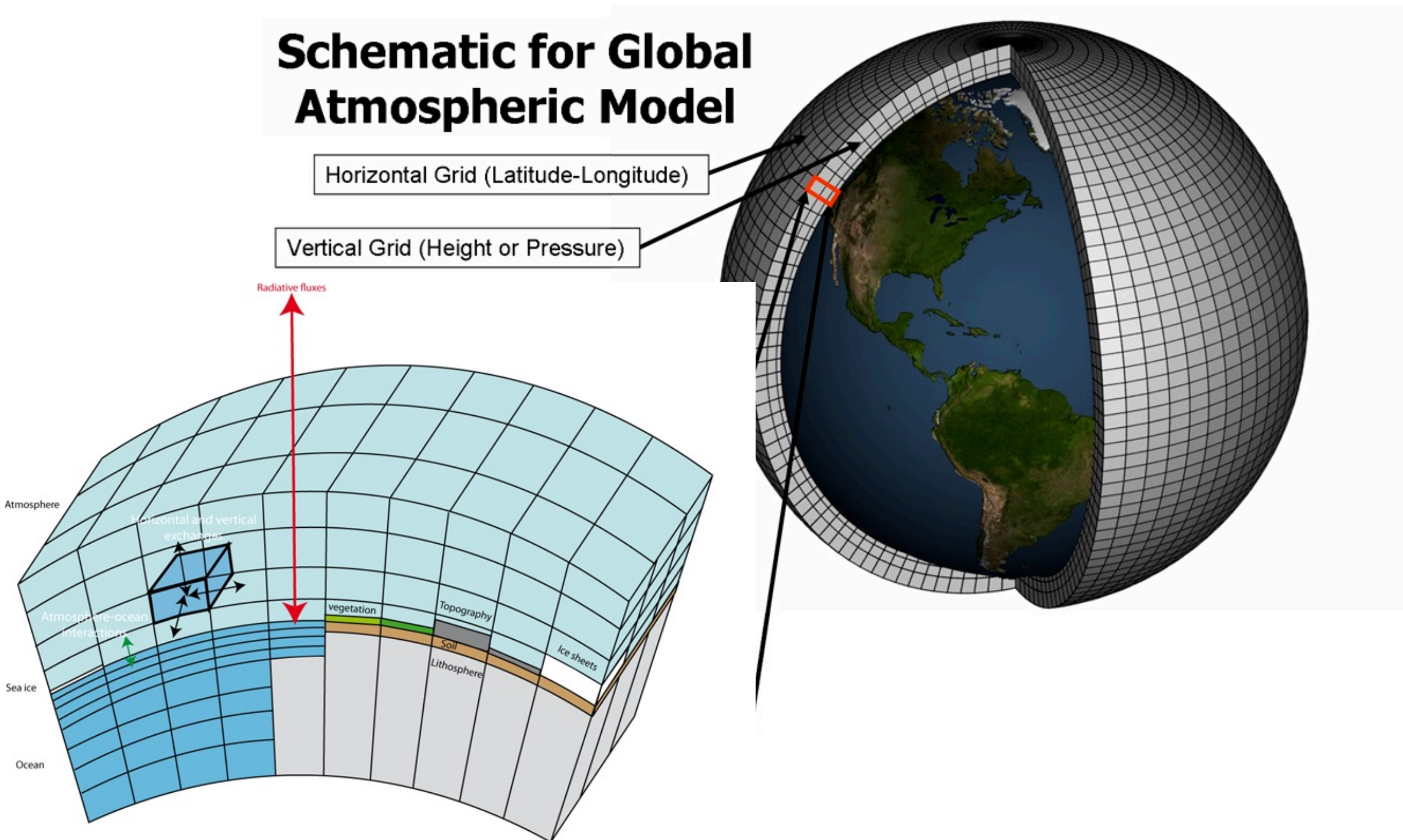
Climate models – what are they?

And different grids for different parts of the model
atmosphere, ocean, land, ice,…



A bit of review:

What do we need to make a model?

(Any model, not necessarily a climate one)

What does a model need?
A very simple analytical example

$$\frac{dC}{dt} = \lambda$$

Requires equations
(hypotheses about underlying physics)

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What are they for climate?

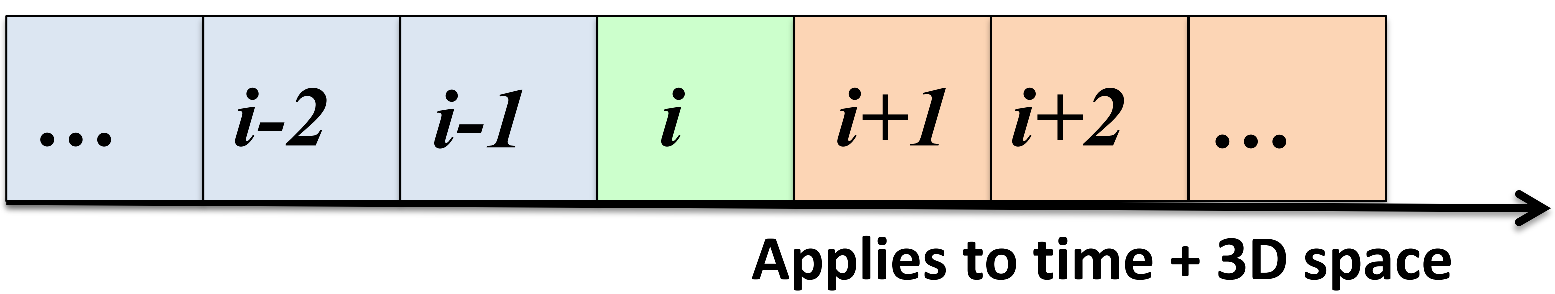
$$\int_{Co}^{Cf} dC = \int_{to}^{tf} \lambda \, dt$$

Requires initial & boundary conditions

$$Cf = \lambda\left(tf - to\right) - Co$$

What does a model need?
A very simple analytical example

Many equations cannot be solved analytically…
What do we have to do to solve them numerically?



Discretization

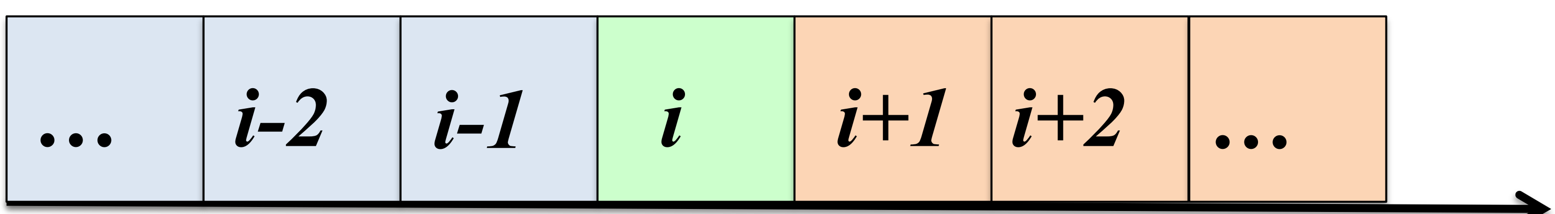
$$\frac{dC}{dt} = \lim_{\Delta t \to 0} \frac{C(t+\Delta t) - C(t)}{\Delta t}$$

Continuum

$$\frac{dC}{dt} \approx \frac{C(t+\Delta t) - C(t)}{\Delta t}, \Delta t > 0$$

Discrete

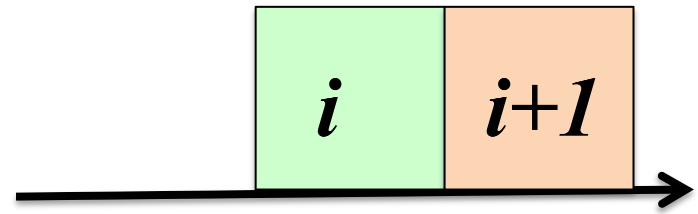
(Taylor series expansion)



Applies to time + 3D space

What does a model need?

