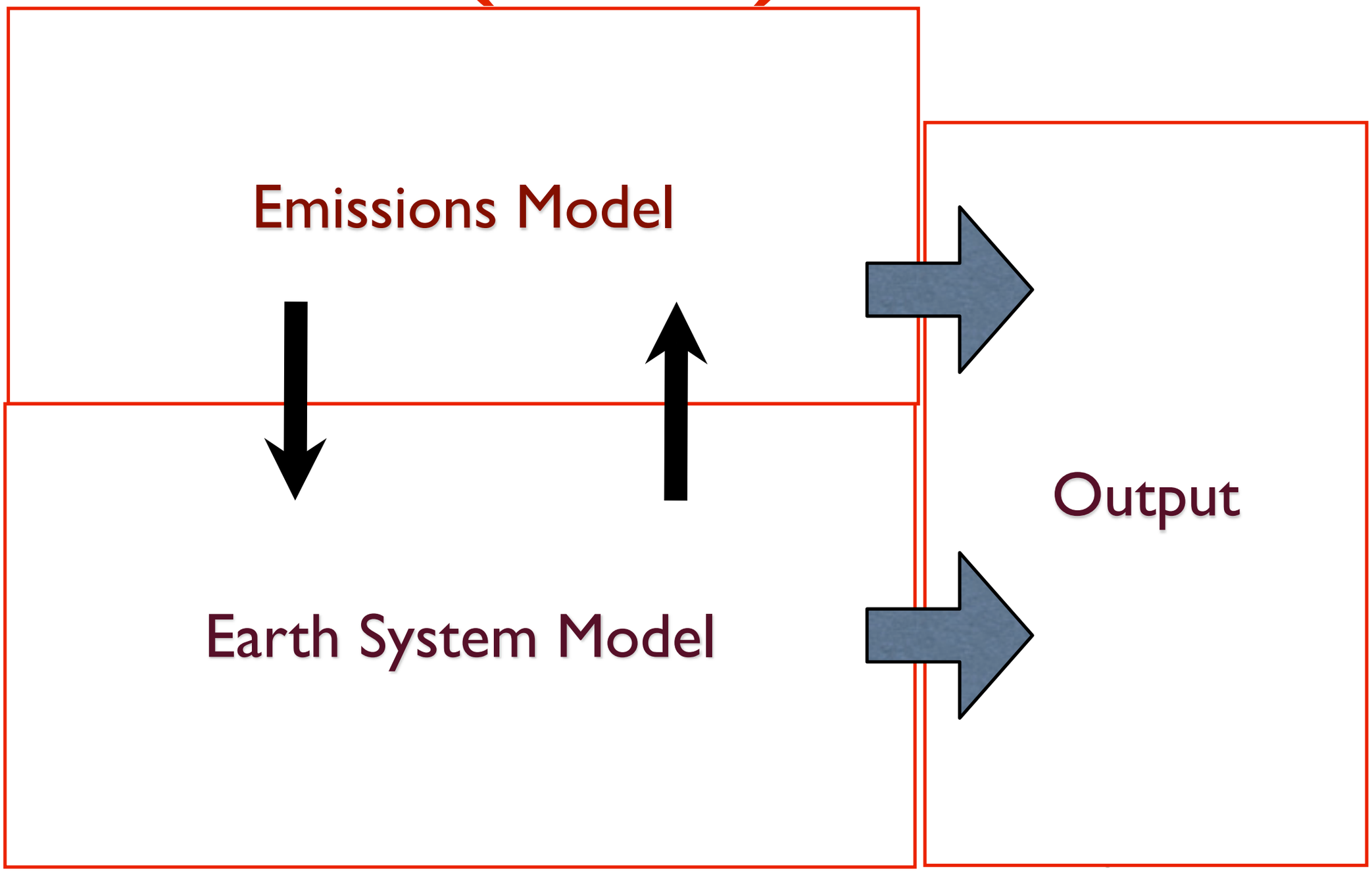


Model Complexity: Structure

* Structure:
  * Reduced dimensions (3D model to 2D)
  * Reduce governing equations
    * Conservation of energy, mass, moisture, momentum, angular momentum
* Resolution



MIT Integrated Global System Model (IGSM2)



Sokolov et al. (2005, JP-Report 124)

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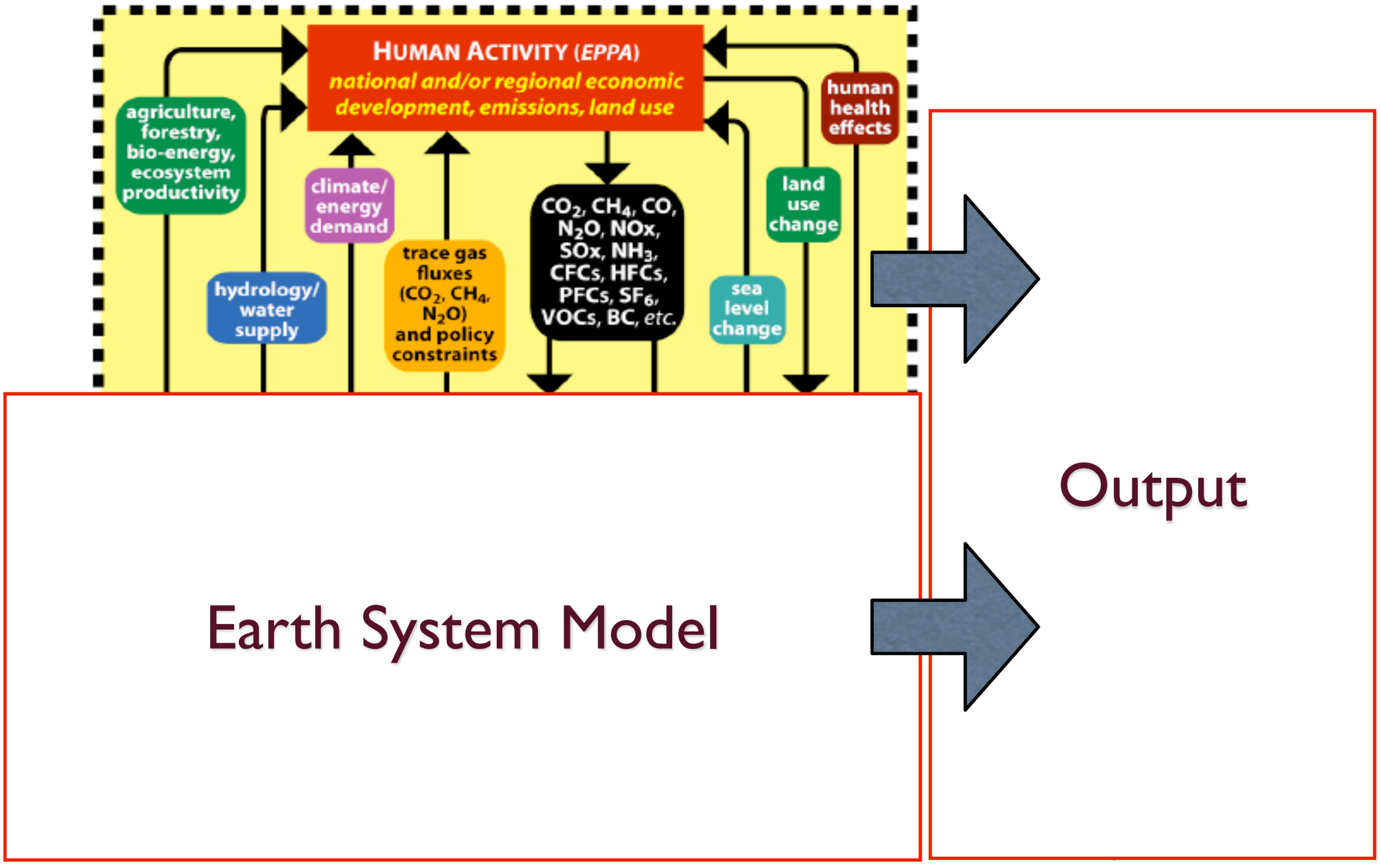

