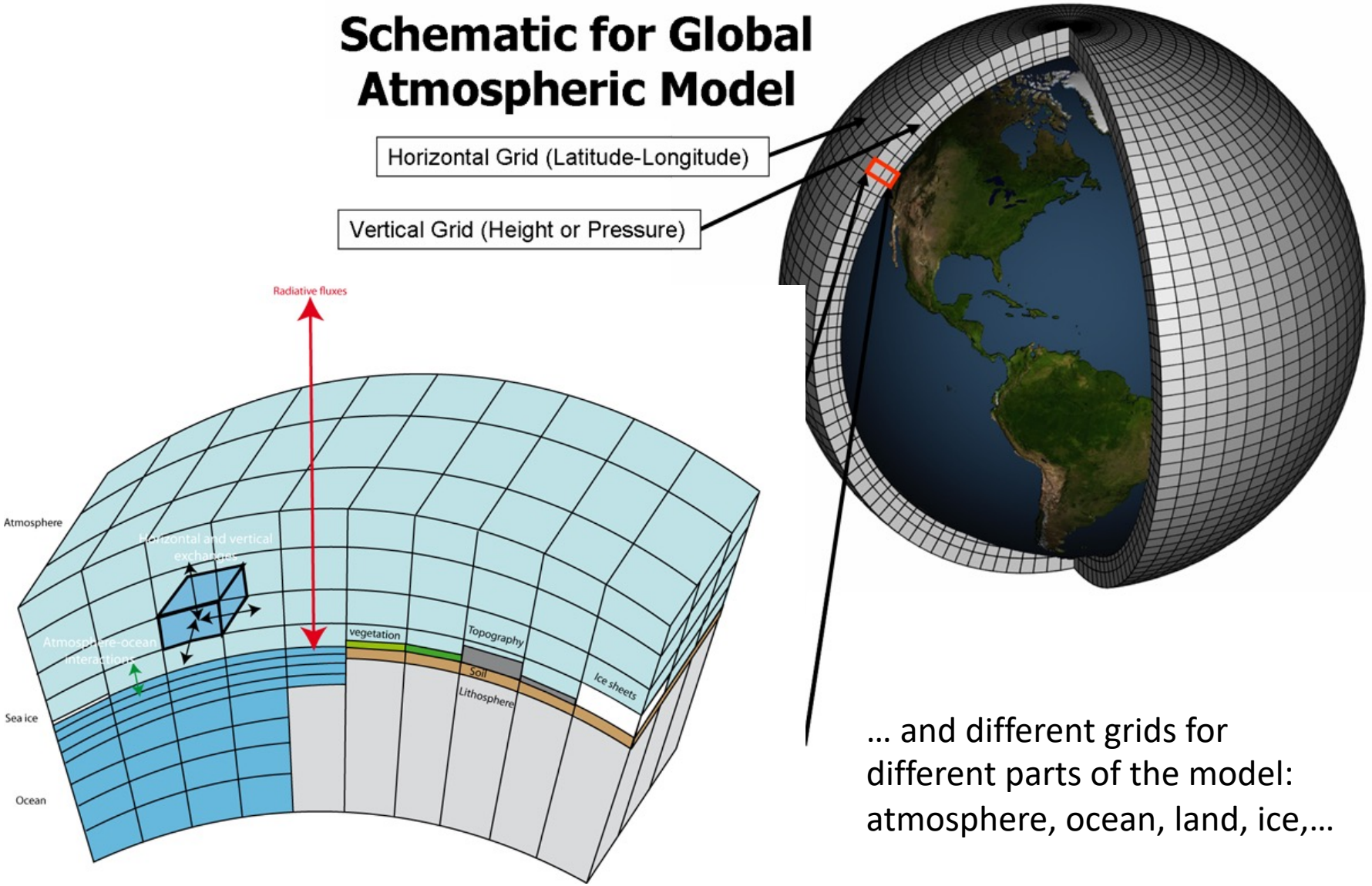
Climate models – what are they?



… 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)

What does a model need?
A very simple analytical example

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

Requires equations
(hypotheses about underlying physics)

What are they for climate?

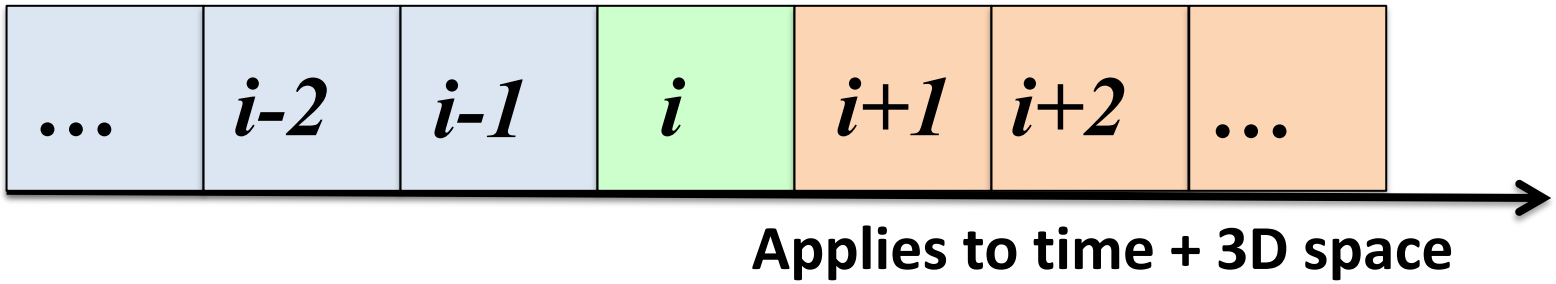
$$\int_{Co}^{Cf} dC = \int_{to}^{tf} \lambda \, dt$$

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

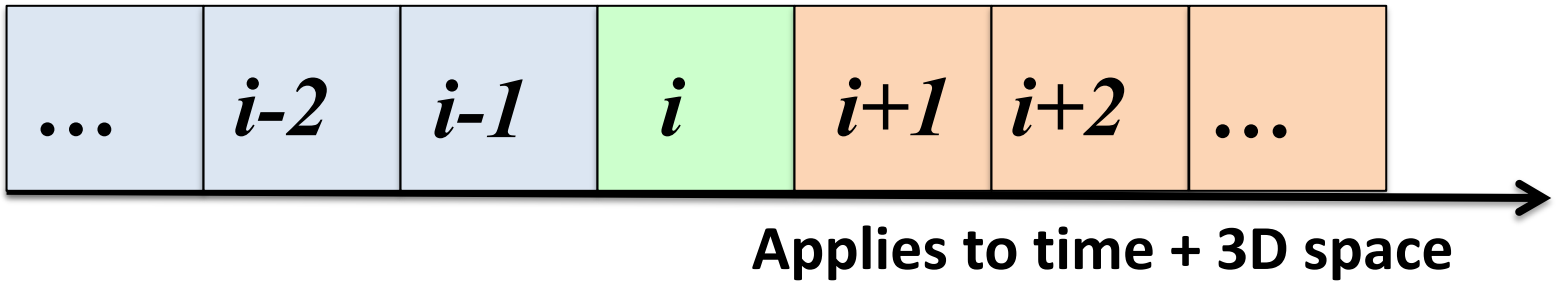
$$\frac{dC}{dt} = \lim_{\Delta t \to 0} \frac{C(t+\Delta t) - C(t)}{\Delta t}$$

Continuum

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

Discrete

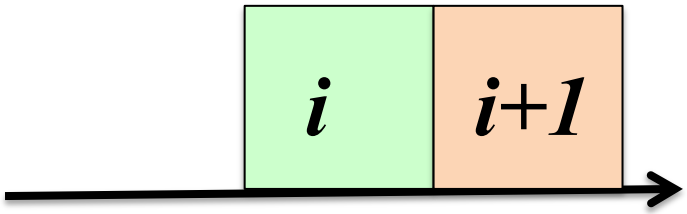
(Taylor series expansion)



In practice, this implies choices of Δx, Δy, Δz, Δt, size of the stencil, numerical stability, computational ability/costs, problem under study, etc.

