Introduction to climate modelling

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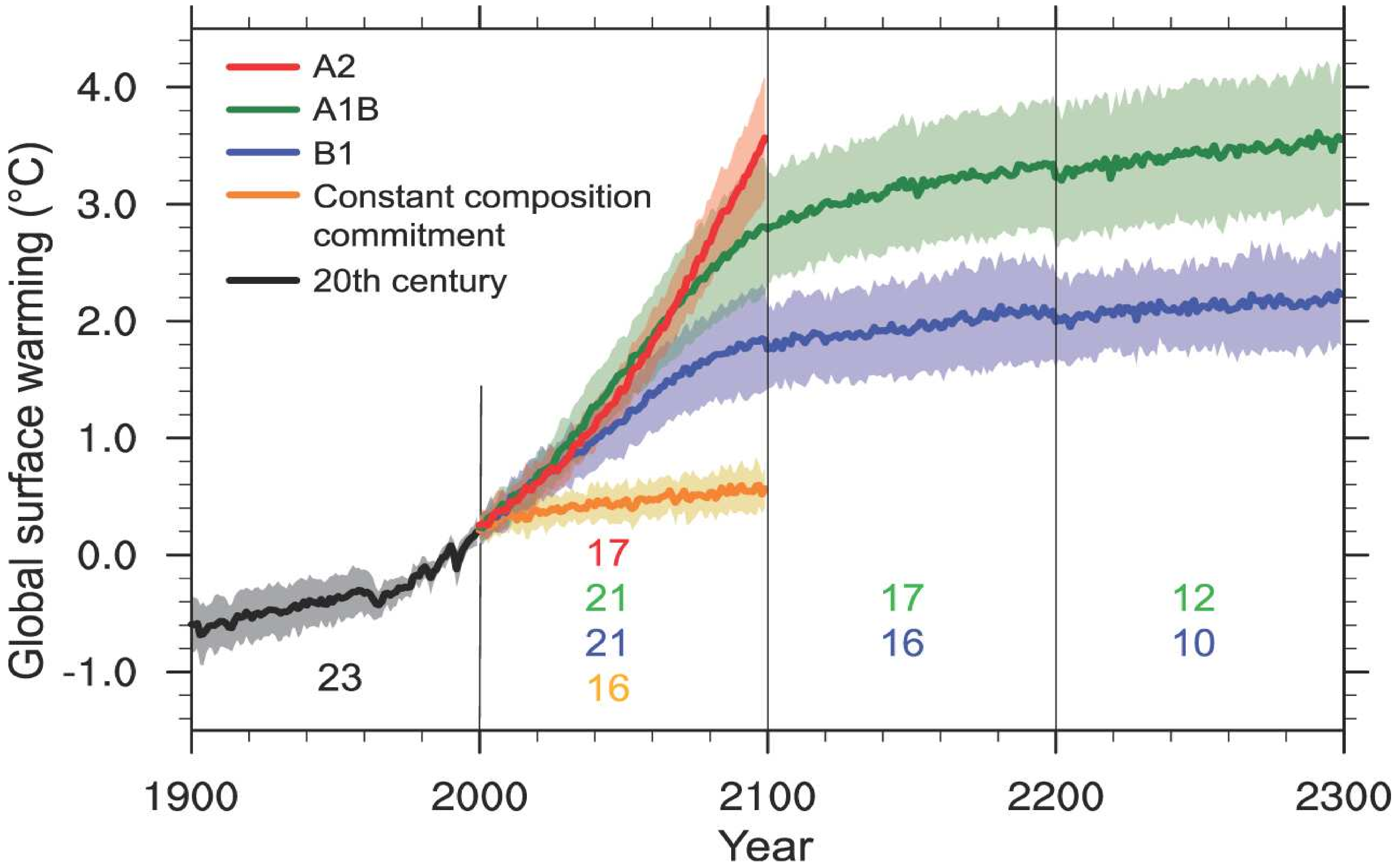
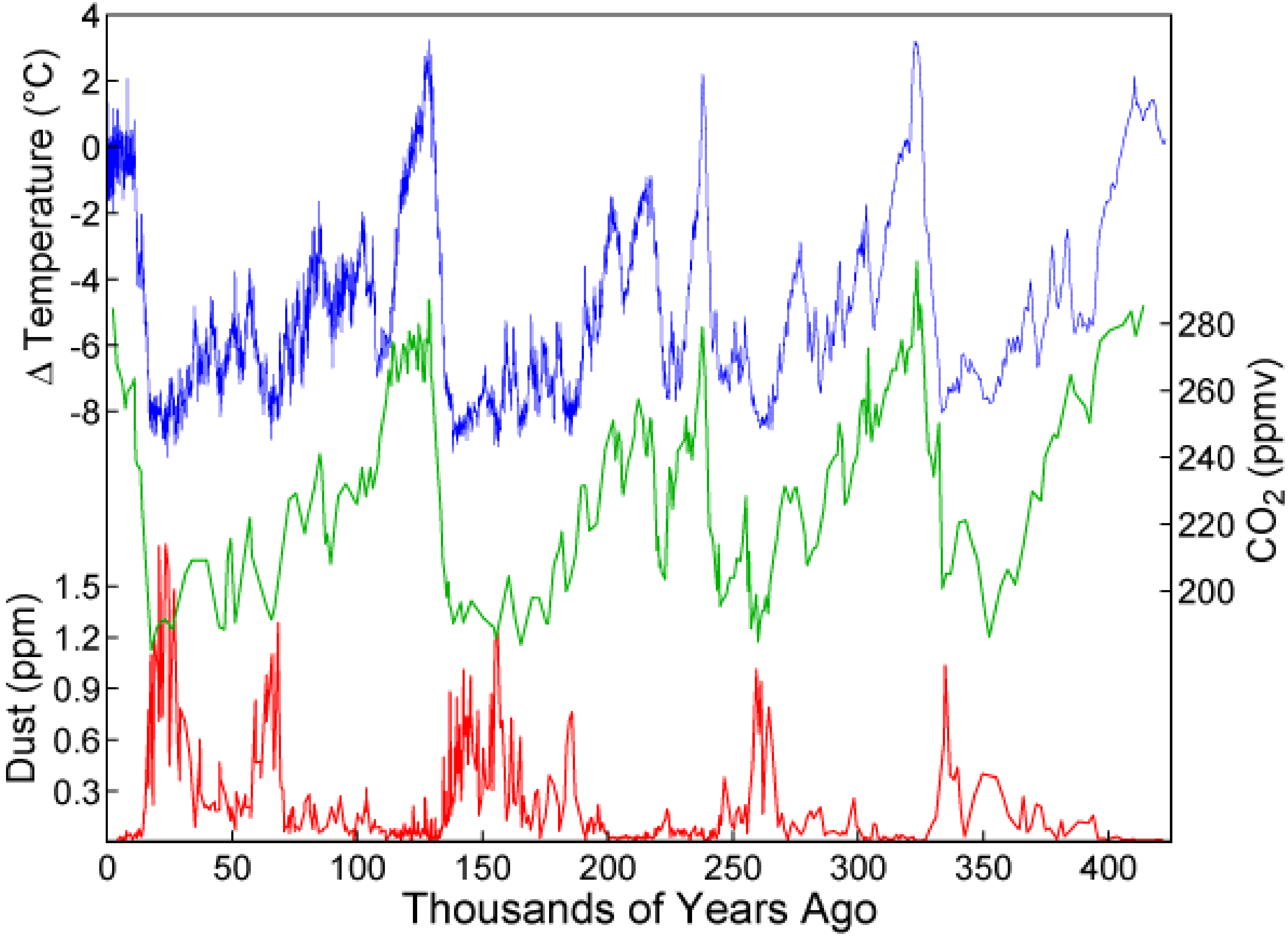
Overview