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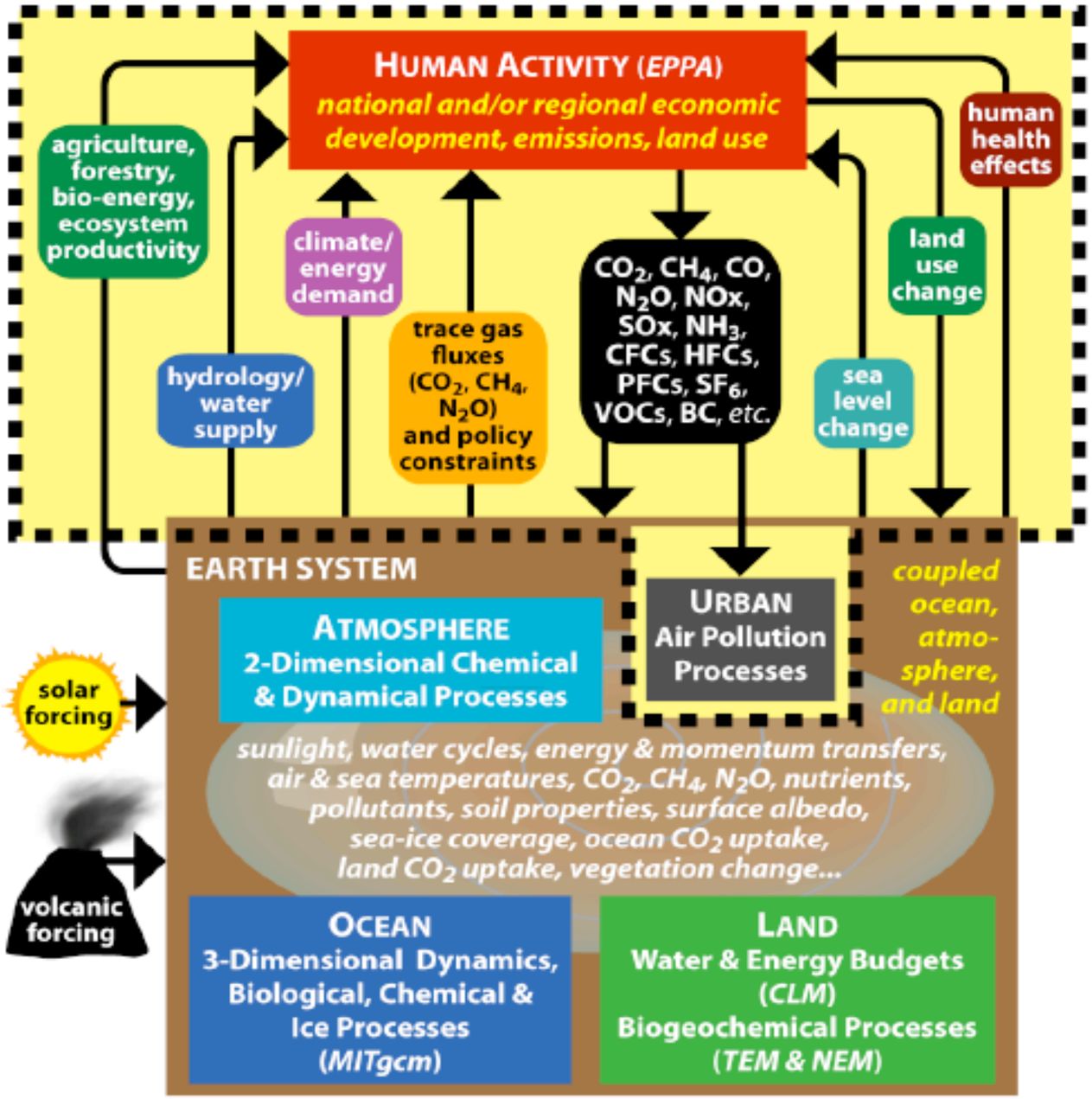

Output

Sokolov et al. (2005, JP-Report 124)

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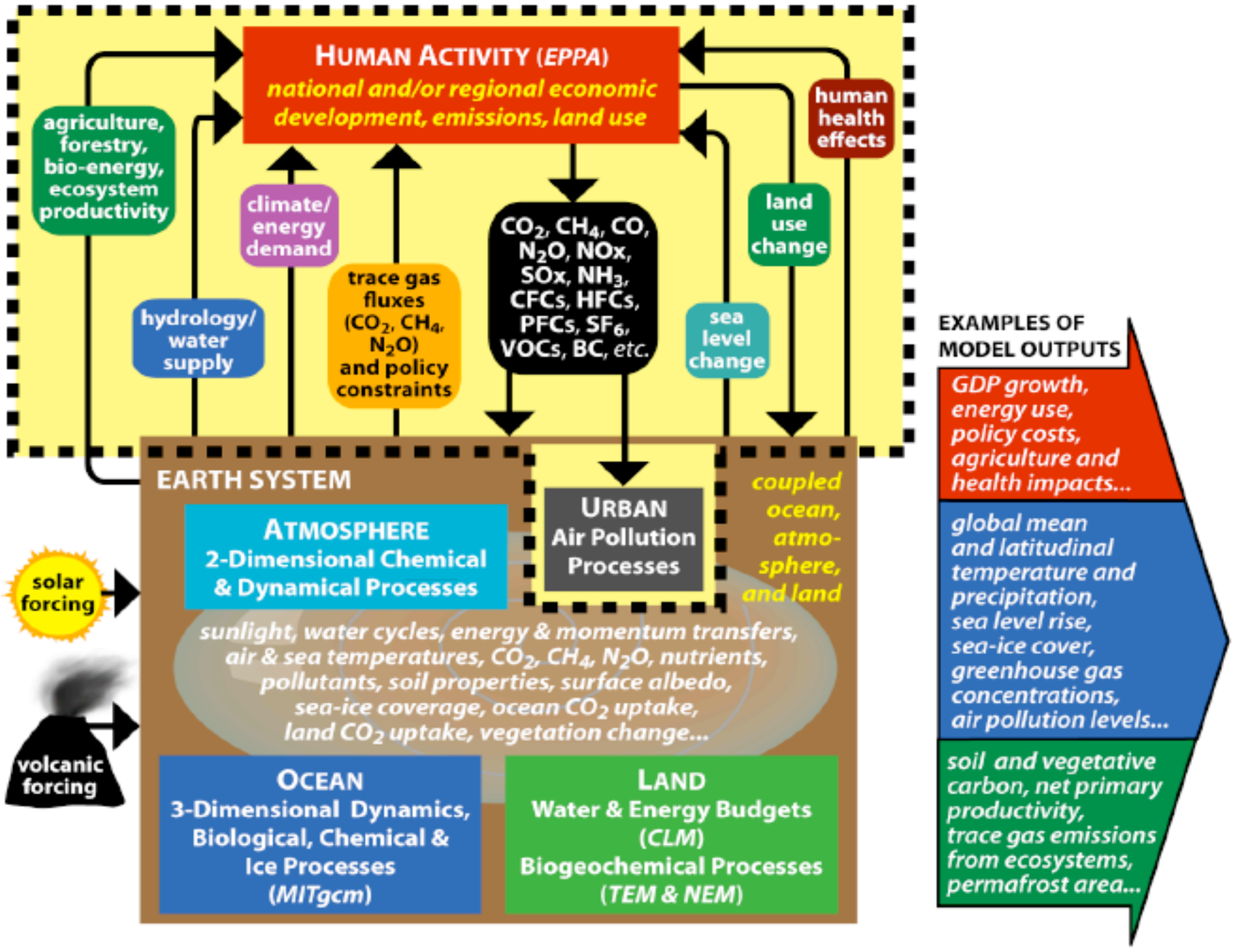

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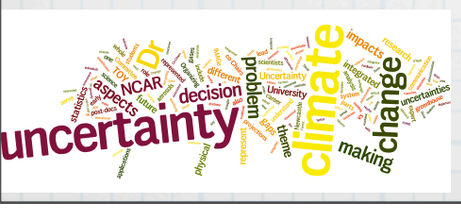
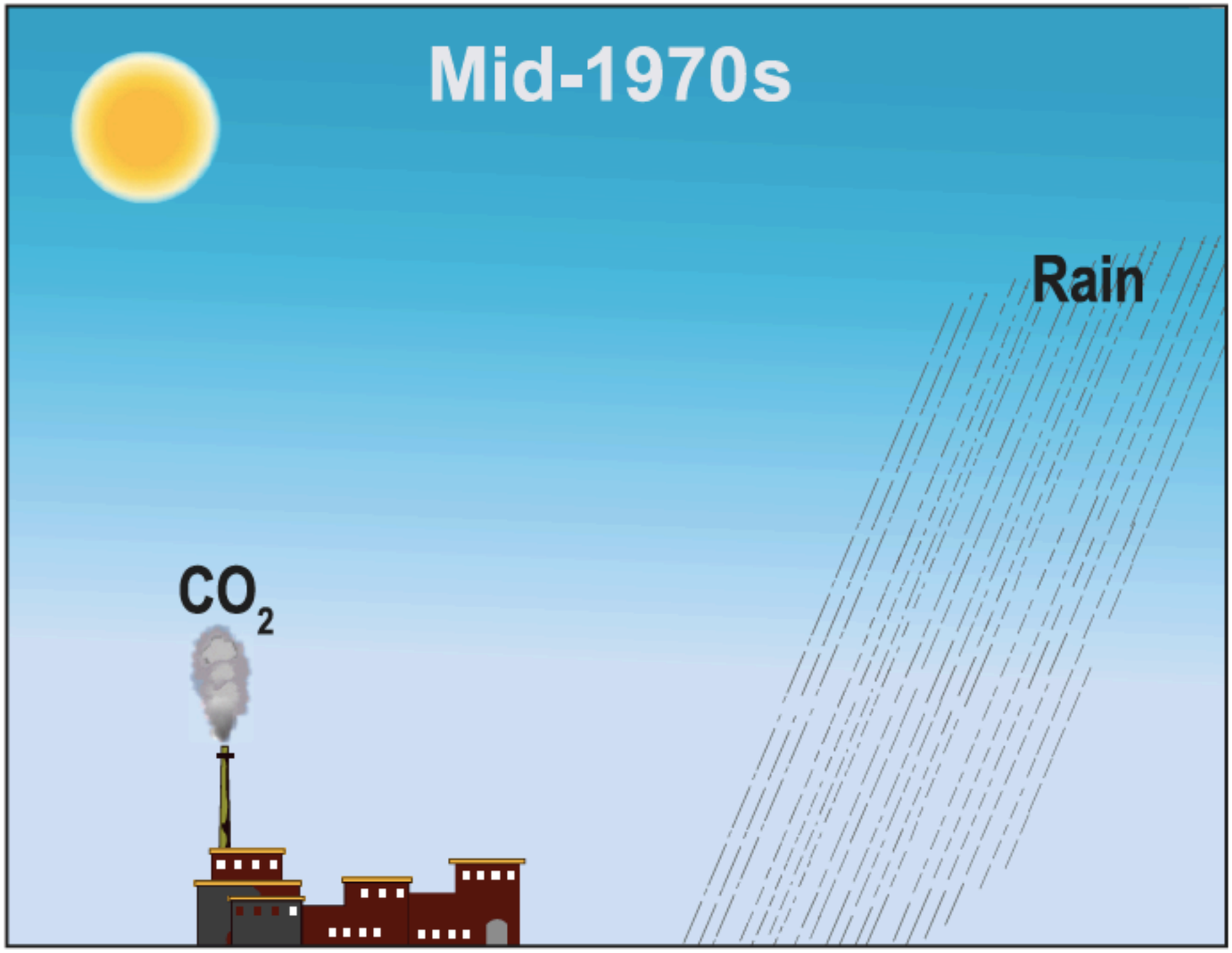
Climate Model History



