Climate/Earth System Modeling
and
Sources of Uncertainties in their Projections

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The Abdus Salam International Centre for Theoretical Physics

Workshop on Uncertainty Quantification in Climate Modeling and Projection

2015 July 13-17

PENNSTATE

ICTP The Abdus Salam International Centre for Theoretical Physics

Climate/Earth System Modeling and Uncertainty in their Projections: Talk outline

- Sources of uncertainty in climate predictions
- Introduction to a Climate Model hierarchy
- Climate System Response
- Characterizing Model uncertainty

What drives uncertainty?

- Socio-economic Processes

- Earth-system Processes

Courtesy of: Ben Booth (Met Office)

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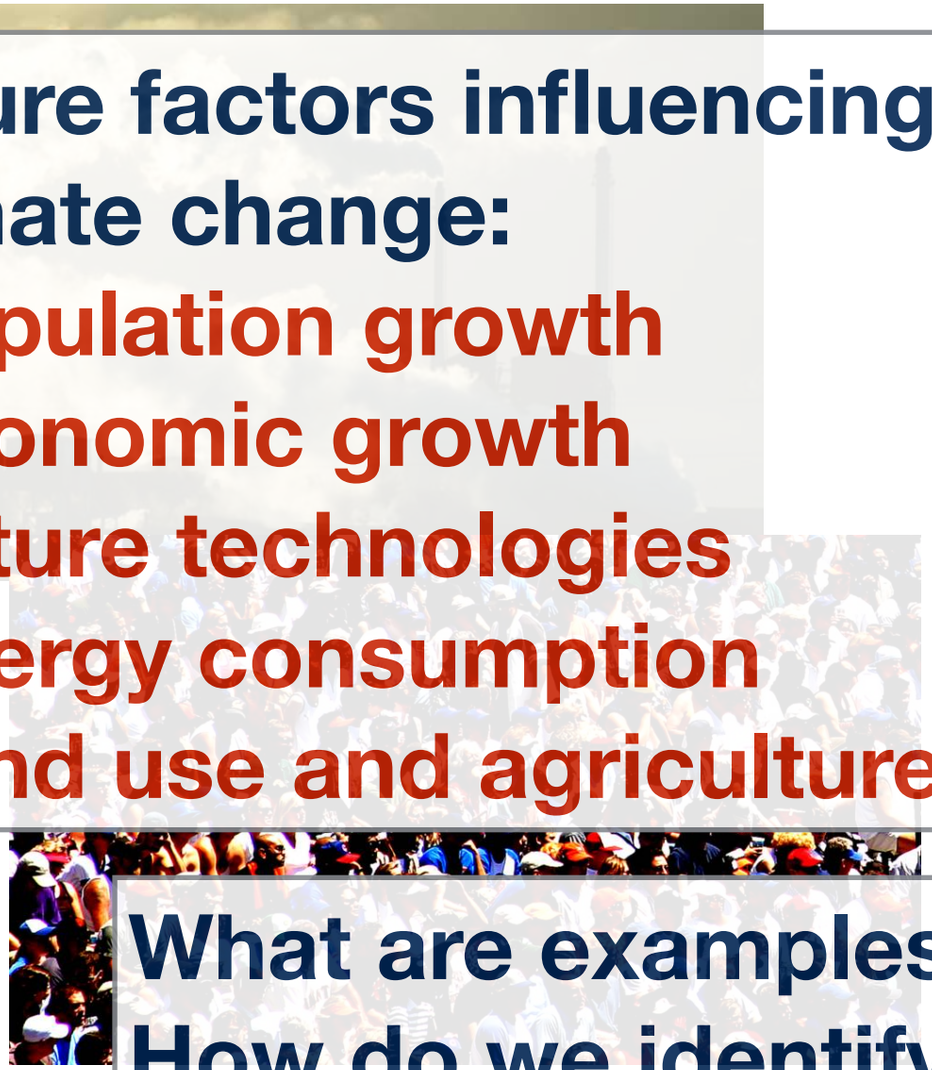
What drives uncertainty?

- Socio-economic Processes
- Earth-system Processes

Future factors influencing climate change:

- **Population growth**
- **Economic growth**
- **Future technologies**
- **Energy consumption**
- **Land use and agriculture**



Key processes influencing climate change:

- **Feedbacks (clouds, sea ice, carbon cycle, …)**
- **Oceanic delay**
- **Strength of forcings**
- **Short term variability**

What are examples of these uncertainties?
How do we identify them?

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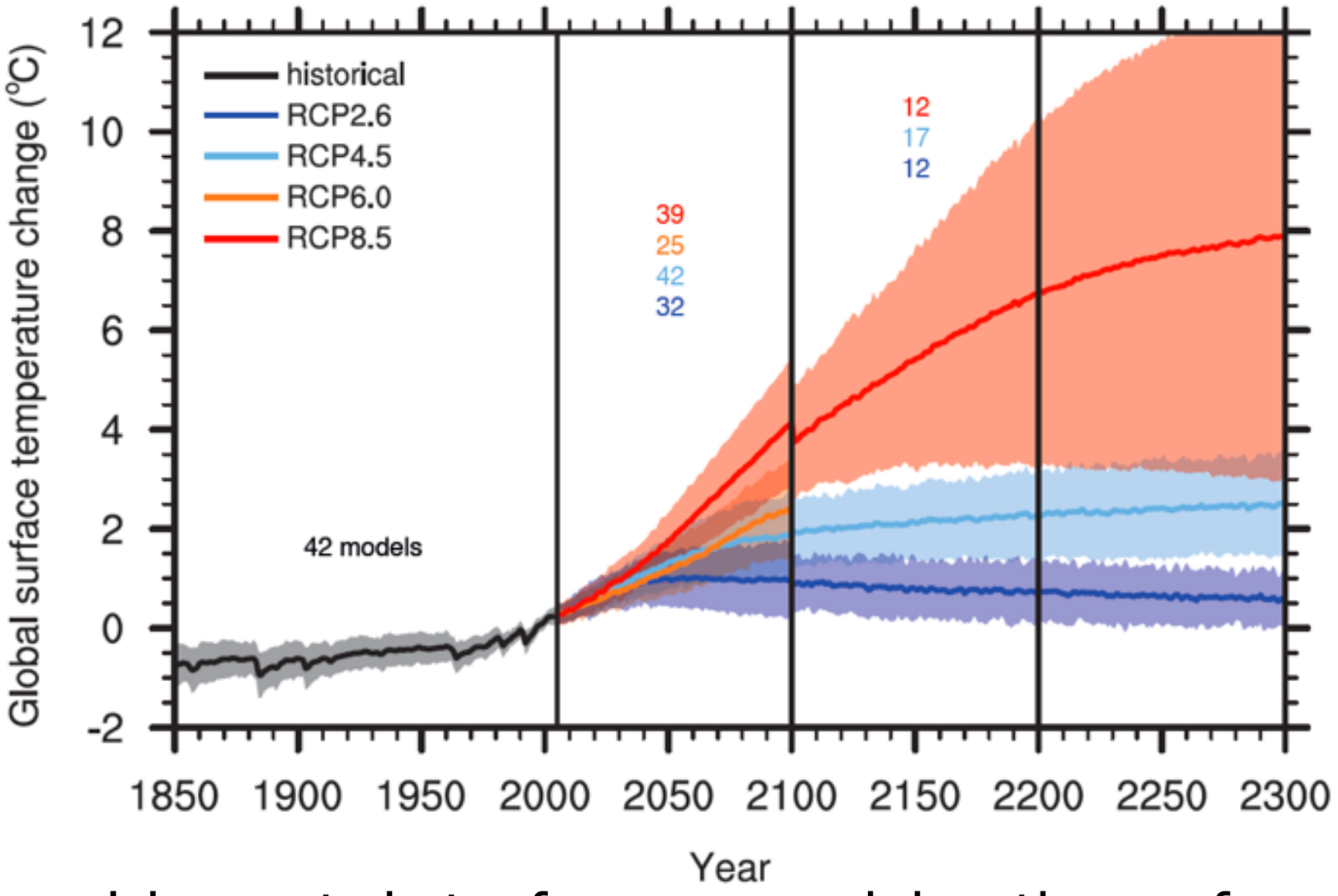
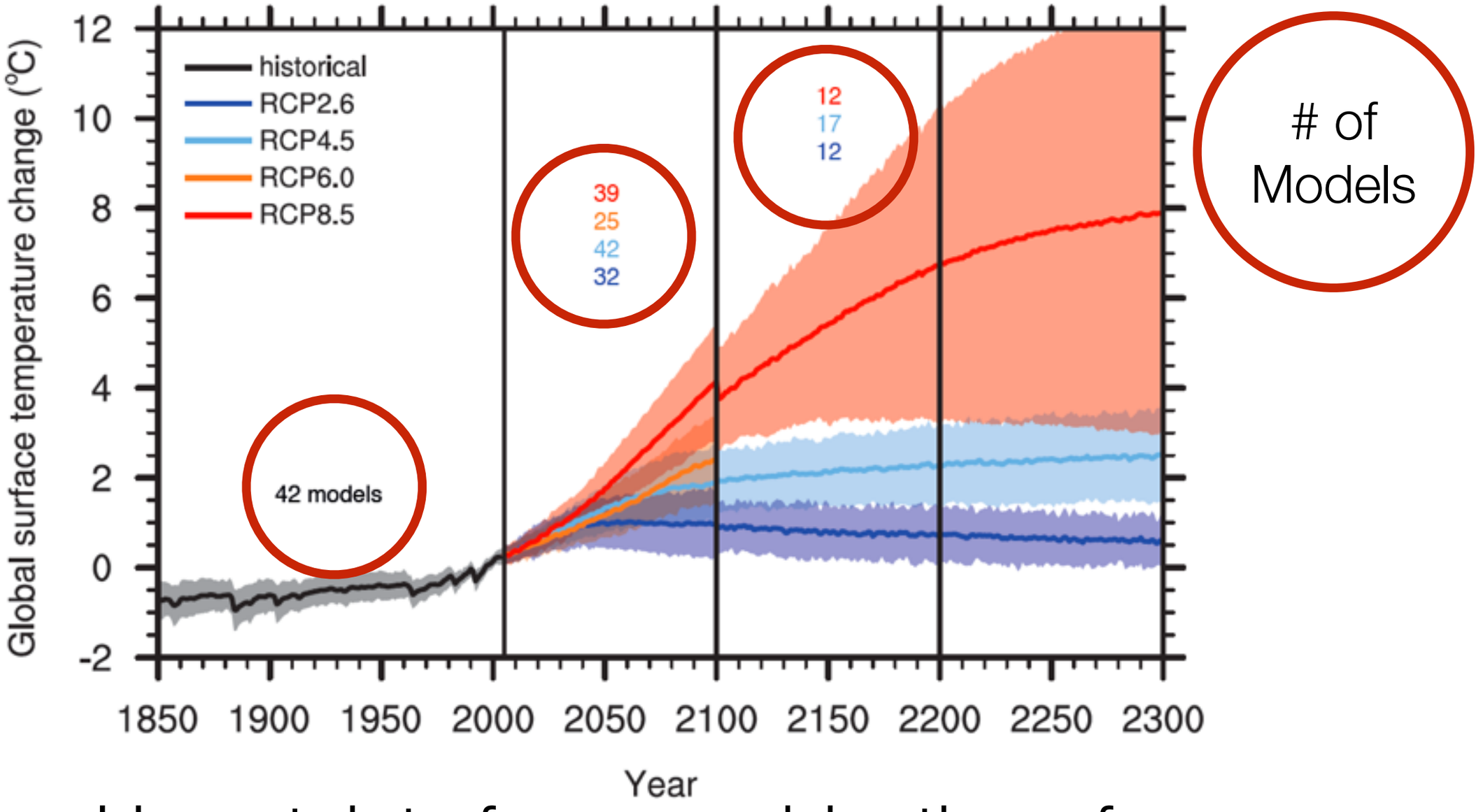
What drives uncertainty?