1. Why do we need climate models?
2. What is a climate model?
3. How does a climate model work?
4. How do you build a climate model?
5. How do you use a climate model?
6. Examples of climate modelling

1. Why do we need climate models?





Δ Temperature (°C)
4
2
0
-2
-4
-6
-8
CO_2 (ppmv)
280
260
240
220
200
Dust (ppm)
1.5
1.2
0.9
0.6
0.3
0
50
100
150
200
250
300
350
400
Thousands of Years Ago

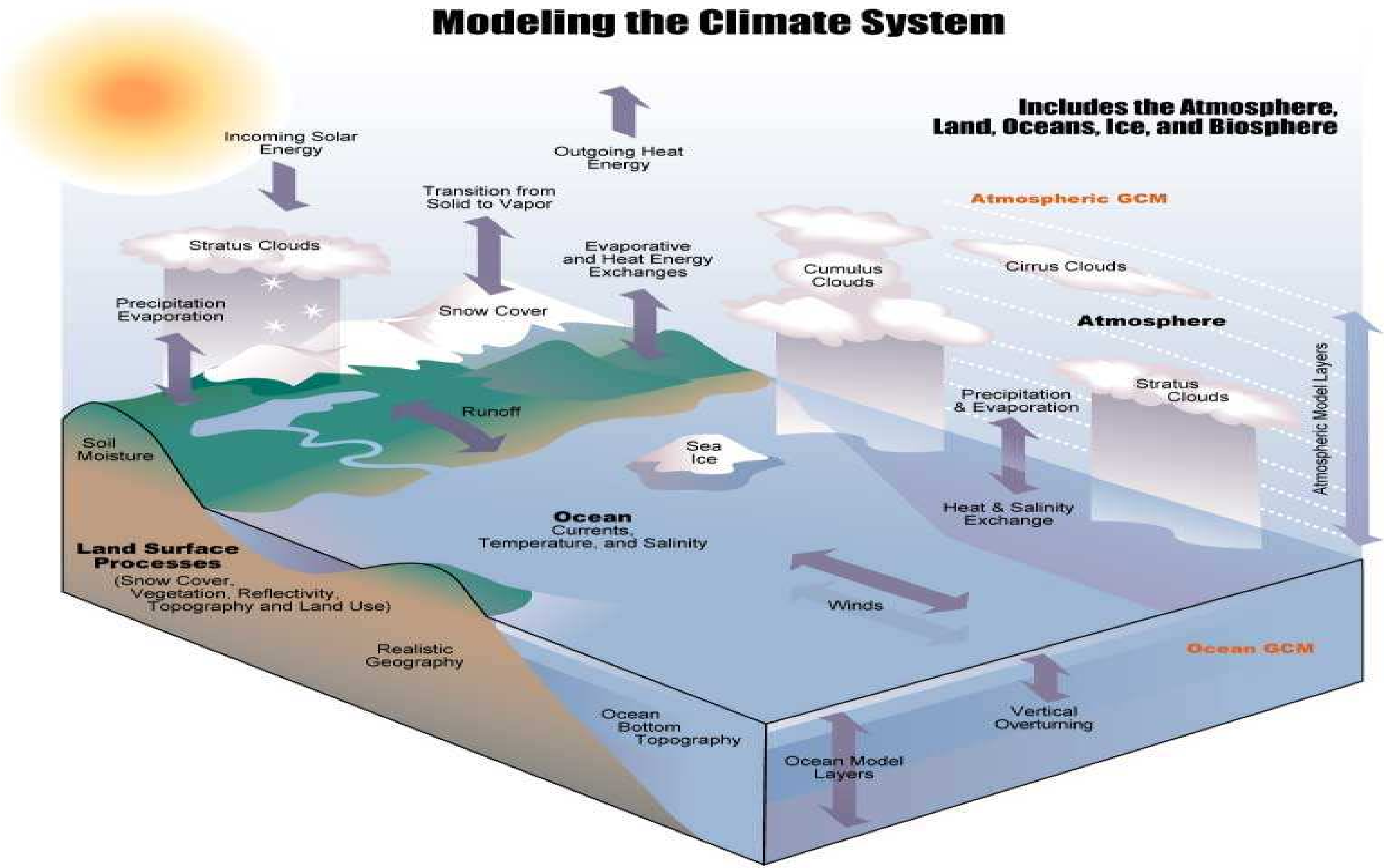
Why do we need climate models?

- There is only one Earth, and we can't (shouldn't) perform experiments on that
- We can't travel in time
- We want to predict possible future climate states
- We want to understand past climatic changes
- We want to explore properties of the climate system
- We want to answer *questions* - these can range from *scientific* questions to *policy* questions

2. What is a climate model?

- A *virtual* Earth
- A computer program (usually very long and complex)
- Solves the fundamental physical equations that describe the evolution of the climate system
- Divides the Earth into discrete components
- Different types of models: simple vs. complex, low-resolution vs. high-resolution, regional vs. global
- A model is a *tool* - the type that you use depends upon the question that you want to answer
- *No* model is a perfect representation of the real world