What does a model need?

A very simple numerical example



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

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

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

Requires discretization of derivatives
and numerical integration
to step forward
from t_i to $t_f = N\Delta T$

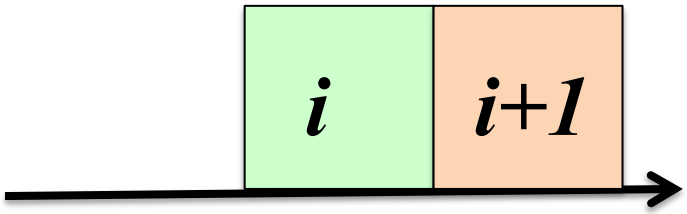
$$C_{i+1} = C_i\left(1 + \lambda \Delta t\right)$$

Forward difference
(aka Forward Euler)

[climate models use much more complex schemes]

What does a model need?

Discretization needed to implement numerically



$$\frac{dC}{dt} = \lambda C \qquad \frac{C_{i+1} - C_i}{\Delta t} = \lambda C_{i+1}$$

Backward difference

(aka backward Euler)

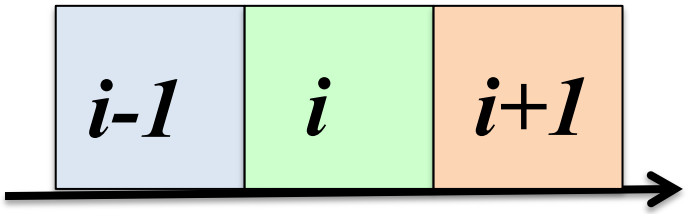
$$C_{i+1} = \lambda \Delta t C_{i+1} + C_i$$

Requires solving an extra equation (implicit scheme)

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

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

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

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)

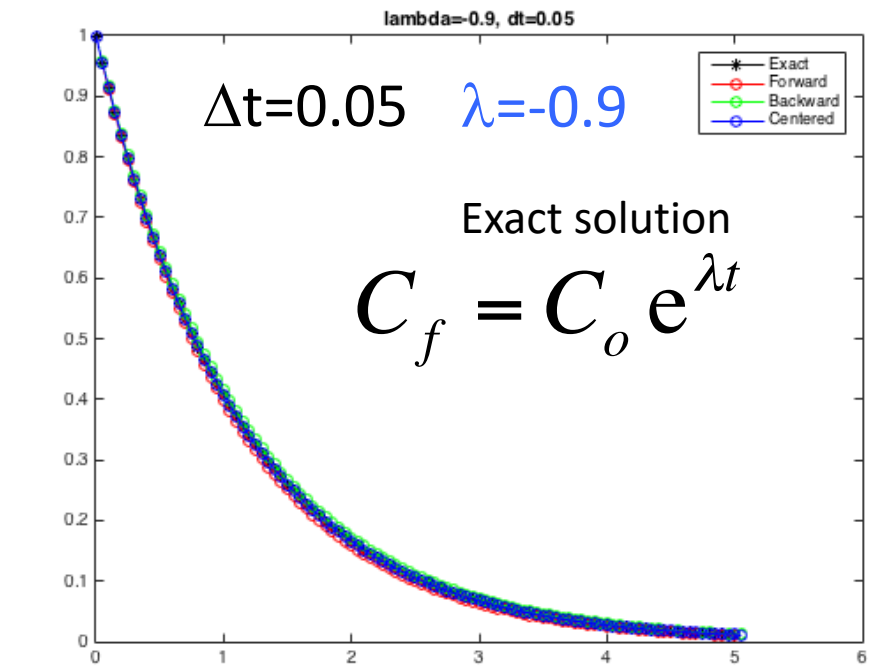
$$C_{i+1} = C_i \frac{1}{1 - \lambda\Delta t} = 1$$

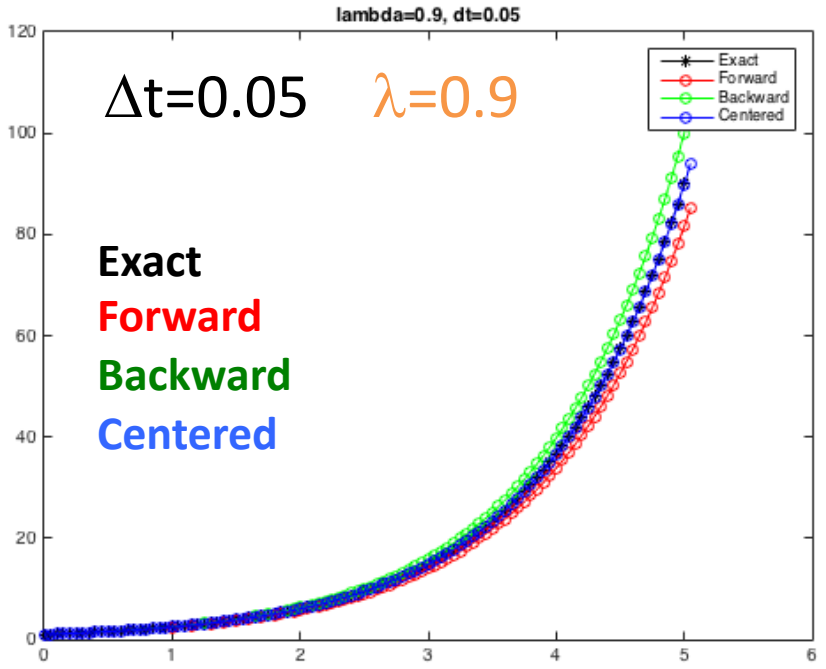
Backward difference
(aka backward Euler)

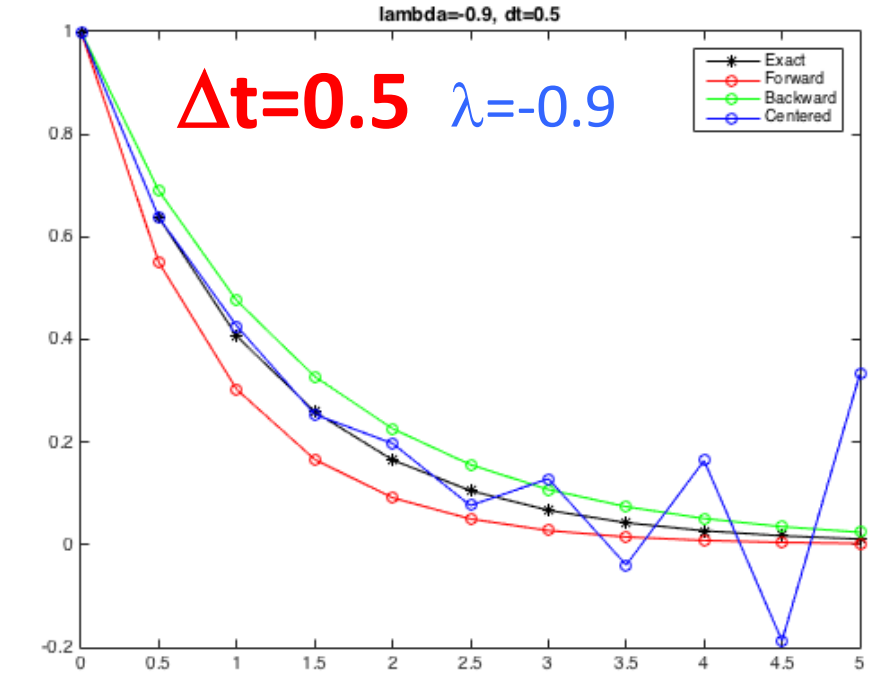
$$C_{i+1} = 2\lambda\Delta t C_i + C_{i-1}$$