Uncertainty from combination of **forcings** and **model response**

(IPCC AR5 WG1 Fig. 12.4)

What drives uncertainty?

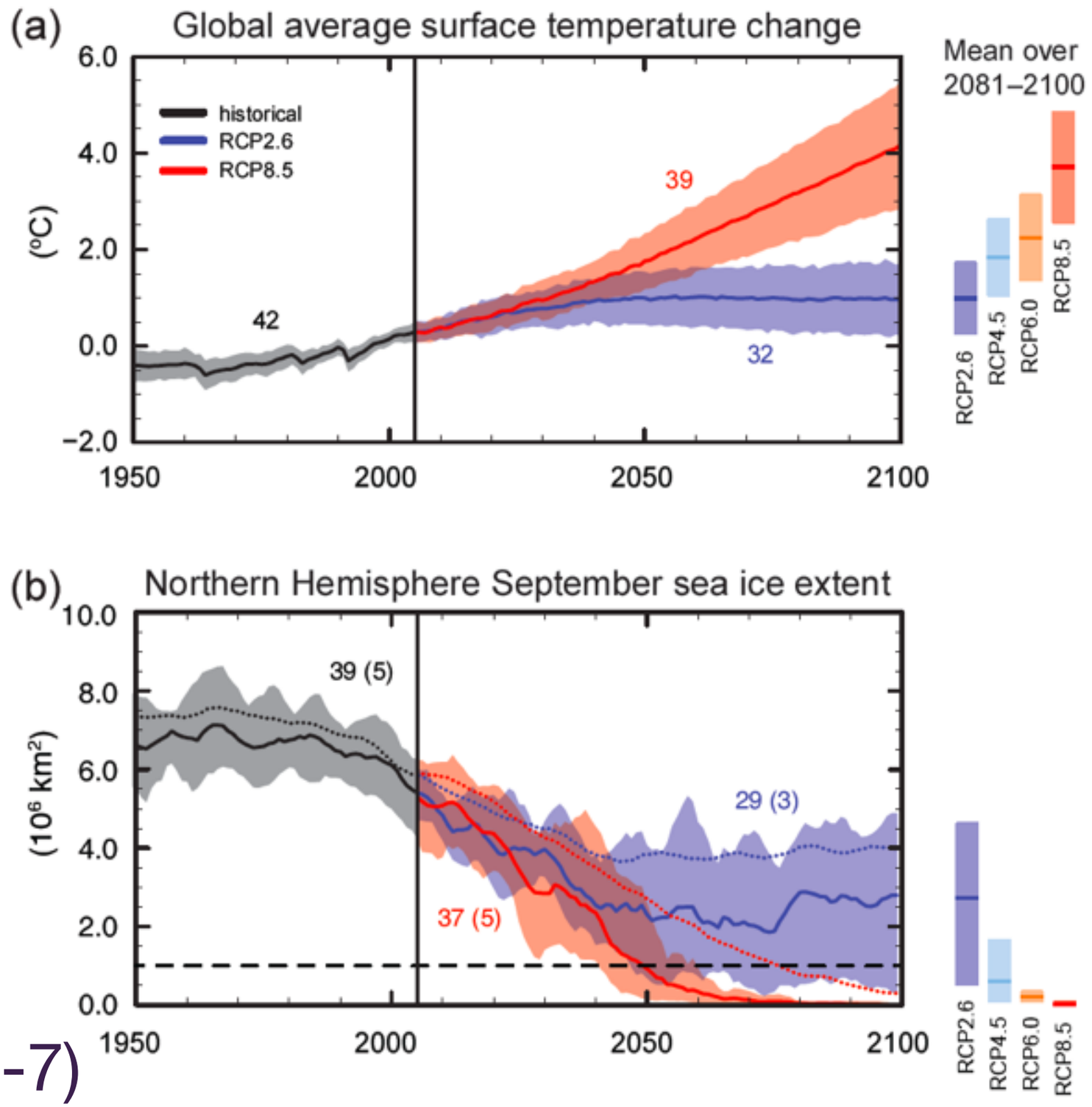


Uncertainty from combination of **forcings** and **model response**

(IPCC AR5 WG1 Fig. 12.4)

What drives uncertainty?

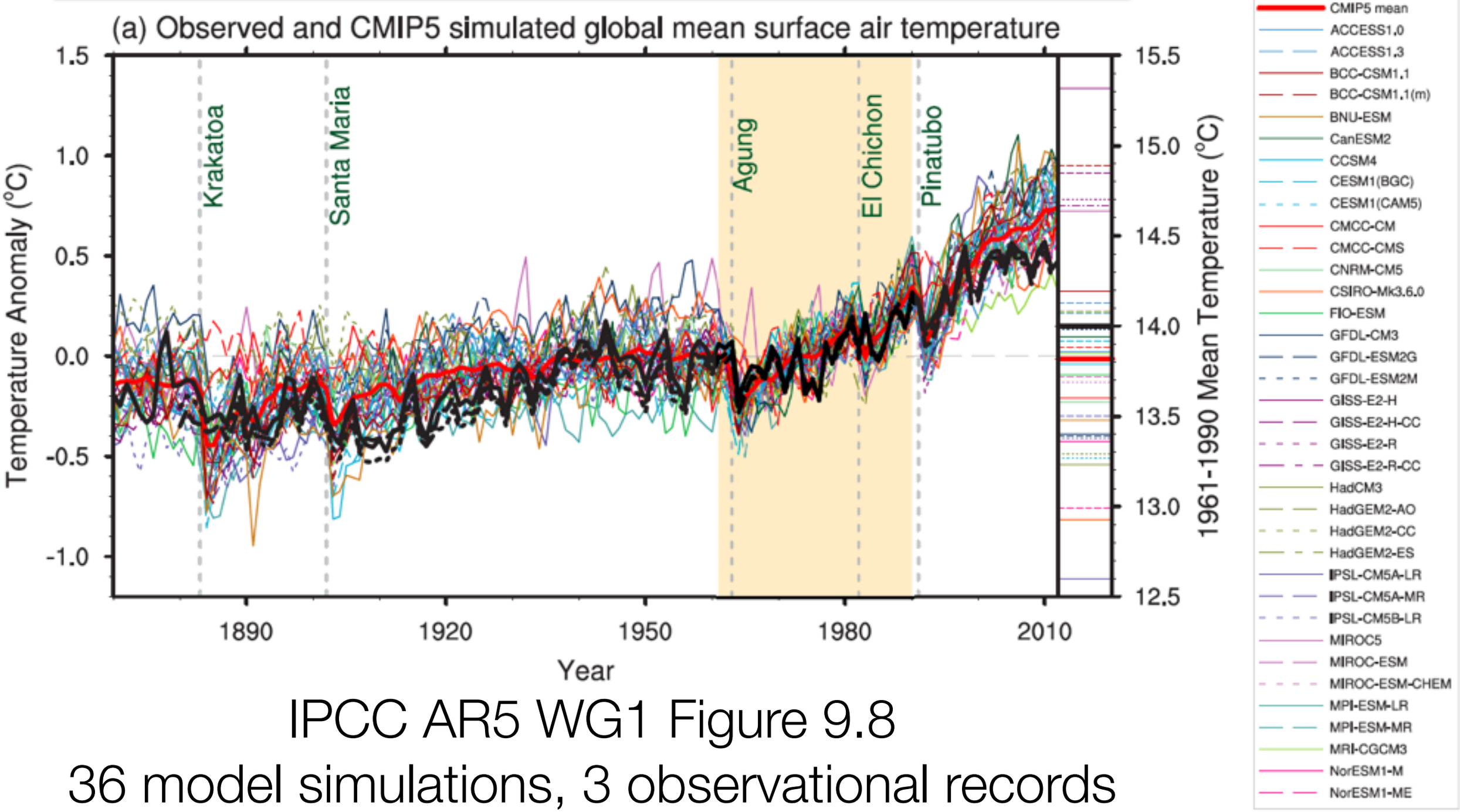
Uncertainty from combination of **forcings** and **model response**