Components/Complexity

Climate Model History



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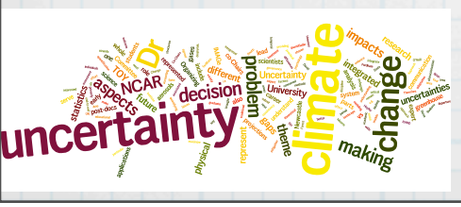

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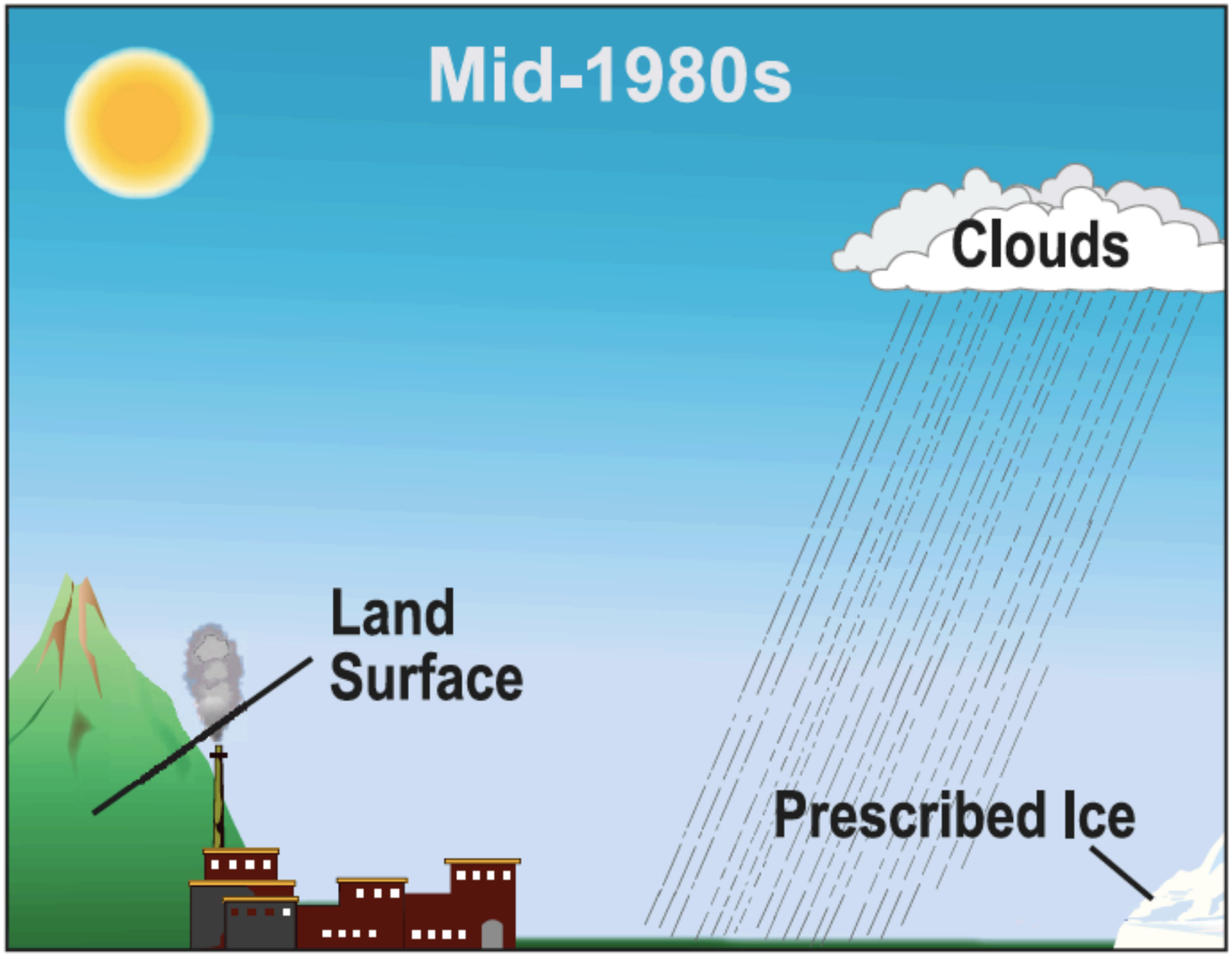

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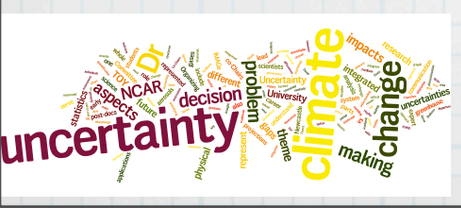

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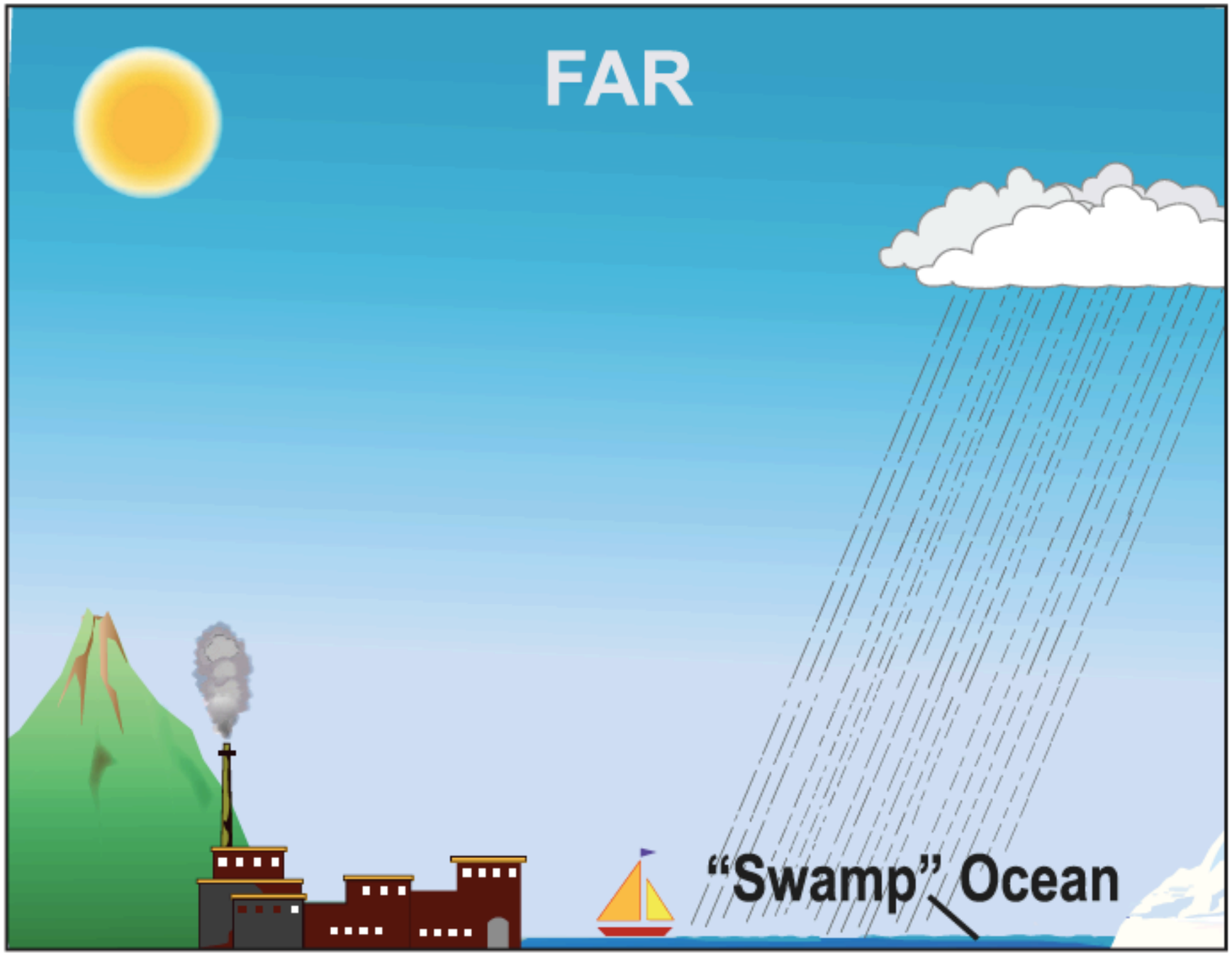