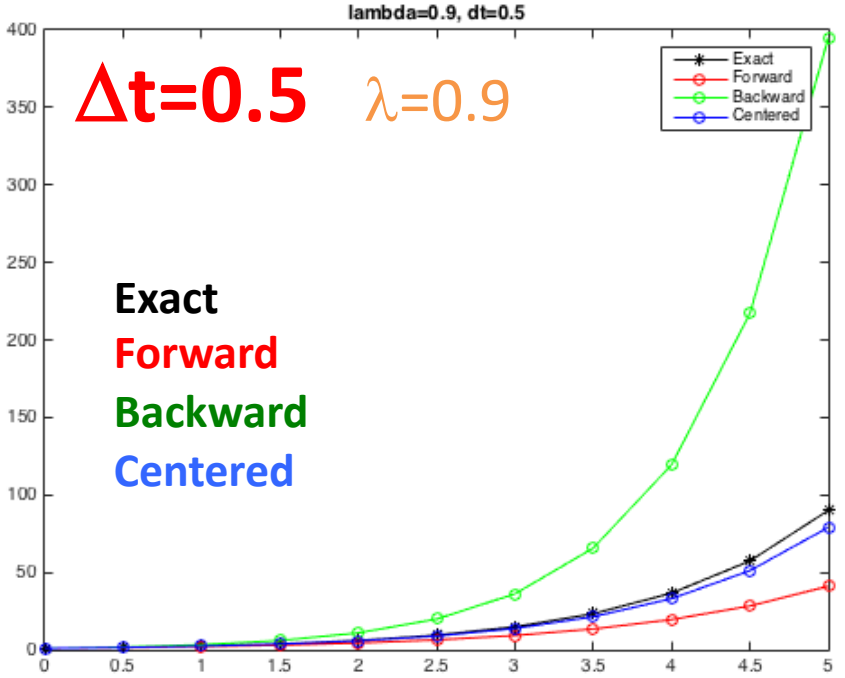
Centered difference

etc…


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

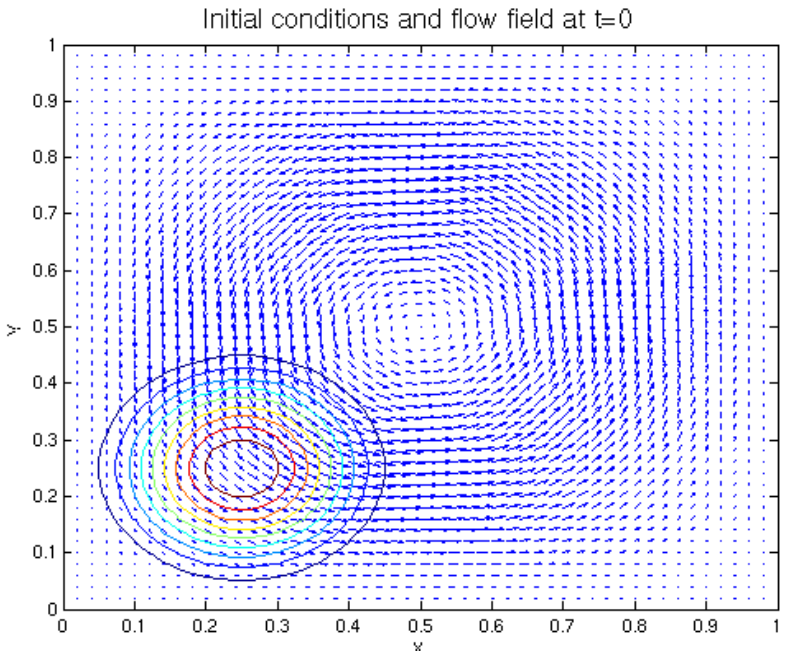

lambda=0.9, dt=0.05
Exact
Forward
Backward
Centered
Δt=0.05
λ=0.9
Exact
Forward
Backward
Centered


lambda=-0.9, dt=0.5
Exact
Forward
Backward
Centered
Δt=0.5
λ=-0.9


lambda=0.9, dt=0.5
Exact
Forward
Backward
Centered
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



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

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

Idealized simulations

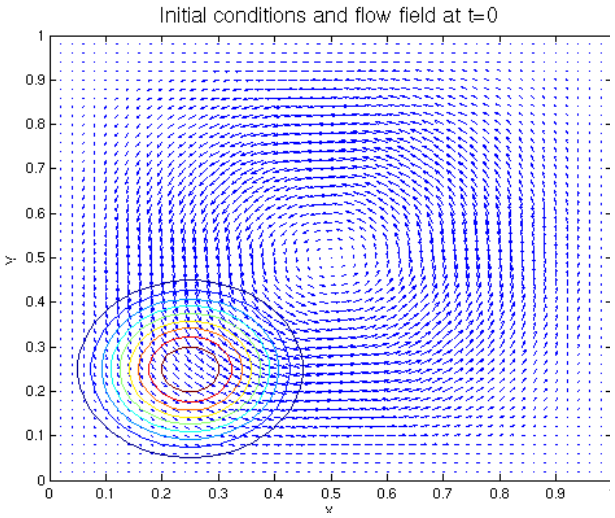
~ numerical equivalent of calibration in a lab

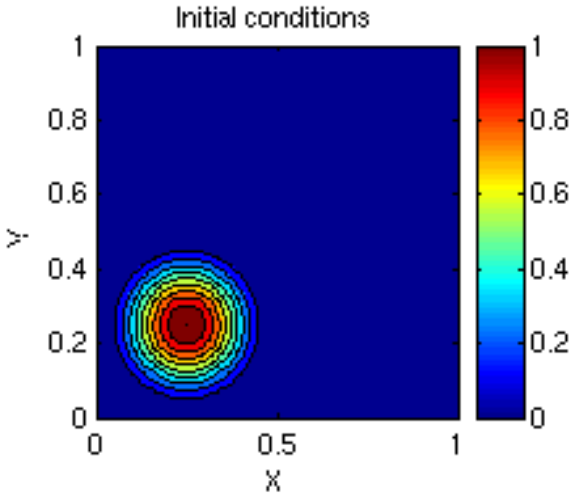
Example:

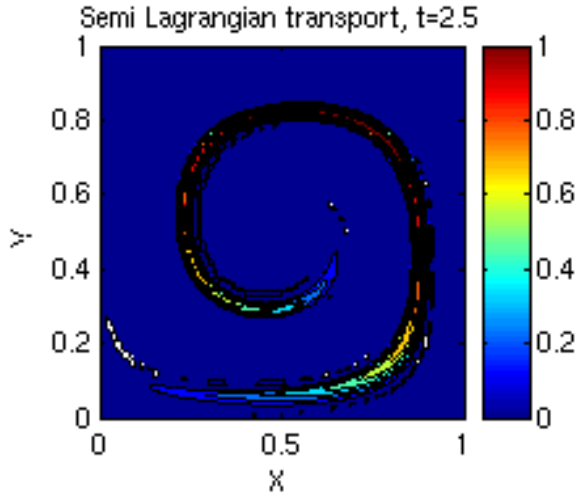
- Purely advective system (no explicit diffusion added)
- flows forward, then flows backwards
  - Ideally, should return to initial values
  - Deviations are indicative of numerical issues