(IPCC AR5 WG1 Fig. SPM-7)

One component of uncertainty is due to internal variability of the climate system

Example 1: Global Mean Surface Temperature

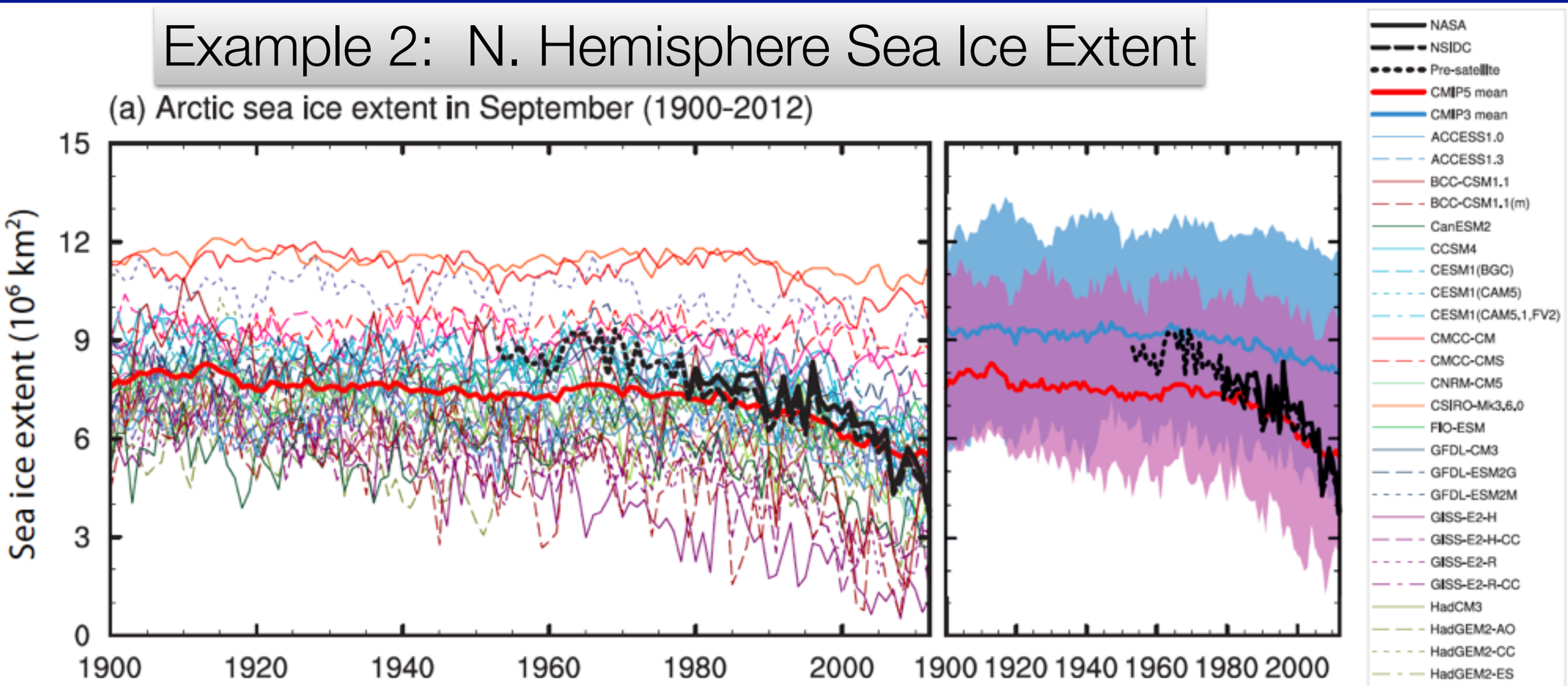


IPCC AR5 WG1 Figure 9.8

36 model simulations, 3 observational records

One component of uncertainty is due to internal variability of the climate system

Example 2: N. Hemisphere Sea Ice Extent



The SPM indicates bounded long term trends but individual models show significant details.

IPCC AR5 WG1 Figure 9.24

37 model simulations, 3 observational records

A second component is uncertainty in the forcing scenarios summarizing human activity.

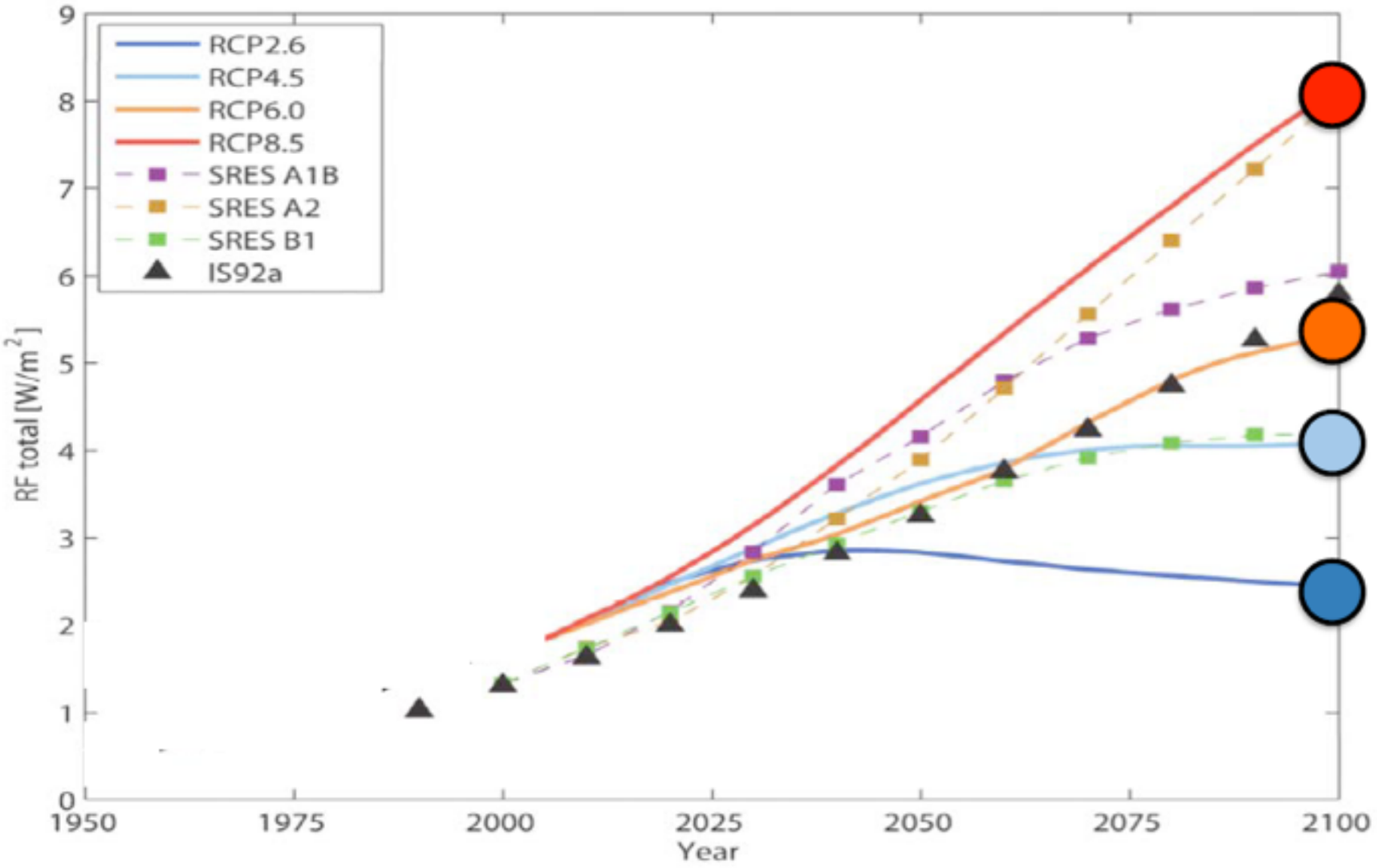
RCP Scenarios have replaced SRES Scenarios (which replaced IS92 Scenarios

RCP := Representative Concentration Pathways

2.6, 4.5, 6.0, & 8.5 := Radiative Forcing at 2100

A second component is uncertainty in the forcing scenarios summarizing human activity.

Total anthropogenic radiative forcing
IS92a (SAR), SRES (TAR/AR4), RCP (AR5)



See Fig.1.15

So far we have focused on internal variability and forcing uncertainty, we leave the uncertainty in model response until later to introduce …

Sources of Uncertainty

- Observational uncertainty (measurements)
- Model uncertainty (representation/epistemic)
- Statistical Uncertainty (i.e., random/aleatoric)
- Chaotic Uncertainty (internal/natural/unforced variability)

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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.

