Earth System modelling: the basics

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Lecture outline

- What is a model and why do we need them?
- Different types of models and their uses
  - Climate models/Earth System Models
- Climate modelling in a nut-shell
- Introduction to some key concepts
  - Parameterization
  - Prediction vs projection
  - Spin-up
  - Validation
  - Uncertainty

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Why do we need models?

- In order to fully understand a system you need to produce a model of the system, test it and validate it

- If you want information away from where you can't make observations you need models (e.g. the future)

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What is a model?

A few suggested definitions:

- "...a model can be a theory or a law or an hypothesis or a structured idea. It can be a role, a relation or an equation. It can be a synthesis of data." (Haggett and Chorley, 1967)
- Graphical, mathematical (symbolic), physical, or verbal representation or simplified version of a concept, phenomenon, relationship, structure, system, or an aspect of the real world. (www.businessdictionary.com)
- A model is a simplified representation of a more complex phenomenon, process or system… (Barnsley, 2007)

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Simplification: good or bad?

- To gain understanding of a complex problem, you often want to simplify that problem (simplification is good)
- However, in order to predict (e.g.) the future we would ideally want the model to be exactly like the thing we are modelling (simplification is bad)

Real world

Model

Space

Time

Space

Time

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Simplification: good or bad?

For the climate system we have no choice! We have to rely on a massive oversimplification of reality

Real world

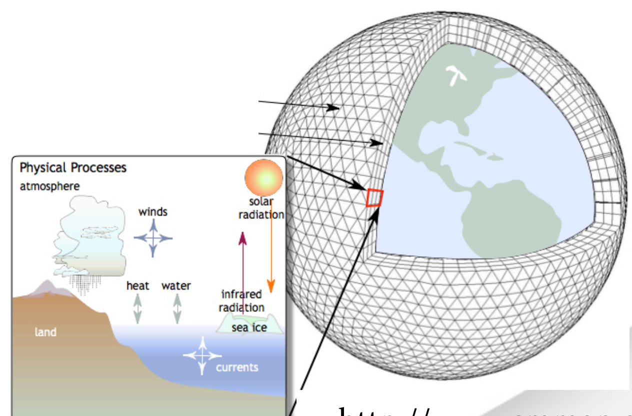
Model

Space (continous)

Time (continous)

Space (discretizised)

Time (discretizised)



http://www.cmmap.org

"... all models are wrong, but some are useful." (Box, 1979) (also http://blogs.plos.org/models/)

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Empirical vs theoretical models

- Empirical models are statistical models derived from observations
  - Example: multiple linear regression ($y=ax_1+bx_2$)
  - Typically can work well within the range of conditions over which they have been trained
- Theoretical models are based on process representation, e.g. based on laws of physics
  - This is your only hope if you want to predict outcomes outside the range of observations

Climate models have a little bit of both ☺

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What do climate modellers do?

Mathematical model

$$\frac{d\mathbf{u}}{dt} + f\mathbf{k}\times\mathbf{u} = -\frac{1}{\rho}\nabla_z p + \mathbf{F}_{\mathbf{u}},$$

$$\frac{\partial p}{\partial z} = -g\rho,$$

$$\frac{1}{\rho}\frac{d\rho}{dt} + \nabla_z\cdot\mathbf{u} + \frac{\partial w}{\partial z} = 0,$$

$$\frac{d\theta}{dt} = F_\theta,$$

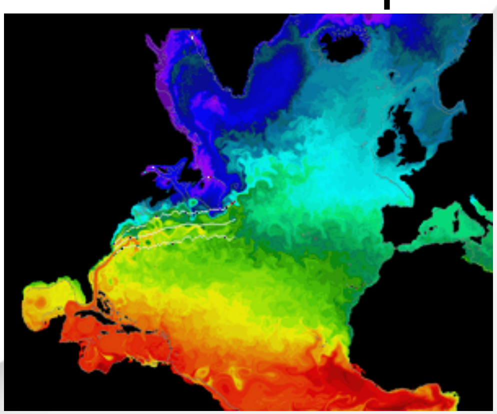
$$\frac{dS}{dt} = F_S.$$

$$\rho = \rho(\theta, S, p),$$

Numerical model

Computer simulation

Model output



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What are climate models used for?

- Gaining and improving our understanding of dynamics and mechanisms; allow us to test importance of various components of the system
- Aiding decision making by simulating "what if" scenarios
- Provide warning of possible future events based on a known set of current conditions (e.g. prediction)

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Earth System Model – the basic

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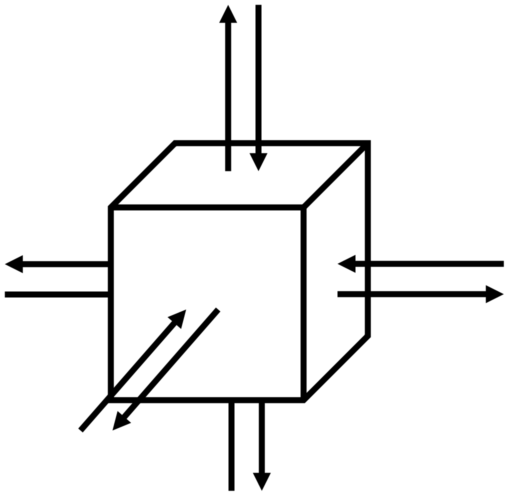
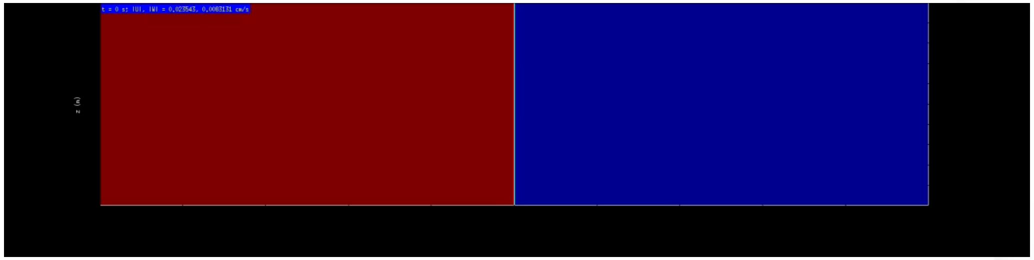
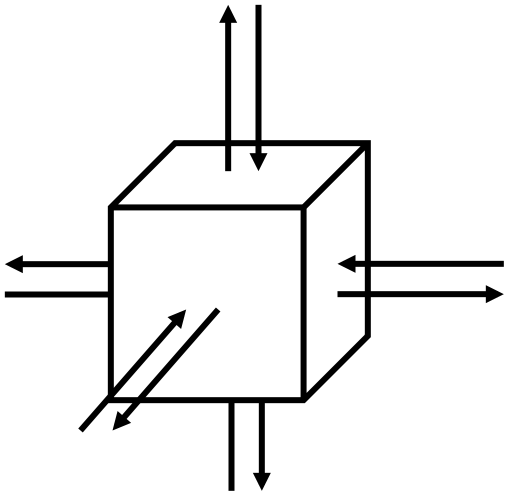


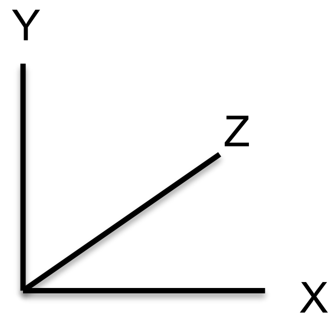
youtube.com/watch?v=GG9hMLKUU90



Dense fluid

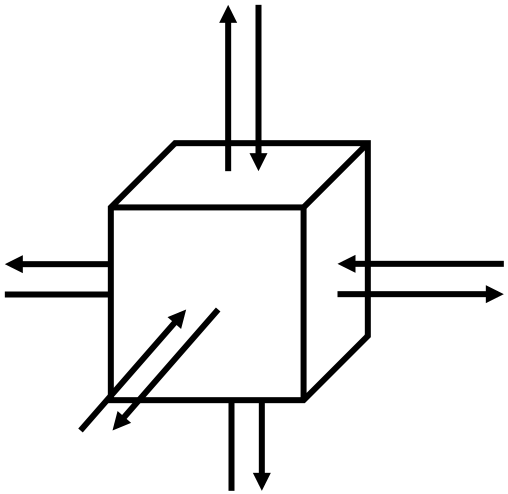
Less dense fluid





To work out the flow, we need to know:

- The pressure
- The velocity (and therefore momentum) in the
  - X
  - Y directions
  - Z



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- The pressure
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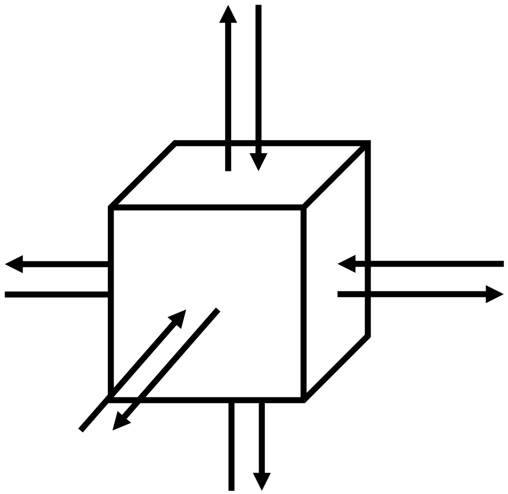
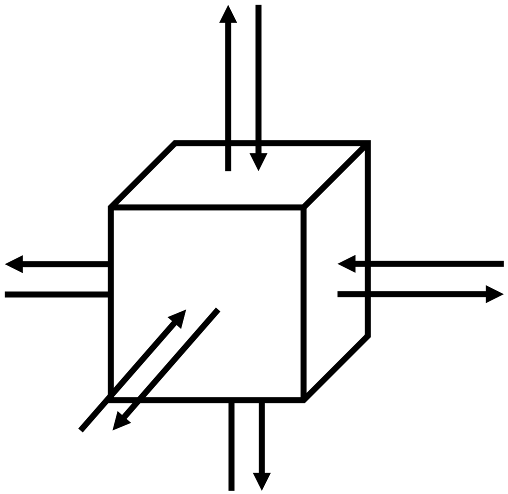
4 unknowns… we need 4 equations to allow us to solve them



Our 4 equations come from:

Conservation of mass:

1) Mass going into box minus mass out of box = change in mass of box



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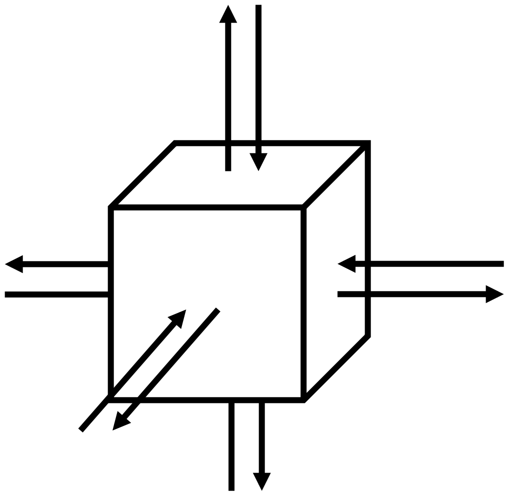

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Conservation of momentum:

2) Momentum in X direction must be conserved
3) Momentum in Y direction must be conserved
4) Momentum in Z direction must be conserved

momentum = mass * velocity

This gives us the Navier-Stokes equations, which can be solved to work out the fluid flow

$$\left\{\begin{aligned} \frac{d\mathbf{u}}{dt} + f\mathbf{k}\times\mathbf{u} &= -\frac{1}{\rho}\nabla_z p + \mathbf{F_u}, \\ \frac{\partial p}{\partial z} &= -g\rho, \\ \frac{1}{\rho}\frac{d\rho}{dt} + \nabla_z\cdot\mathbf{u} + \frac{\partial w}{\partial z} &= 0, \end{aligned}\right.$$

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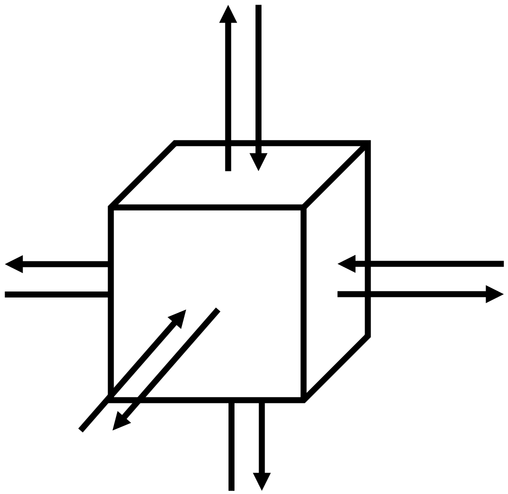

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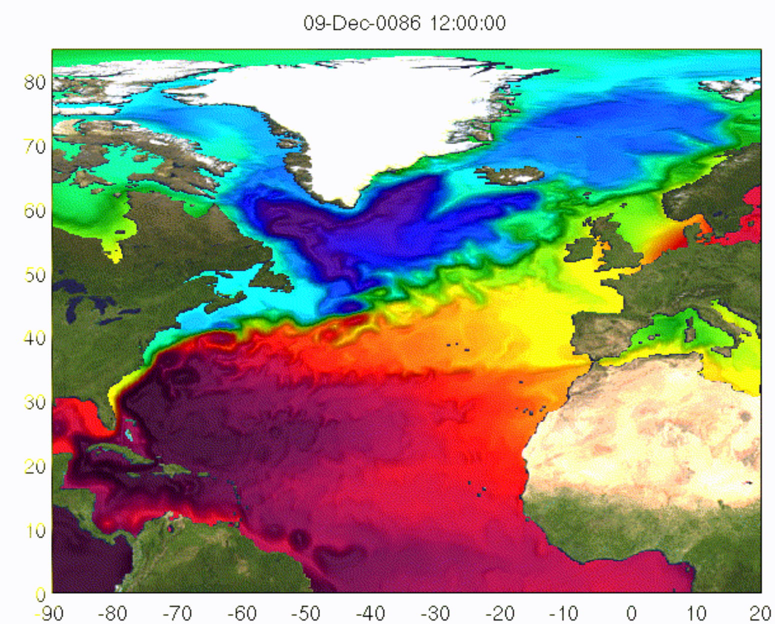
And it works quite well ☺



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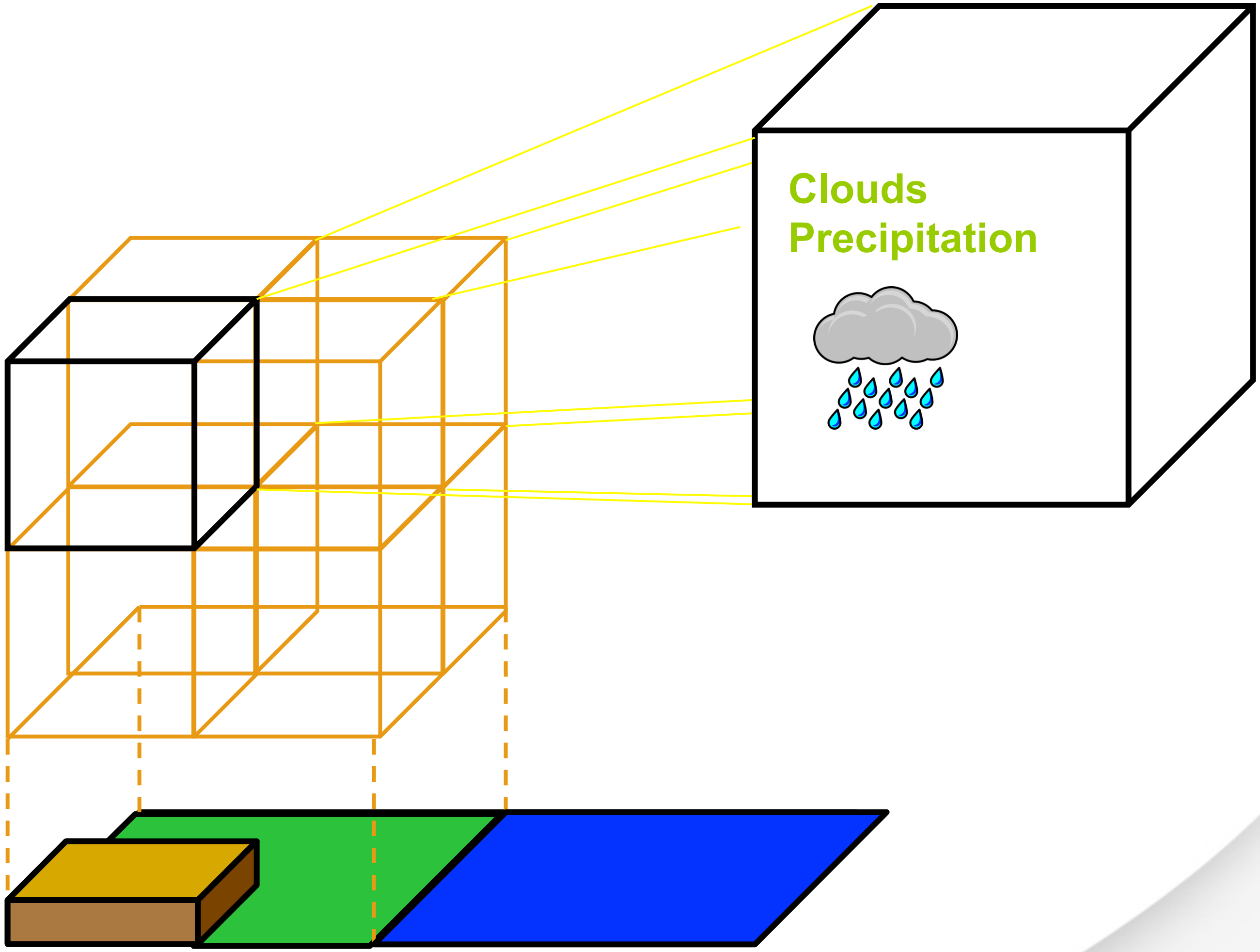
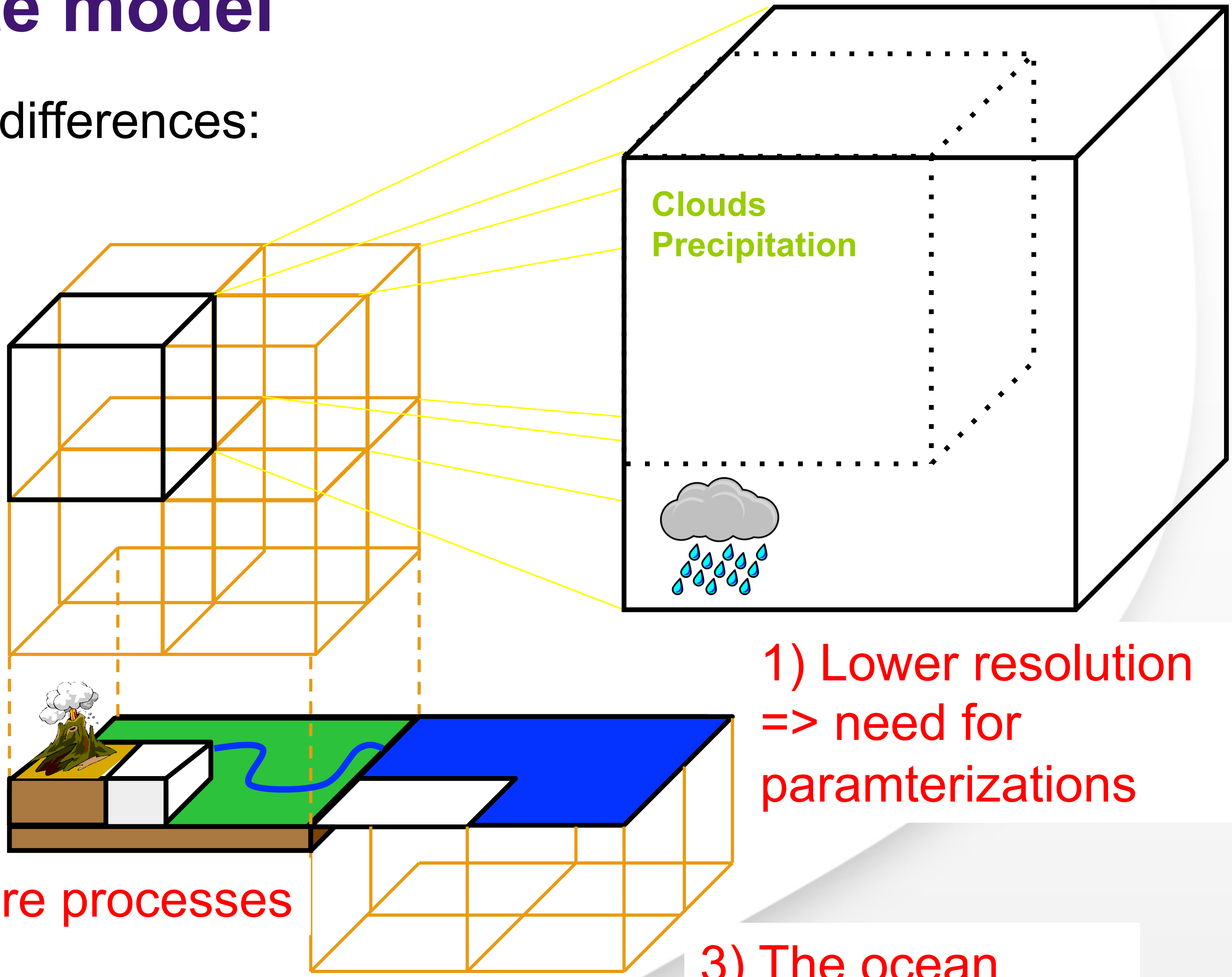
Weather model