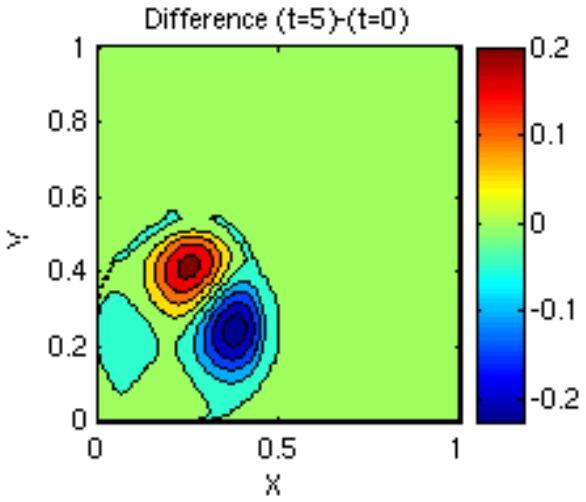
Testing the numerical core

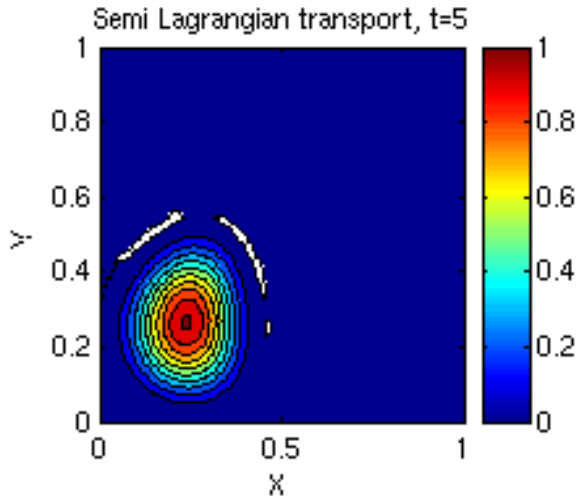
…when we don't have an exact solution to compare to











This highlights the problem of numerical diffusion

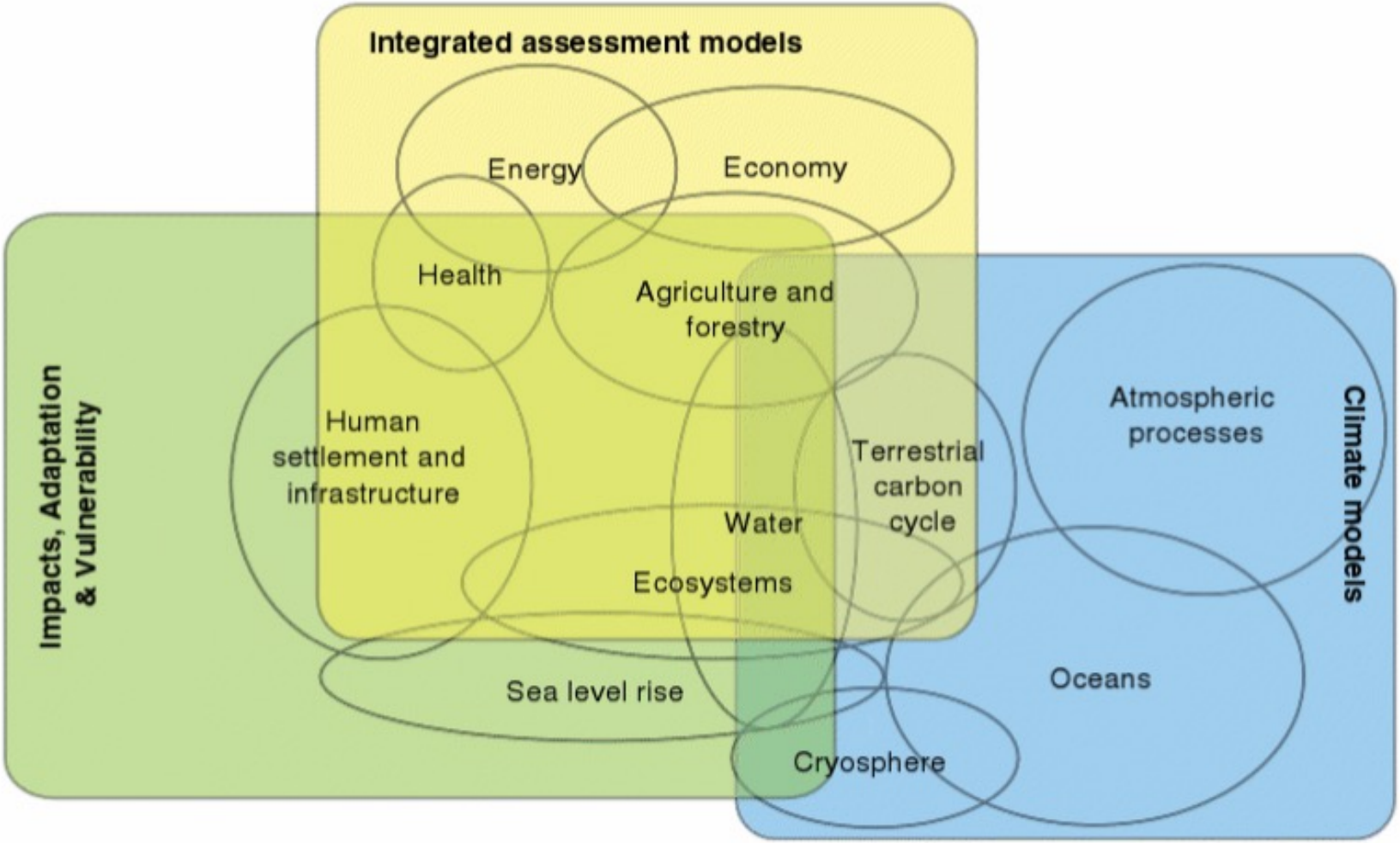
Each scheme will have its own weaknesses and strengths (and conservation properties)

What does a numerical model need?