A virtual Earth



A computer program

```
c...  Calculate density
      p2 = p*p
      p3 = p*p2
      do i = 1, imt
        s15(i) = s(i)*sqrt(s(i))
        s2(i) = s(i)*s(i)
        t2(i) = t(i)*t(i)
        t3(i) = t(i)*t2(i)
        t4(i) = t(i)*t3(i)
        rho(i) = (a0 + a1*t(i) + a2*t2(i) + a3*t3(i) + a4*s(i) +
     &             a5*s(i)*t(i) + a6*s2(i) + a7*p + a8*p*t2(i) +
     &             a9*p*s(i) + a10*p2 + a11*p2*t2(i)) /
     &            (b0 + b1*t(i) + b2*t2(i) + b3*t3(i) + b4*t4(i) +
     &             b5*s(i) + b6*s(i)*t(i) + b7*s(i)*t3(i) + b8*s15(i) +
     &             b9*s15(i)*t2(i) + b10*p + b11*p2*t3(i) + b12*p3*t(i))
      end do
```

Solves fundamental physical equations

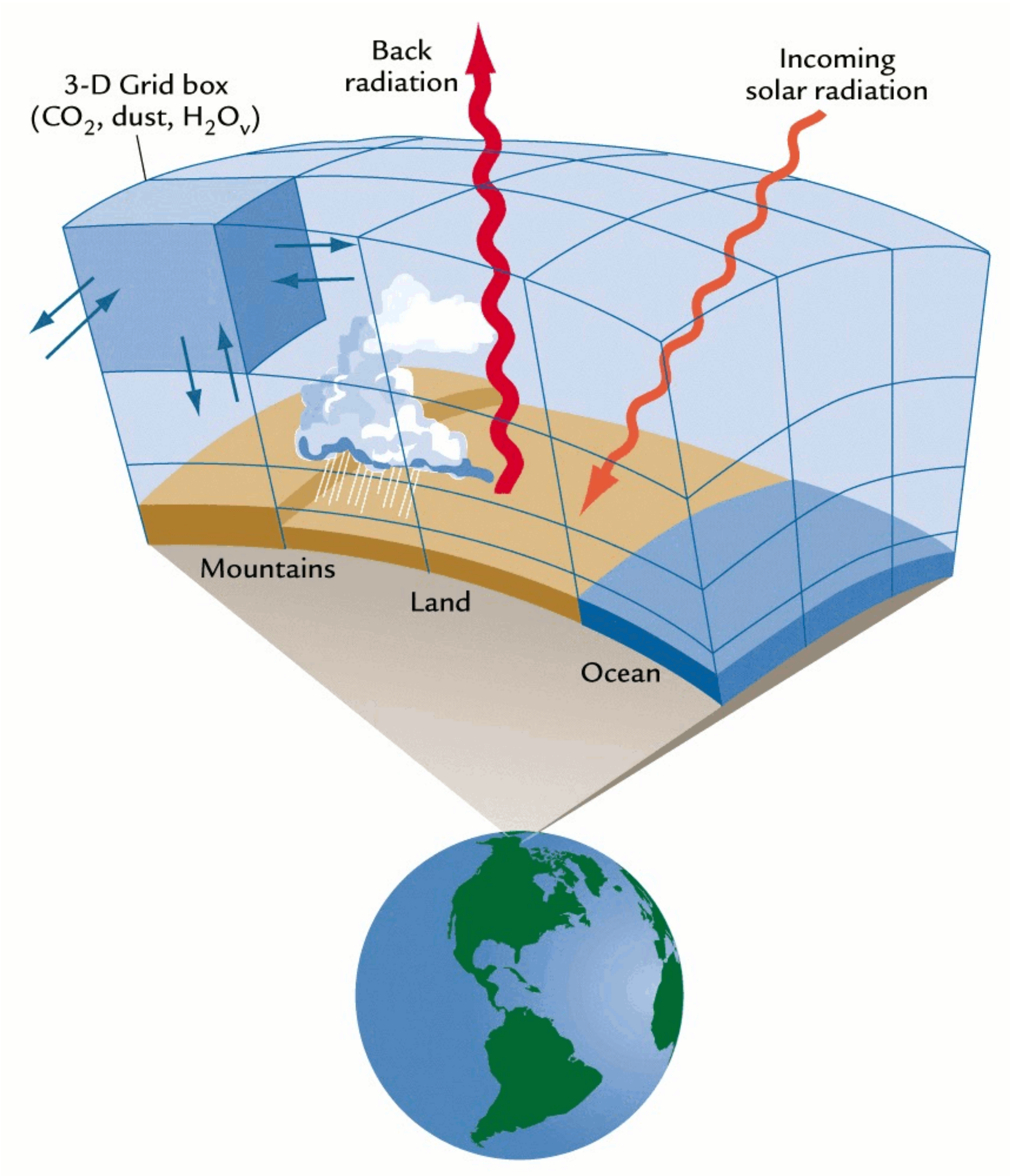
$$\rho(S, \theta, p) = \frac{P_1(S, \theta, p)}{P_2(S, \theta, p)} \tag{1}$$