Climate model

The main differences:



1) Lower resolution
=> need for
paramterizations

2) More processes

3) The ocean

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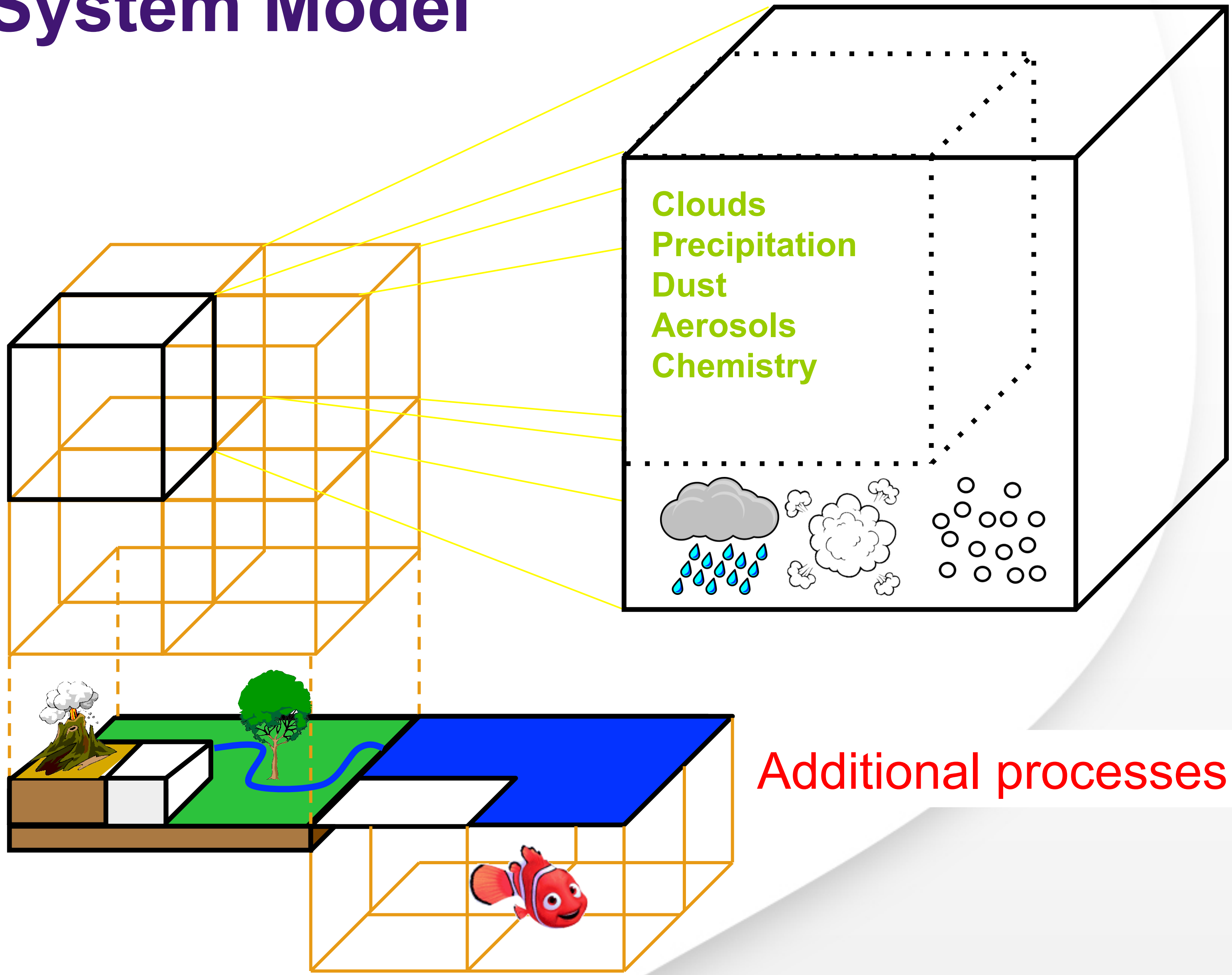
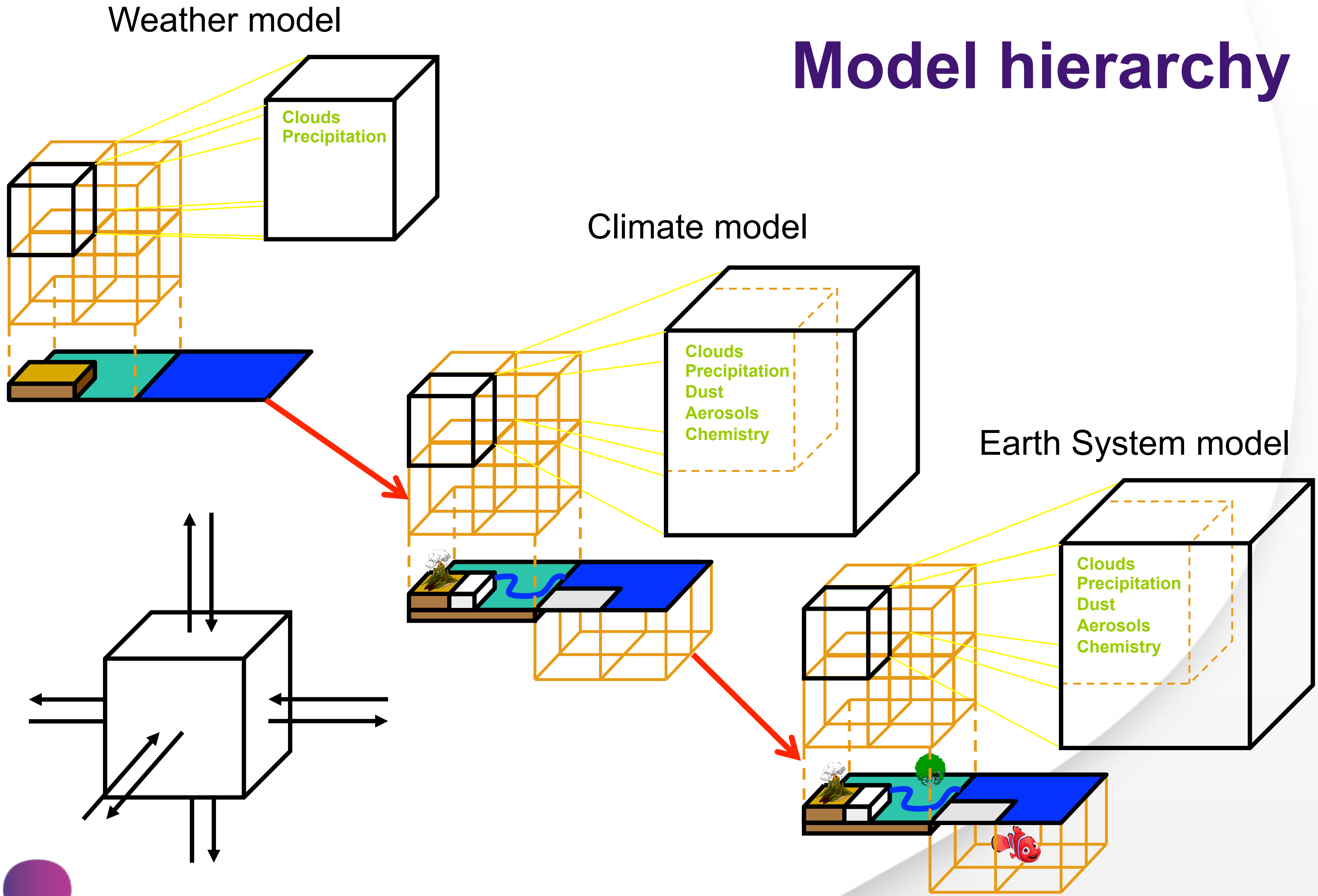
Earth System Model



Additional processes

Model hierarchy



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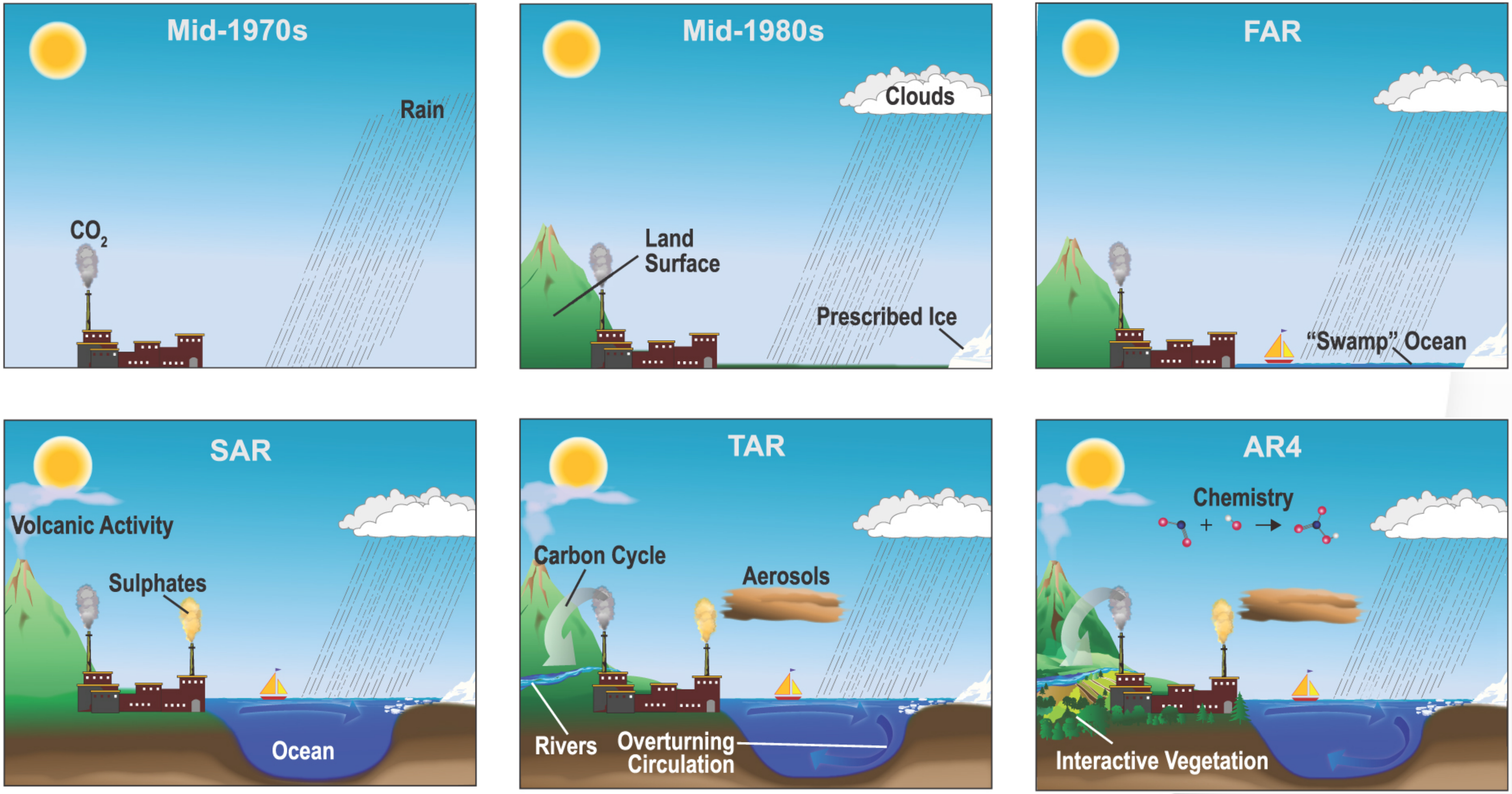
The world in climate models



FAR: First Assessment Report (IPCC 1990)
SAR: Second Assessment report (IPCC 1996)
TAR: Third Assessment Report (IPCC 2001)

Source: IPCC AR4 WG1

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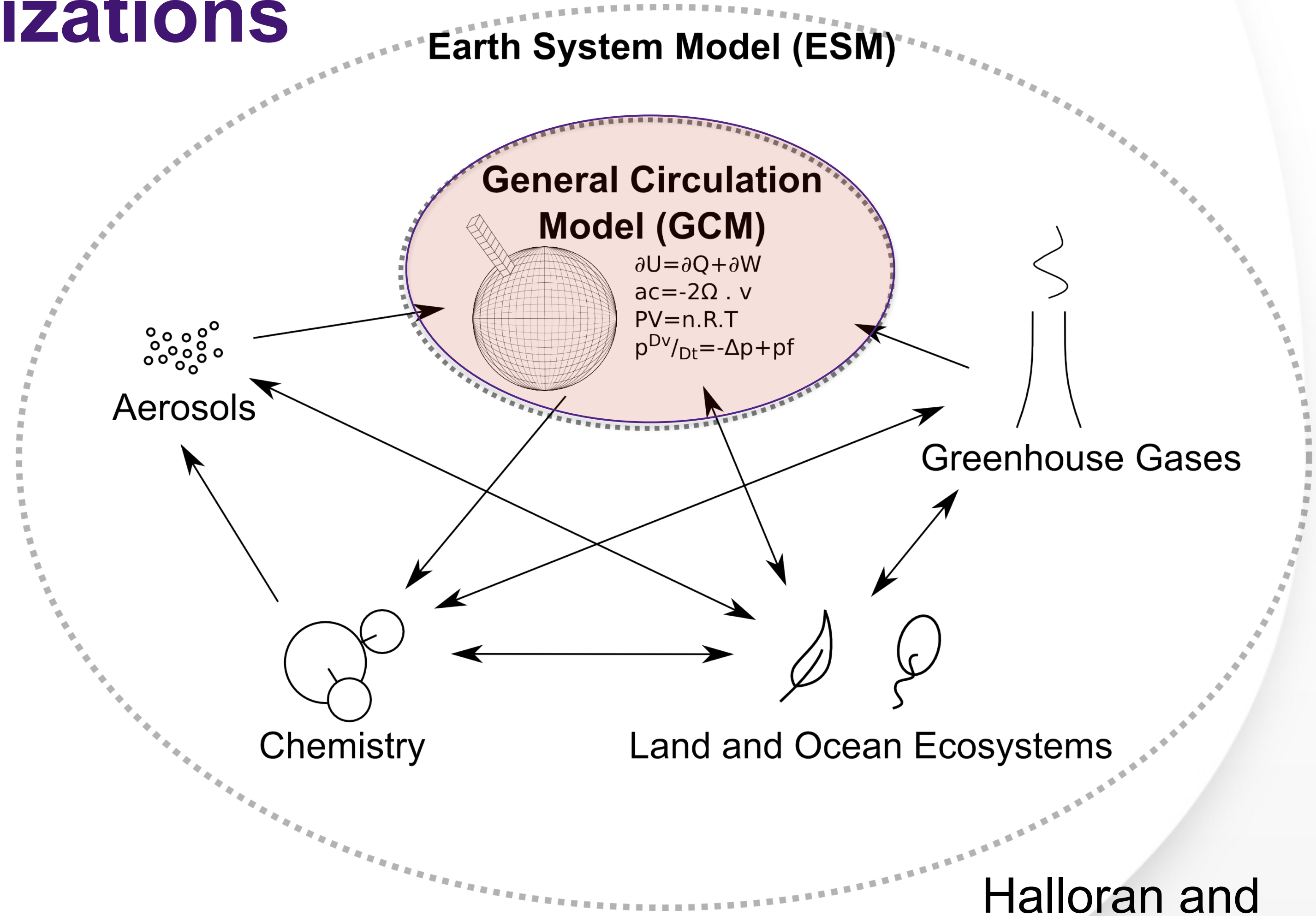
Some basic concepts

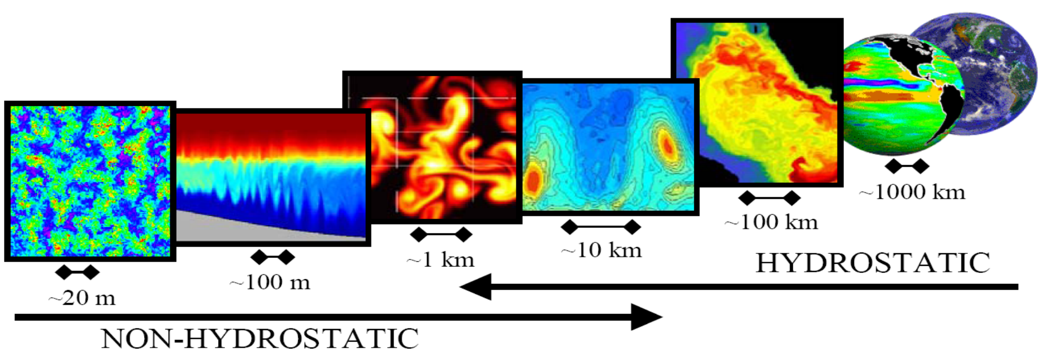
- Paramterisation
- Prediction vs projection
- Spin up
- Forcing and variability
- Validation
- Uncertainty

Parmeterizations

The flow of air and water based on fundamental physics, but some processes can not be resolved by the model => paramterizations