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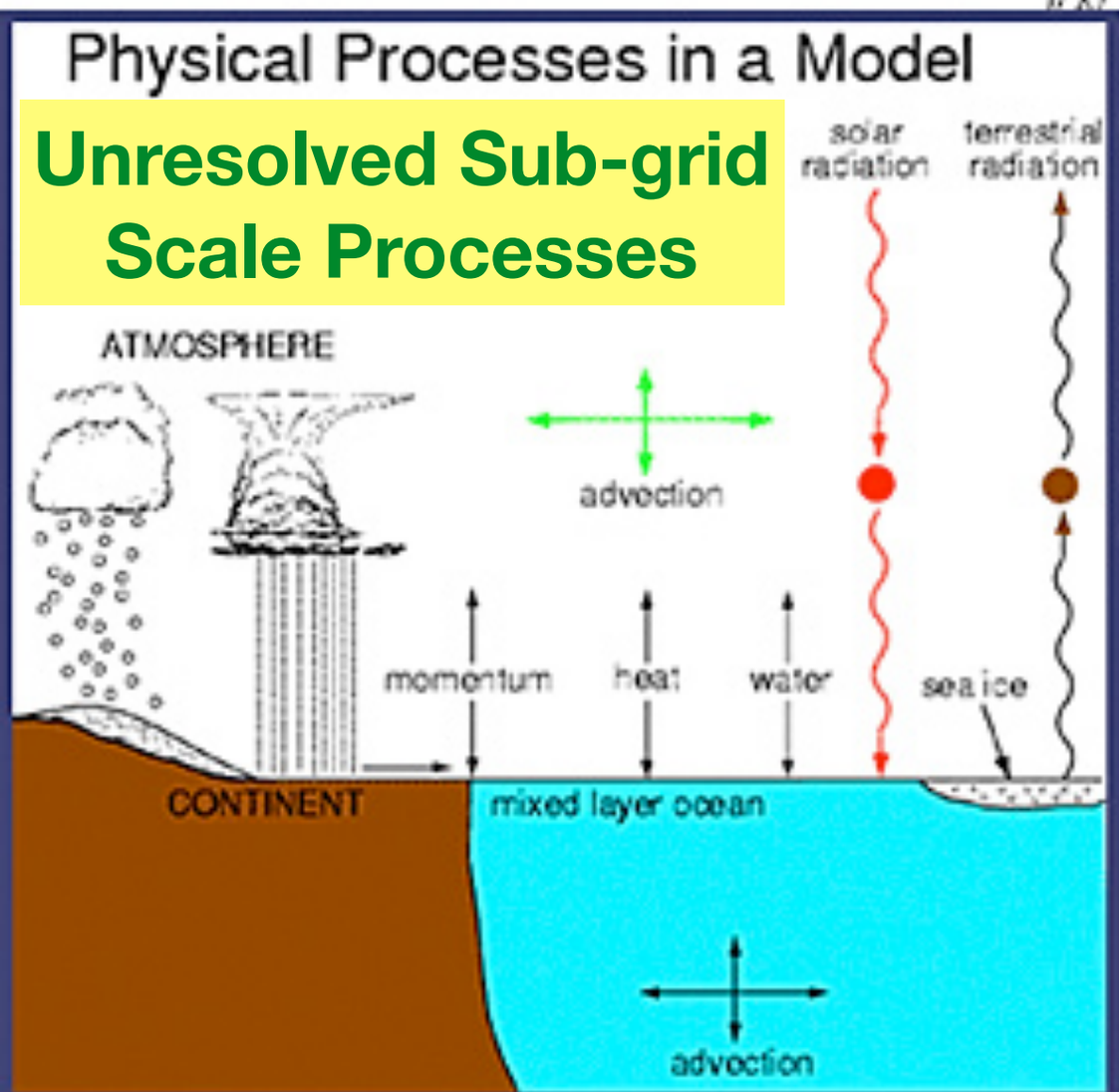
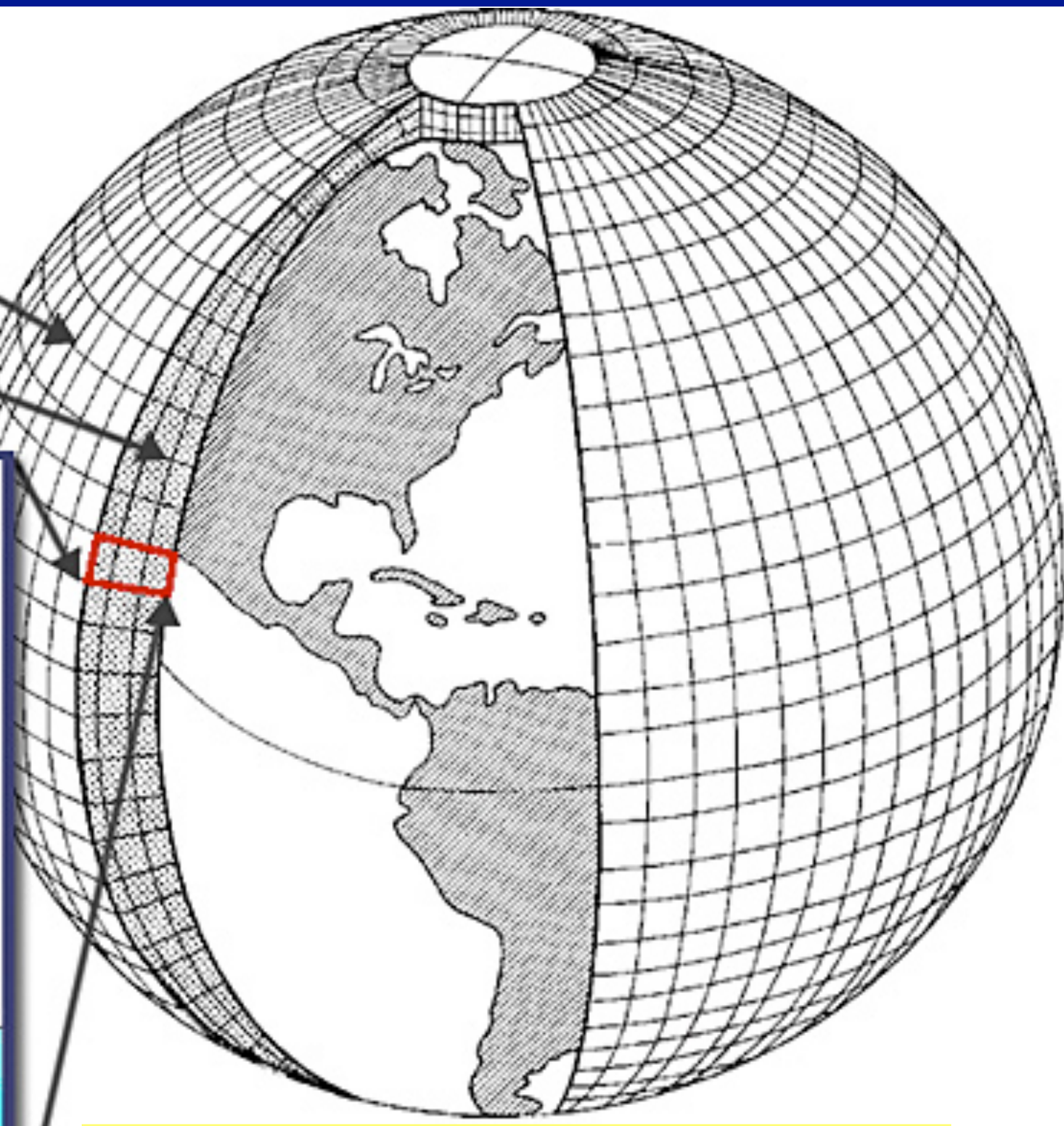
Building a Climate Model: Discretization for Numerical Solution of PDEs

Schematic for Global Atmospheric Model

Horizontal Grid (latitude - longitude)

Vertical Grid (height or pressure)





Resolved Large-scale Processes

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**

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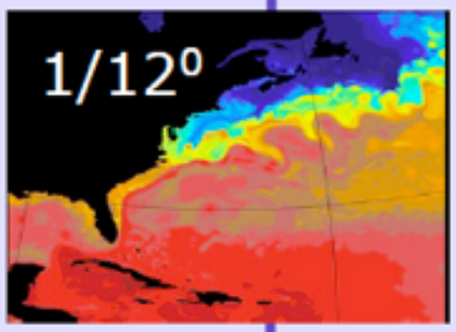
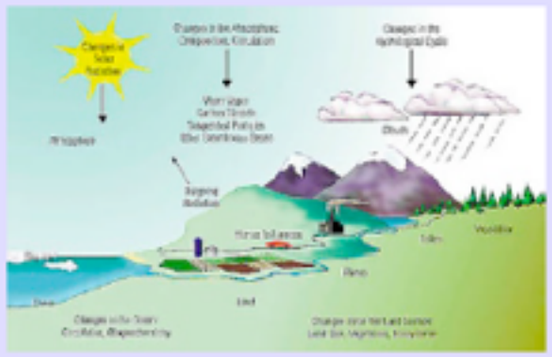
What limits our ability to understand uncertainty in models?

Climate GCMs

Facing up to the demands of resolution, complexity and uncertainty in Earth System Modelling: Is there a choice?