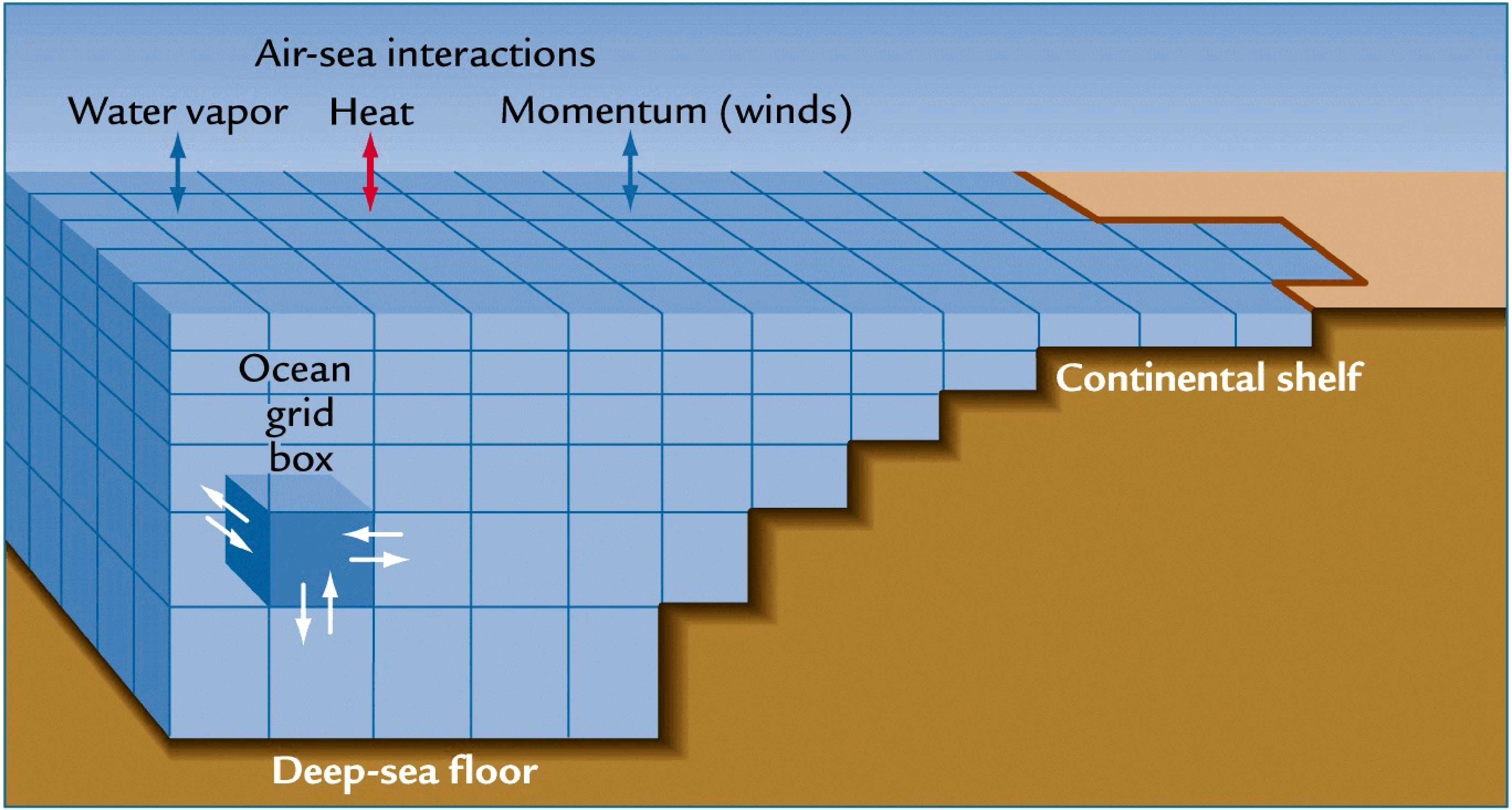
where

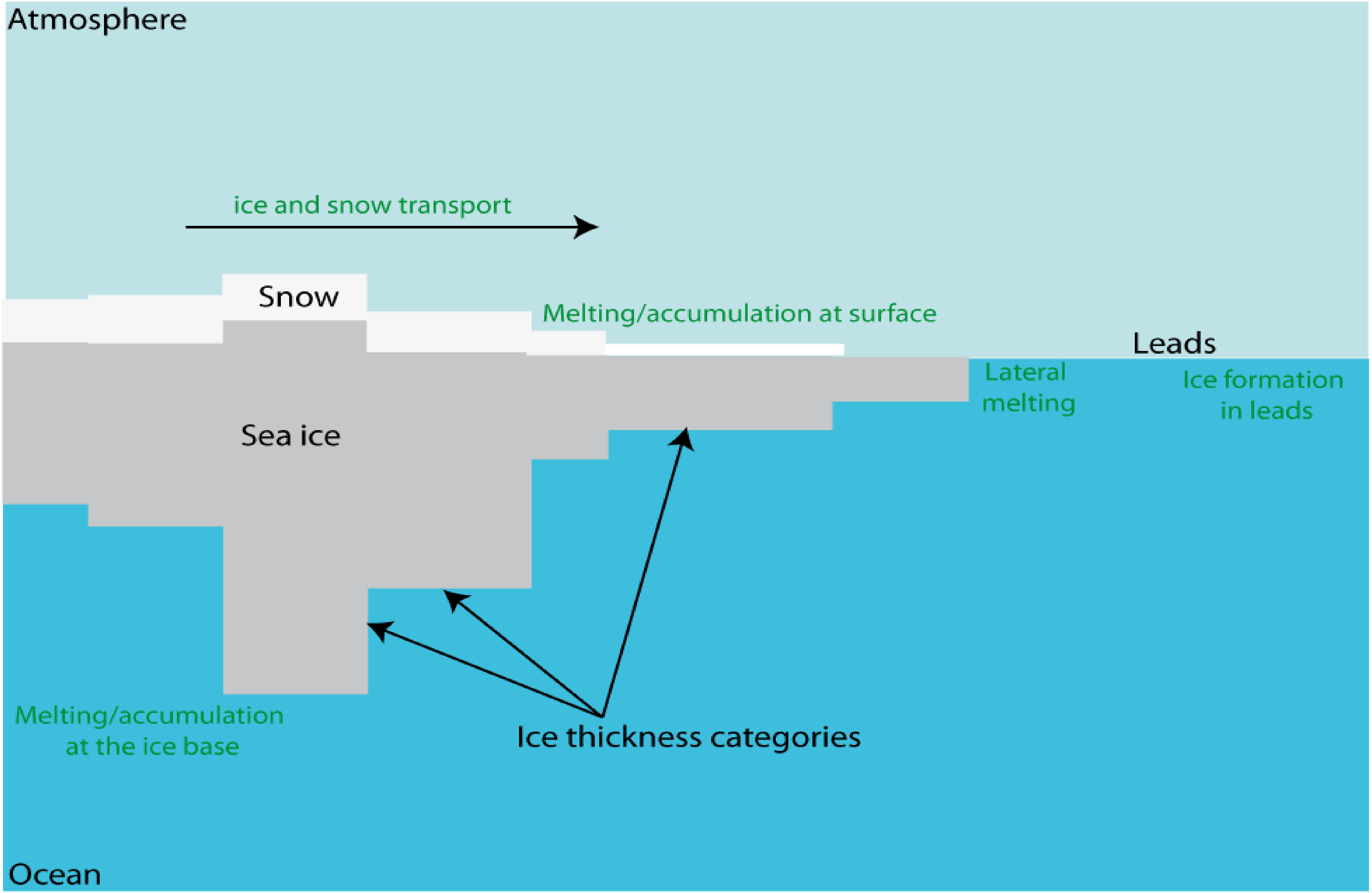
$$\begin{aligned} P_1(S, \theta, p) &= a_0 + a_1\theta + a_2\theta^2 + a_3\theta^3 + a_4 S \\ &+ a_5 S\theta + a_6 S^2 + a_7 p + a_8 p\theta^2 \\ &+ a_9 pS + a_{10} p^2 + a_{11} p^2\theta^2 \end{aligned} \tag{2}$$

$$\begin{aligned} P_2(S, \theta, p) &= b_0 + b_1\theta + b_2\theta^2 + b_3\theta^3 + b_4\theta^4 \\ &+ b_5 S + b_6 S\theta + b_7 S\theta^3 + b_8 S^{\frac{3}{2}} \\ &+ b_9 S^{\frac{3}{2}}\theta^2 + b_{10} p + b_{11} p^2\theta^3 + b_{12} p^3\theta \end{aligned} \tag{3}$$