Halloran and Lowe, 2013



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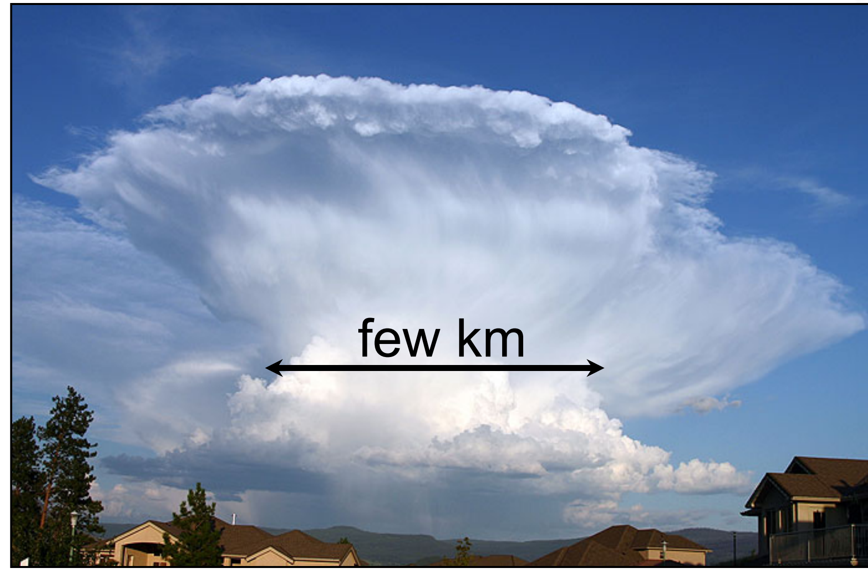
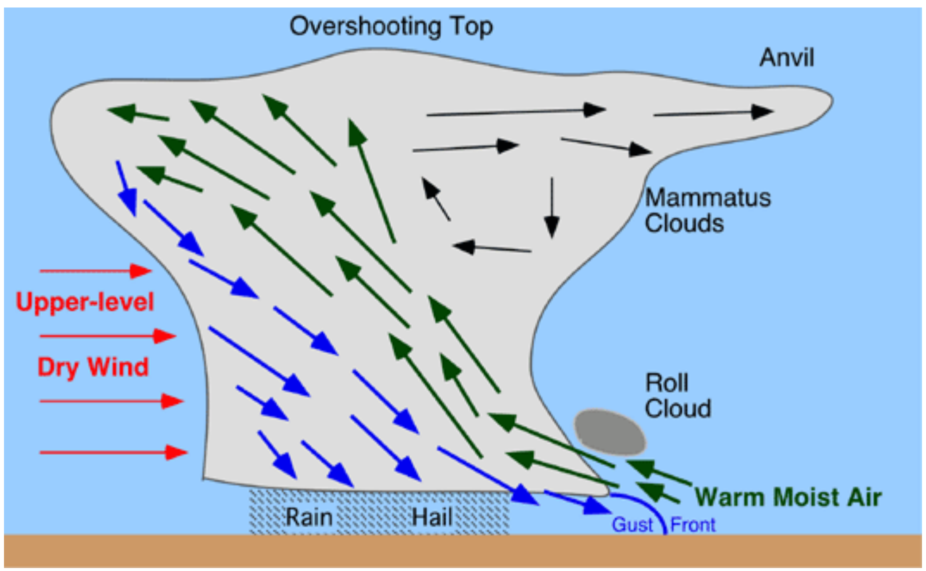
Important processes smaller than a grid box:

e.g., thunderstorms (atmospheric convection)



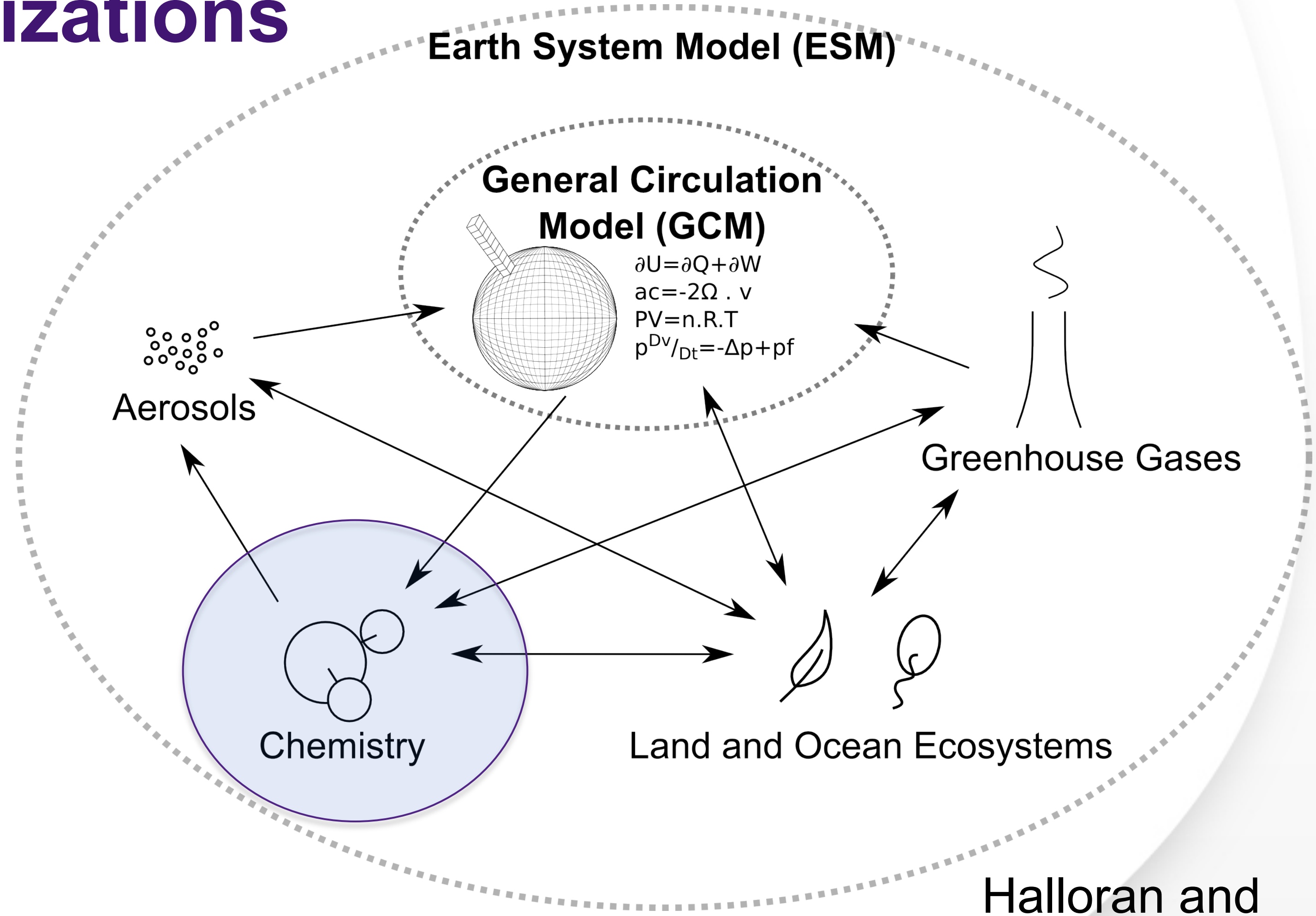


What's a model to do?

Parameterization: Represent the effects of the unresolved processes on the grid. Assume that unresolved processes are at least partly driven by the resolved climate.

Parmeterizations

Chemistry also based on physics, but in practice full chemistry often is too complex …



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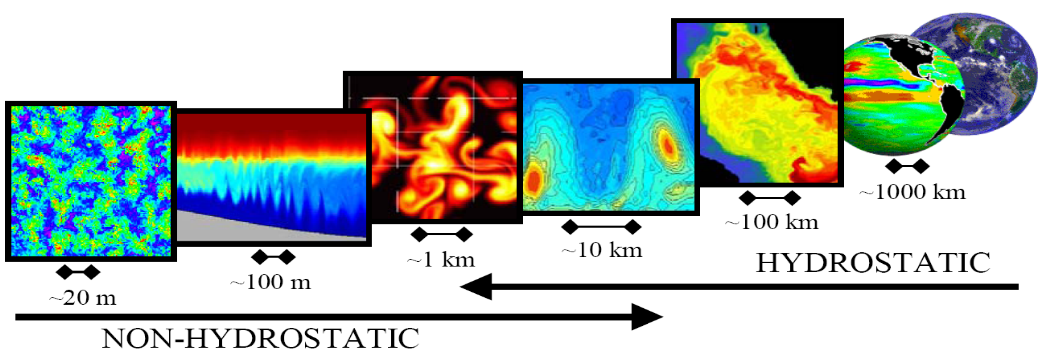

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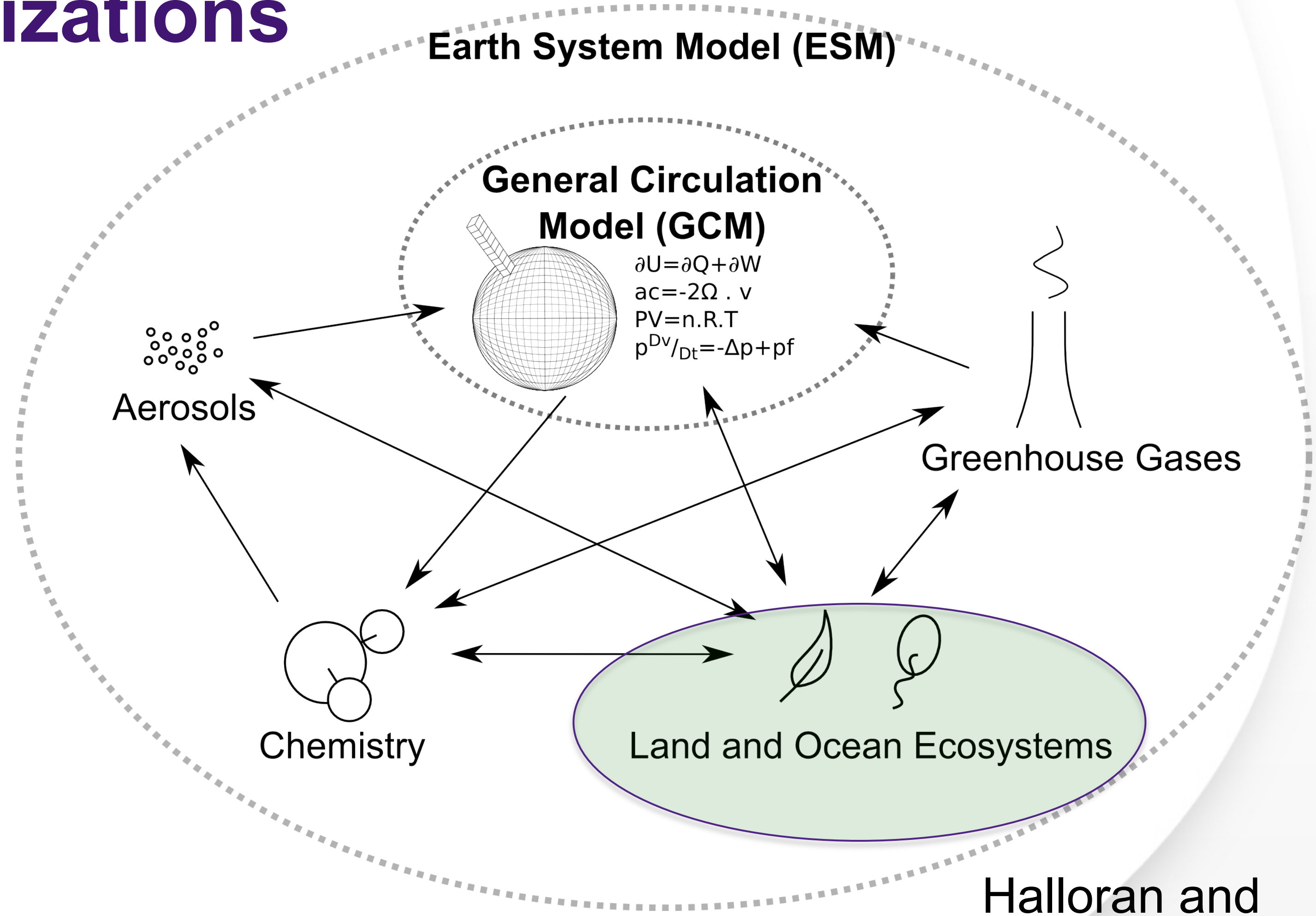
Parmeterizations

Biology can not be solved explicitly; based on empirical relationships



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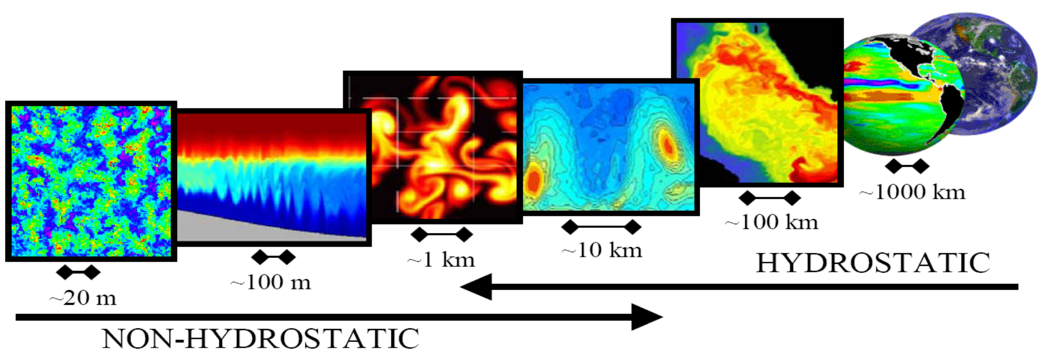

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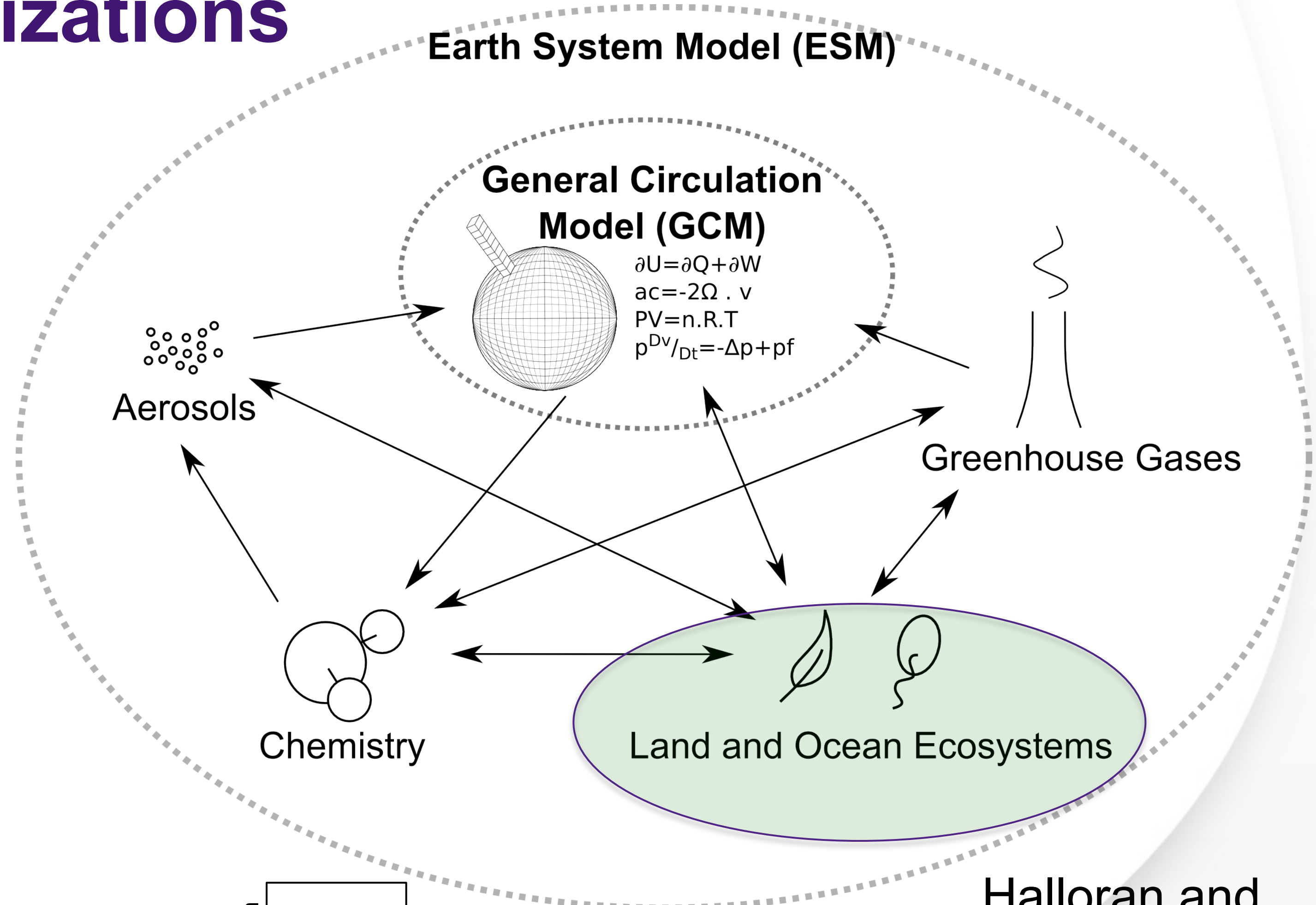

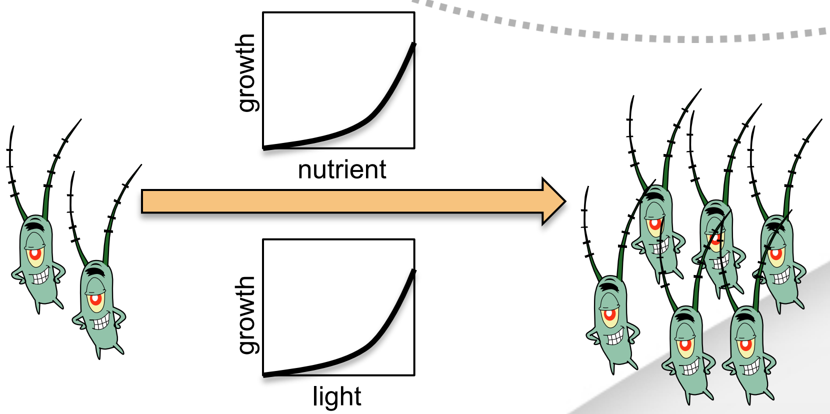

Halloran and Lowe, 2013

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Prediction vs projection

- A *prediction* involves starting from present-day conditions and simulating into the future (e.g. like weather forecast)
- A *projection* is typically a “what if” scenario; you want to know the system response to some **forcing** (e.g. anthropogenic)

Question: why is not necessarily a good idea to start from observations in a projection?