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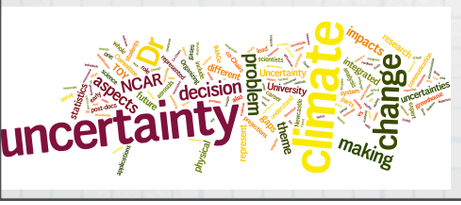

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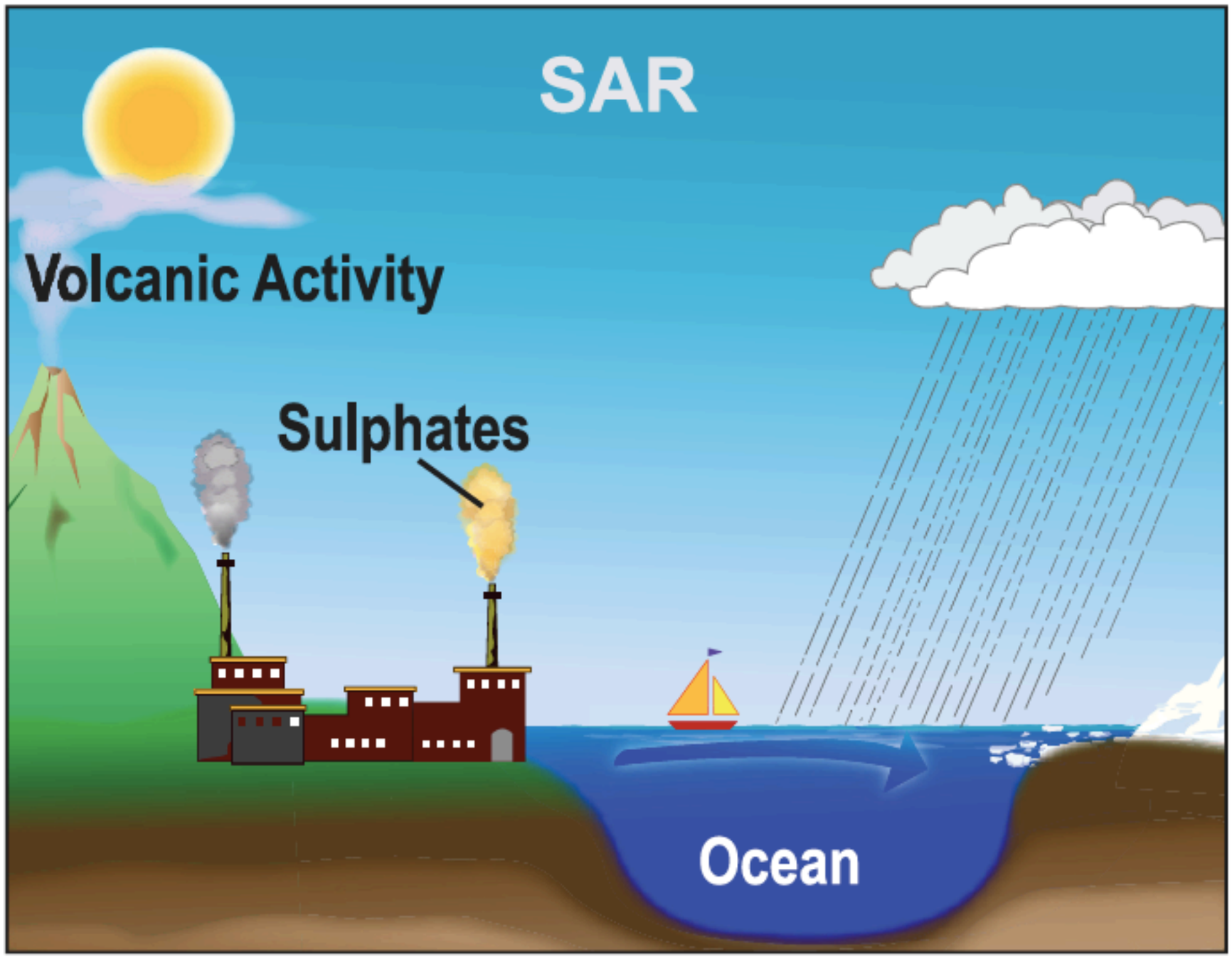

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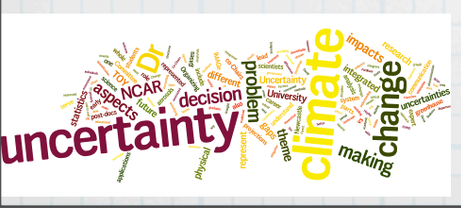

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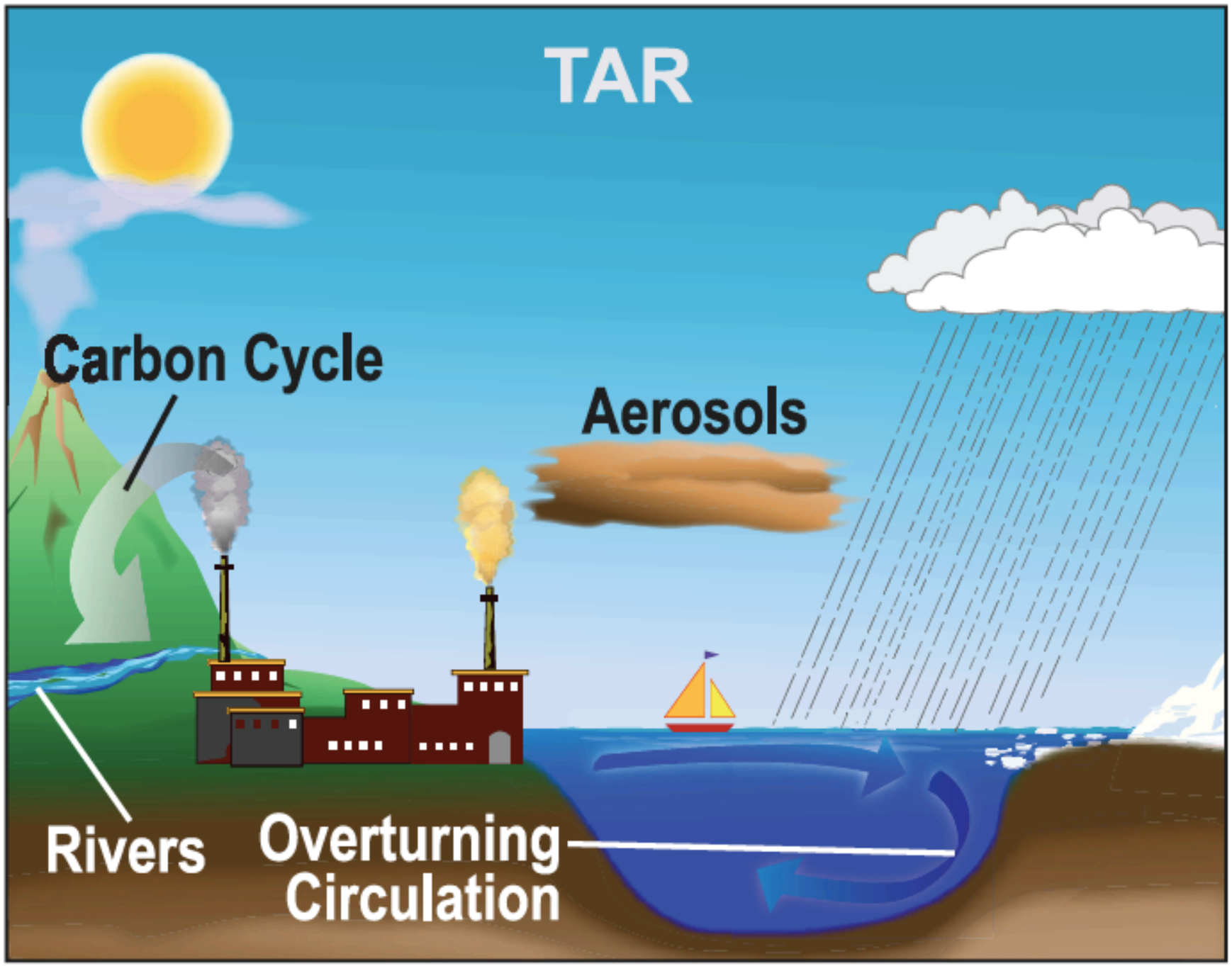