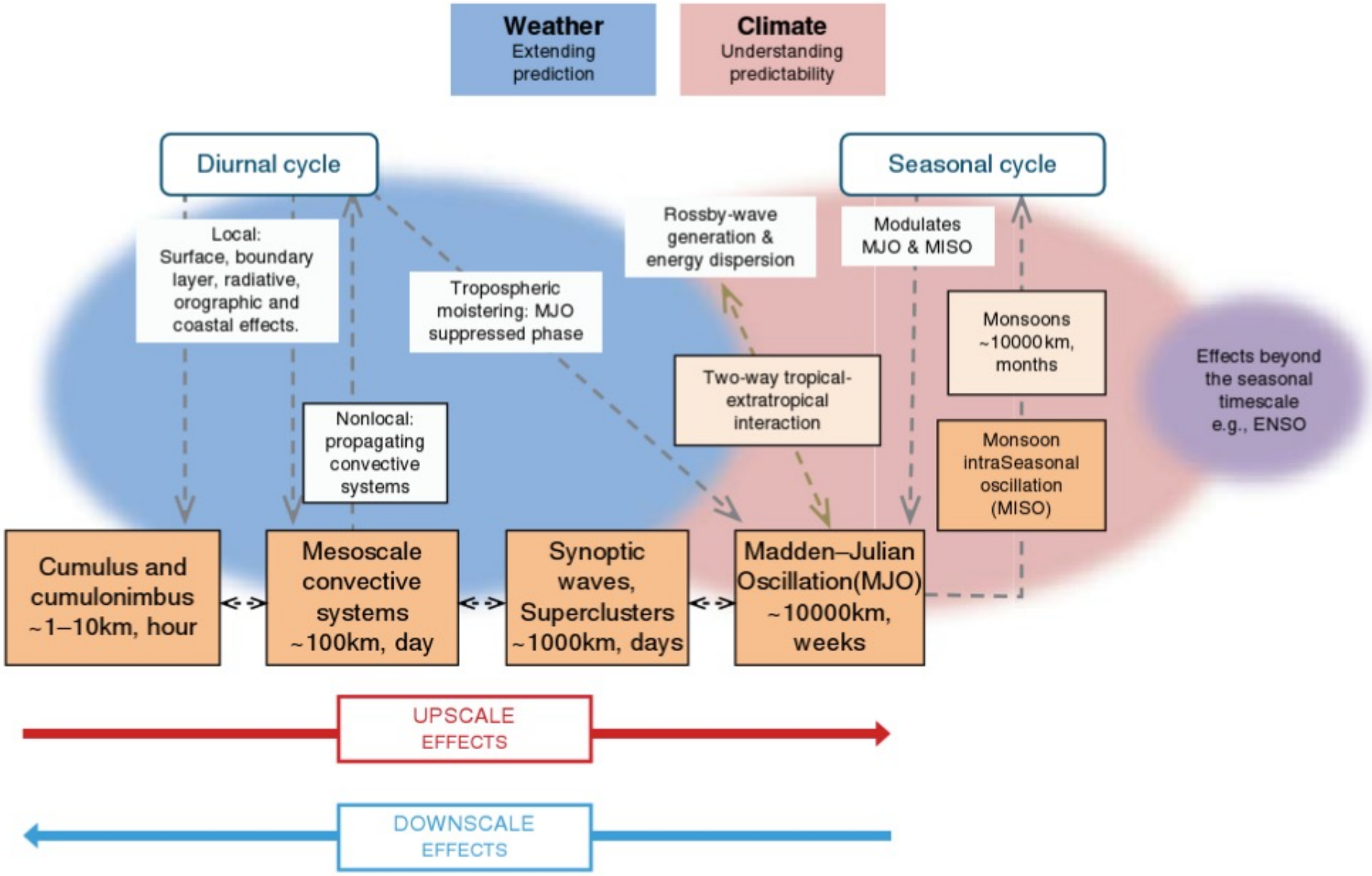
summary

- 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 – some physics can be neglected/simplified)

Why model climate?

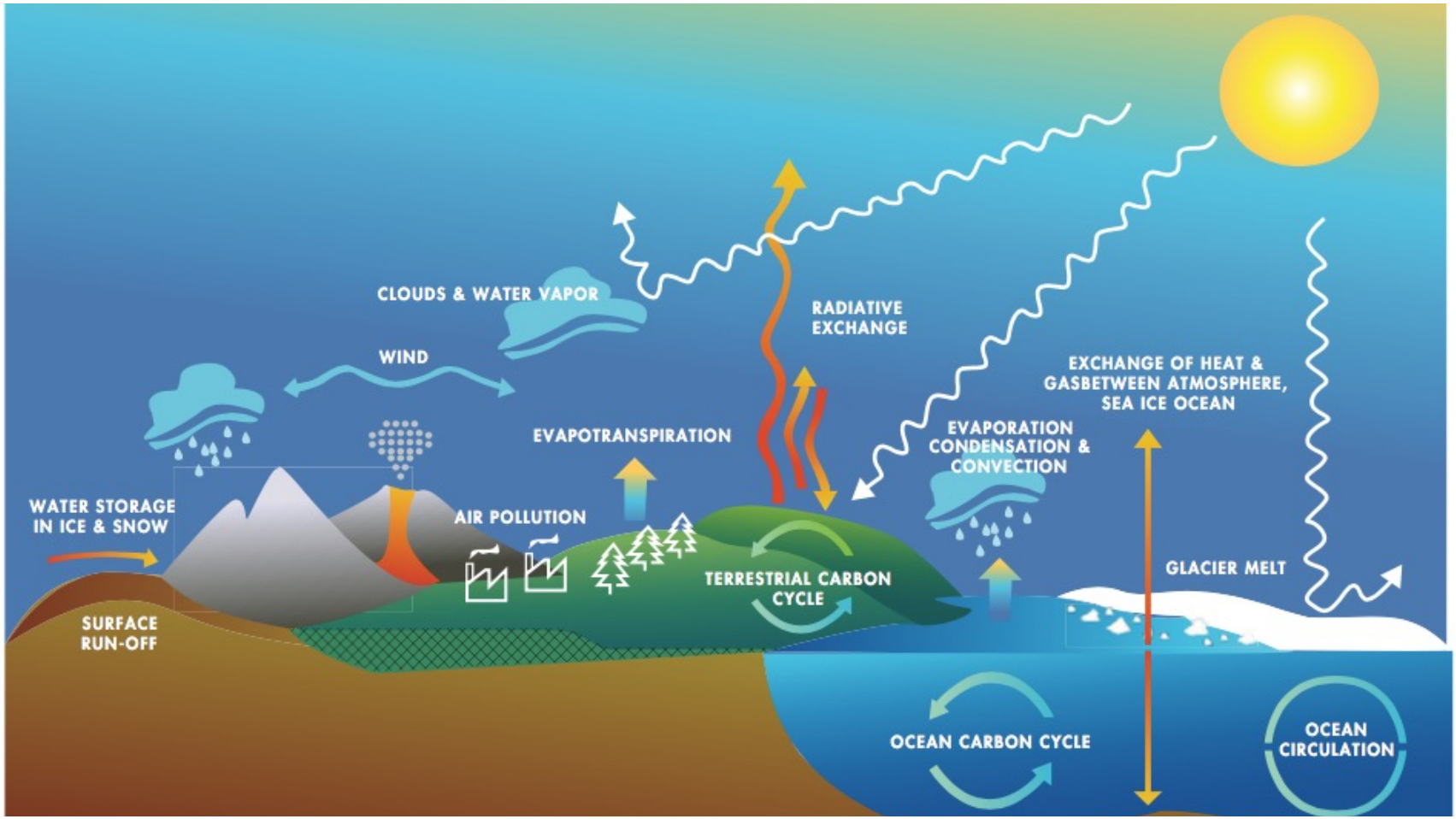


Weather and climate – bridging the gap



INTEGRATED ASSESSMENT MODELLING

What are coupled climate models?