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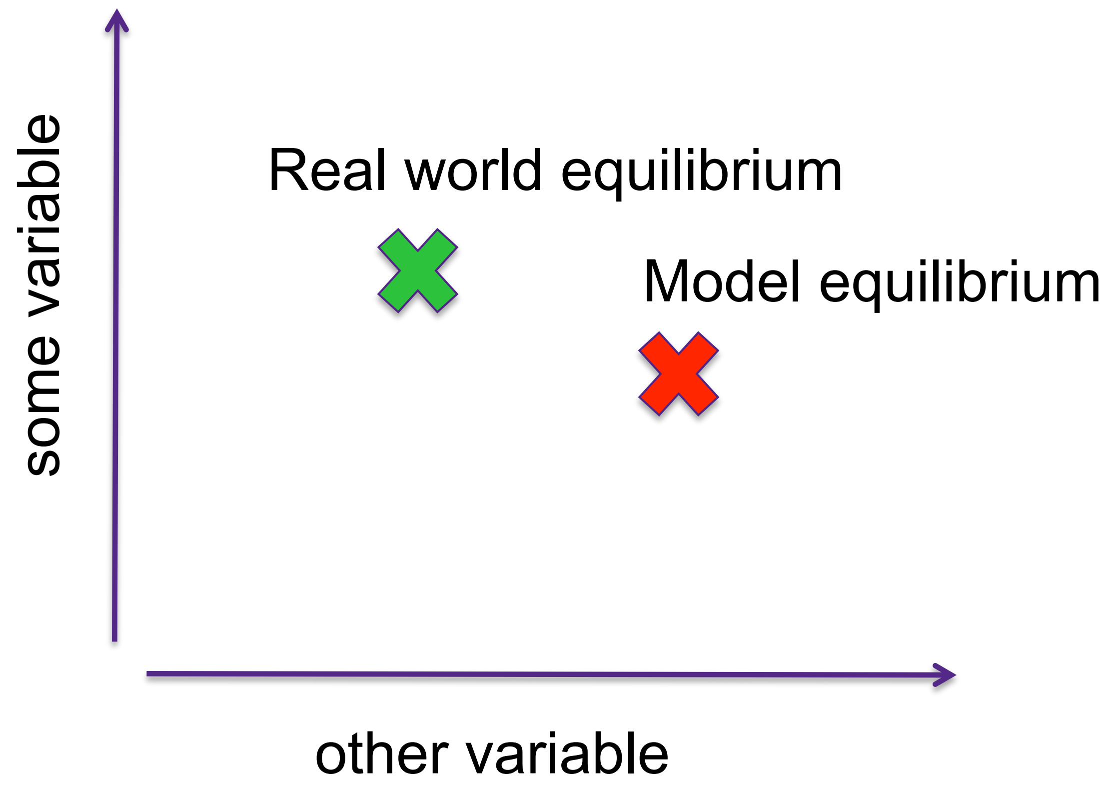
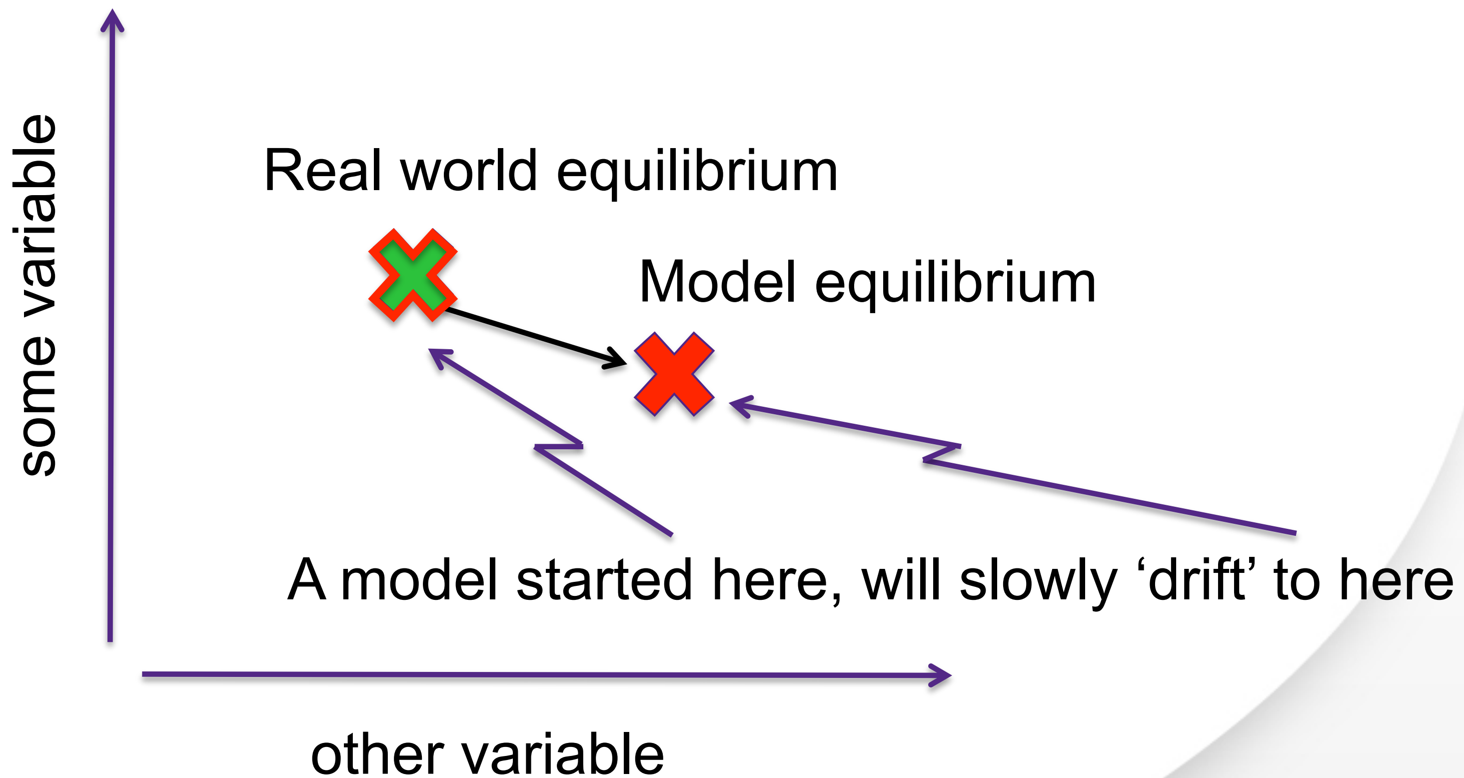
Prediction vs projection



Prediction vs projection



Solution: you need to “spin-up” your model, i.e. run it towards equilibrium

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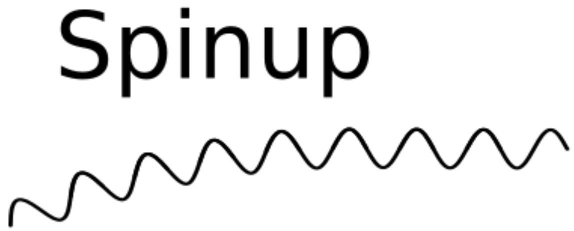
General set-up of model runs



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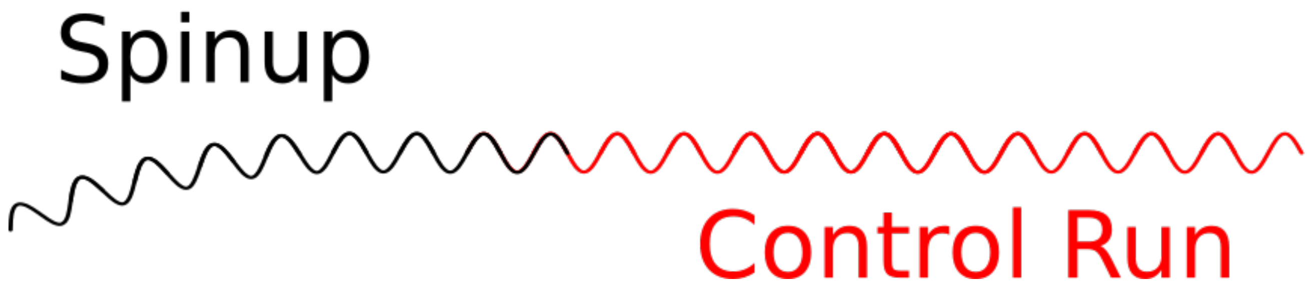

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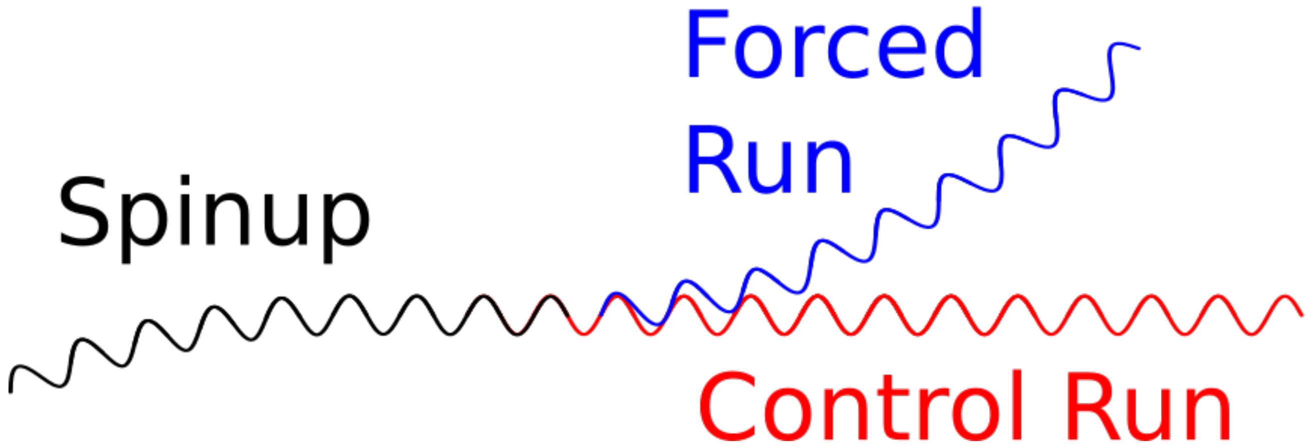

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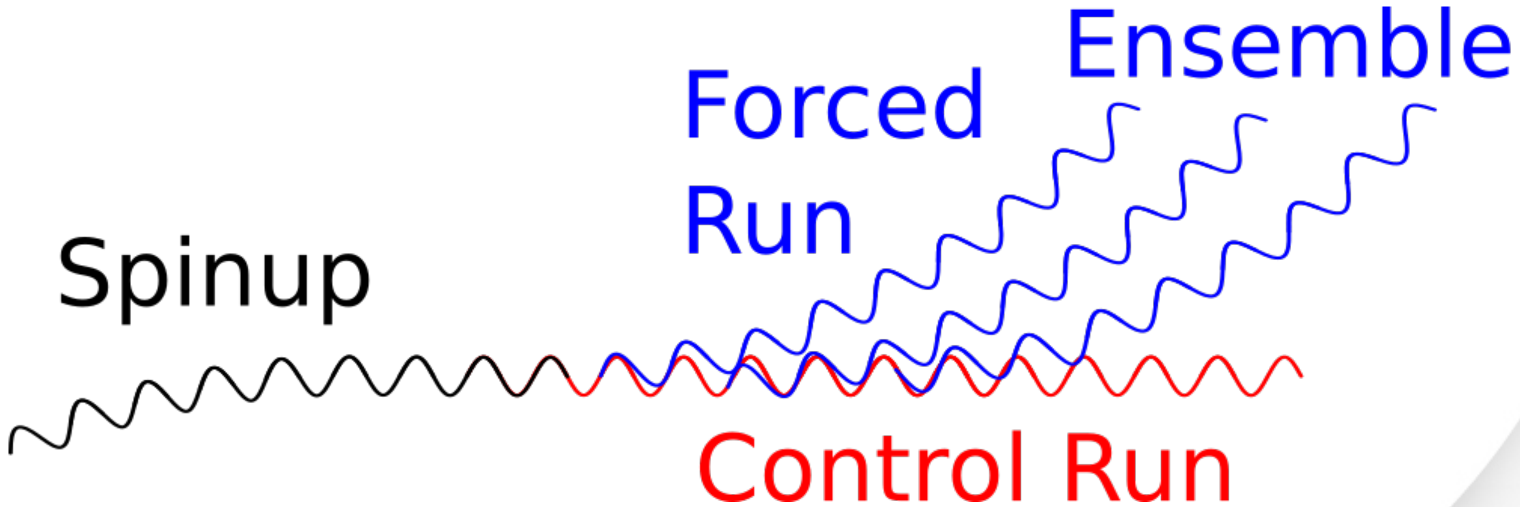
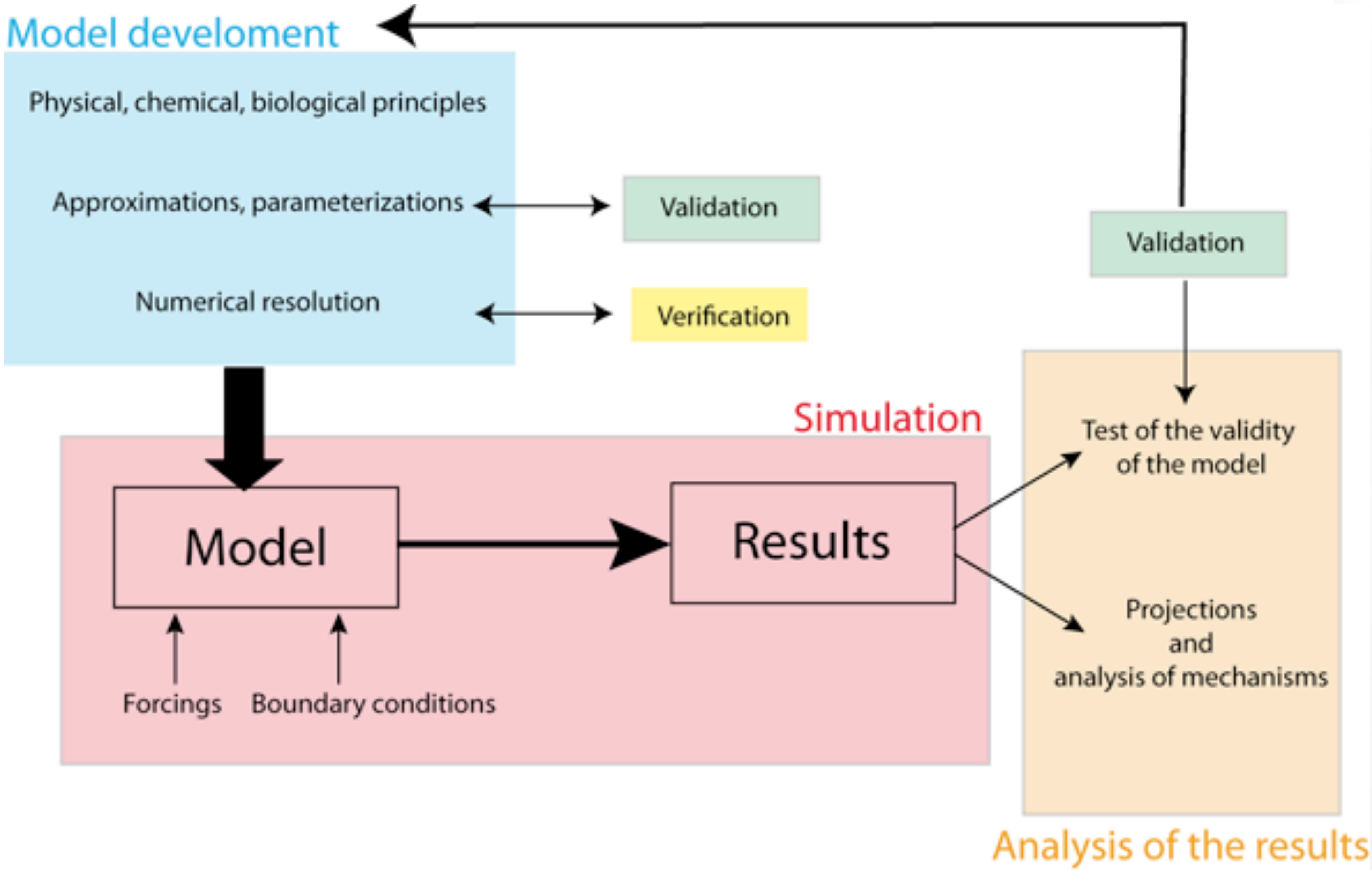
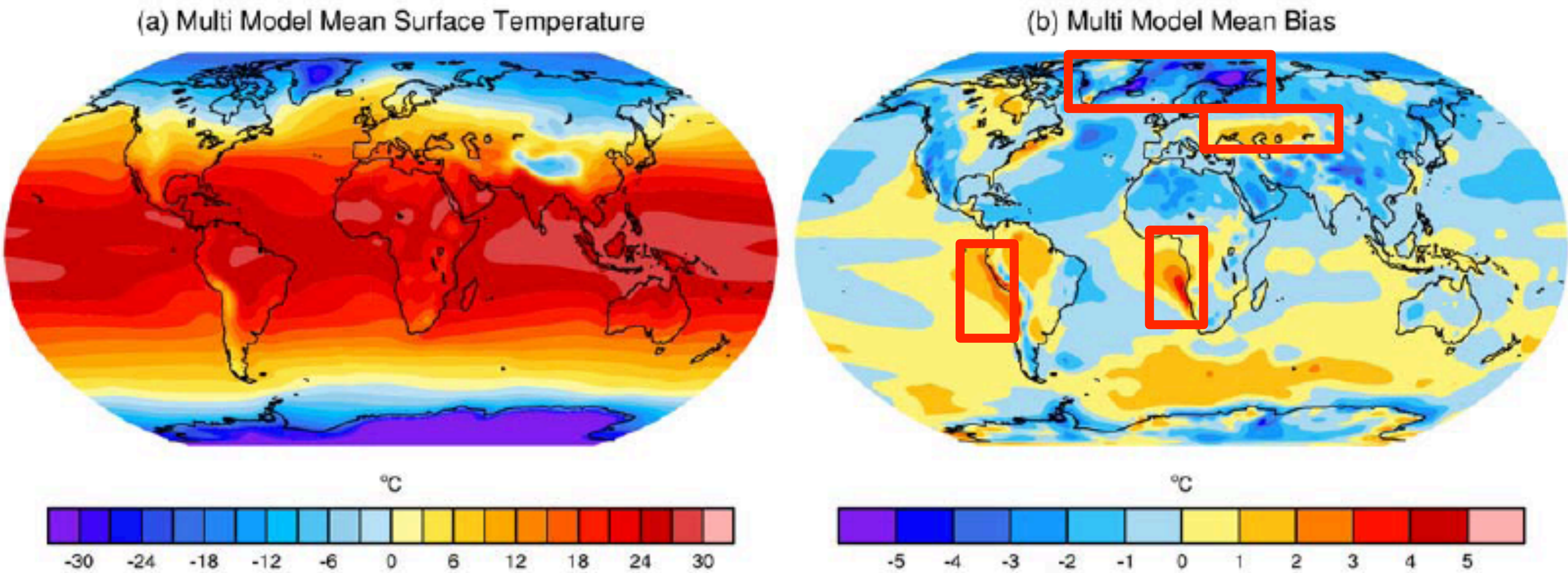


Model development



http://www.elic.ucl.ac.be/textbook/chapter3_node11.xml

Model validation



The ability of climate models to simulate surface temperature has improved in many, though not all, important aspects relative to the generation of models assessed in the AR4

IPCC AR5 (2013)