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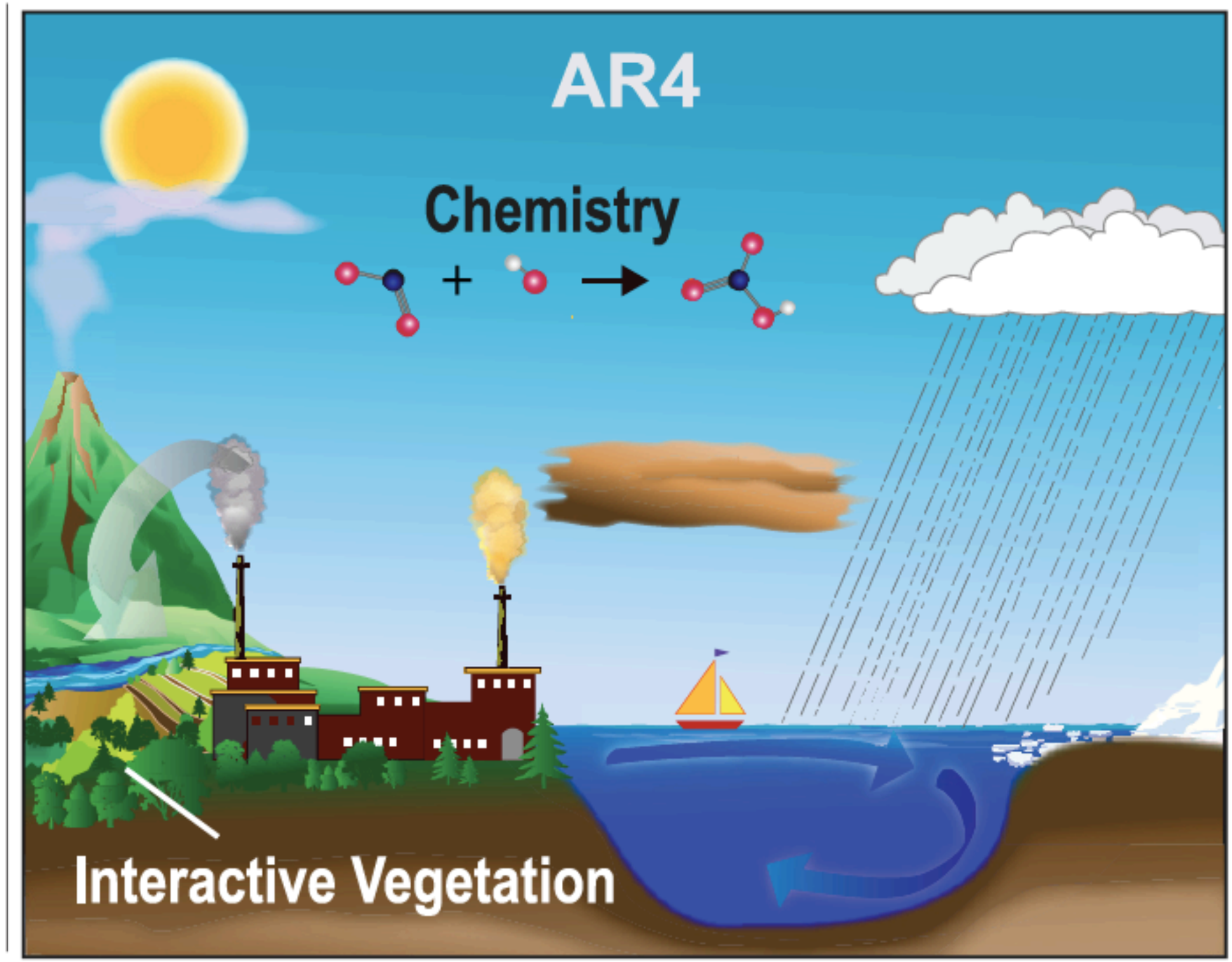

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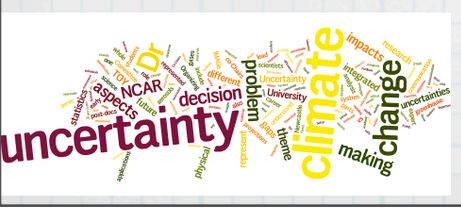

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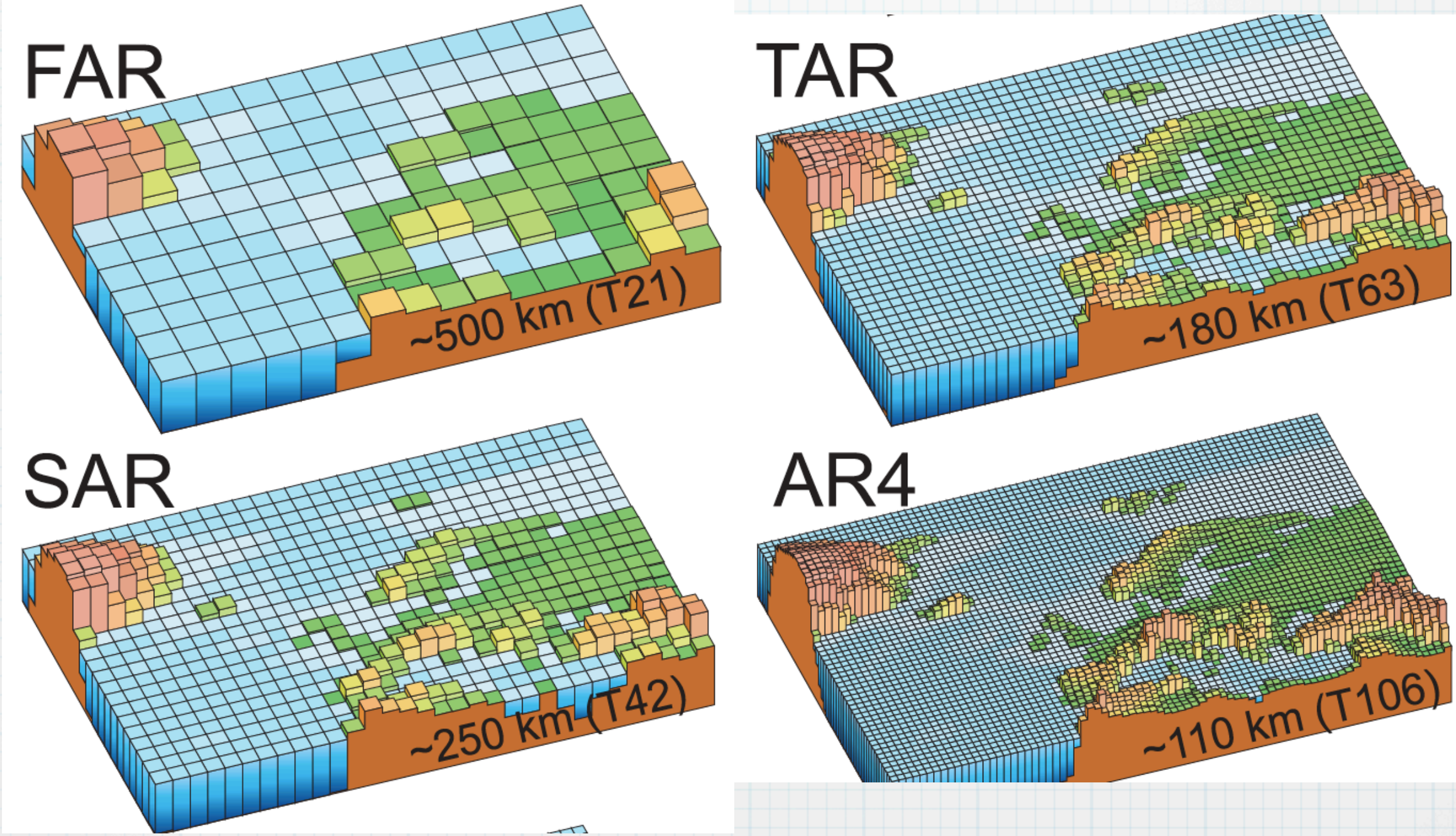

From IPCC Fourth Assessment Report

What matters for long-term climate prediction?

* Controls on:
  * Long-term warming
  * Delay by ocean
  * Net forcing

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* Controls on:
  * Long-term warming
  * Delay by ocean
  * Net forcing

- Uncertainties in:
  - Climate Sensitivity
  - Rate of Ocean Heat Uptake
  - Forcing by Aerosols, Carbon-cycle

Major Climate Projection Uncertainties

Consider the energy balance equation for the global-mean surface temperature anomaly (ΔT):

$$c_p \frac{d\Delta T(t)}{dt} = F(t) - \lambda \Delta T(t) - \Phi_o(K_v)$$

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Change in global mean heat content

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Change in global mean heat content

Future Forcings

Net Feedbacks
$\lambda = 1/S$

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Future Forcings

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Flux of heat into deep-ocean