A very simple numerical example



$$\boxed{\frac{dC}{dt} = \lambda C}$$

$$\frac{dC}{dt} = \lim_{\Delta t \to 0} \frac{C(t+\Delta t) - C(t)}{\Delta t}$$

$$\frac{C_{i+1} - C_i}{t_{i+1} - t_i} = \lambda C_i$$

Requires discretization of derivatives

and numerical integration to step forward from t*i* to *tf=NΔT*

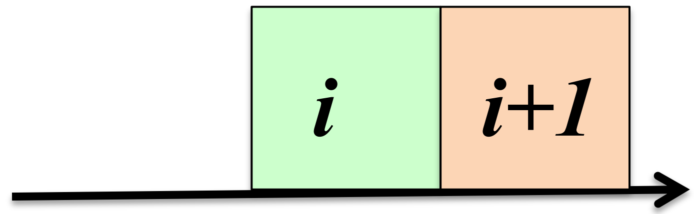
$$C_{i+1} = C_i \left(1 + \lambda \Delta t\right)$$

Forward difference

(aka Forward Euler)

What does a model need?

Discretization needed to implement numerically



$$\frac{dC}{dt} = \lambda C$$

$$\frac{C_{i+1} - C_i}{\Delta t} = \lambda C_{i+1}$$

Backward difference

(aka backward Euler)

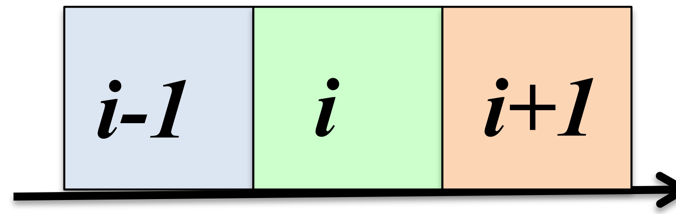
$$C_{i+1} = \lambda \Delta t C_{i+1} + C_i$$

$$C_{i+1} = C_i \frac{1}{1 - \lambda \Delta t}$$

Requires solving an extra equation (implicit scheme)

What does a model need?

Discretization needed to implement numerically



$$\frac{dC}{dt} = \lambda C$$

$$\frac{C_{i+1} - C_{i-1}}{2\Delta t} = \lambda C_i$$

Centered difference

$$\boxed{C_{i+1} = 2\lambda \Delta t C_i + C_{i-1}}$$

Requires knowing more things from more points

The "dynamical/numerical core" of a model matters … a lot!

- System of equation (partial differentials in 3D)
- **Discretization** and **integration** scheme
  - These 3 are mathematically all valid but can produce very different answers when implemented…

$$C_{i+1} = C_i\left(1+\lambda\Delta t\right)$$

Forward difference
(aka Forward Euler)

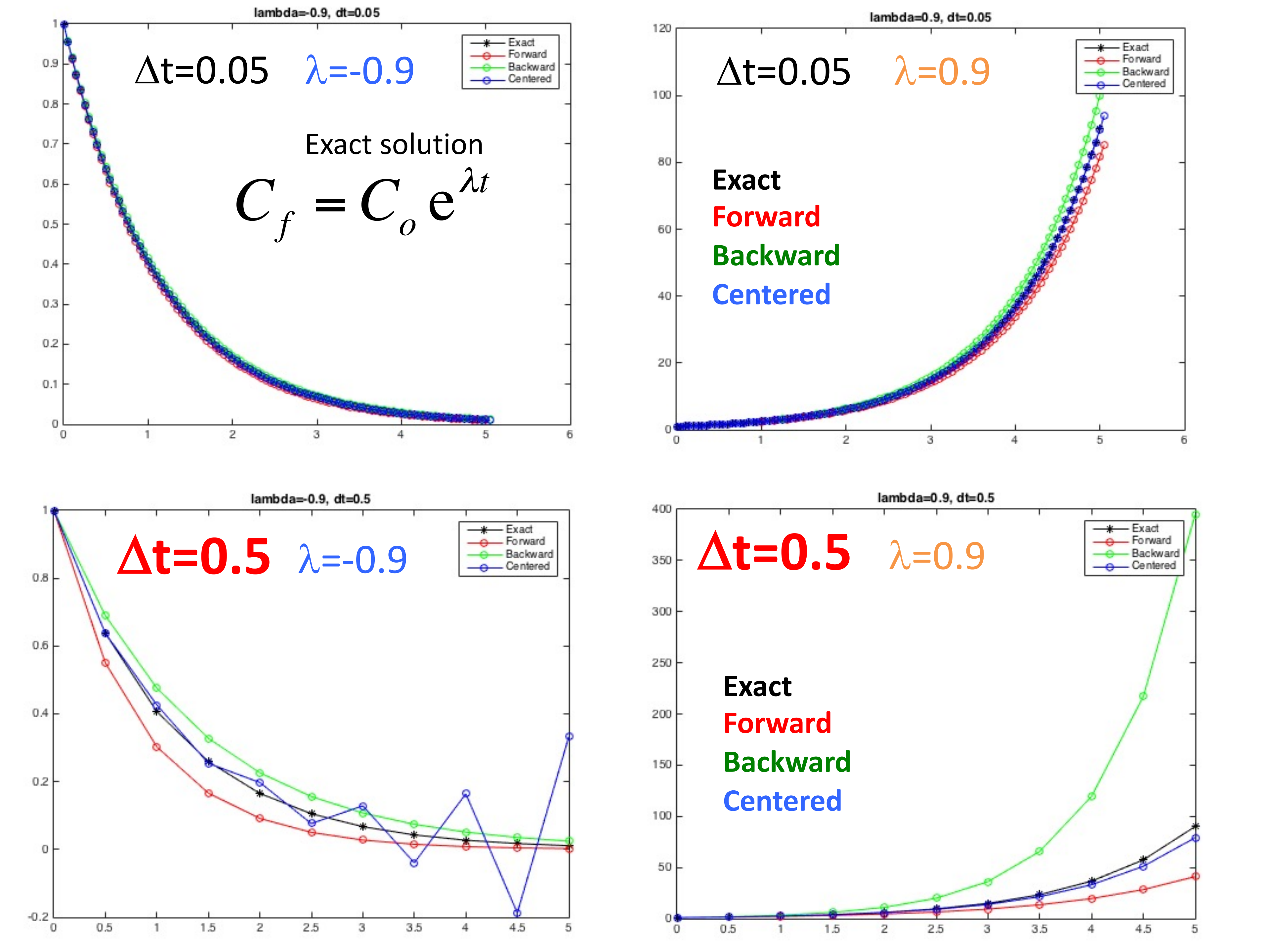
$$C_{i+1} = C_i \frac{1}{1-\lambda\Delta t} = 1$$