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

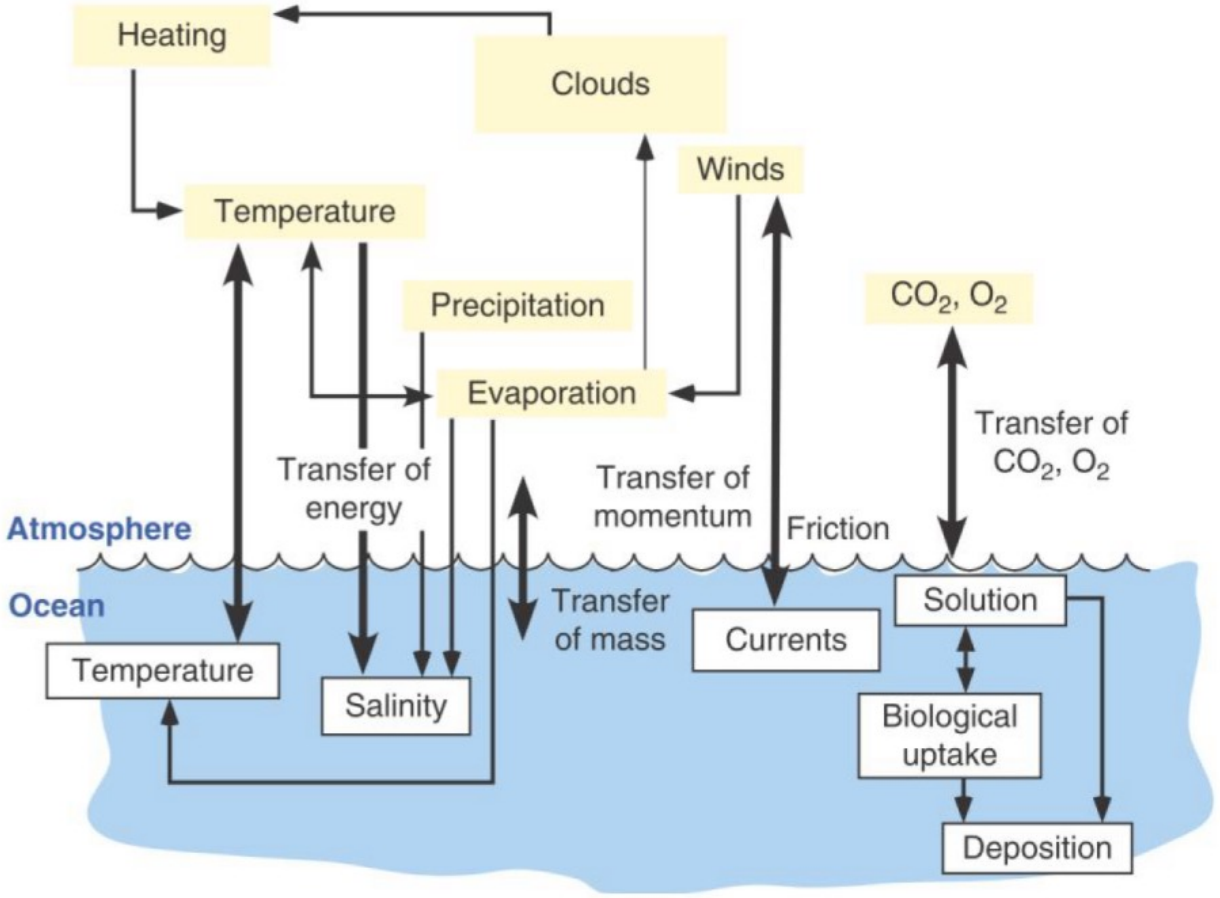


Figure 3.2 A representation of the major coupling mechanisms between the atmosphere and ocean subsystems. The relative importance of these coupling mechanisms varies with latitude. The feedback between atmospheric temperature and oceanic salinity is interesting because it is a strong atmospheric forcing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

The "coupler" is the heart of climate models

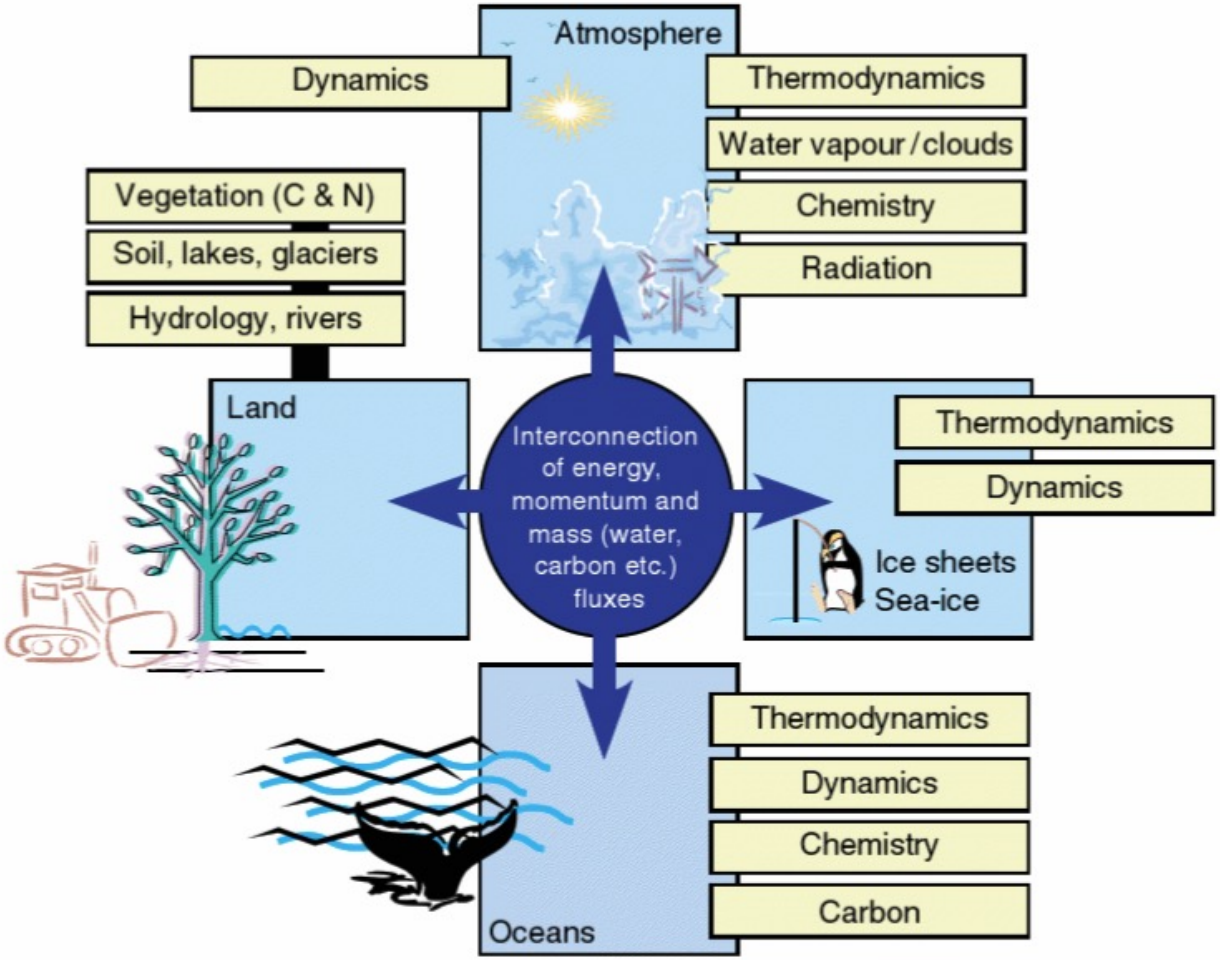
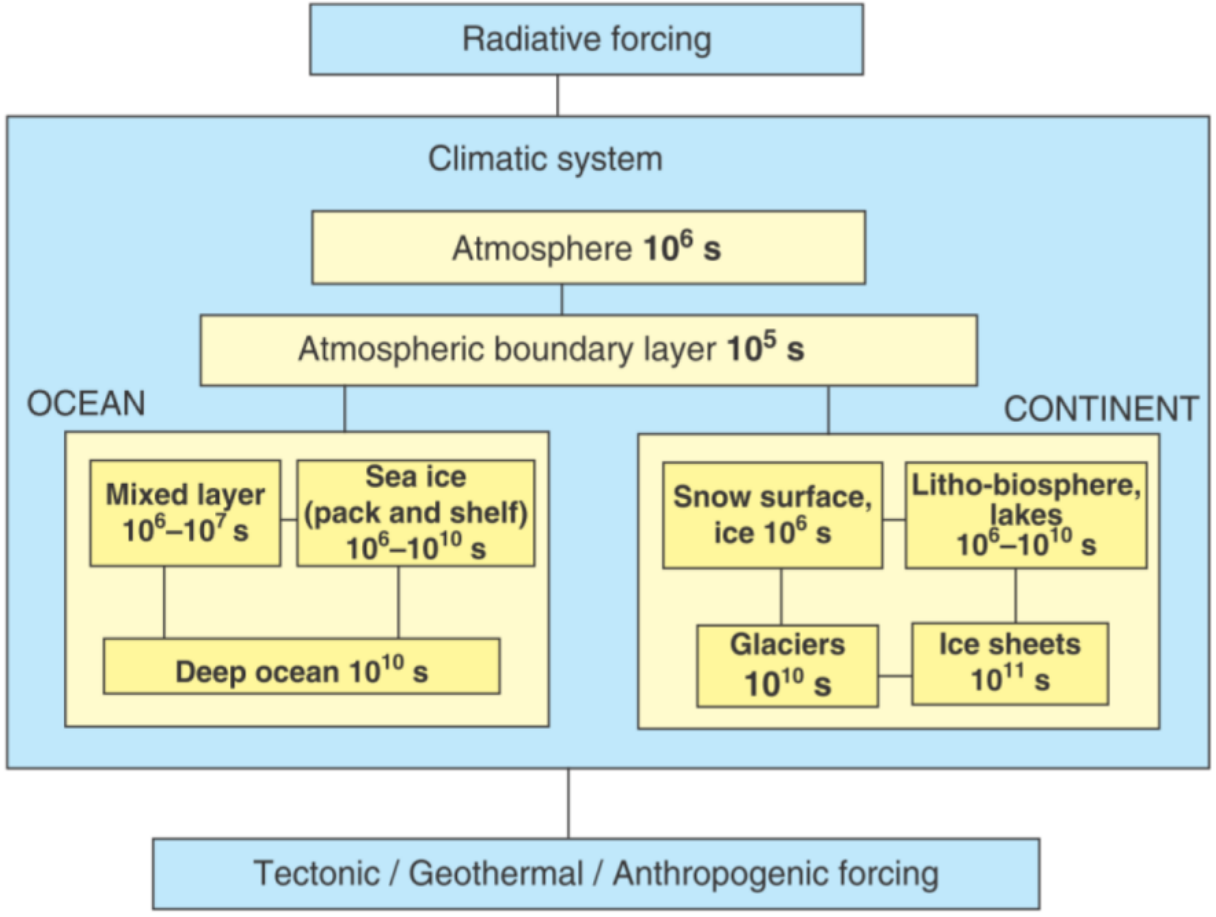