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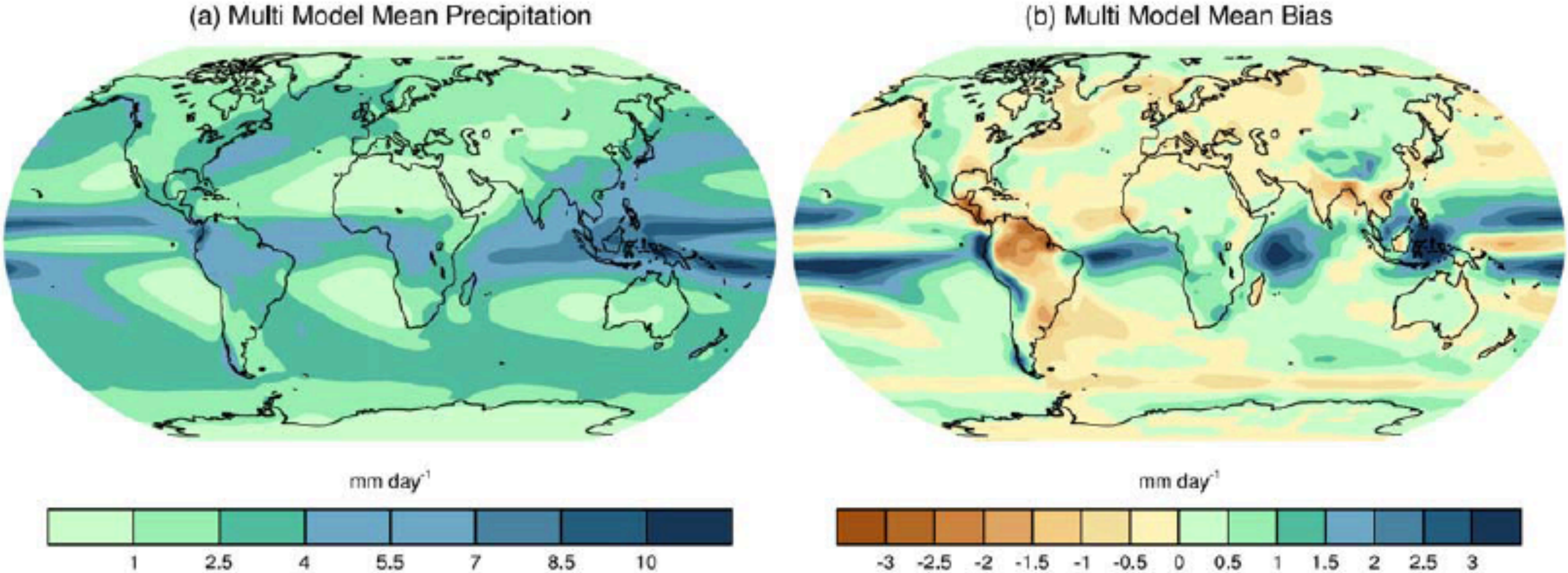
Model validation



The simulation of large-scale patterns of precipitation has improved somewhat since the AR4, although models continue to perform less well for precipitation than for surface temperature

IPCC AR5 (2013)

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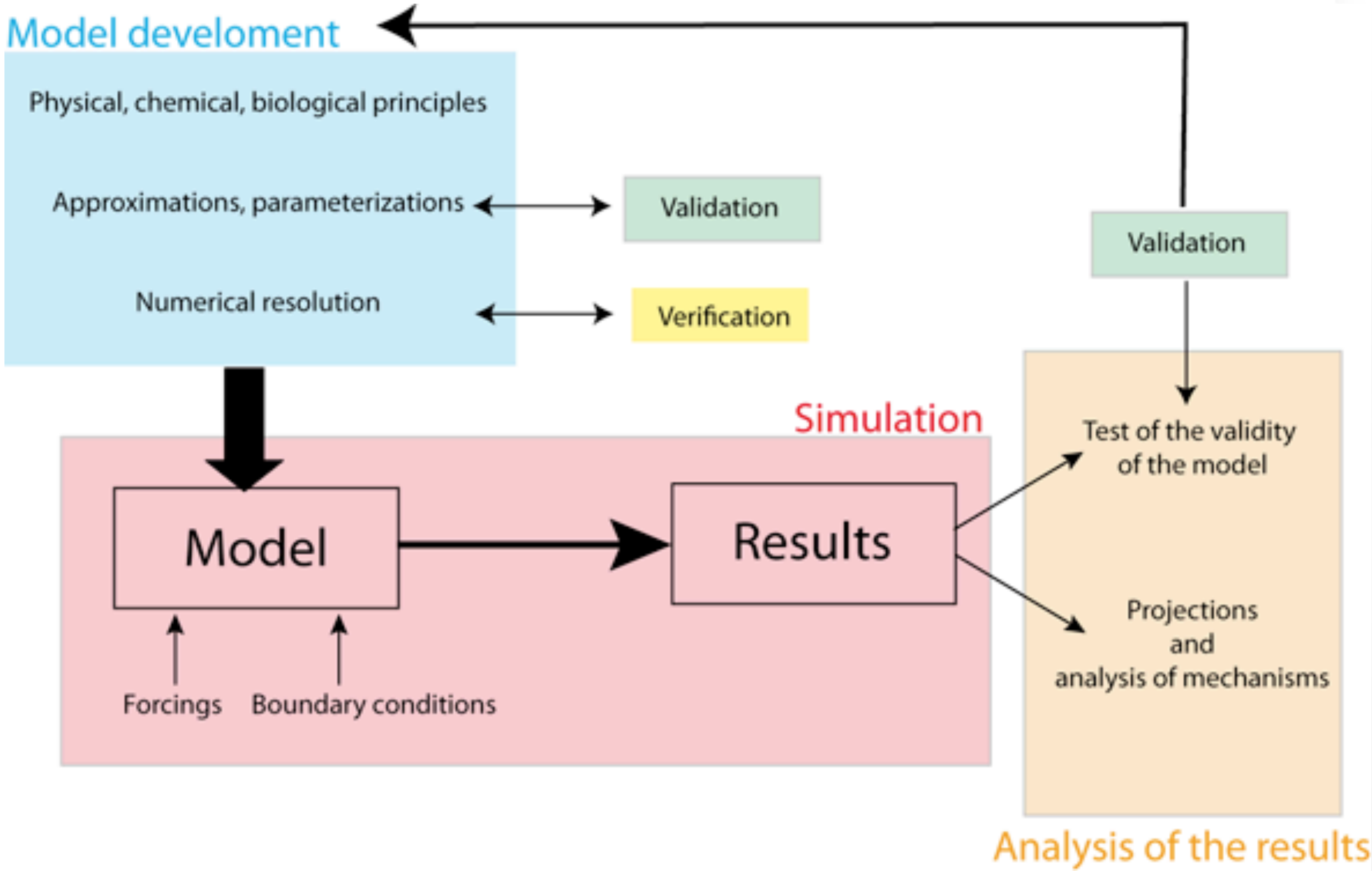
Model development



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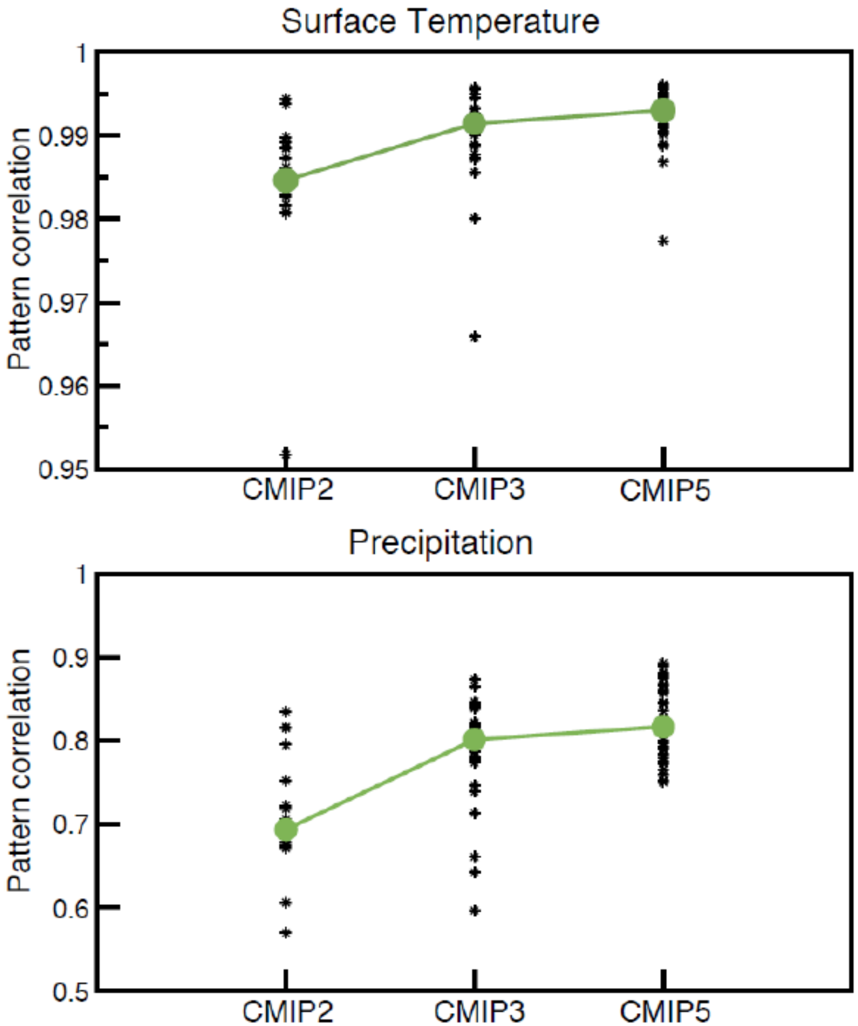
Model validation



Improvement in model performance is evident by the increase in correlation for successive model generations

Figure: The black symbols indicate correlation coefficient for individual models, and the large green symbols indicate the median value

IPCC AR5 (2013)

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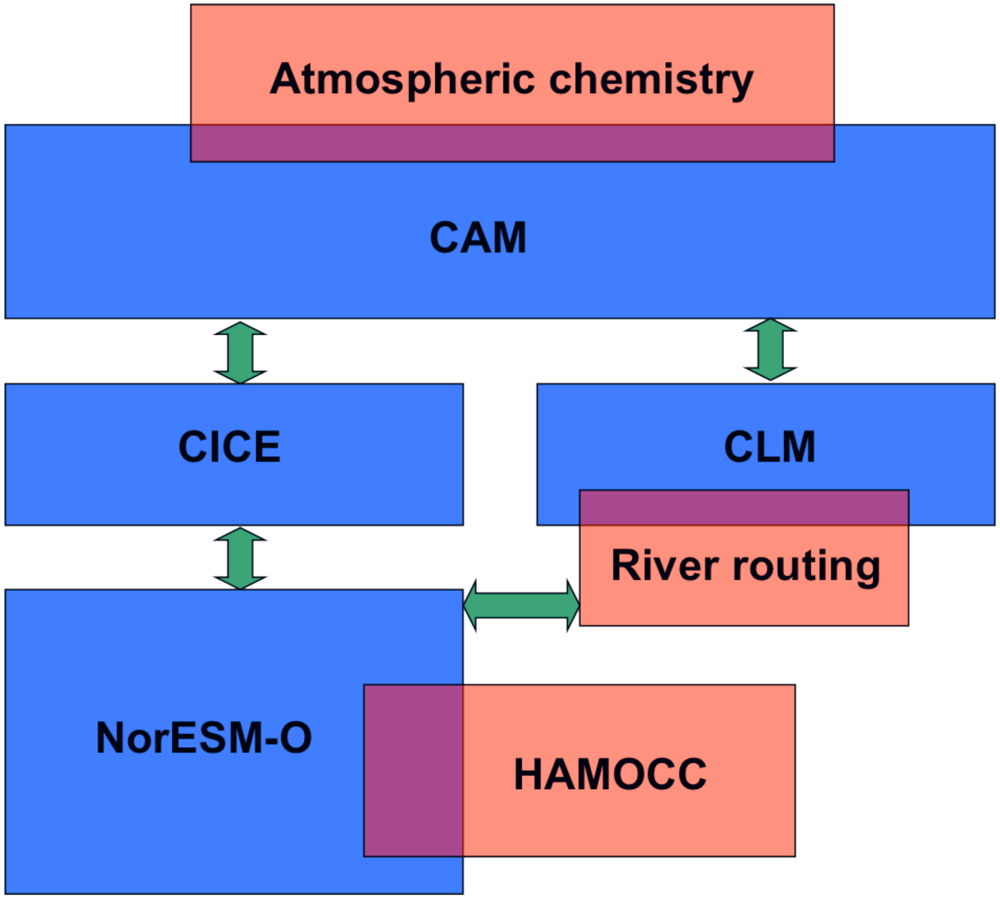
Some examples from NorESM

Norwegian Earth System Model (NorESM)



Courtesy: Mats Bentsen, Uni

Variant of CESM from NCAR with key modifications:

1. Aerosol life cycle and cloud interaction from Oslo (CAM-OSLO)
2. Isopycnic coordinate ocean model (NorESM-O) based on MICOM
3. Hamburg Ocean Carbon Cycle biogeochemistry model (HAMOCC) adapted to isopycnic coordinates
4. Ensemble Kalman-filter assimilation adapted to isopycnic coordinates

Components in blue communicate through a coupling component.

Components in red are subroutines of blue components.

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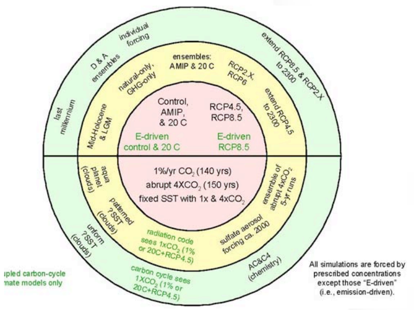
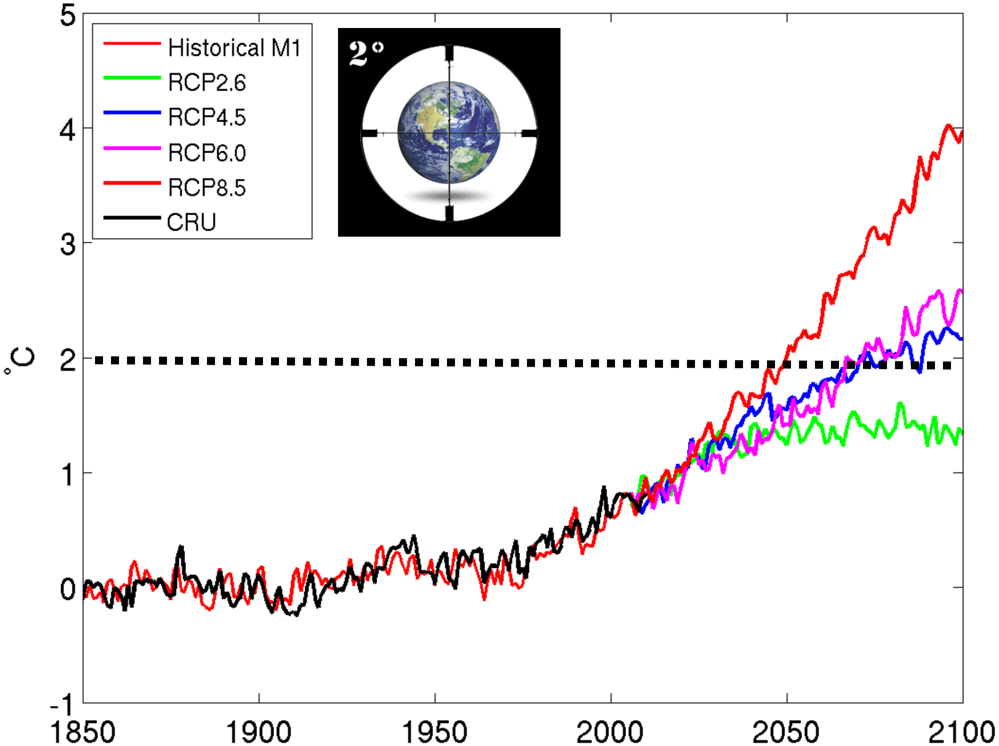
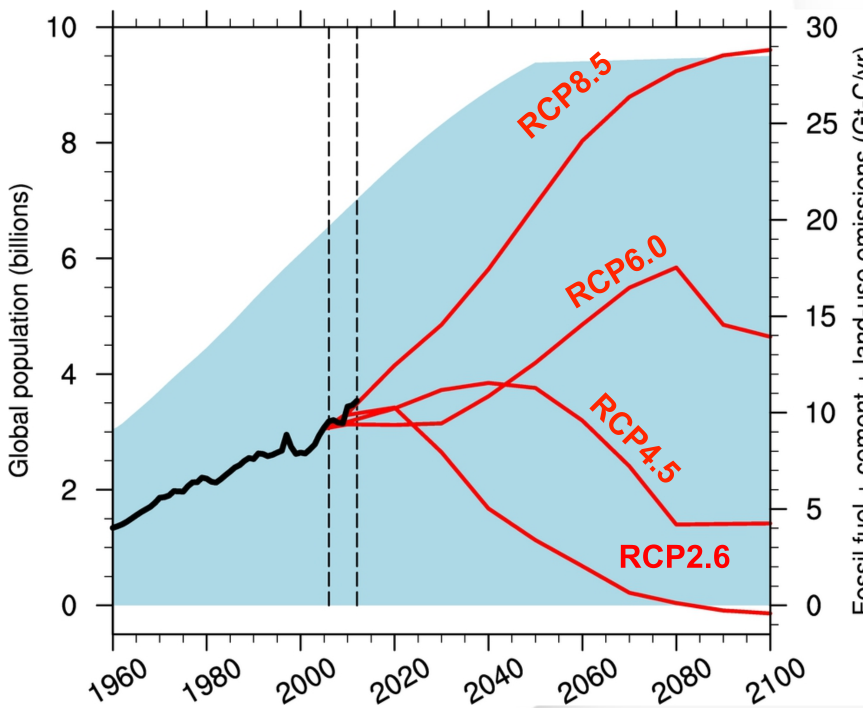
Climate projections



Simulated global temperature





Future climate simulated by NorESM for 4 different scenarios

Contributing to CMIP

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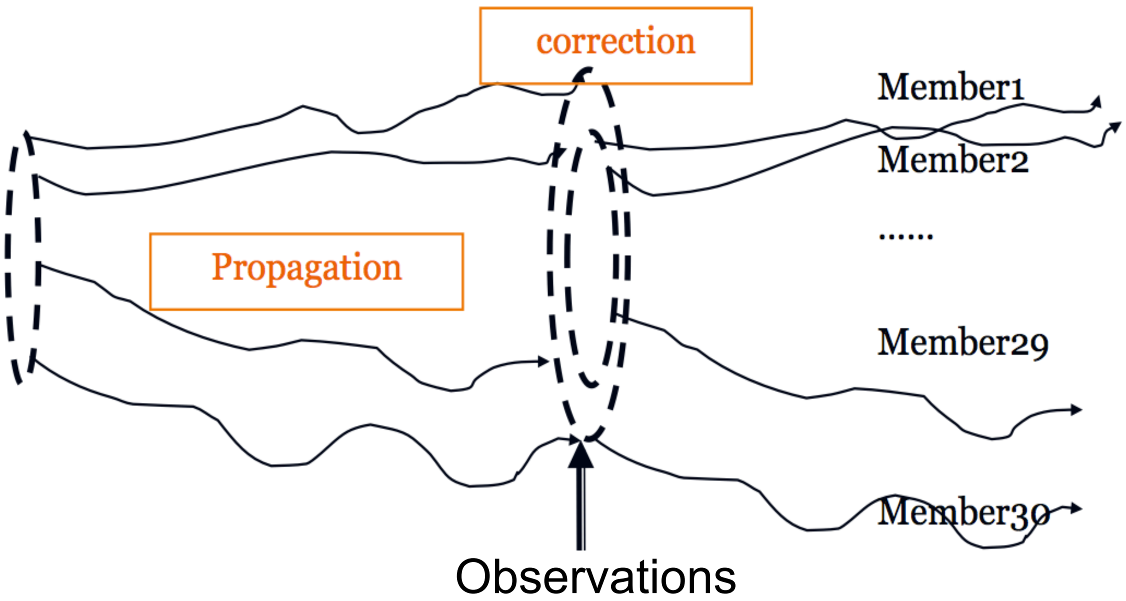
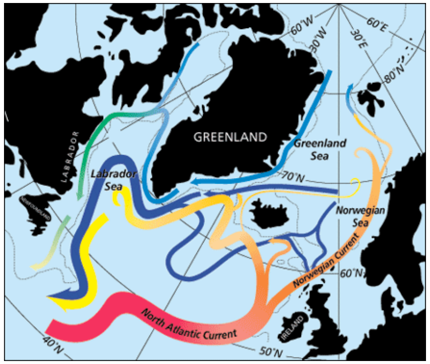
Climate prediction