Backward difference
(aka backward Euler)

$$C_{i+1} = 2\lambda\Delta t C_i + C_{i-1}$$

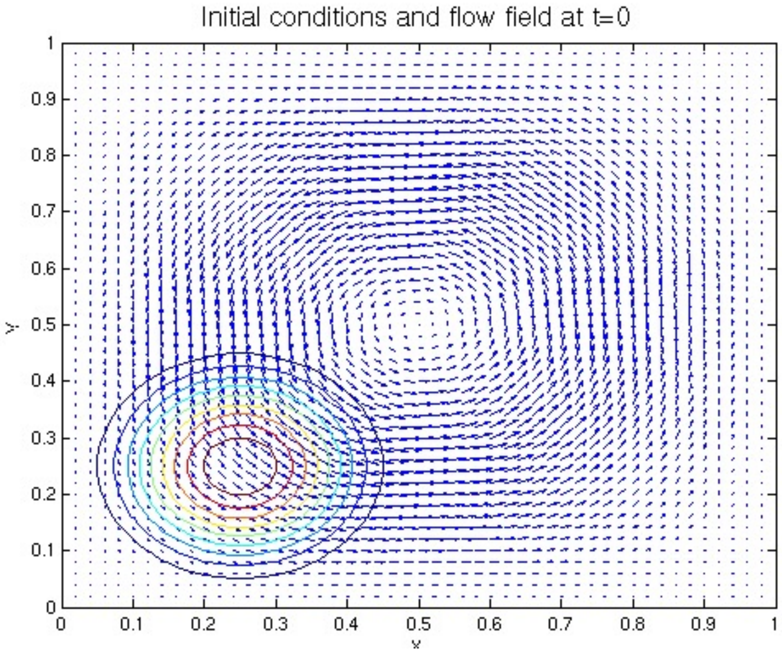
Centered difference

etc…


lambda=-0.9, dt=0.05
Δt=0.05 λ=-0.9
Exact solution
$$C_f = C_o e^{\lambda t}$$
Exact
Forward
Backward
Centered
lambda=0.9, dt=0.05
Δt=0.05 λ=0.9
Exact
Forward
Backward
Centered
lambda=-0.9, dt=0.5
Δt=0.5 λ=-0.9
Exact
Forward
Backward
Centered
lambda=0.9, dt=0.5
Δt=0.5 λ=0.9
Exact
Forward
Backward
Centered

Testing the numerical core

...when we don't have an exact solution to compare to



Idealized simulations

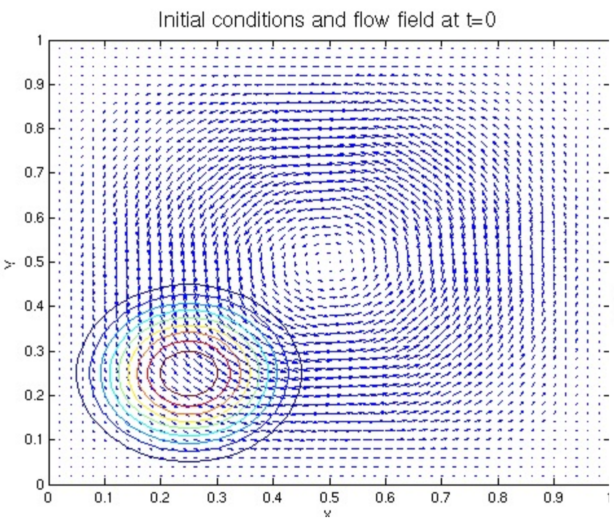
~ numerical equivalent of calibration in a lab

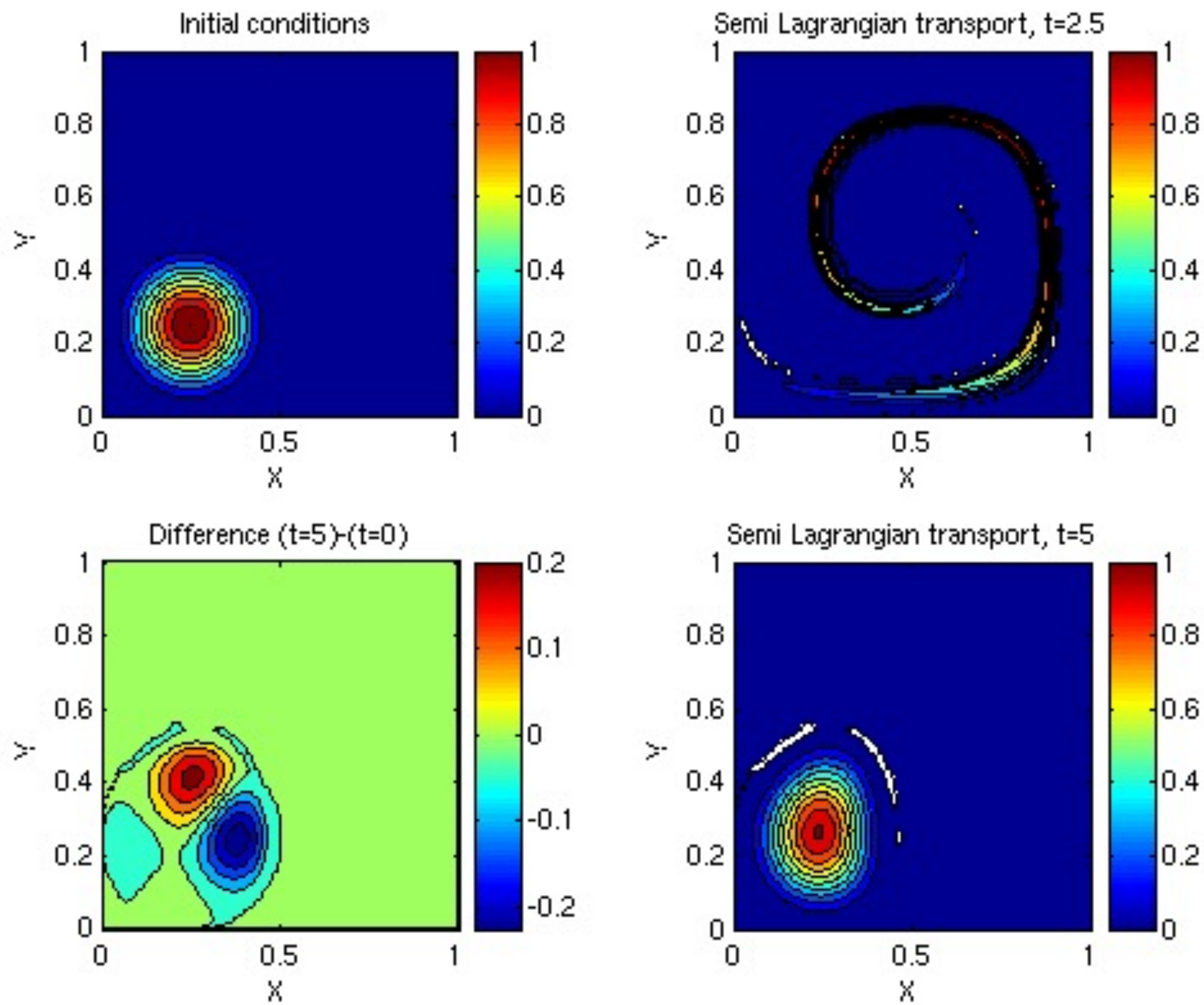
$$u(x,y) = \sin^2(\pi x)\sin(2\pi y)\cos(\pi t/5)$$