Figure 5.1 Modern coupled ocean–atmosphere models are constructed as modular components connected by a coupler (*centre*), a program that transfers fluxes between the model components. In recent years, significant effort has been devoted to formal software design and the development of portable 'plug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

COUPLING COUNSELLING

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**

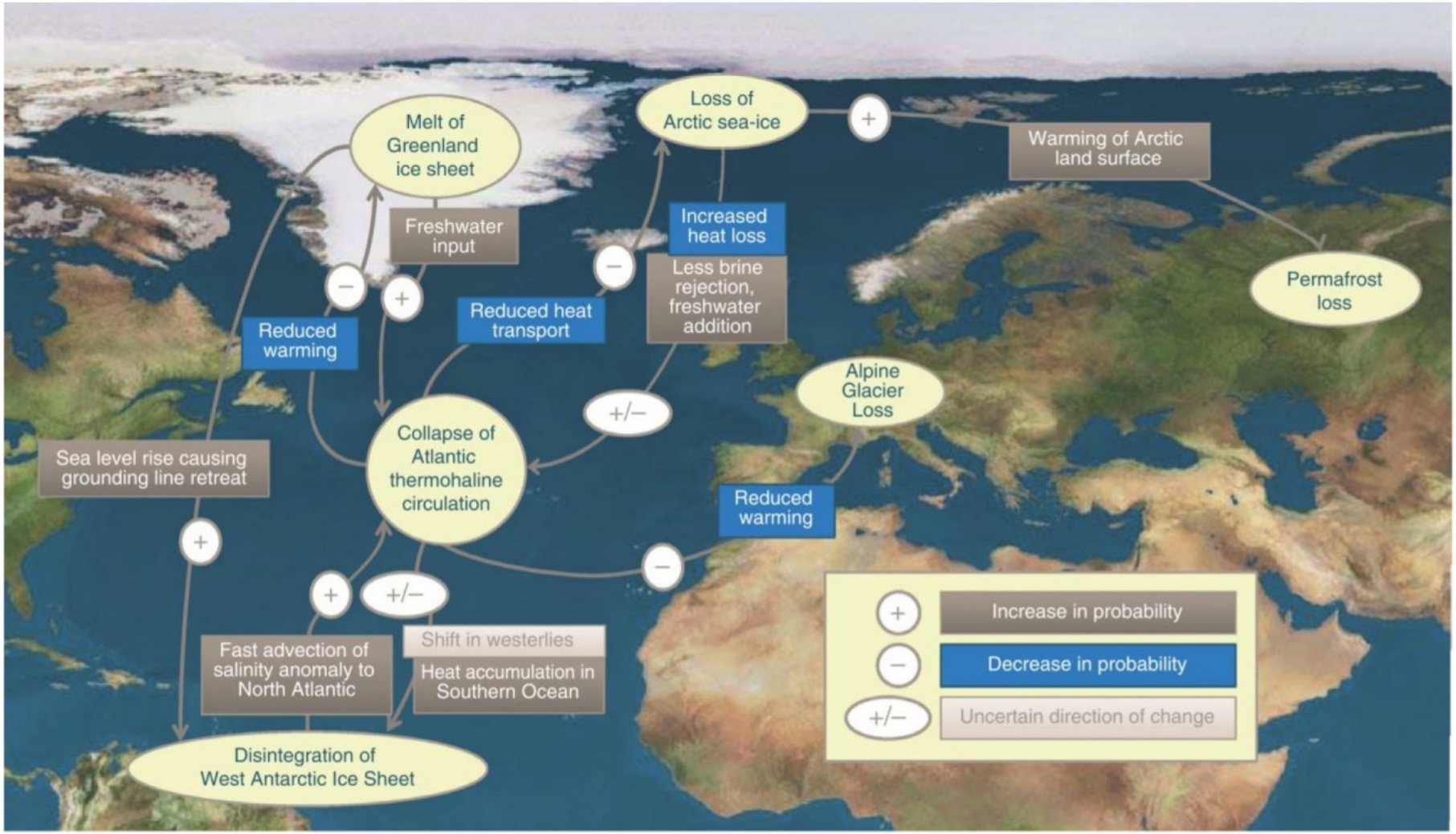


Figure 4.24 Schematic of the large set of potential links between possible 'tipping elements' in the north Atlantic and its surrounding lands. The likely direction of changes caused by global warming is shown. Source: After Levermann et al. (2012a). Reproduced with permission of Springer Science+Business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

What is model “coupling”?