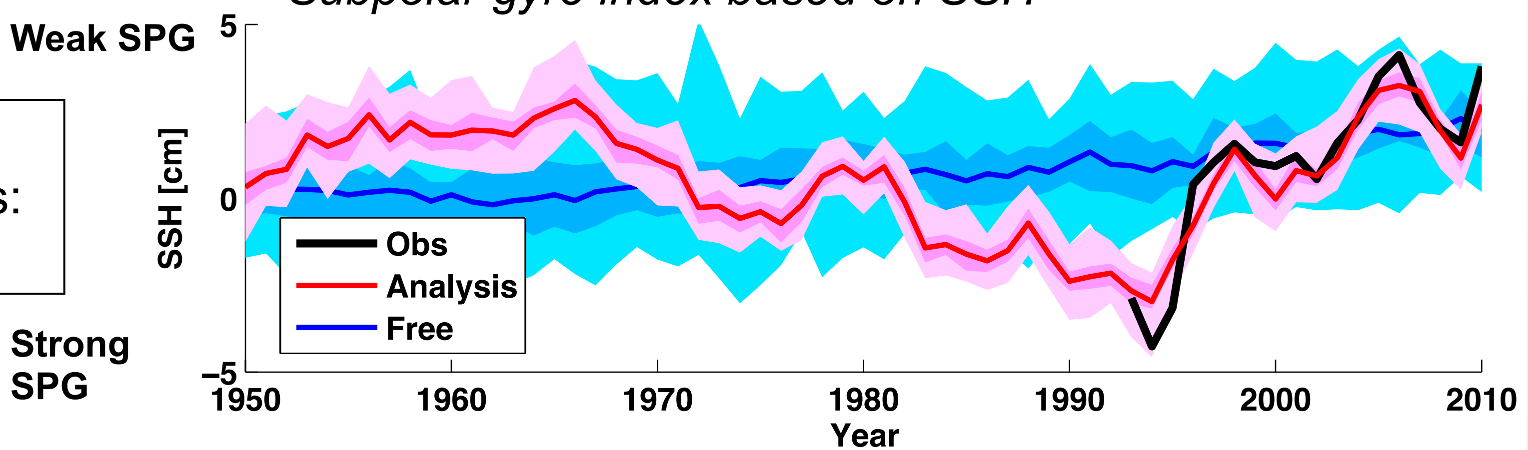


- Norwegian Climate Prediction Model (NorCPM)
- Bjerknes Centre collaboration
- Using Ensemble Kalman filter assimilation methods developed at NERSC



Subpolar gyre index based on SSH

Assimilated observations:
SST only



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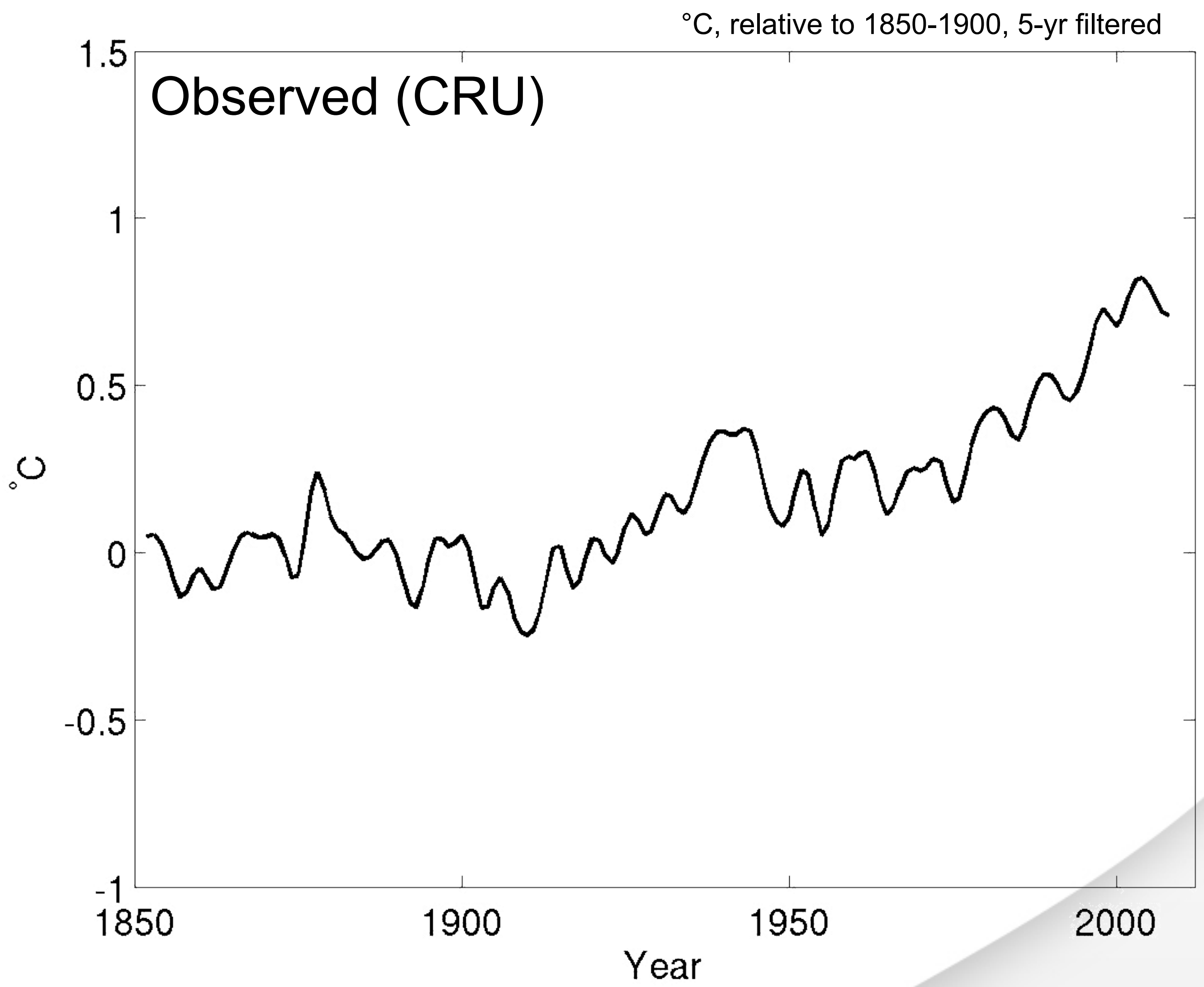
Courtesy: F. Counillon, NERSC

Simulated vs observed global temperature



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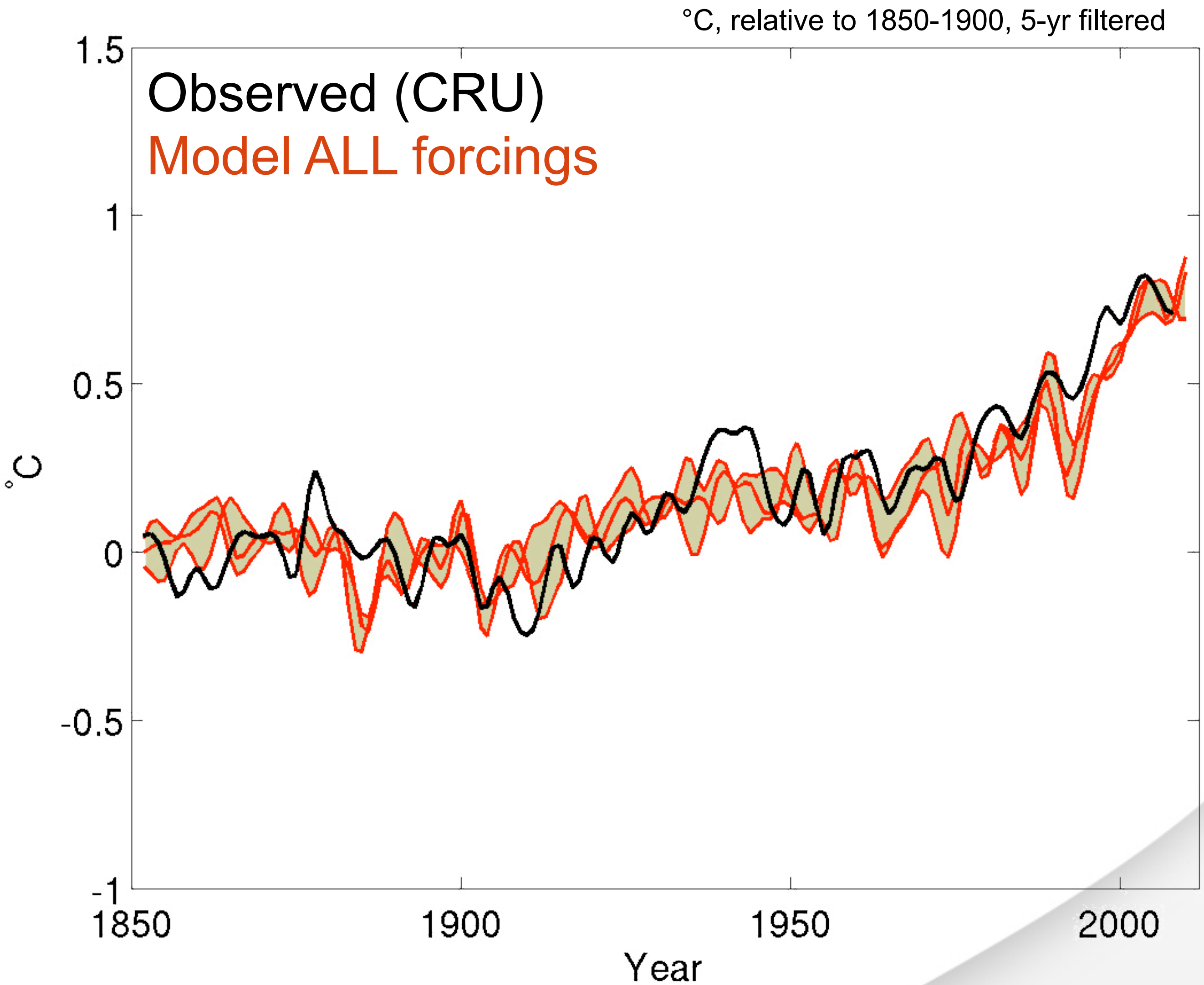

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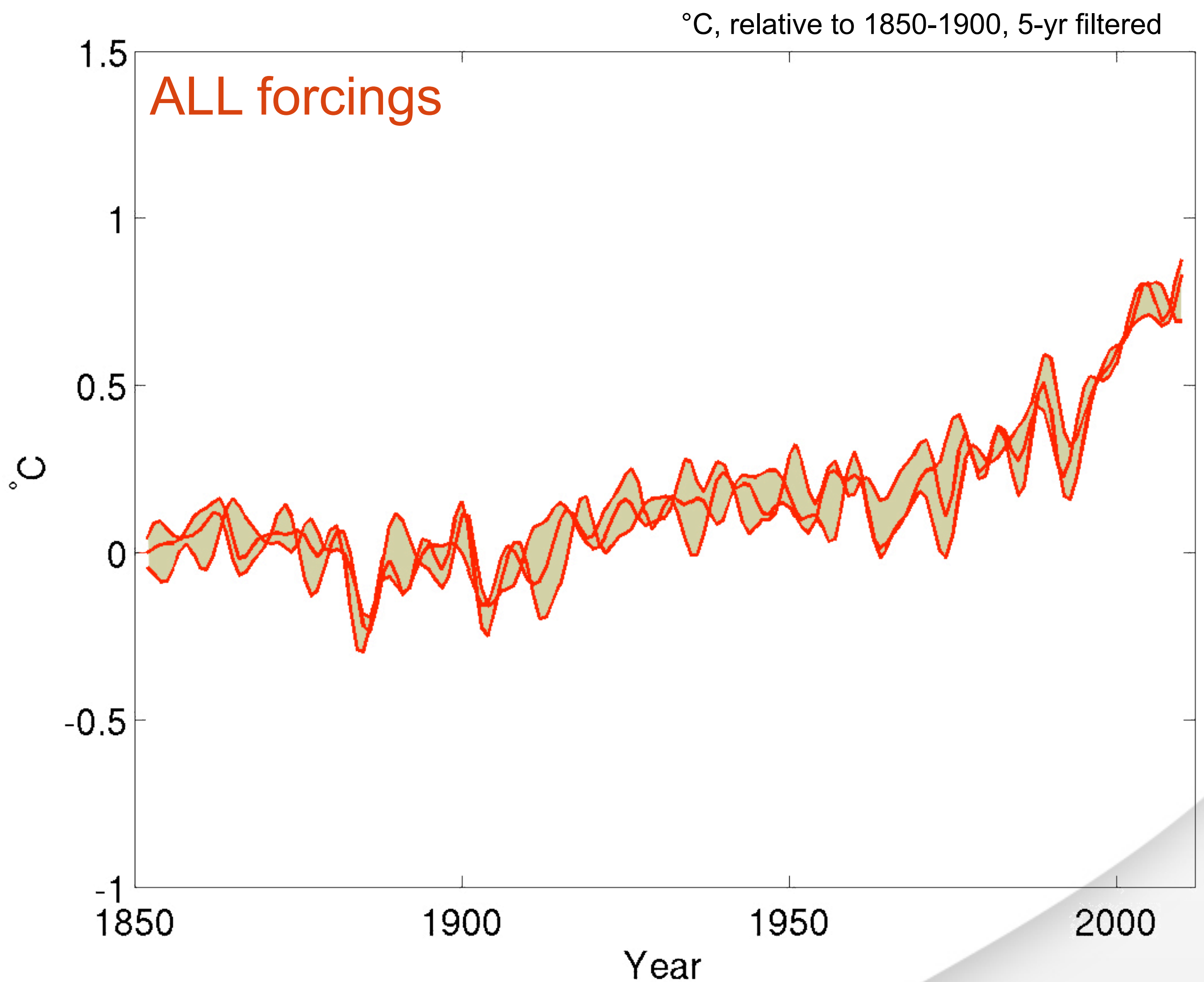
Natural vs human-induced forcings



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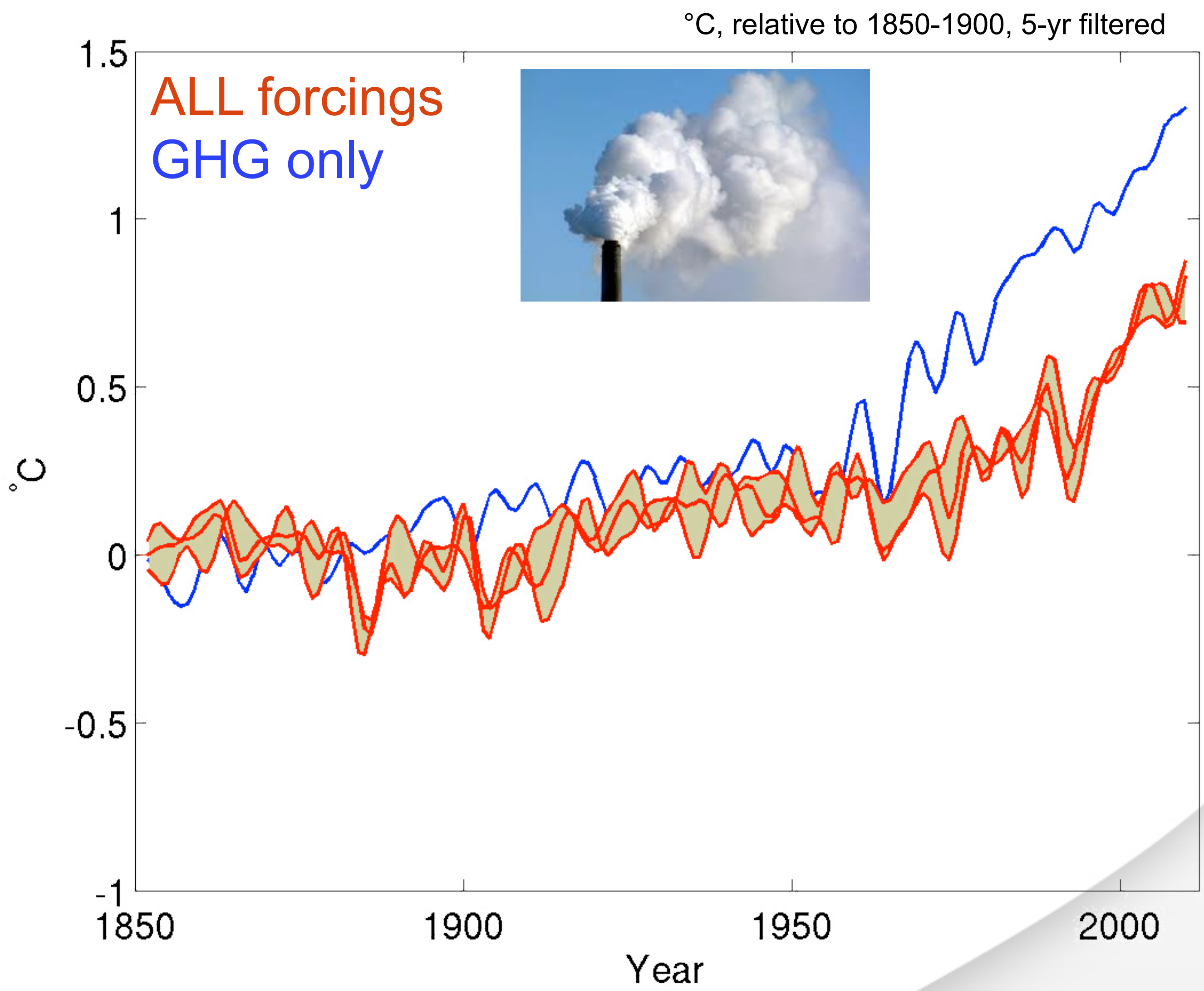