$$v(x,y) = -\sin^2(\pi y)\sin(2\pi x)\cos(\pi t/5)$$

Testing the numerical core

...when we don't have an exact solution to compare to





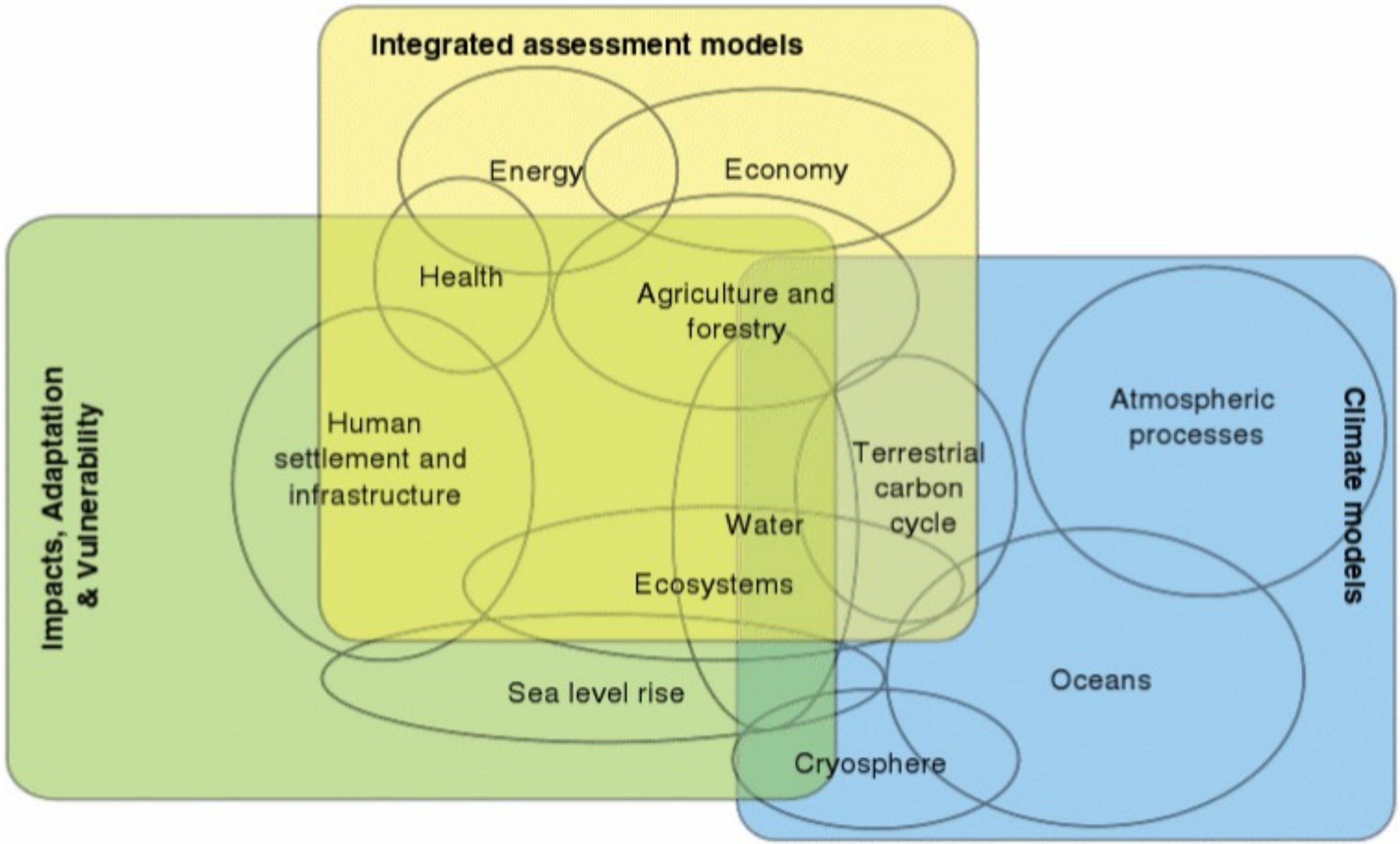
This highlights the problem of numerical diffusion

What does a numerical model need?

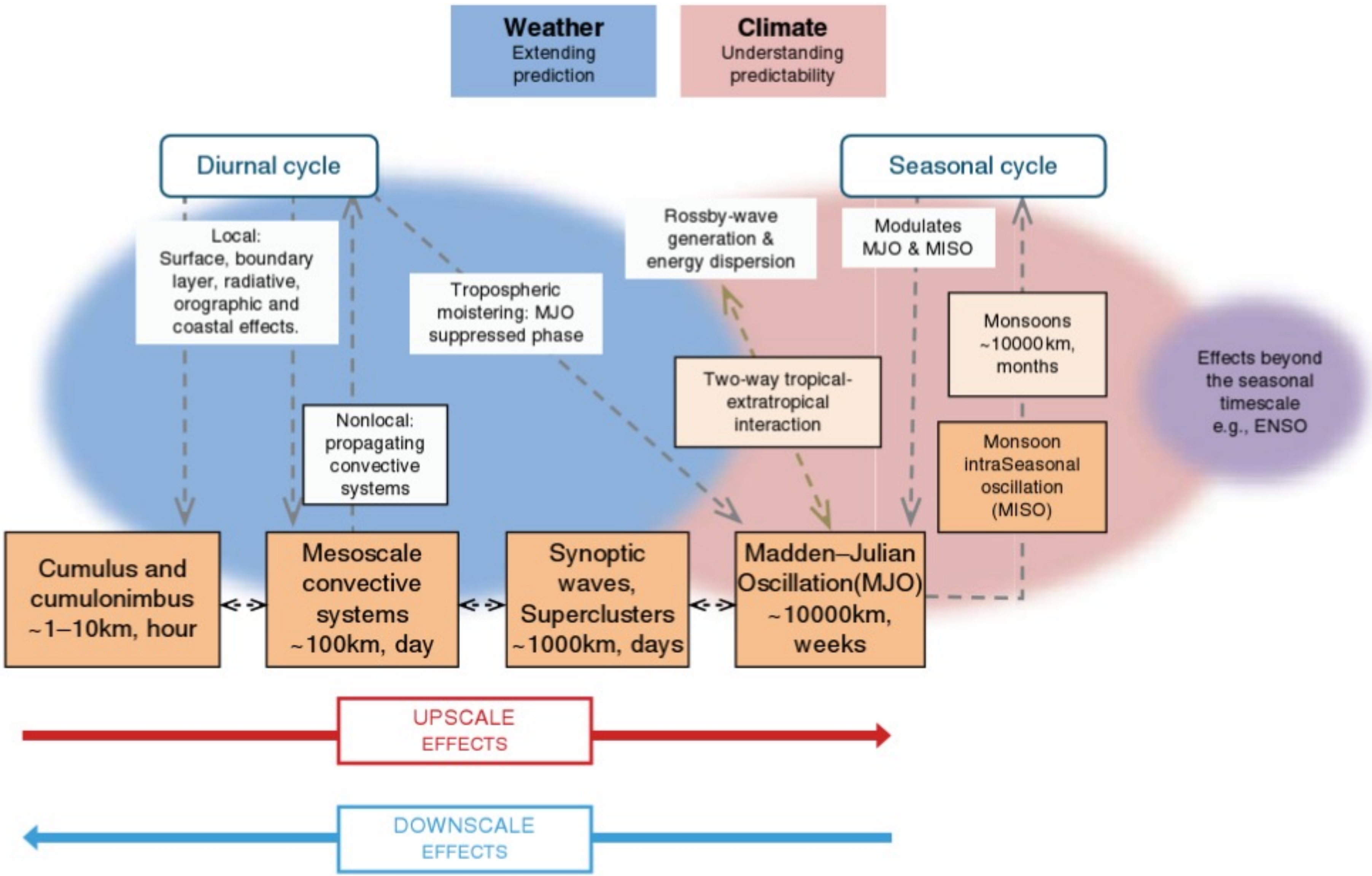
summary

- Need equations (+ parameterizations)
  - Output = function(input)
- Need a starting point
  - Boundary conditions
- Must define time and space scales of interest
  - Integration time step
  - Spatial resolution of the grid
  - Duration of model run
  - Decisions about time/space scales also translate into "filtering" the equations
    - (parts of the equations can be neglected and the equations simplified)

Why model climate?