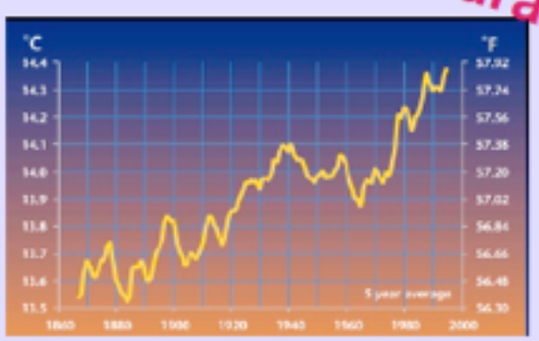


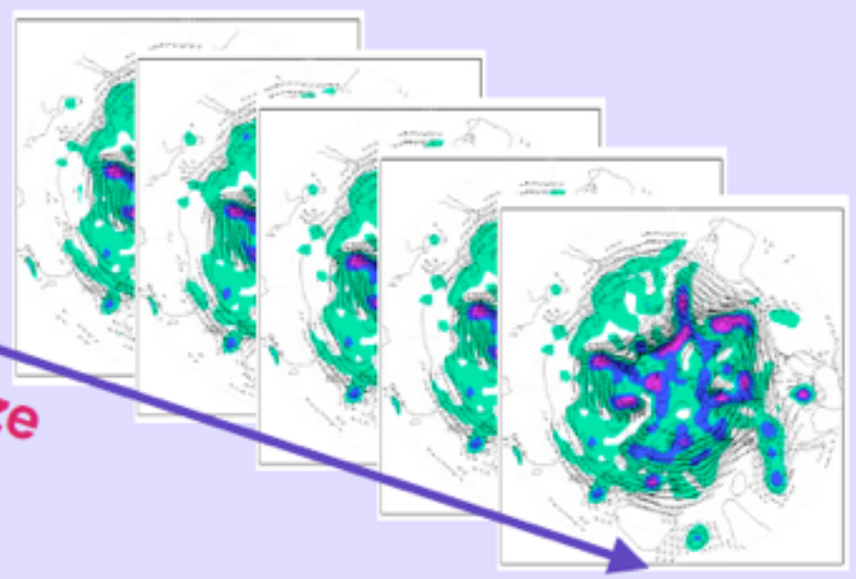
Resolution

Computing Resources

Complexity

Duration and/or Ensemble size





Courtesy Julia Slingo

E. Guilyardi - ESA/CCI Frascati, September 2010

Courtesy of Julia Slingo (via Eric Guilyardi)

Model Complexity: Structure

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

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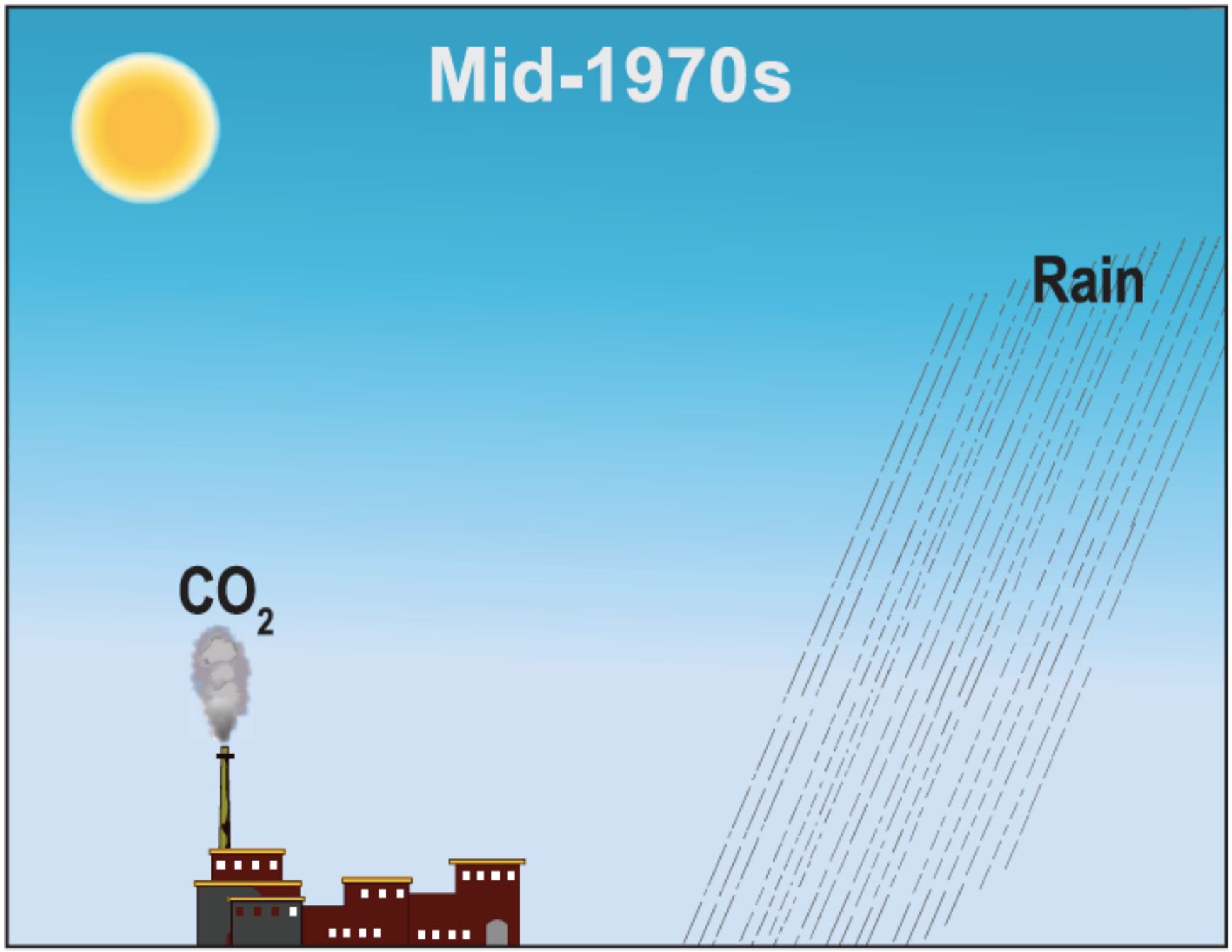
Climate Model History



Components/Complexity

(from IPCC AR4)

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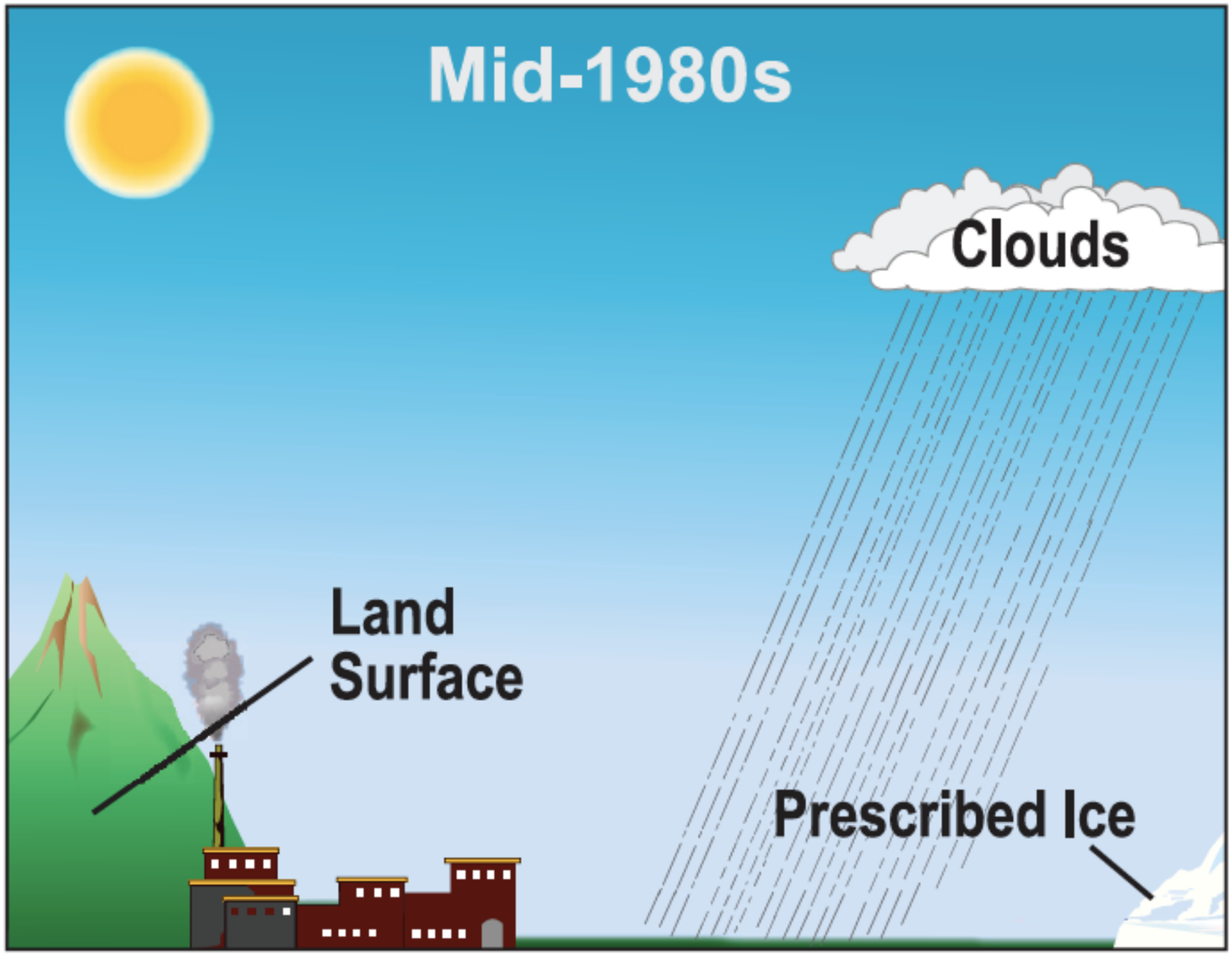
Climate Model History