Divides the Earth into discrete components




Air-sea interactions
Water vapor
Heat
Momentum (winds)
Ocean grid box
Continental shelf
Deep-sea floor


Atmosphere
ice and snow transport
Snow
Melting/accumulation at surface
Leads
Lateral melting
Ice formation in leads
Sea ice
Melting/accumulation at the ice base
Ice thickness categories
Ocean

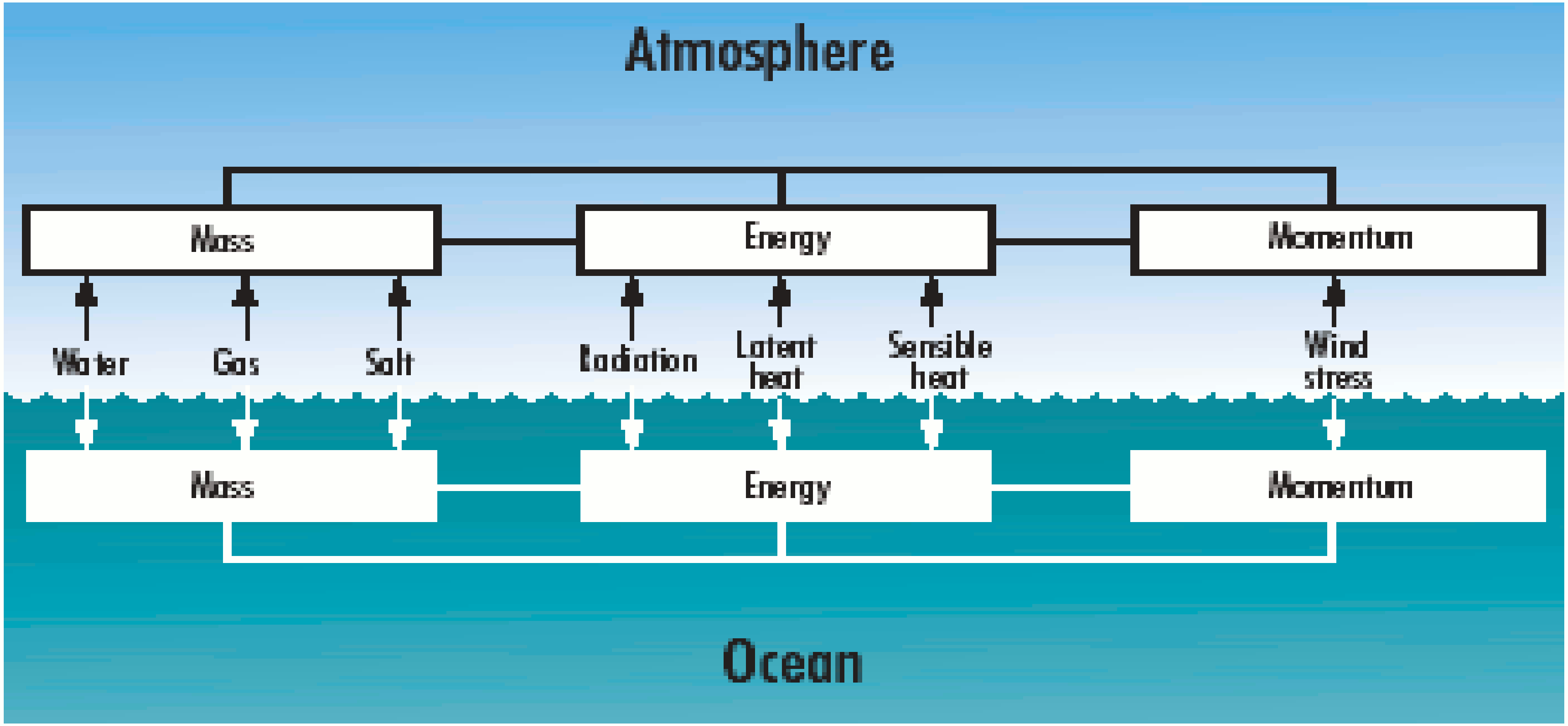


Figure 53. A schematic representation of the essential components of a fully coupled general circulation model, based on the conservation of mass, energy and momentum in the atmosphere and ocean, and the physical processes involved in the coupling between them.