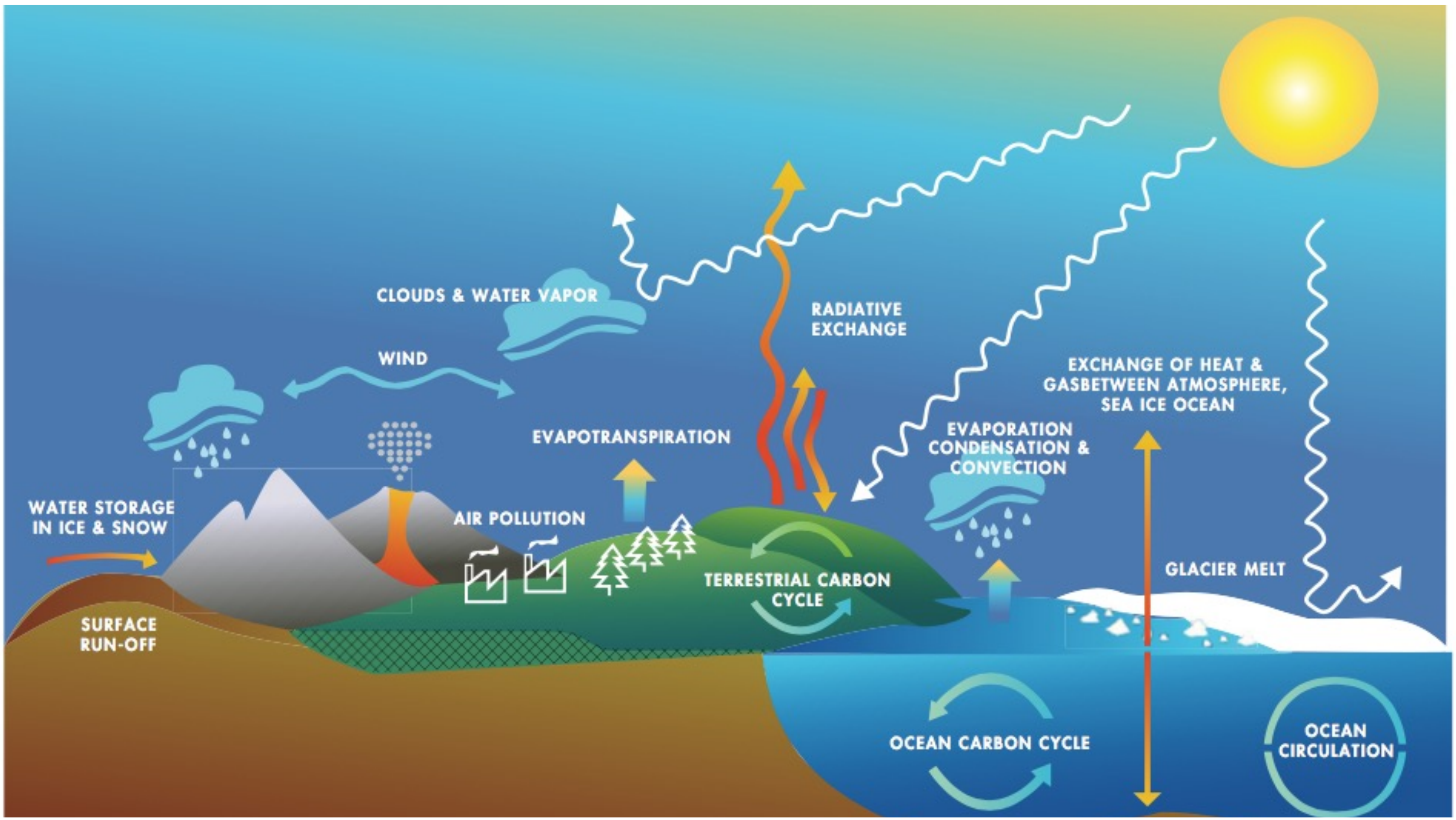


Weather and climate – bridging the gap




INTEGRATED ASSESSMENT MODELLING
THEN, OF COURSE, THERE'S THE POLITICAL CLIMATE...
DAILY NEWS

What are coupled climate models?



A few key major coupling mechanisms between the ocean and the atmosphere

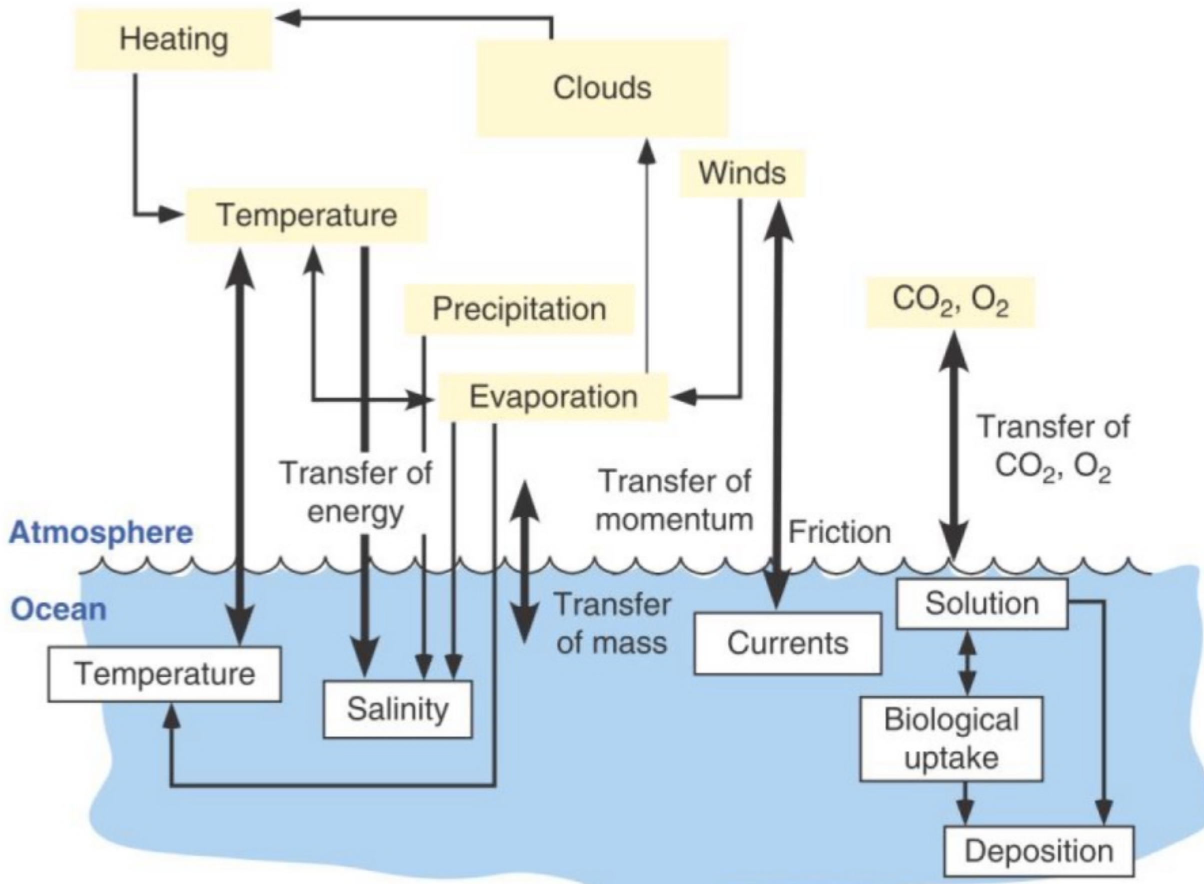


Figure 3.2 A representation of the major coupling mechanisms between the atmosphere and ocean subsystems. The relative importance of these coupling mechanisms varies with latitude. The feedback between atmospheric temperature and oceanic salinity is interesting because it is a strong atmospheric forcing of the ocean.