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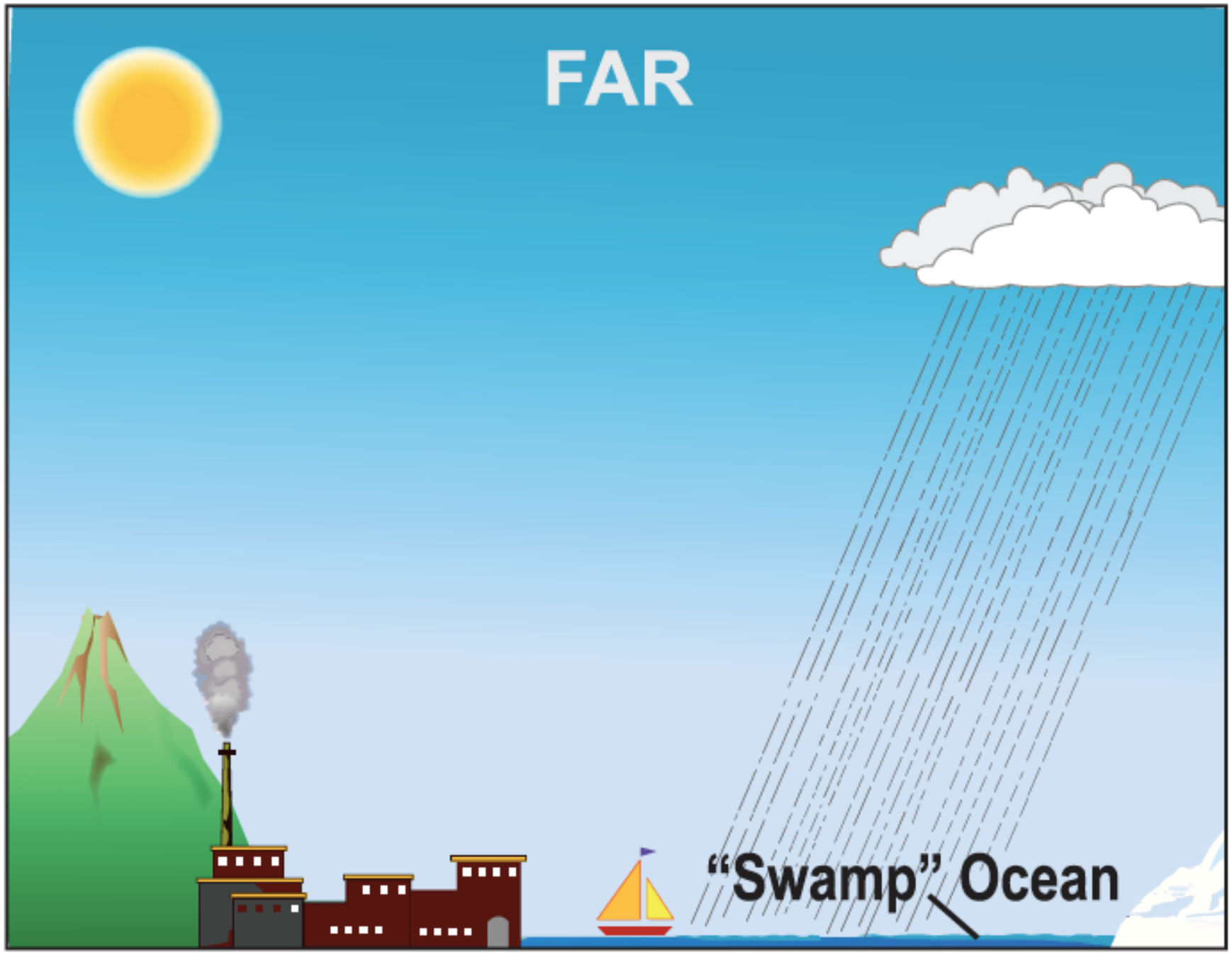

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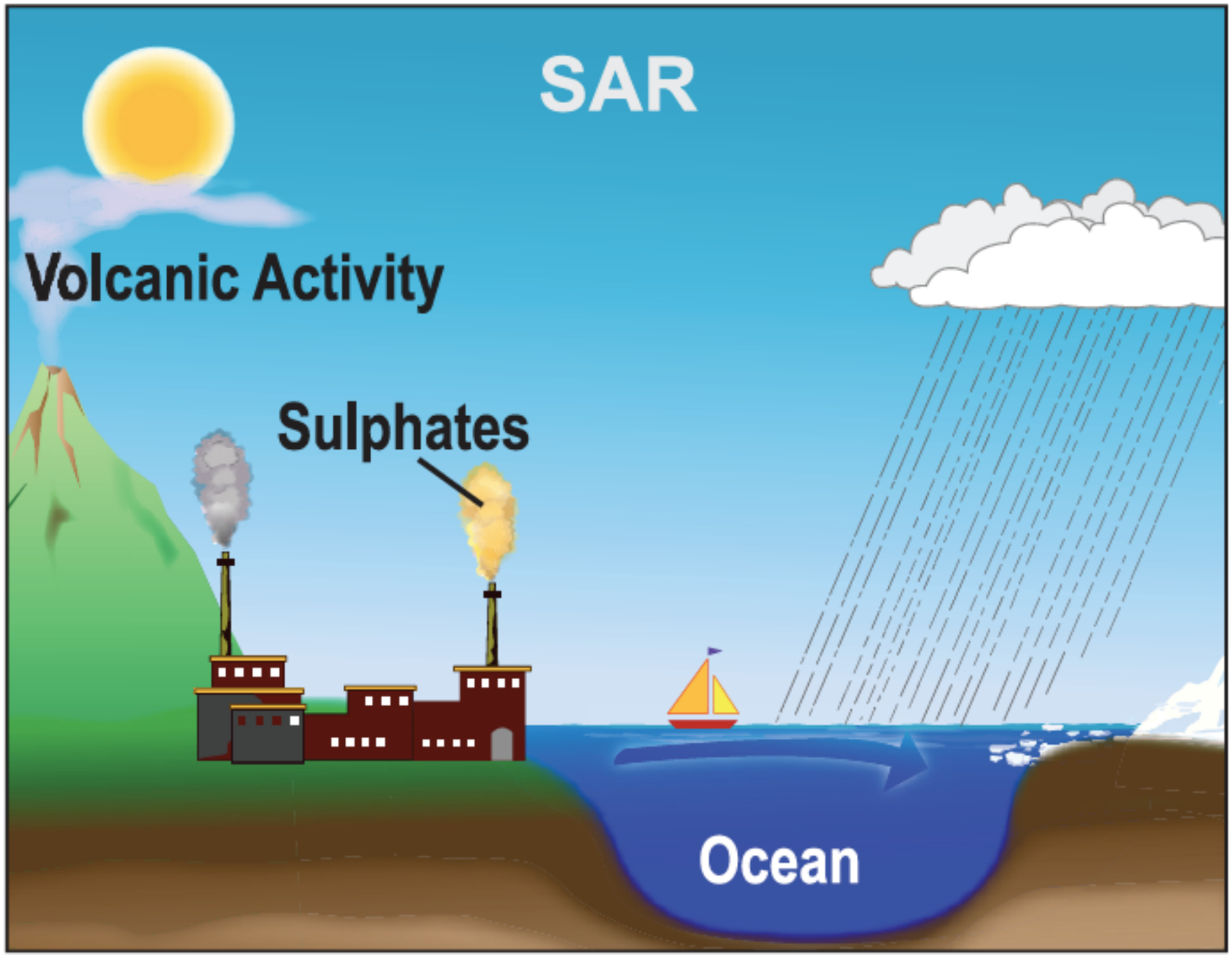

Components/Complexity

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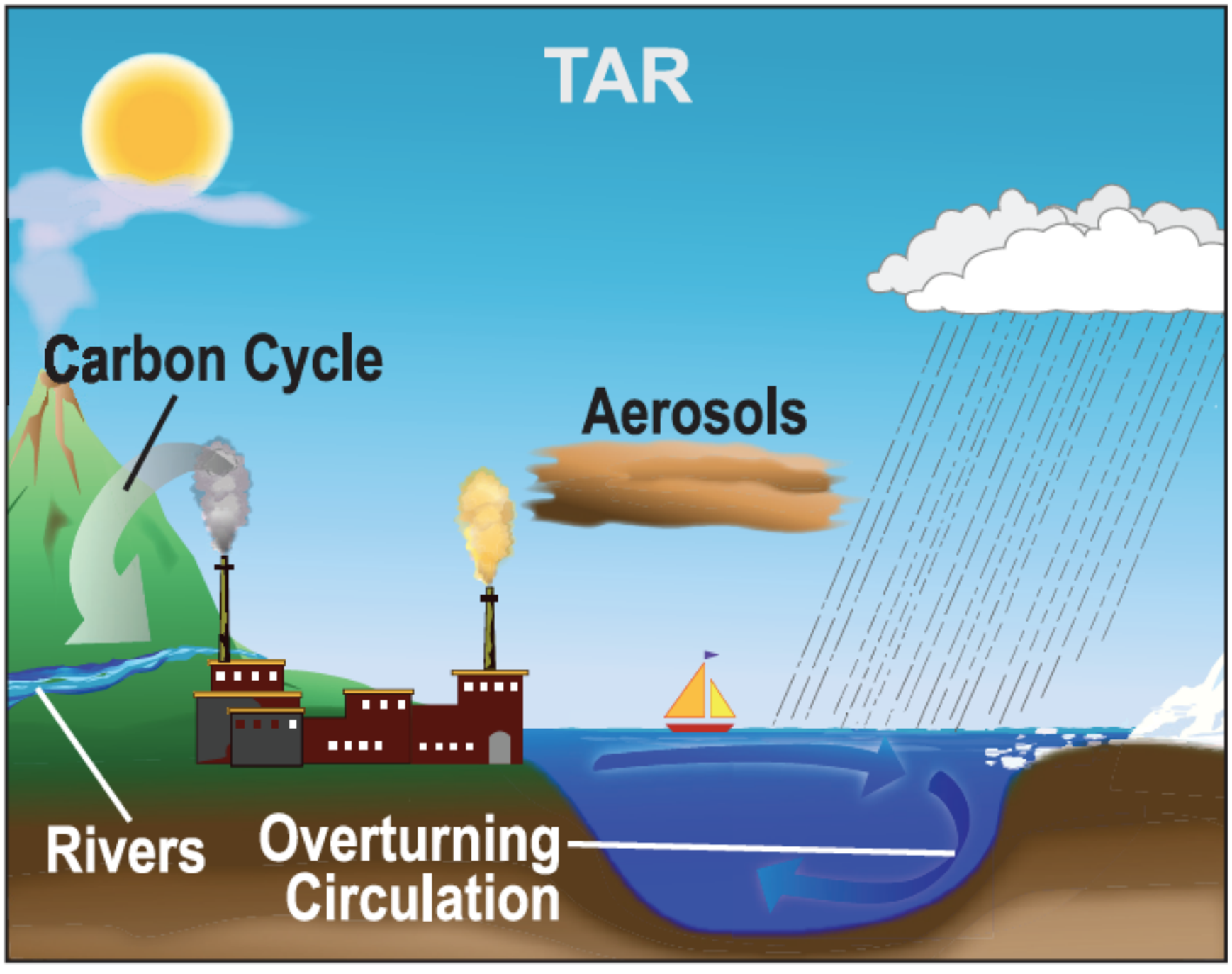