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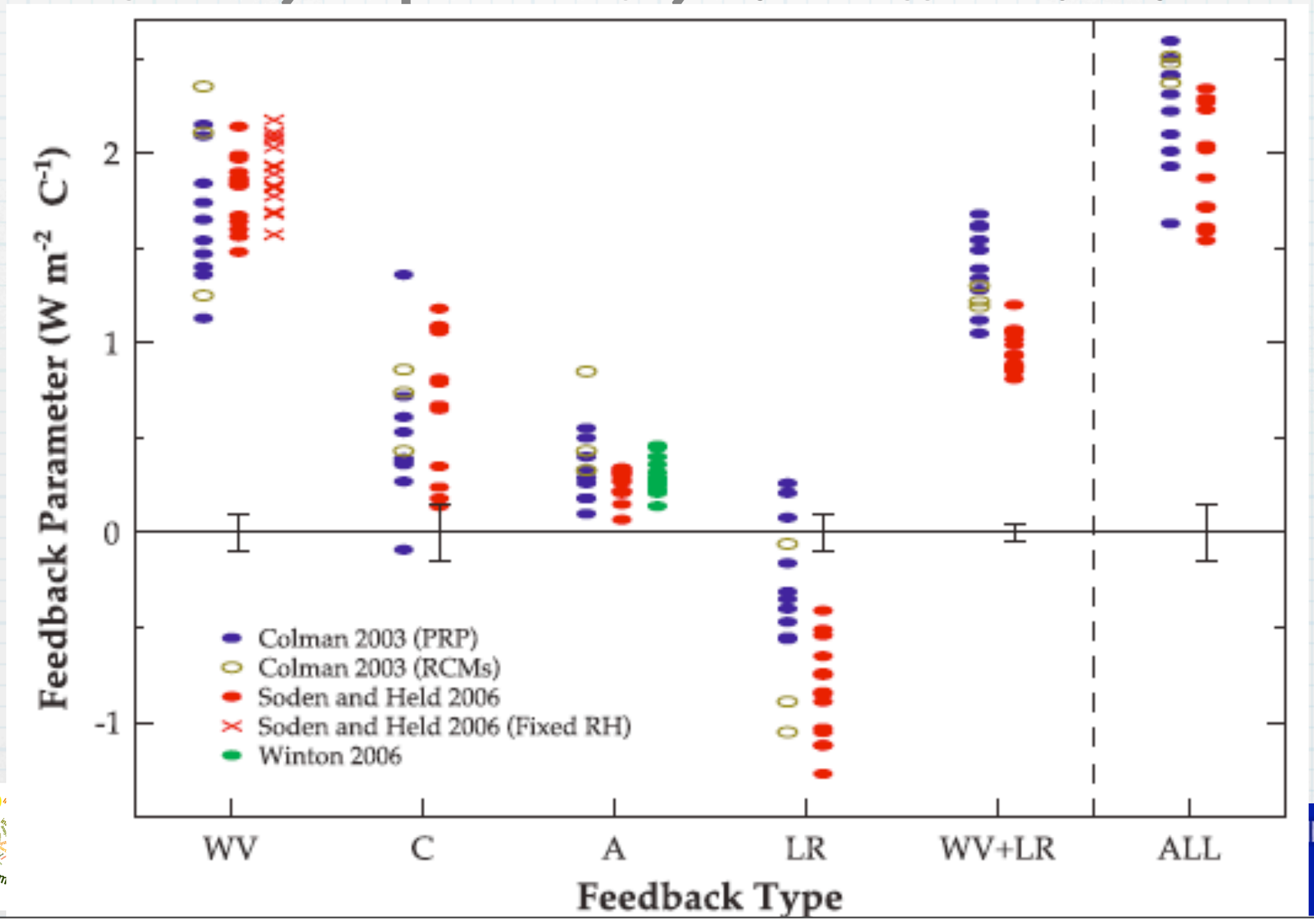
Change in global mean heat content	Future Forcings	Net Feedbacks $\lambda = 1/S$	Flux of heat into deep-ocean

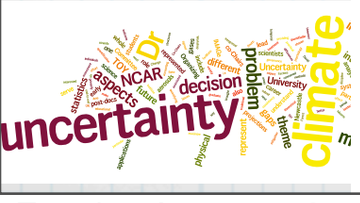
Conceptually: This is a good framework for organizing where the uncertainty exists.

In practice: For state-of-the-art models, each uncertainty is an aggregate quantity and cannot be identified with any one specific model component or process.

Uncertainty in Atmospheric Model Feedbacks

* Uncertainty in Water Vapor, Cloud, Albedo, Lapse Rate, and All Combined

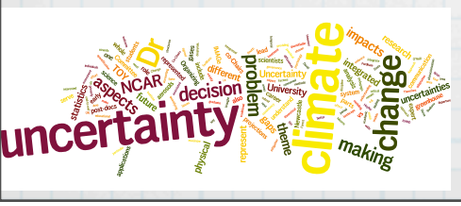




Characterizing Model Uncertainty

* Multi-model Ensemble (MME)
* Perturbed Physics Ensemble (PPE)

(Or Perturbed Parameter Ensemble)

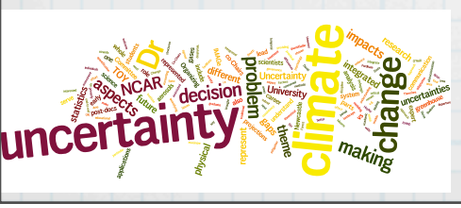


Model Intercomparison Projects = MIPs

* All modeling groups contribute model results for specified scenarios
* Each group creates its "best" model
* Samples Structural Uncertainty due to model development choices

Model Intercomparison Projects = MIPs

- Examples:
  - AMIP = Atmospheric-GCM MIP
  - CMIP = Coupled-AOGCM MIP
  - PMIP = Paleoclimate MIP
  - CFMIP = Cloud Feedback MIP
- CMIP1, CMIP2, CMIP3, CMIP5, ...
  - New models, new MIP.
- Program for Climate Model Diagnostics and Intercomparison = PCMDI



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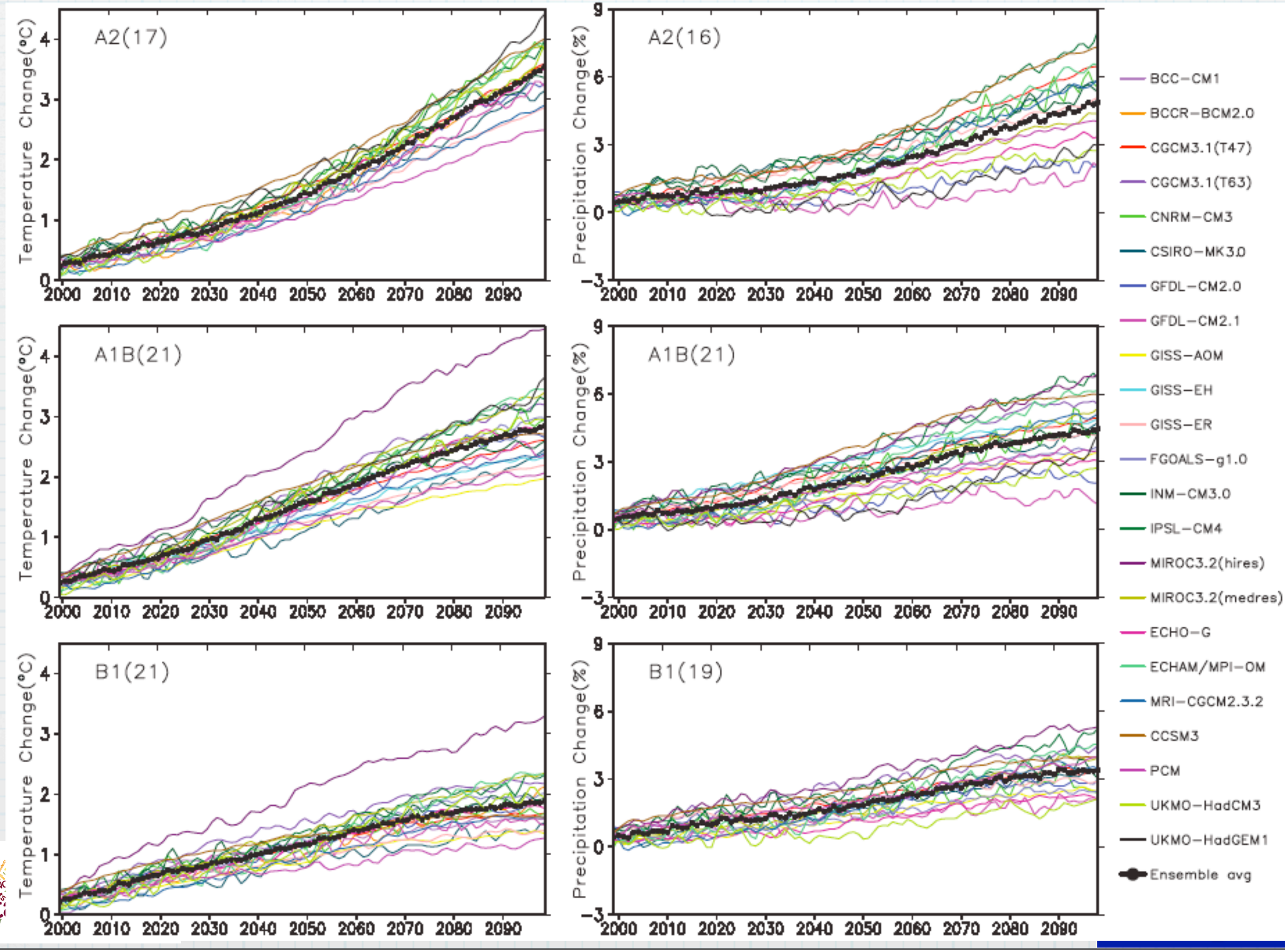
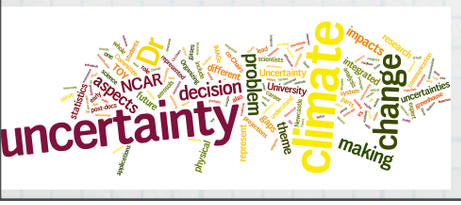
Example CMIP3: IPCC AR4, Chapter 10



Perturbed Physics Ensembles (PPE)