The "**coupler**" is the heart of climate models

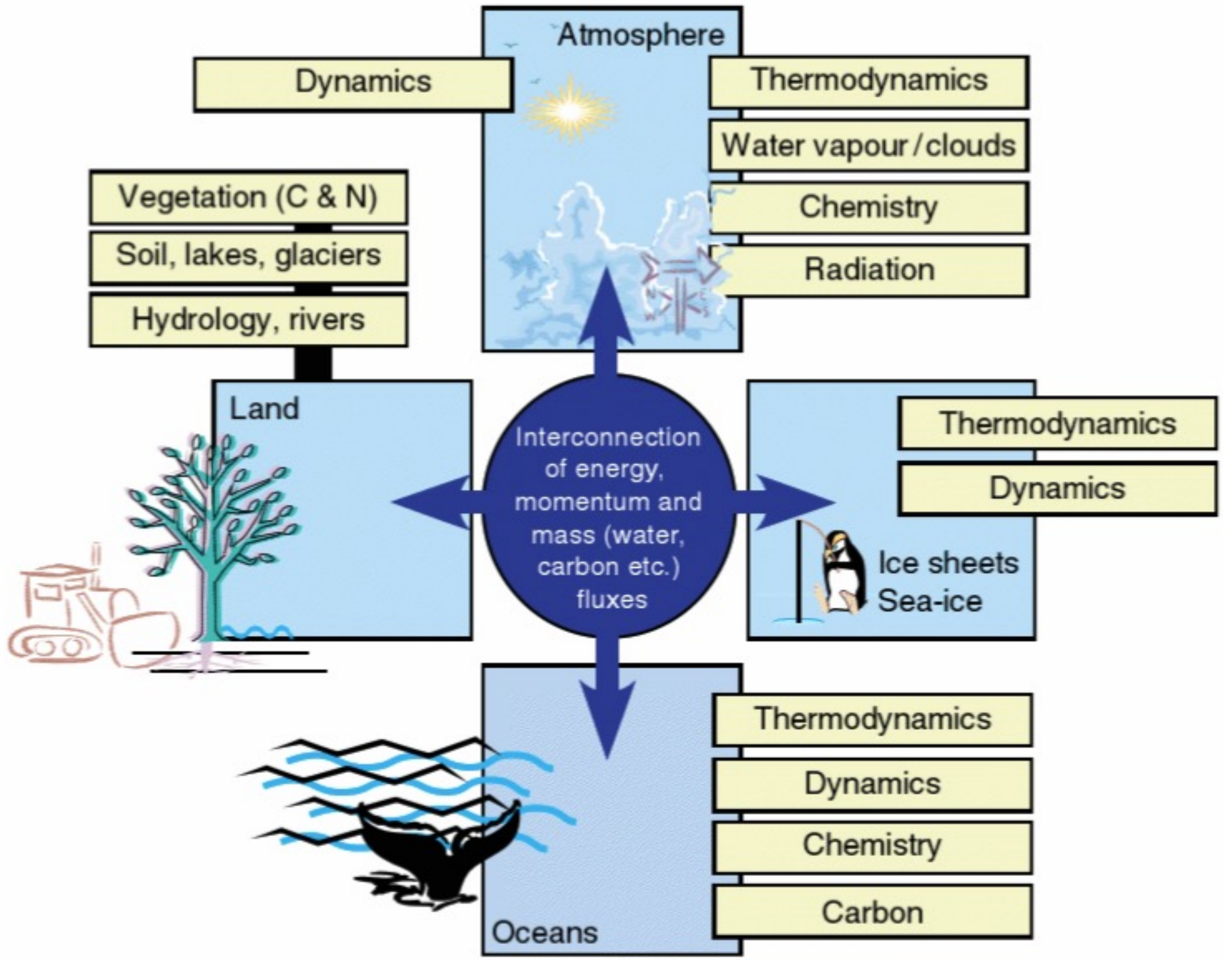
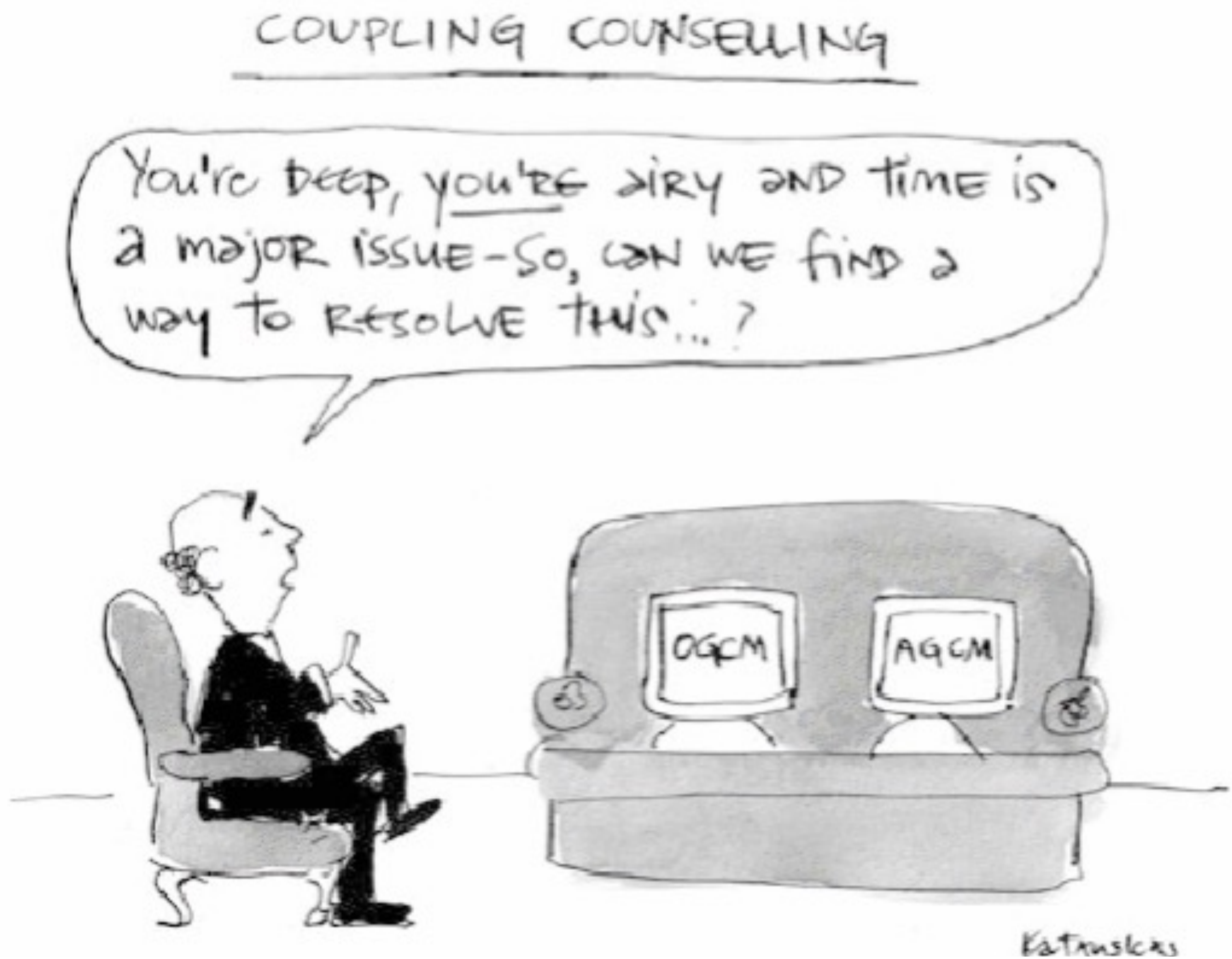
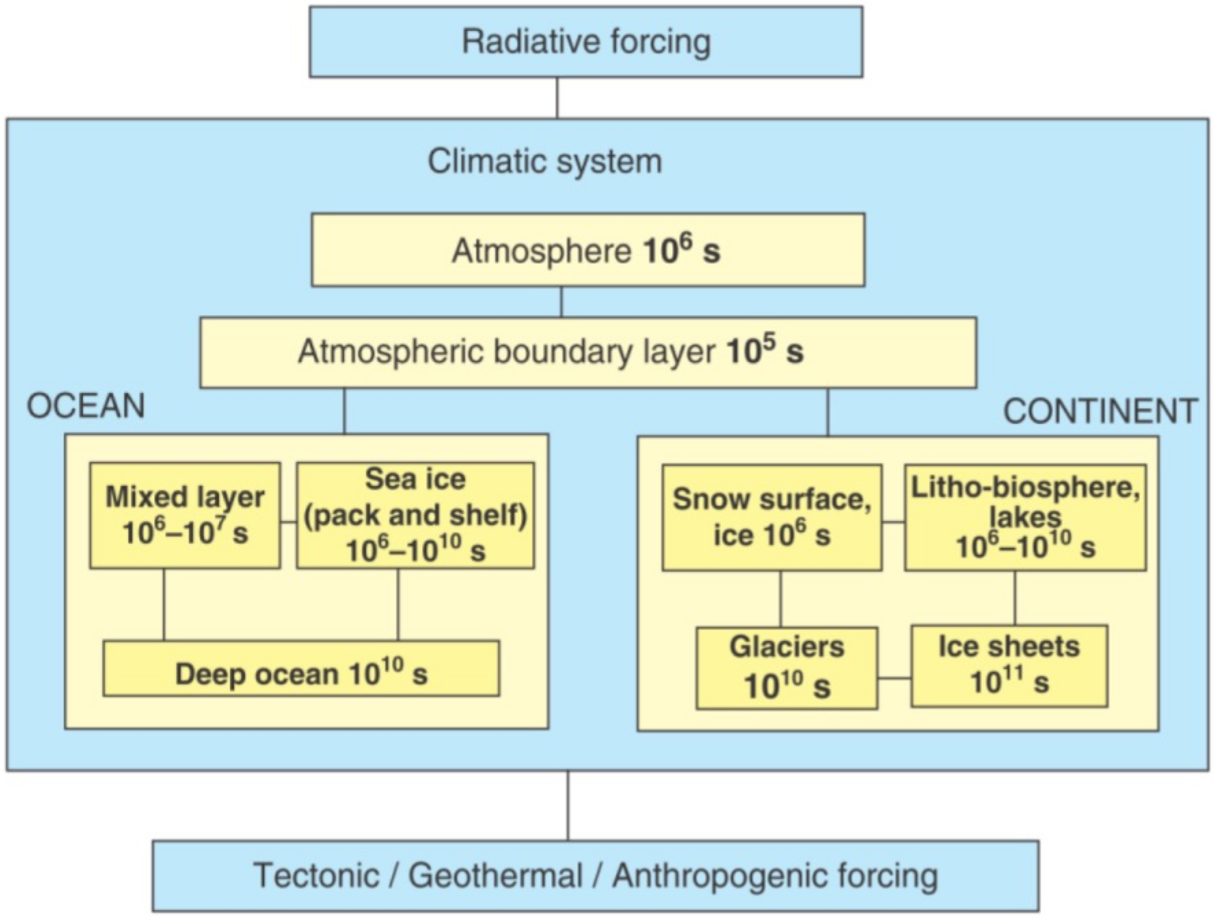