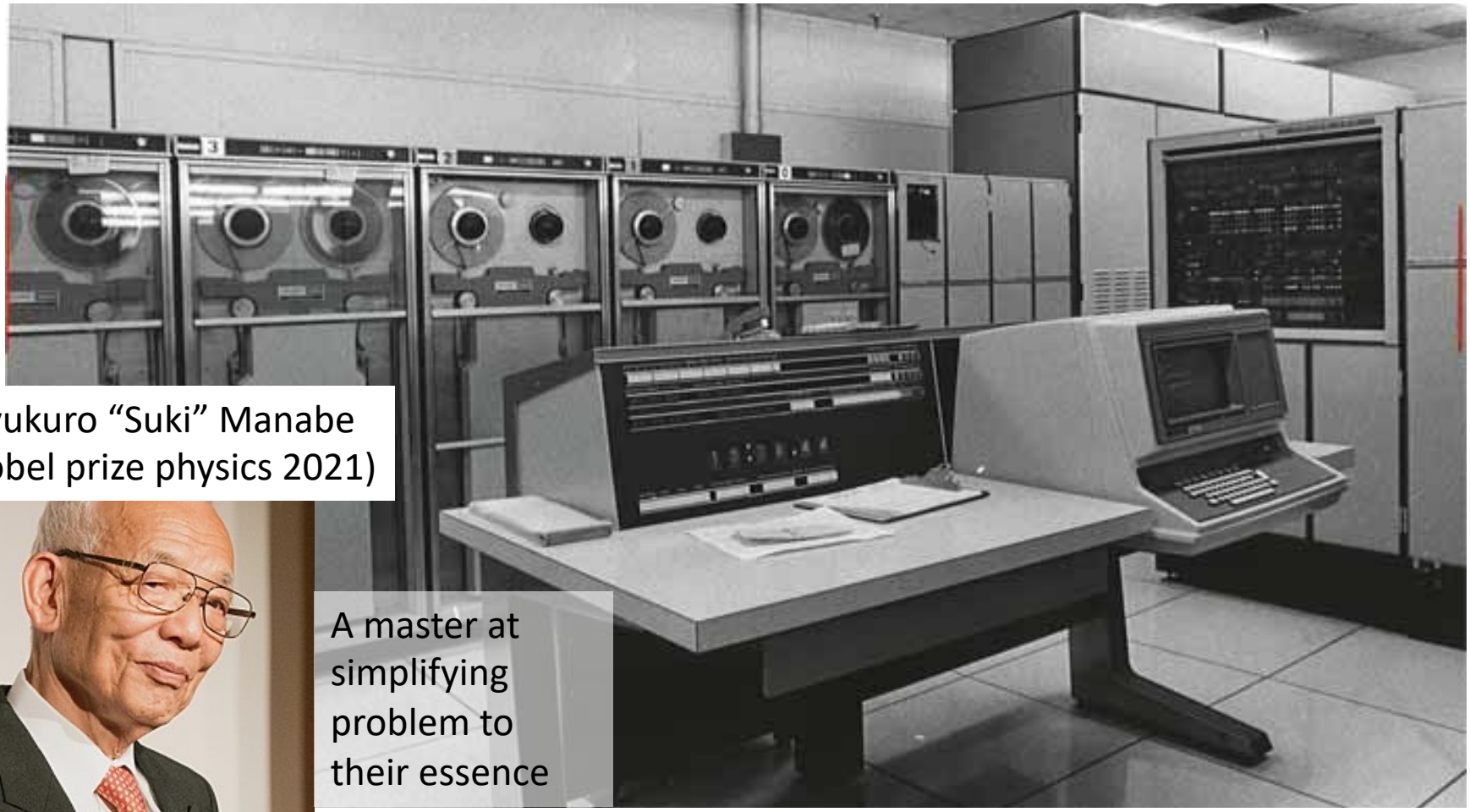
- Exchanges of properties at the interfaces:
  - Heat
  - Water
  - Momentum
  - Energy
- Modules are run quite independently, but regularly exchange information about each other’s states to calculate exchange fluxes
- Challenges:
  - Grids of various modules may not match
    - E.g. part of an atmospheric 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

1. 模型耦合的定义：
模型耦合是指在模型接口之间进行属性的交换，包括：
热量（Heat）
水（Water）
动量（Momentum）
能量（Energy）
这些属性通过接口传递，用于模型模块之间的交互。
2. 模块的运行方式：
各模块相对独立地运行，但它们需要定期交换状态信息。
这些信息交换用于计算 交换通量（exchange fluxes），确保模块间的动态交
3. 模型耦合面临的挑战：
网格不匹配（Grids of various modules may not match）：
比如，大气网格可能涵盖海洋、陆地和海冰区域，这会导致模块间的空间分
属性守恒（Properties must be conserved）：
在耦合过程中需要确保能量、质量等属性守恒。
时间尺度差异（Characteristic time-scales differ）：
每个模块的时间尺度可能不同，这会影响积分时步的选择。

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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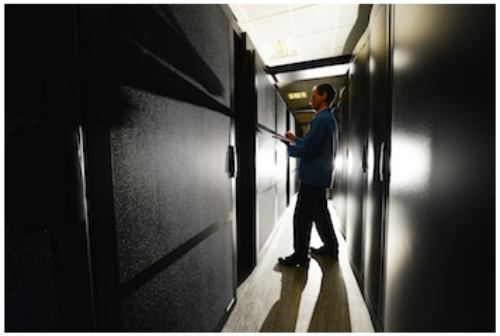
5h

ARCHER HPC Ser...

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**
- **…**

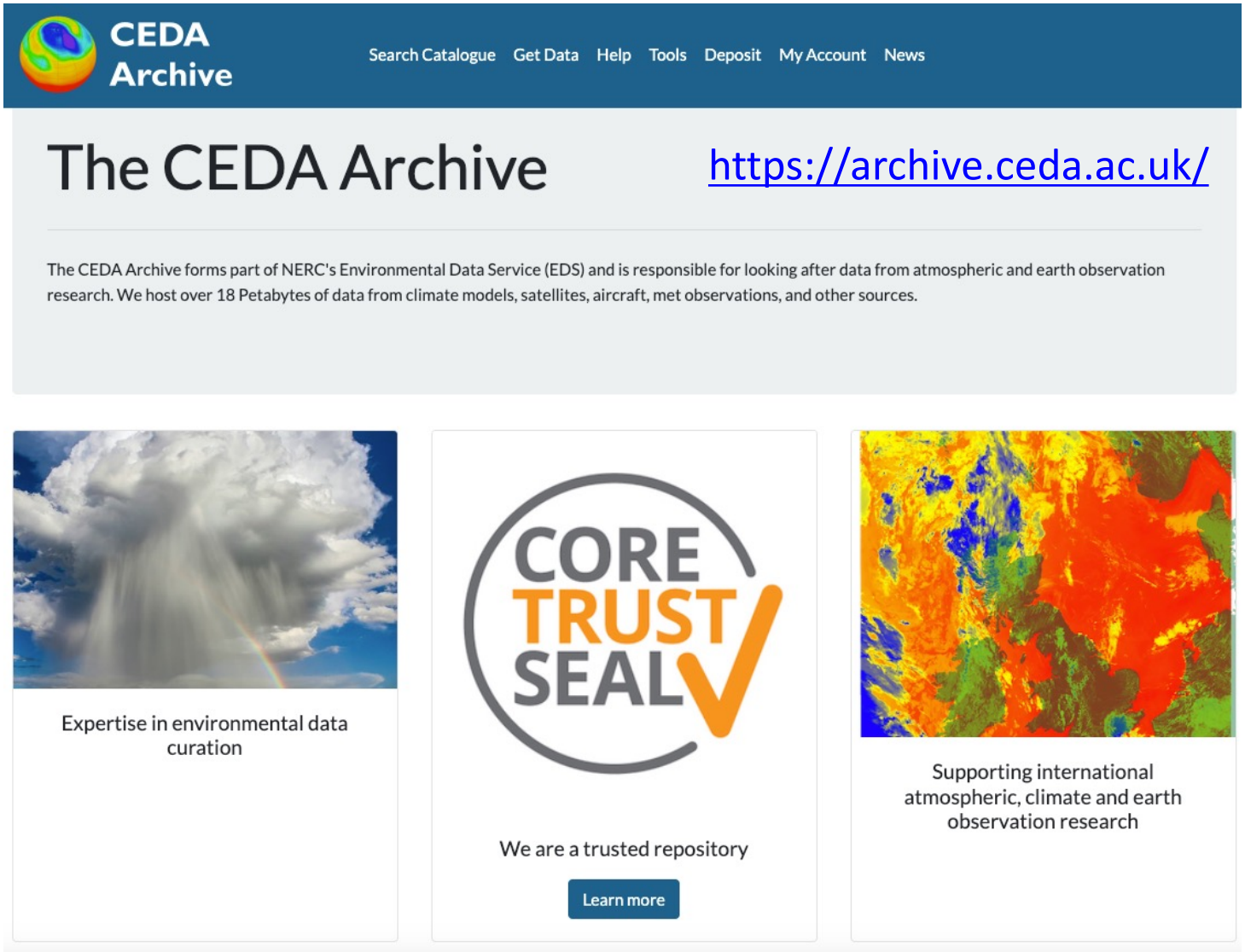
All of this requires substantial data management infrastructure

Input data

Initial conditions
Boundary conditions
Observations

Output data

Model results
4D data!
(very large!)

Derived or interpreted products

For non-expert 'consumers'