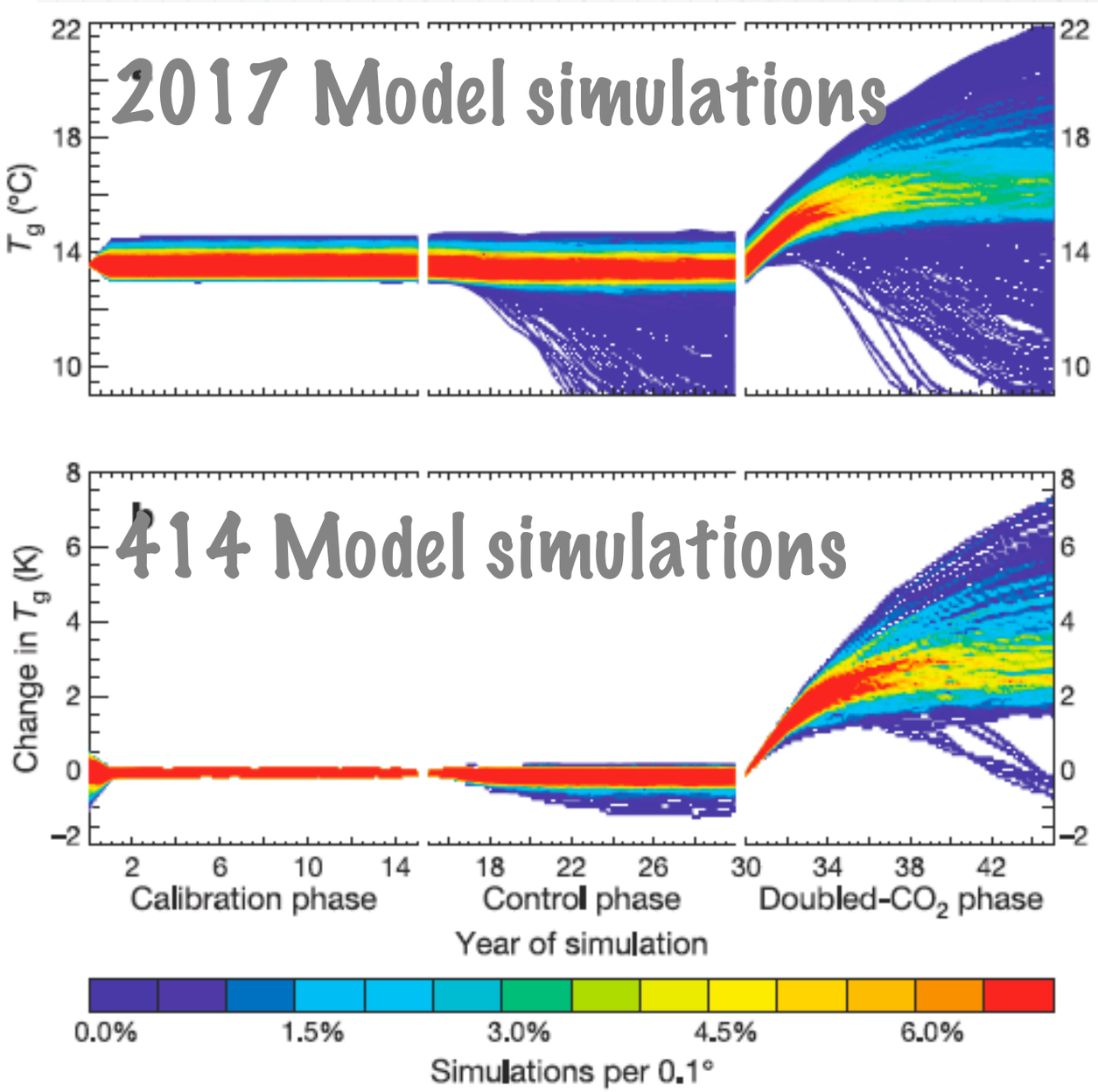
* Single-model framework
  * Individual model parameters varied to adjust physics components
* Samples parametric uncertainty leading to model response uncertainty
* Focus on perturbing feedbacks in the climate system

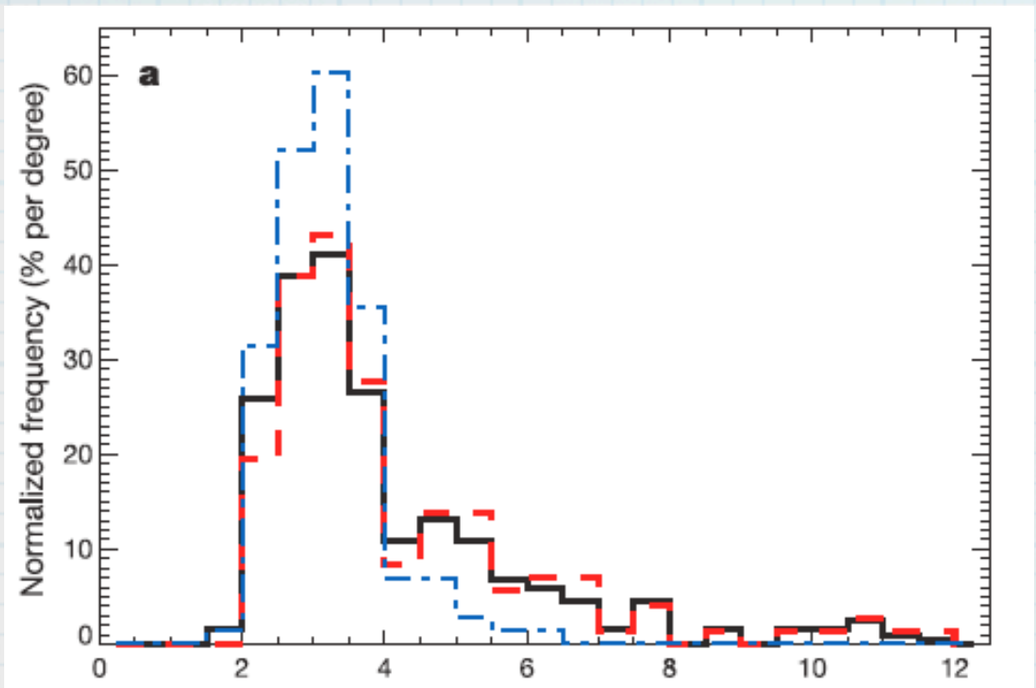


Perturbed Physics Ensembles (PPE)

Uncertainty in predictions of the climate response to rising levels of greenhouse gases

D. A. Stainforth[1], T. Aina[1], C. Christensen[2], M. Collins[3], N. Faull[1], D. J. Frame[1], J. A. Kettleborough[4], S. Knight[1], A. Martin[2], J. M. Murphy C. Piani[1], D. Sexton[3], L. A. Smith[5], R. A. Spicer[6], A. J. Thorpe[7] & M. R. Allen[1]





Climate Sensitivity

Figure 1 Frequency distributions of T_g (colours indicate density of trajectories per 0.1 K interval) through the three phases of the simulation. **a**, Frequency distribution of the 2,017 distinct independent simulations. **b**, Frequency distribution of the 414 model versions. In **b**, T_g is shown relative to the value at the end of the calibration phase and where initial-condition ensemble members exist, their mean has been taken for each time point.

Returning to Simpler Models

* Example of Uncertainty Propagation using the IGSM2 System
* Sample uncertainty across multiple components

Included Uncertainties

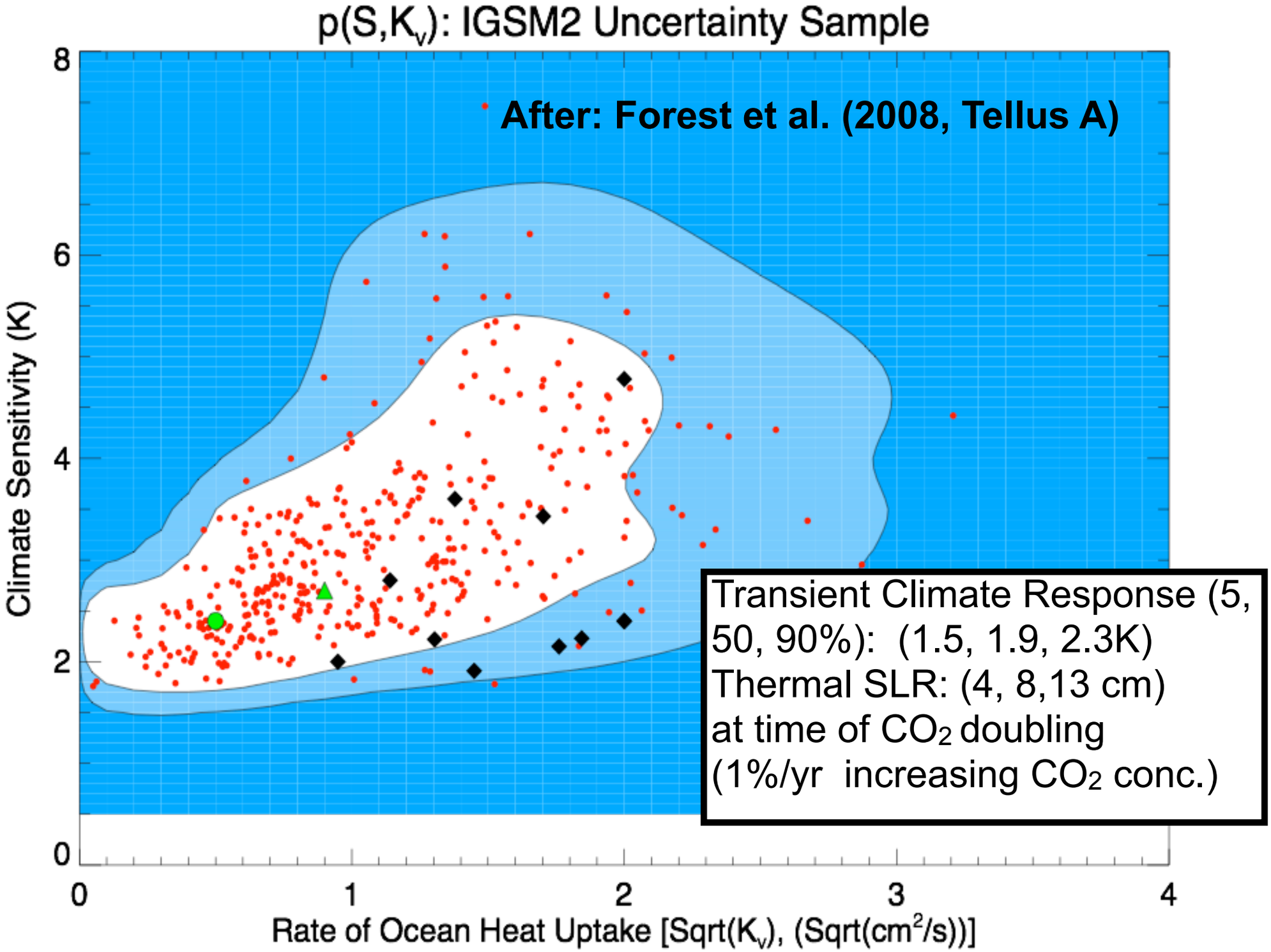
- **Emissions Uncertainty from MIT EPPA4**
  - Population: 6-13 billion, Energy Resources, Efficiency/ Technology
- **Climate System Response**