Figure 5.1 Modern coupled ocean–atmosphere models are constructed as modular components connected by a coupler (*centre*), a program that transfers fluxes between the model components. In recent years, significant effort has been devoted to formal software design and the development of portable 'plug compatible' climate submodels, meaning that development can focus on model process improvement rather than on operational and computational aspects of the model.


COUPLING COUNSELLING
You're deep, you're airy and time is a major issue–so, can we find a way to resolve this...?
OGCM
AGCM
Katauskas

Interconnecting reservoirs with their own time-scales



10^5 s=1.5 days

10^6 s=11 days

10^7 s=4 months

10^{10} s= 300 years

Figure 2.3 A schematic representation of the domains of the climate system with their estimated equilibration times. The timescales can be seen in tabular form in Table 1.8 and this representation can be compared with one that is more typical of EMICs in Figure 4.20. Source: Saltzman (1983). Reproduced with permission of Elsevier.

Why coupling the models in the first place?
Teleconnections and nonlinear **feedbacks**

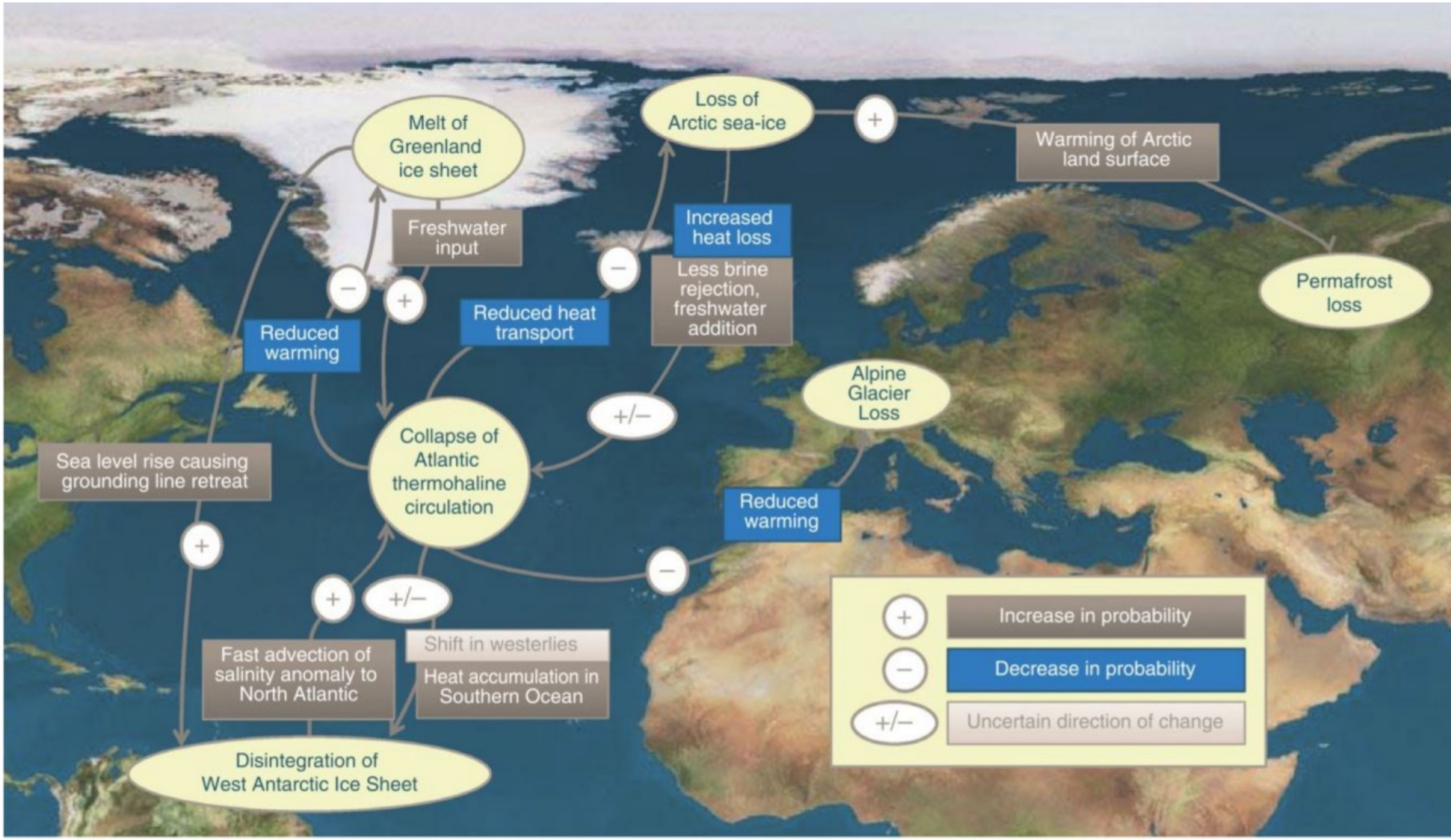
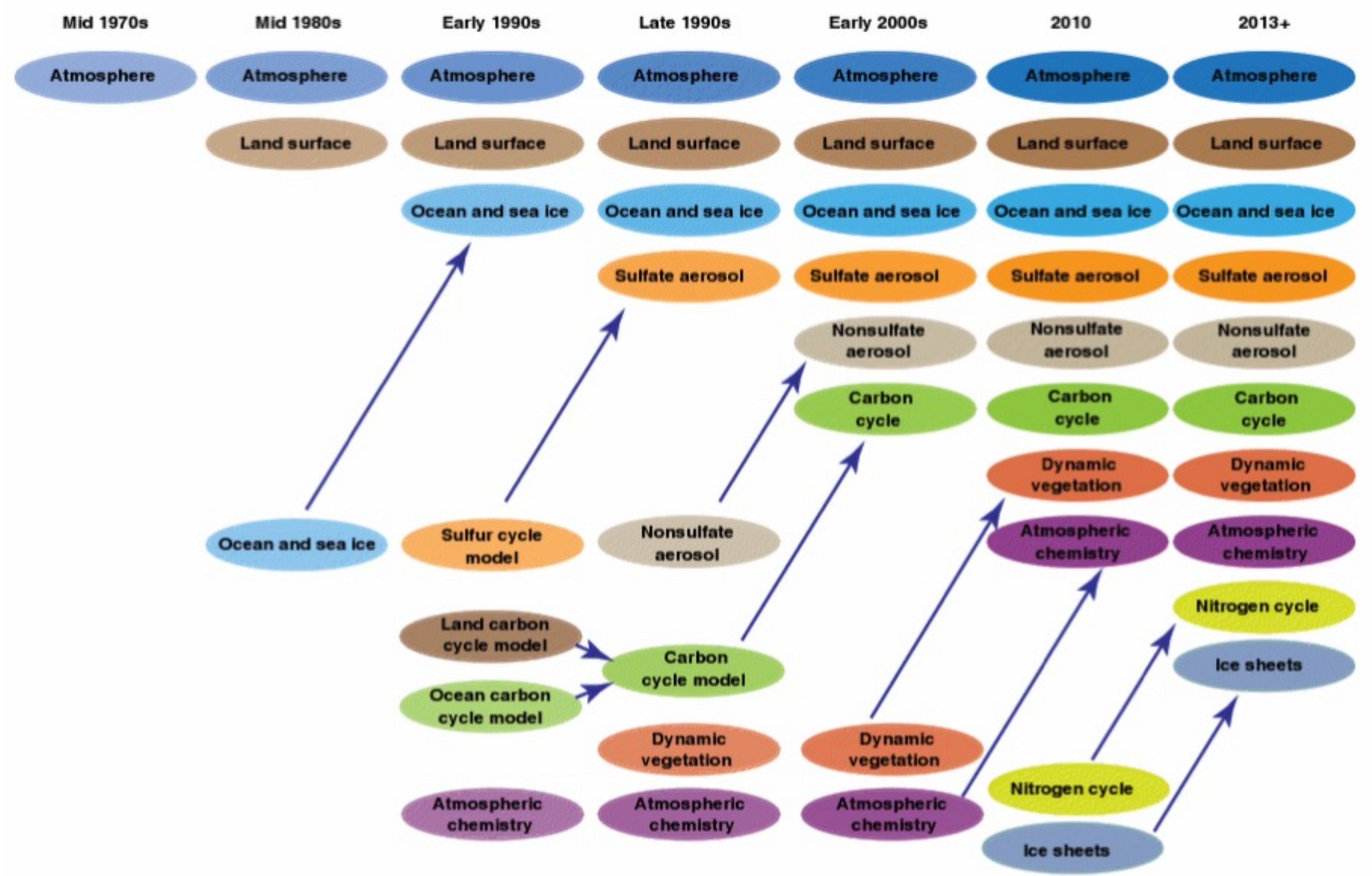


Figure 4.24 Schematic of the large set of potential links between possible 'tipping elements' in the north Atlantic and its surrounding lands. The likely direction of changes caused by global warming is shown. Source: After Levermann et al. (2012a). Reproduced with permission of Springer Science+Business Media.

What is model “**coupling**”?

- Exchanges of properties at the interfaces:
  - Heat
  - Water
  - Momentum
  - Energy
- Modules are run quite independently, but regularly exchange information about each other’s states to calculate exchange fluxes
- Challenges:
  - Grids of various modules may not match
    - E.g. part of an atmospheric grid box covers ocean+land+sea-ice
  - Properties must be conserved
  - Characteristic time-scales in each module differ affecting the time-step of integration needed

Model complexity : need vs greed and the need for speed



Model complexity vs resolution

Late 1960s: UNIVAC 1108 (0.5MB of memory!)

Syukuro “Suki” Manabe
(Nobel prize physics 2021)

A master at simplifying problem to their essence