Components/Complexity

(from IPCC AR4)

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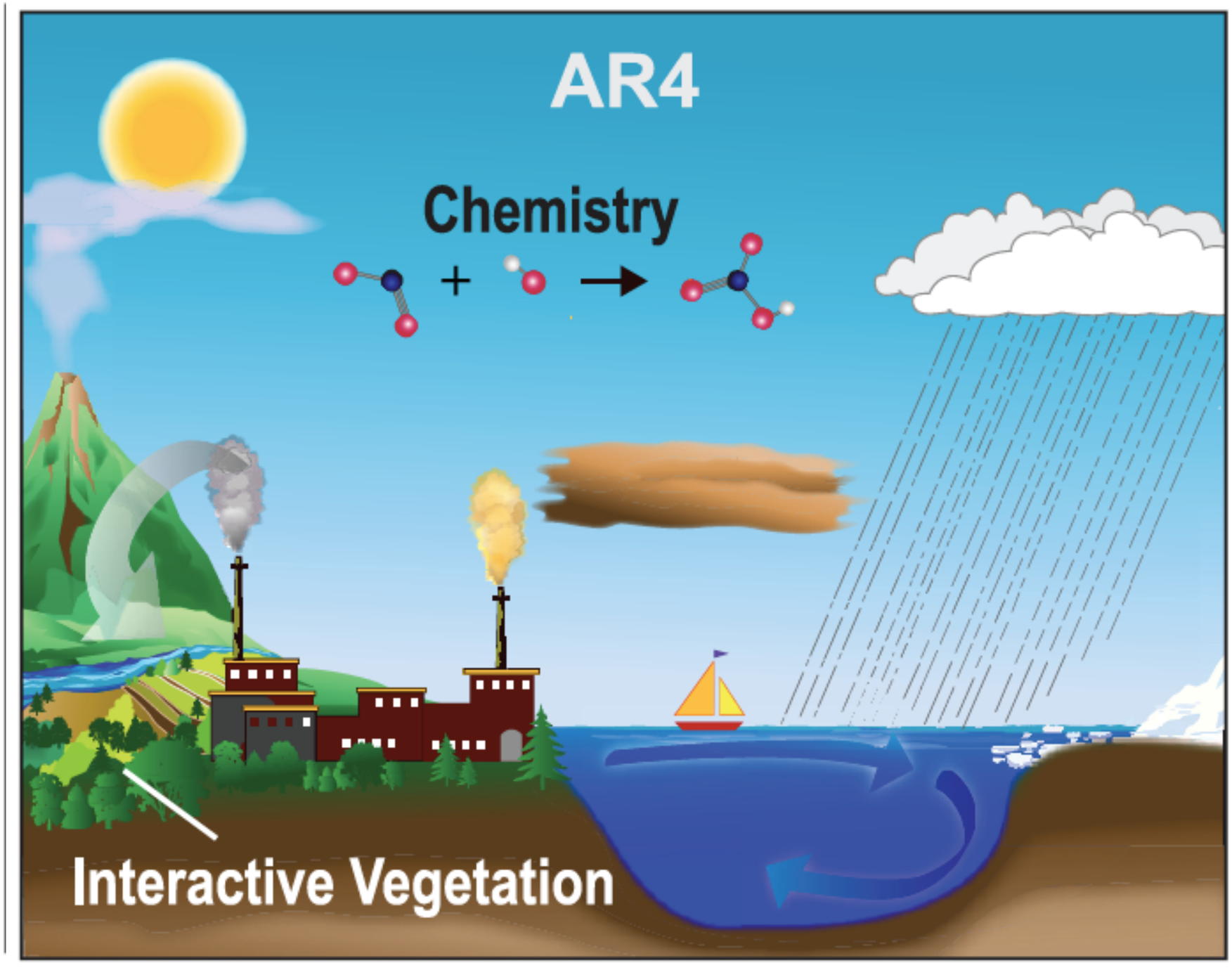

Components/Complexity

(from IPCC AR4)

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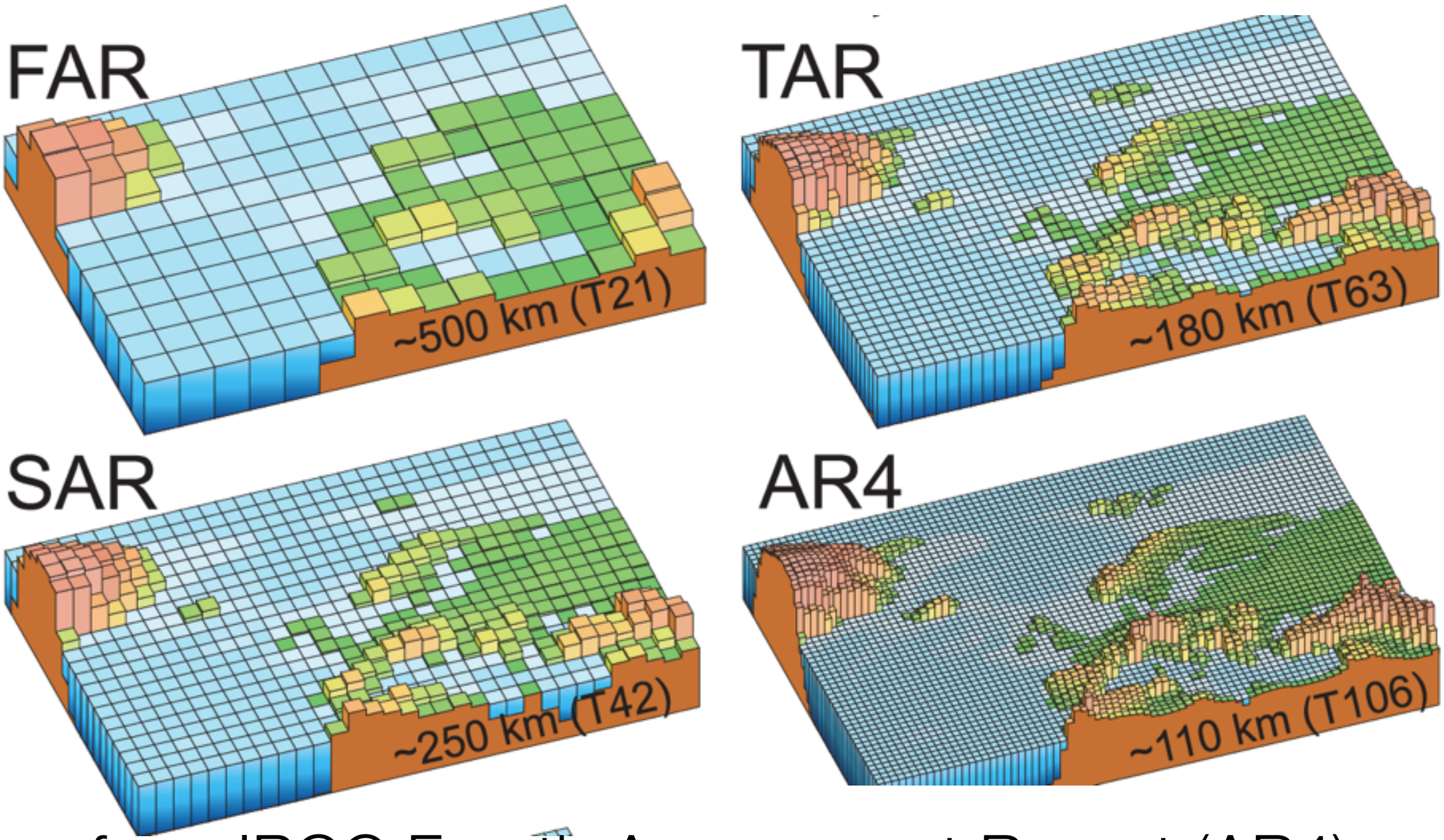
Climate Model History



from IPCC Fourth Assessment Report (AR4)

(Note: these are best resolutions at that time.)