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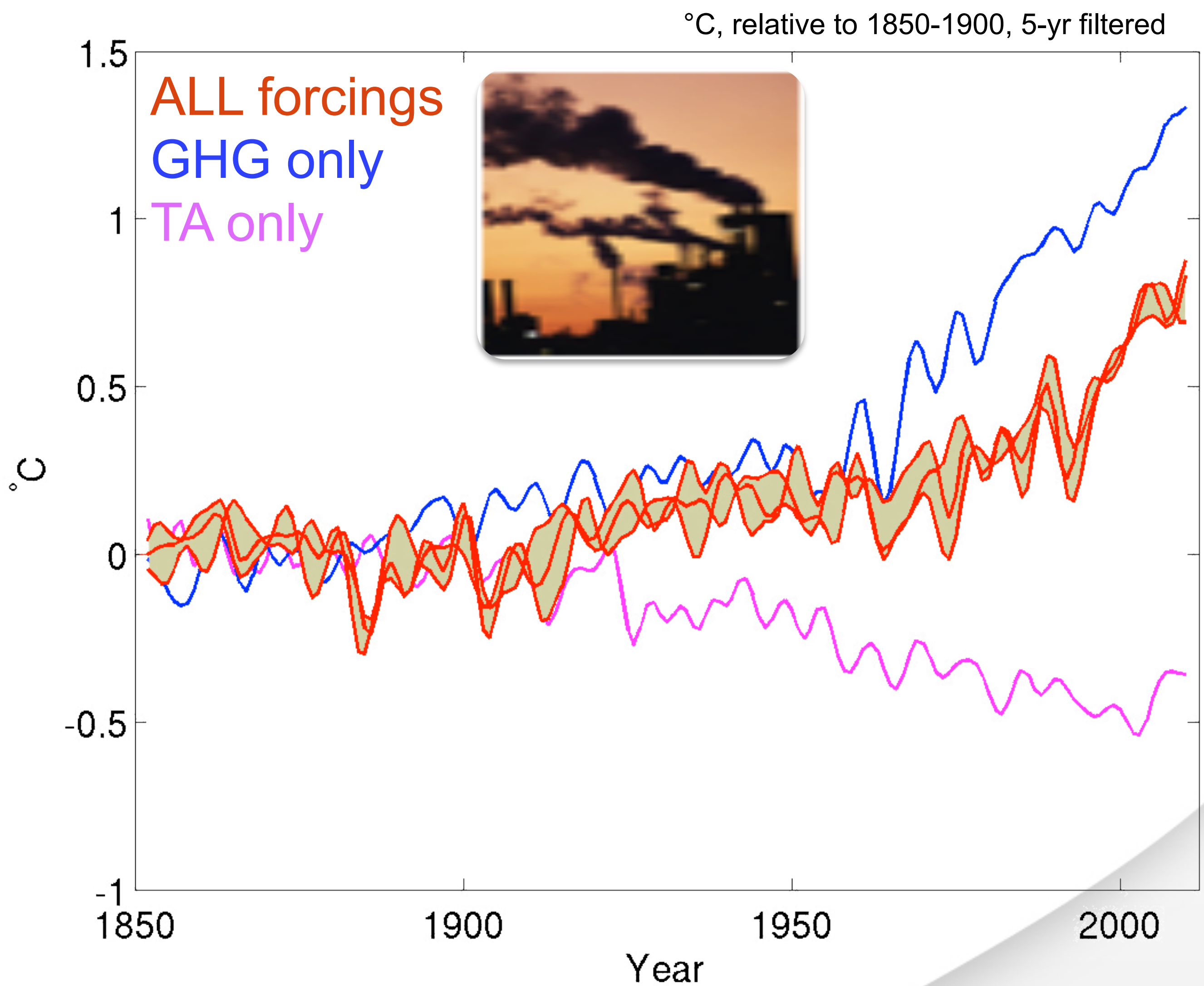

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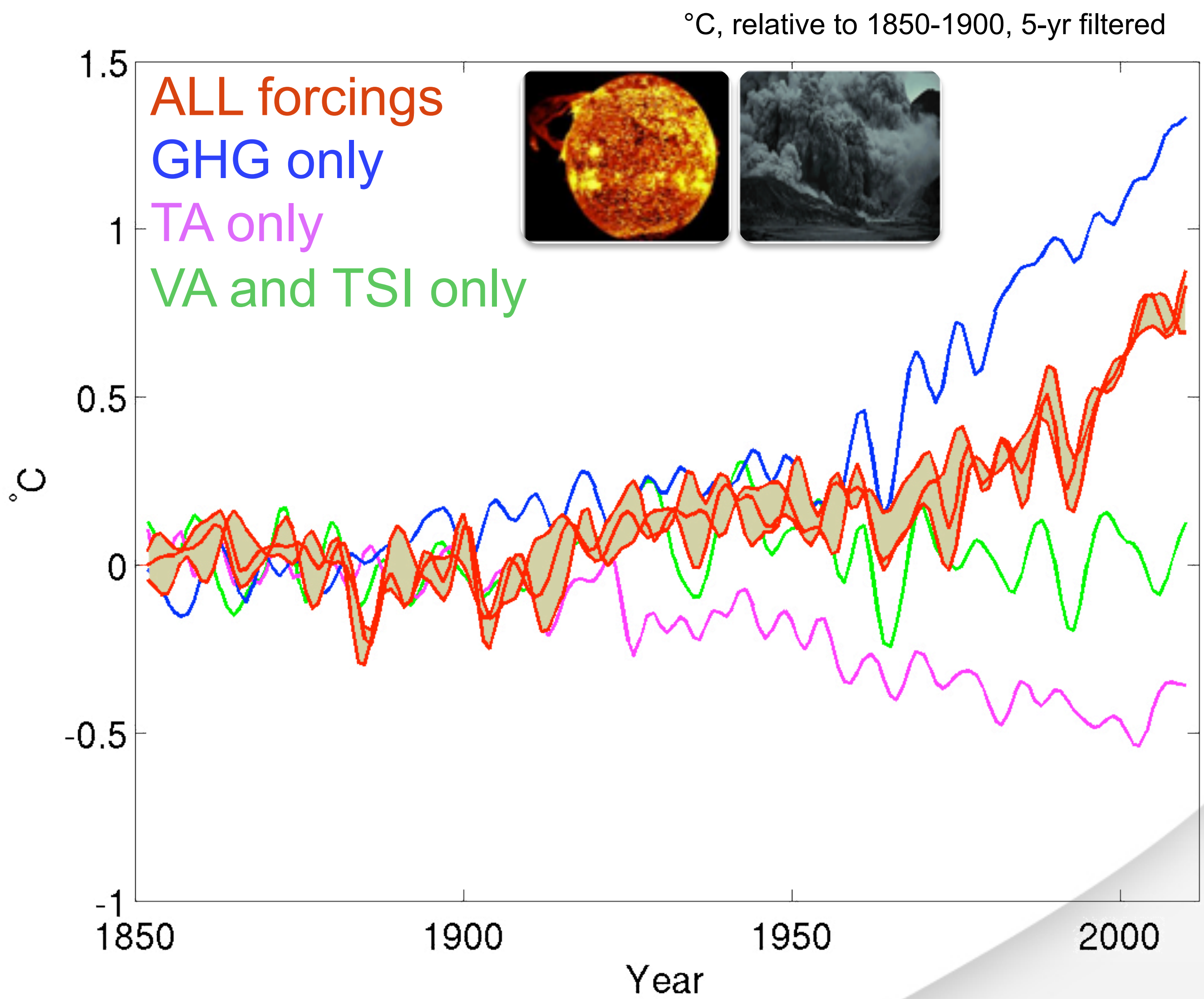

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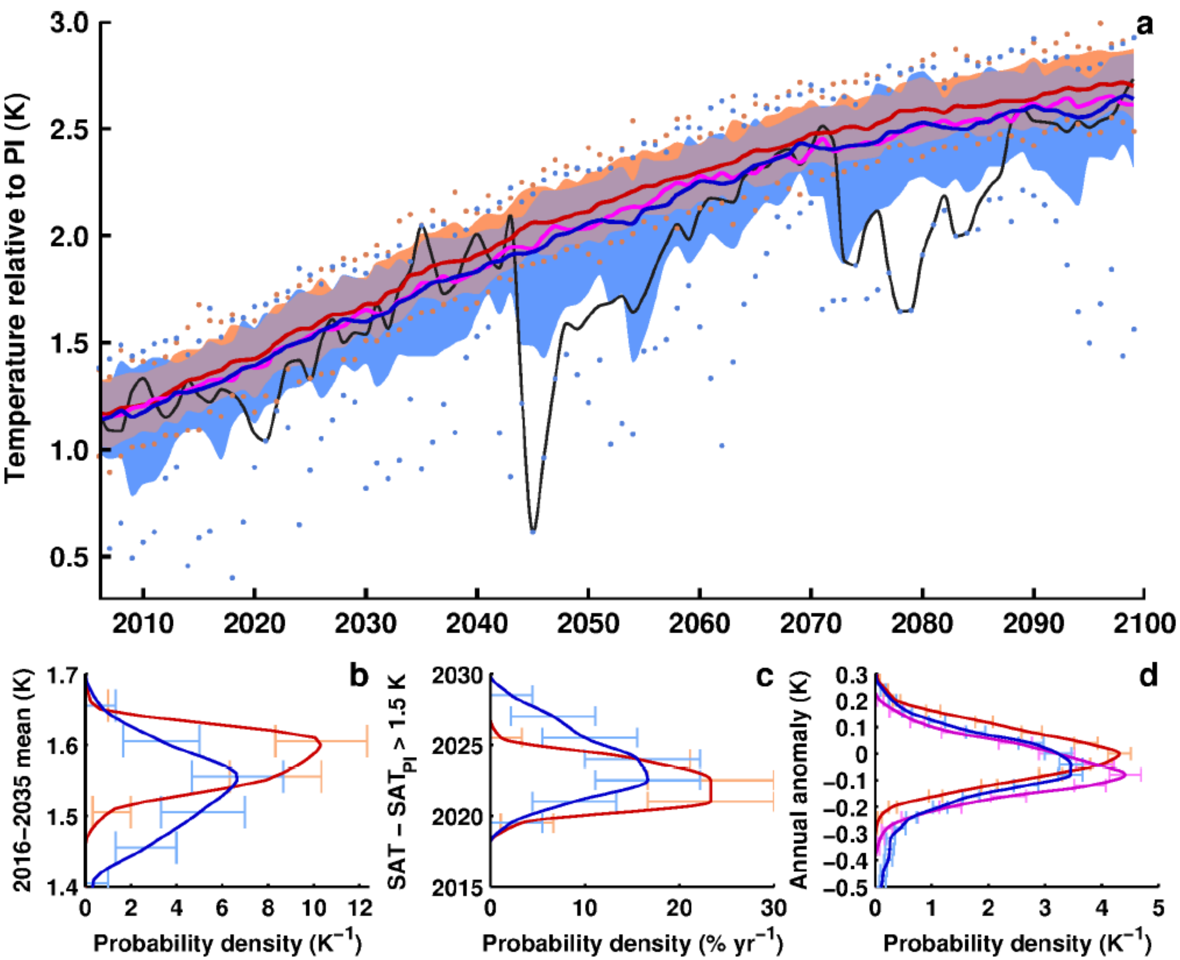
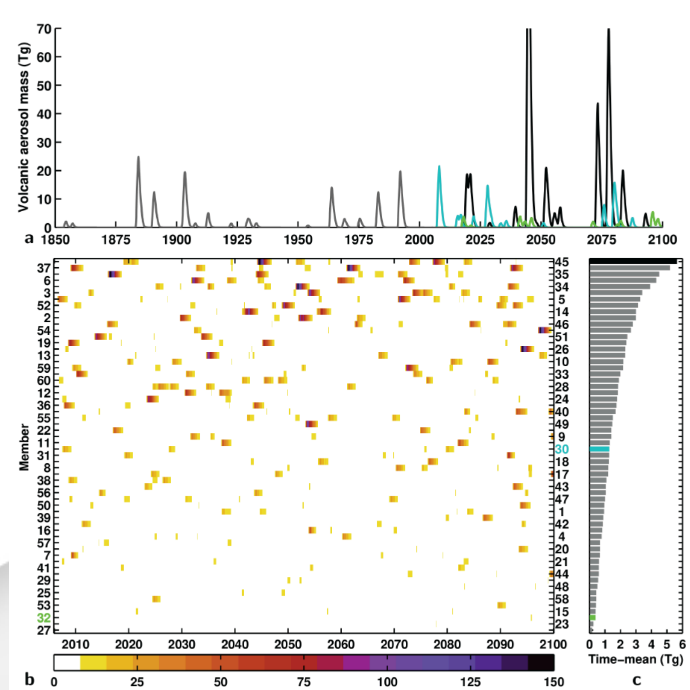
Volcanic eruptions as a wildcard for future climate



A future with higher volcanic activity than in the recent past would lead to a more variable climate, with potentially more extremes



Bethke et al. 2017, *Nature Clim. Change*

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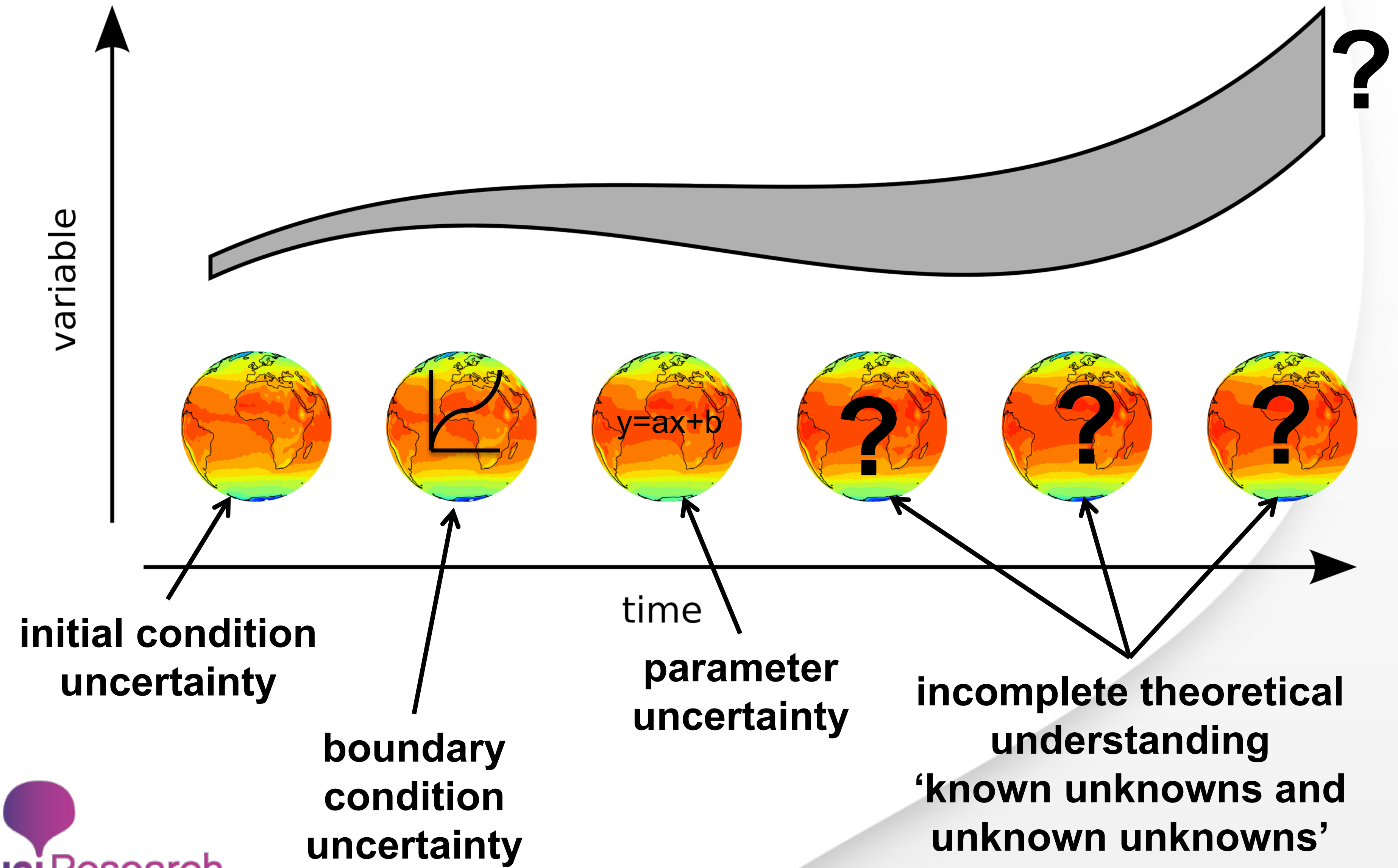
Uncertainty in climate models



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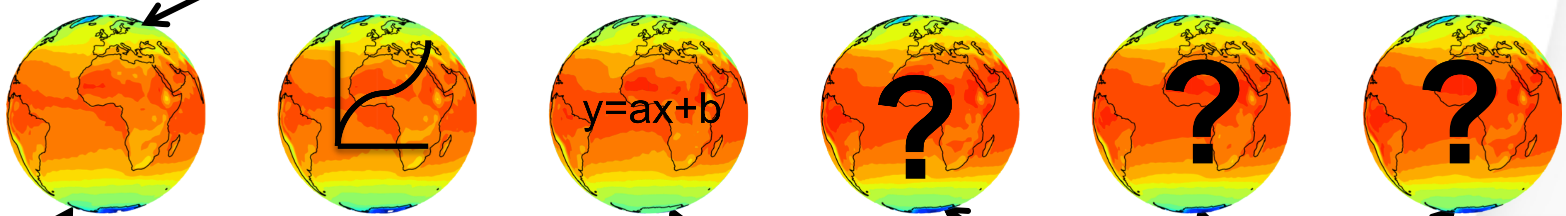
Uncertainty in climate models

Solved by starting simulations from range of conditions generated my model's internal variability – ensemble approach



initial condition uncertainty

boundary condition uncertainty

parameter uncertainty

incomplete theoretical understanding
'known unknowns and unknown unknowns'