https://en.wikipedia.org/wiki/Syukuro_Manabe

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5h

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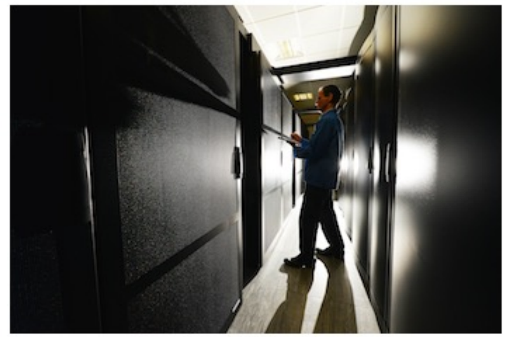
About ARCHER



ARCHER is the latest UK National Supercomputing Service. The ARCHER Service started in November 2013 and is expected to run for 5 years. ARCHER provides a *capability* resource to allow researchers to run simulations and calculations that require large numbers of processing cores working in a tightly-coupled, parallel fashion.

- Research on ARCHER in The Conversation (April 2014)
- ARCHER supercomputer plays key role in bid to create Google Earth for human body (The Independent)
- The ARCHER YouTube Channel

The ARCHER Service is based around a Cray XC30 supercomputer (more details below) and is provided by the ARCHER Partners: EPSRC, NERC, EPCC, Cray Inc. and The University of Edinburgh. Staff from the partners provide the management, administration, and technical support to keep the system running in a way that maximises the research output of ARCHER. Expertise to support the UK research community in the use of ARCHER is provided by EPCC and Cray Inc. and researchers can also apply for longer term software development support through the eCSE programme.

- eCSE Programme - software development support.
- People - The people who provide the ARCHER service.
- Partners - The partners providing the ARCHER service.

ARCHER Hardware

The ARCHER hardware consists of the Cray XC30 MPP supercomputer, external login nodes and postprocessing nodes, and the associated filesystems. There are 4920 compute nodes in ARCHER phase 2 and each compute node has two 12-core Intel Ivy Bridge series processors giving a total of 118,080 processing cores. Each node has a total of 64 GB of memory with a subset of large memory nodes having 128 GB.

A high-performance Lustre storage system is available to all compute nodes. There is no local disk on the compute nodes as they are housed in 4-node blades (the image below shows an XC30 blade with 4 compute nodes).

The UK' shared supercomputing facility

Cray XC30
4920 nodes x
12 cores
= 118080 CPUs

Each node as
64GB memory

High costs!

- **Financial**
- **Energy**
- **People**
- **Data storage**
- **Data analysis**
- **...**