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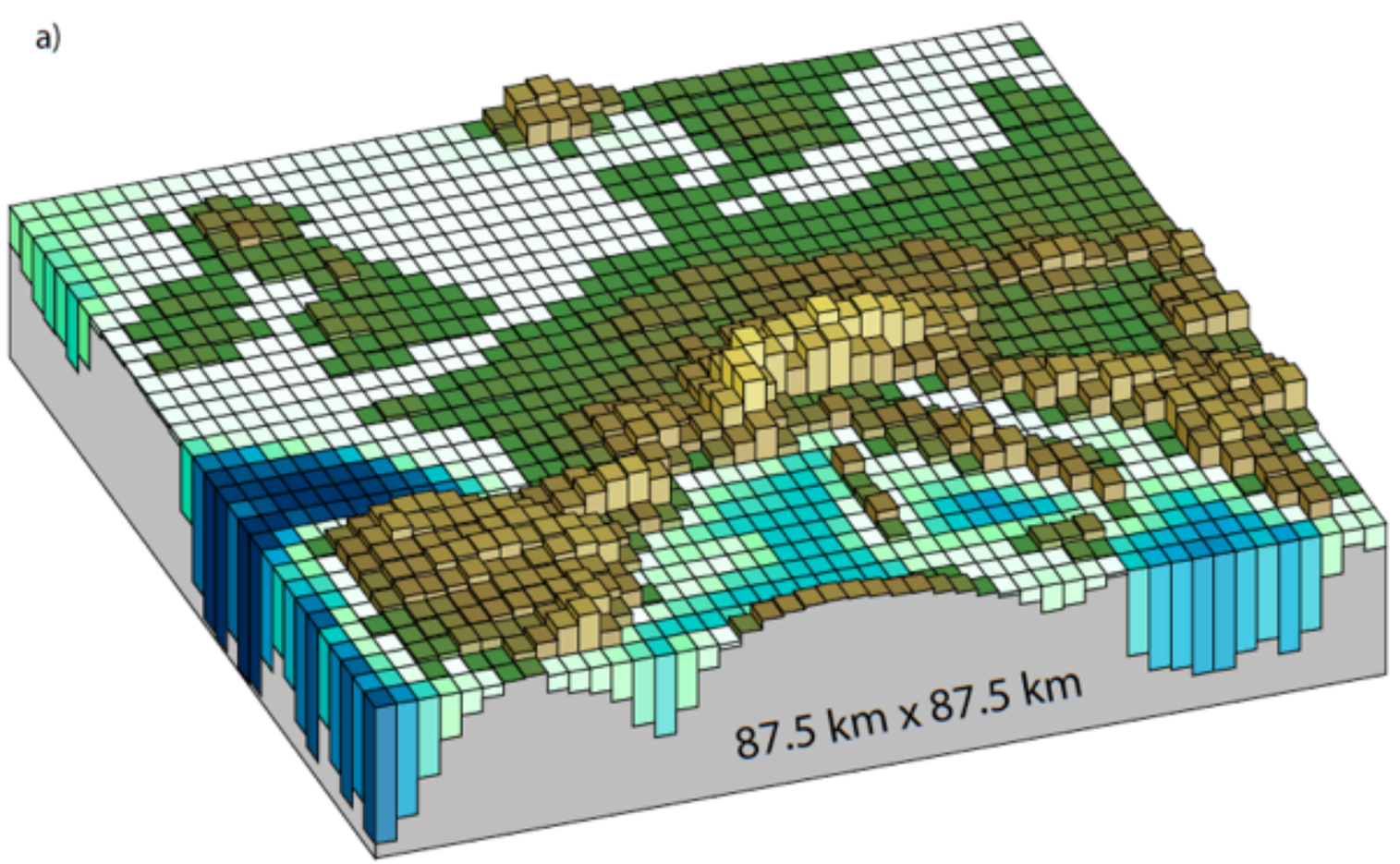
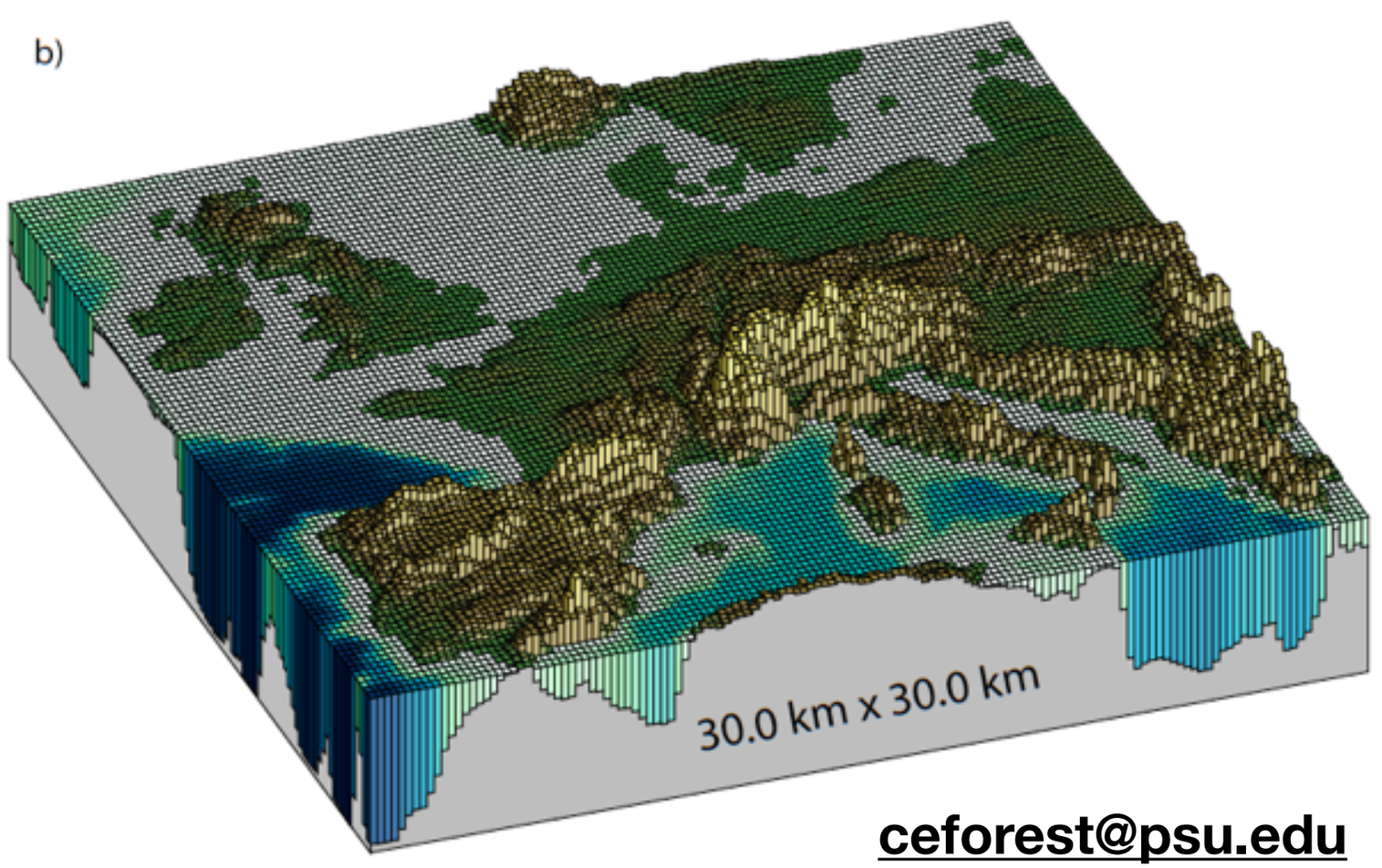
Climate Model History

Most model resolutions

IPCC AR5 WG1 Figure 1.14





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Contributions of specific model components to overall uncertainty

Sources of uncertainties in climate models	Contribution to overall uncertainty
Implementation of numerics	small
Representation of dynamics	small
Representation of sub-gridscale processes	Significant (short & long timescales)
Natural climate variability	Significant (short & long timescales)
Impact of atmospheric composition on radiative balance	Less significant

Courtesy of: Ben Booth (Met Office)

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Characterizing Model Uncertainty

- **Multi-model Ensemble (MME)**
    - Assesses Structural Uncertainty
- **Perturbed Physics (aka Parameter) Ensemble (PPE)**
    - Assesses Parametric Uncertainty
- **Initial Condition Ensembles**
    - Assesses Internal Variability Uncertainty

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Characterizing Model Uncertainty

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    - Assesses Internal Variability Uncertainty

More details of these will be discussed in my lecture on Wednesday.

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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
  - CFMIP = Cloud Feedback MIP
  - GeoMIP = Geo-engineering MIP
- CMIP1, CMIP2, CMIP3, CMIP5, ...
  - New models, new MIP.
- Program for Climate Model Diagnostics and Intercomparison = PCMDI

Summary so far…

What does characterizing uncertainty mean?

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What does characterizing uncertainty mean?

- Here is my climate model… a pair of dice.

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What does characterizing uncertainty mean?

- Here is my climate model… a pair of dice.
- We roll the dice to predict some future event.

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The Problem: Model Predictions have multiple sources of uncertainty…

- Aleatoric uncertainty: getting a random number

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The Problem: Model Predictions have multiple sources of uncertainty…

- Epistemic uncertainty: getting the model right (South America v. Europe)

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The Problem: Model Predictions have multiple sources of uncertainty…

- Epistemic uncertainty: getting the model right (multiple initial conditions)

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The Problem: Model Predictions have multiple sources of uncertainty…

- Epistemic uncertainty: getting the model right (the right physics)

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The Problem: Model Predictions have multiple sources of uncertainty…

- Epistemic uncertainty: getting the model right (the right model structure)

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But the real problem is:
What if the world is actually this?

- Multiple levels of uncertainty: aleatoric & epistemic

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But the real problem is:
What if the world is actually this?
And we can only observe it this well?

- Multiple levels of observational uncertainty: aleatoric & epistemic

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Thank you!
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Questions?