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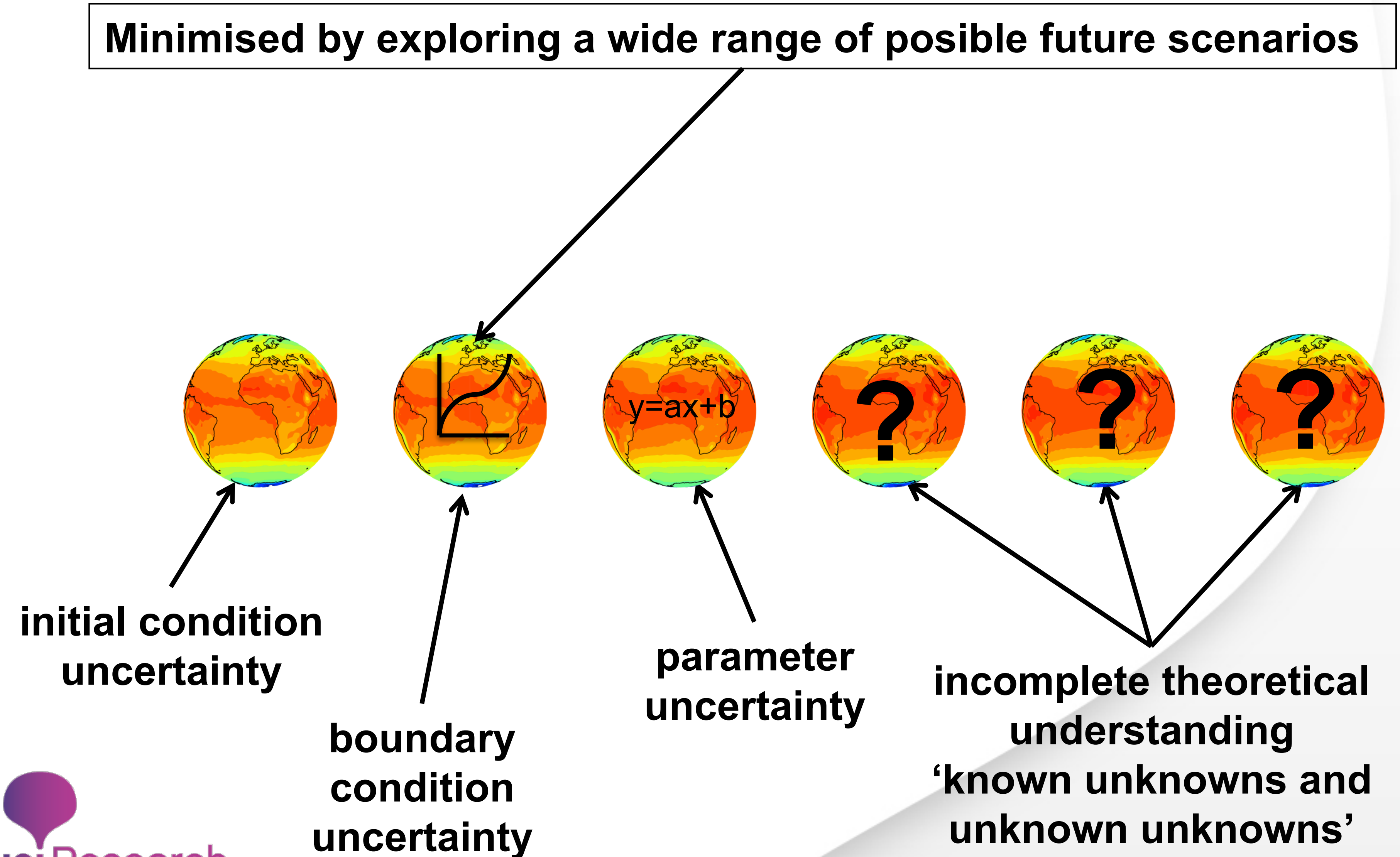
Uncertainty in climate models



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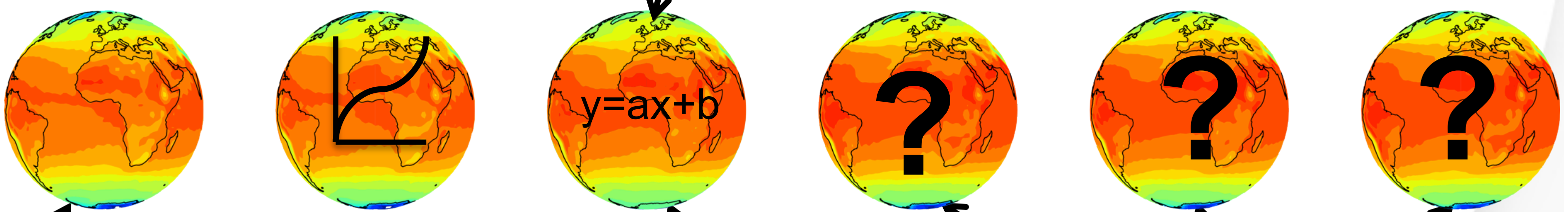
Uncertainty in climate models

Minimised by using sets of models 'ensembles' which each use different parameters (either by chance of selected systematically) – or by moving to higher resolution (bigger computers), one can reduce the number of parameterisations



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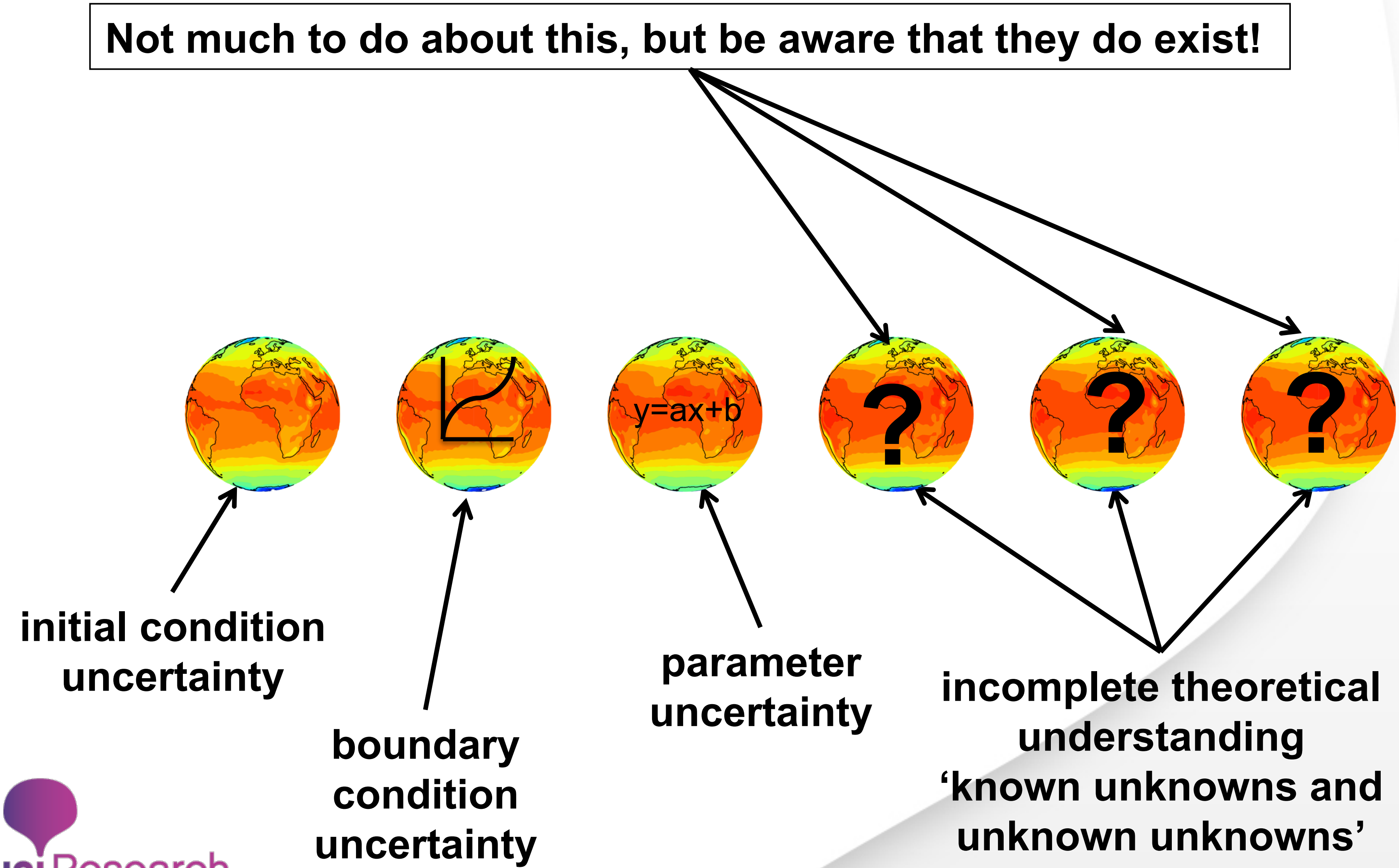
Uncertainty in climate models



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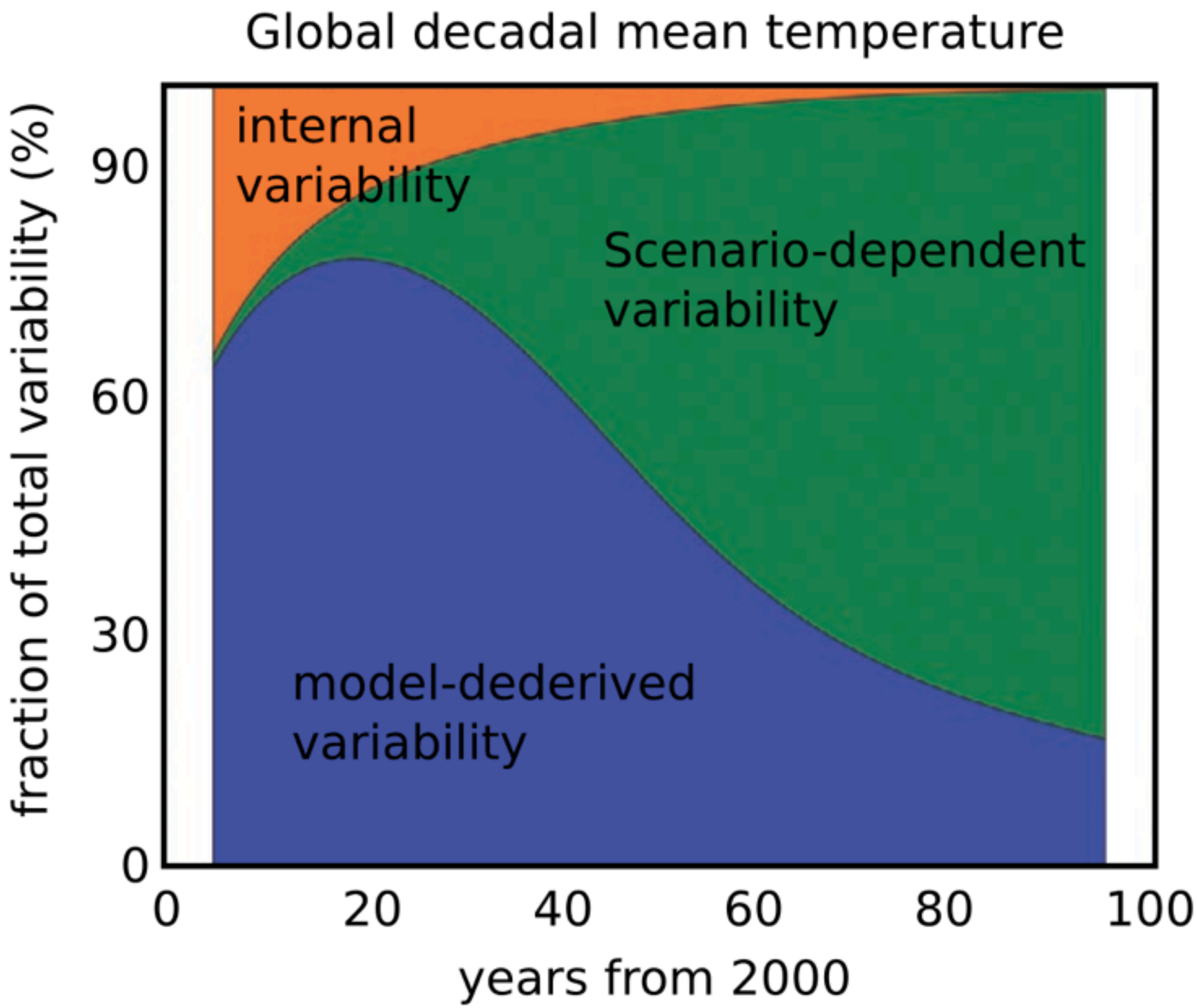
Uncertainty in climate models



Modified from Hawkins and Sutton, 2009

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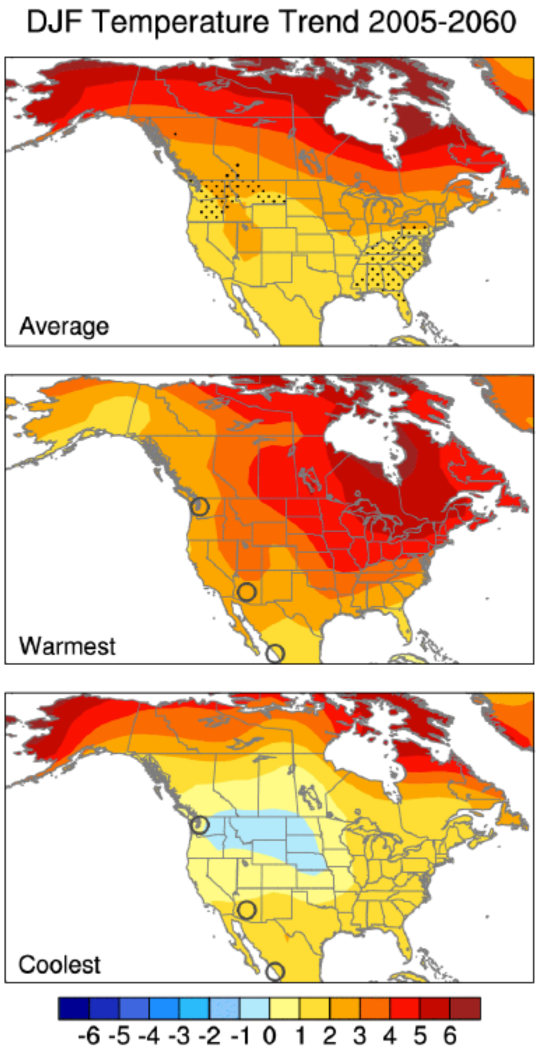
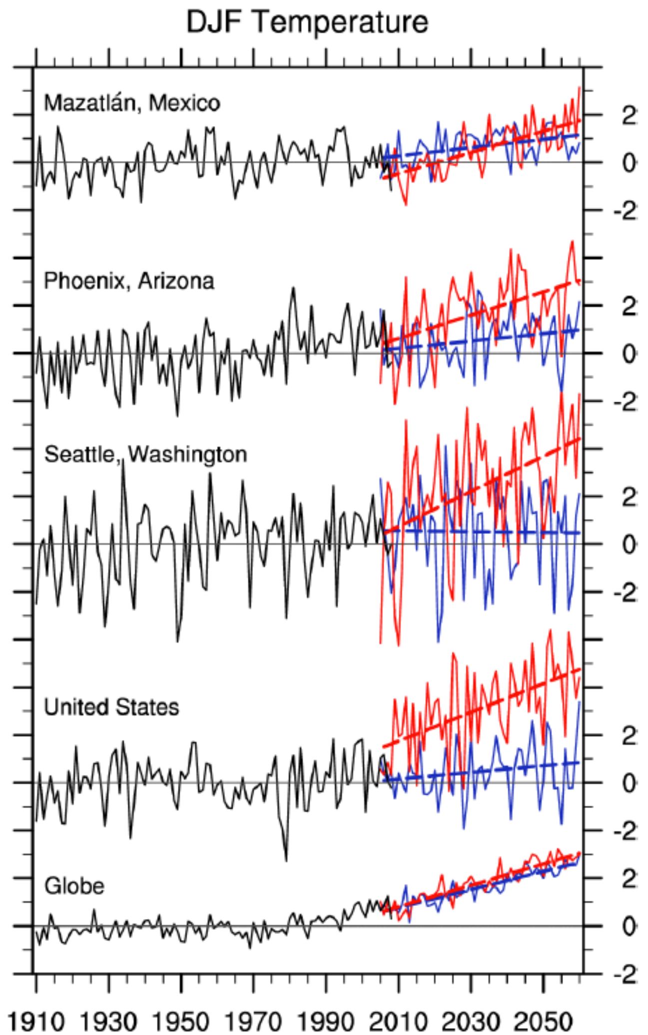
Natural variability and uncertainty

Temperature

“Uncertainty in the Backyard: Communicating the Role of Natural Variability in Future North American Climate”

Deser et al. 2012, *Nature Climate Change*





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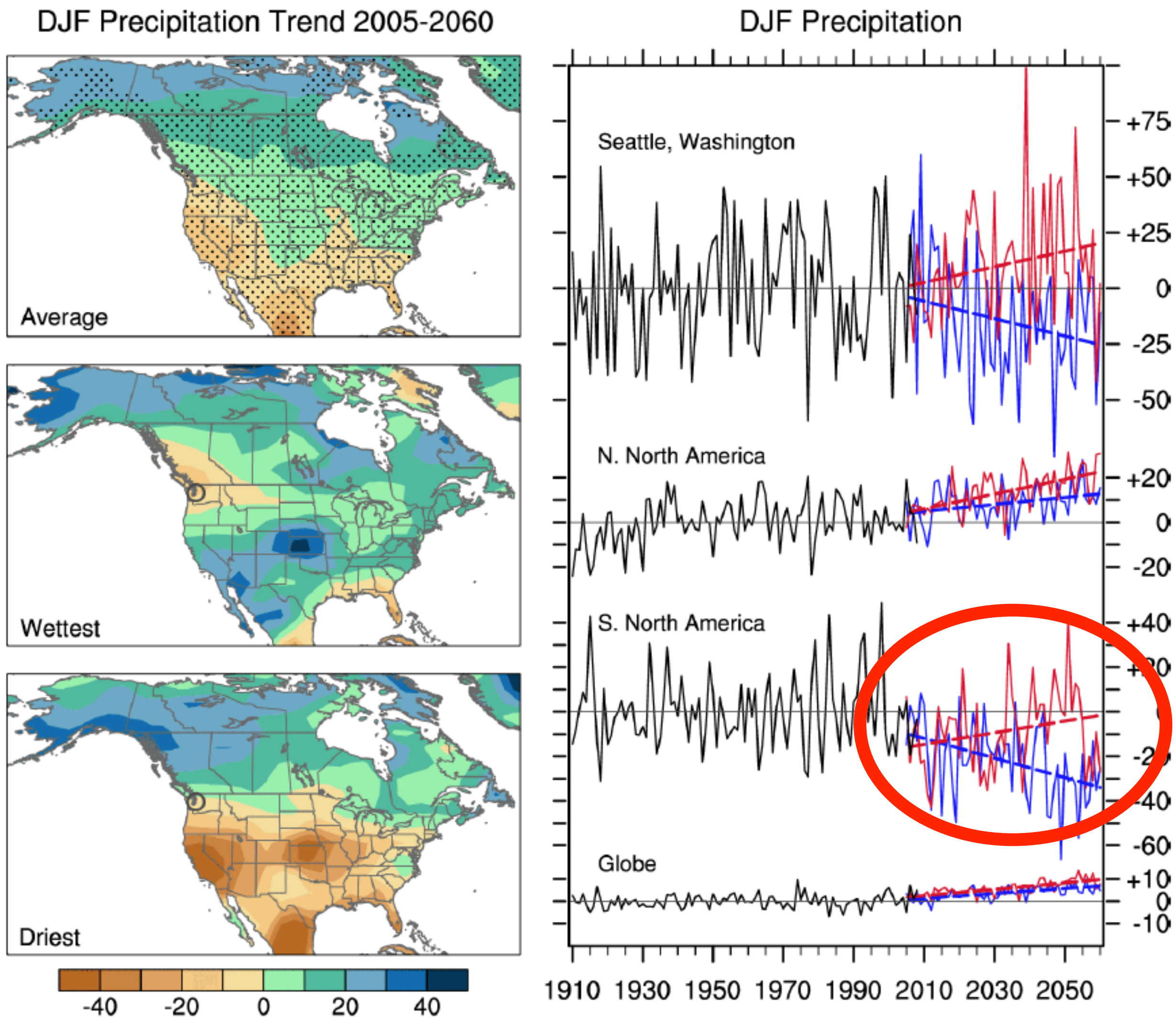
Natural variability and uncertainty

Precipitation

"Uncertainty in the Backyard: Communicating the Role of Natural Variability in Future North American Climate"

Deser et al. 2012, *Nature Climate Change*



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Summary

- Models are simplified representations of more complex systems
- Climate models are a mixture of theoretical models (laws of physics) and empirical models (parameterizations)
- Many sources of uncertainty:
  - Initial condition, boundary conditions, model deficiencies + +
- All models are wrong, but some are useful

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