(Calibrated in Forest et al. 2008)

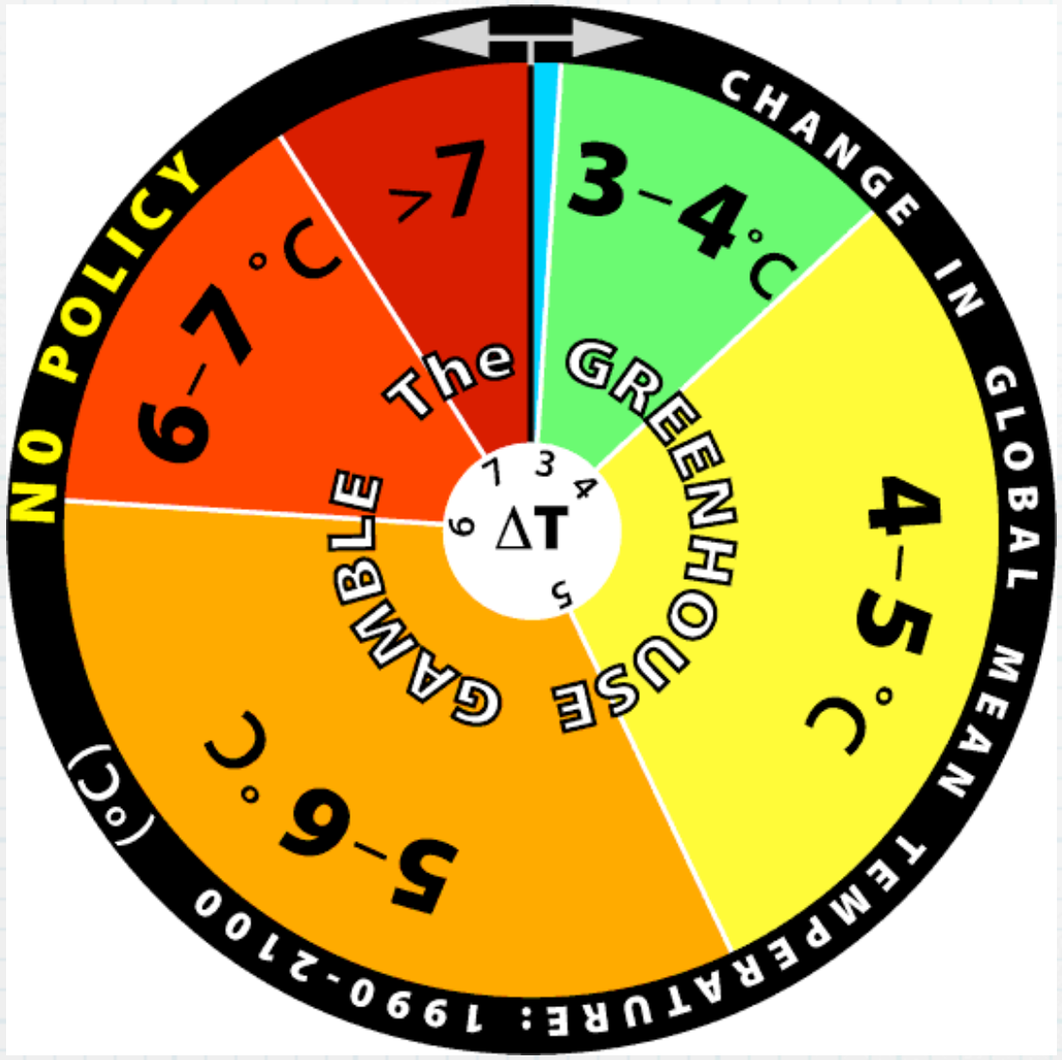
  - Climate Sensitivity
  - Rate of Heat uptake by Deep Ocean
  - Radiative Forcing Strength of Aerosols
- **Carbon Cycle Uncertainty**:
  - CO_2 Fertilization Effect on Ecosystem
  - Rate of Carbon Uptake by Deep-Ocean
- **Trends in Precip. Freq. on CH_4 + N_2O**

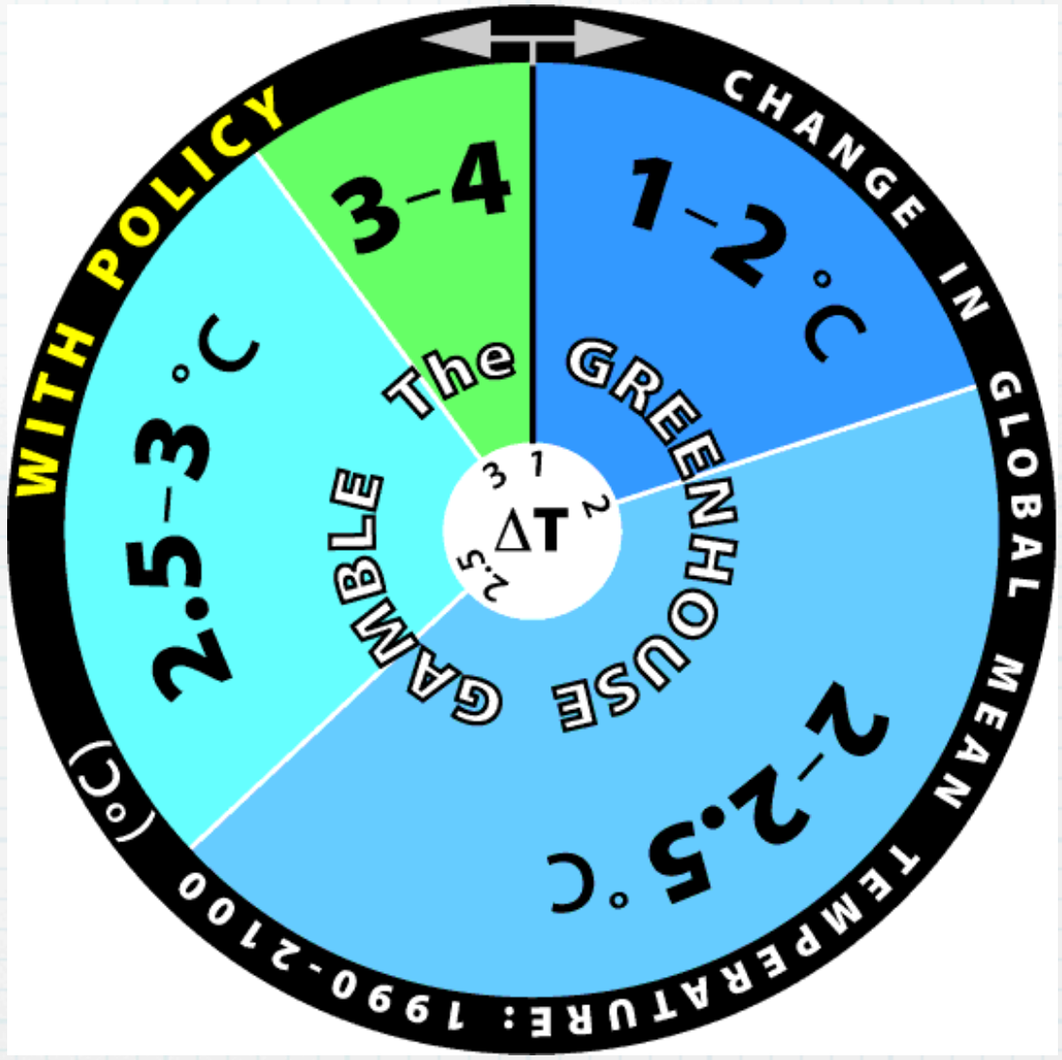
  (Statistics scaled using by AR4 model trends)

Climate Sensitivity and Ocean Heat Update Consistent with Observations



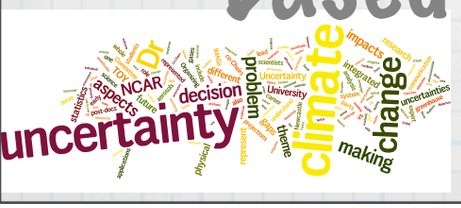
Uncertainty in Global Climate Response in 2100





Global-mean, Decadal-mean, Surface Air Temperature

Based on Sokolov et al. (2009); Webster et al. (2011)



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The Uncertainty Cake