Different types of models

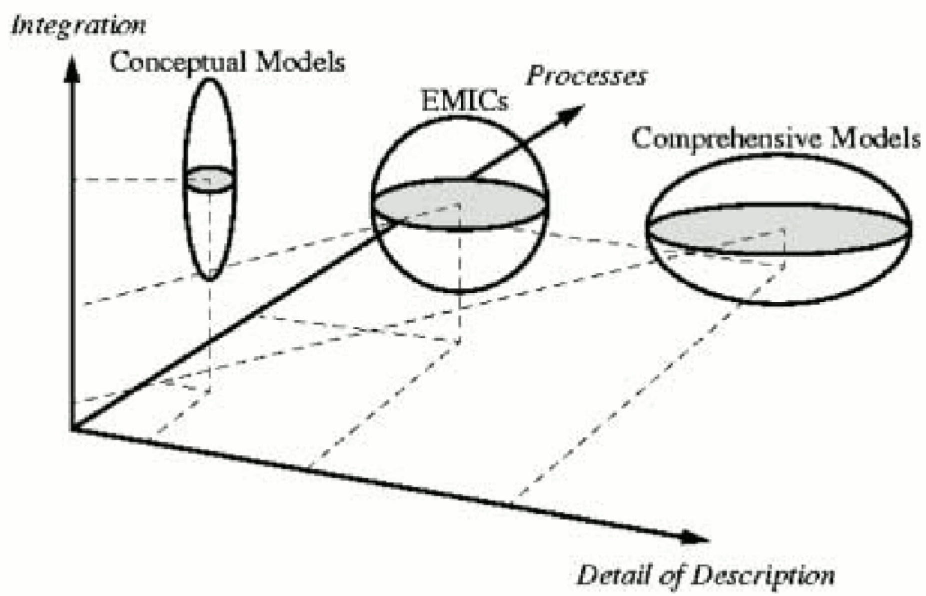


Fig. 1. Pictorial definition of EMICs. Adapted from Claussen (2000)

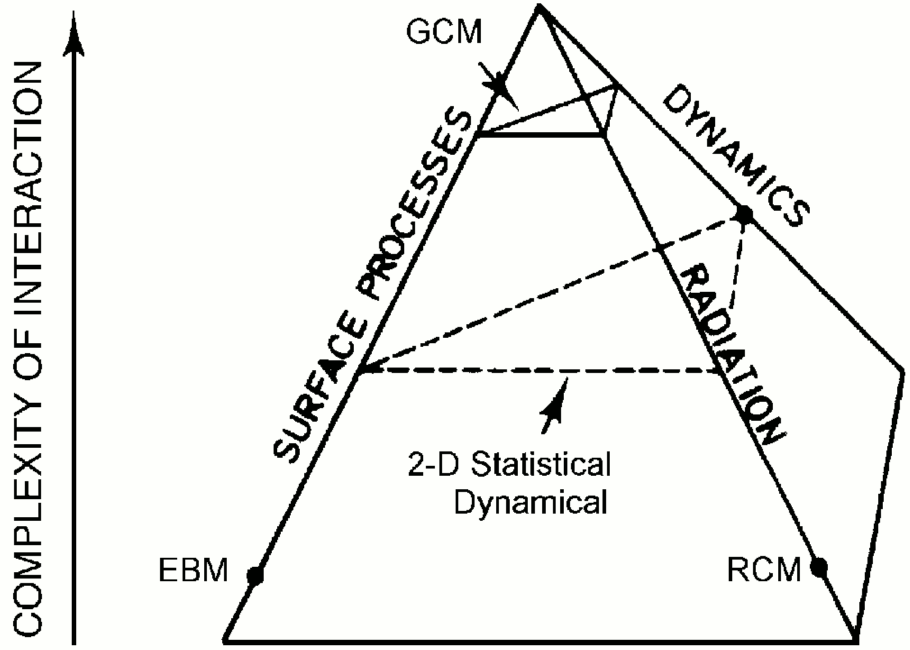
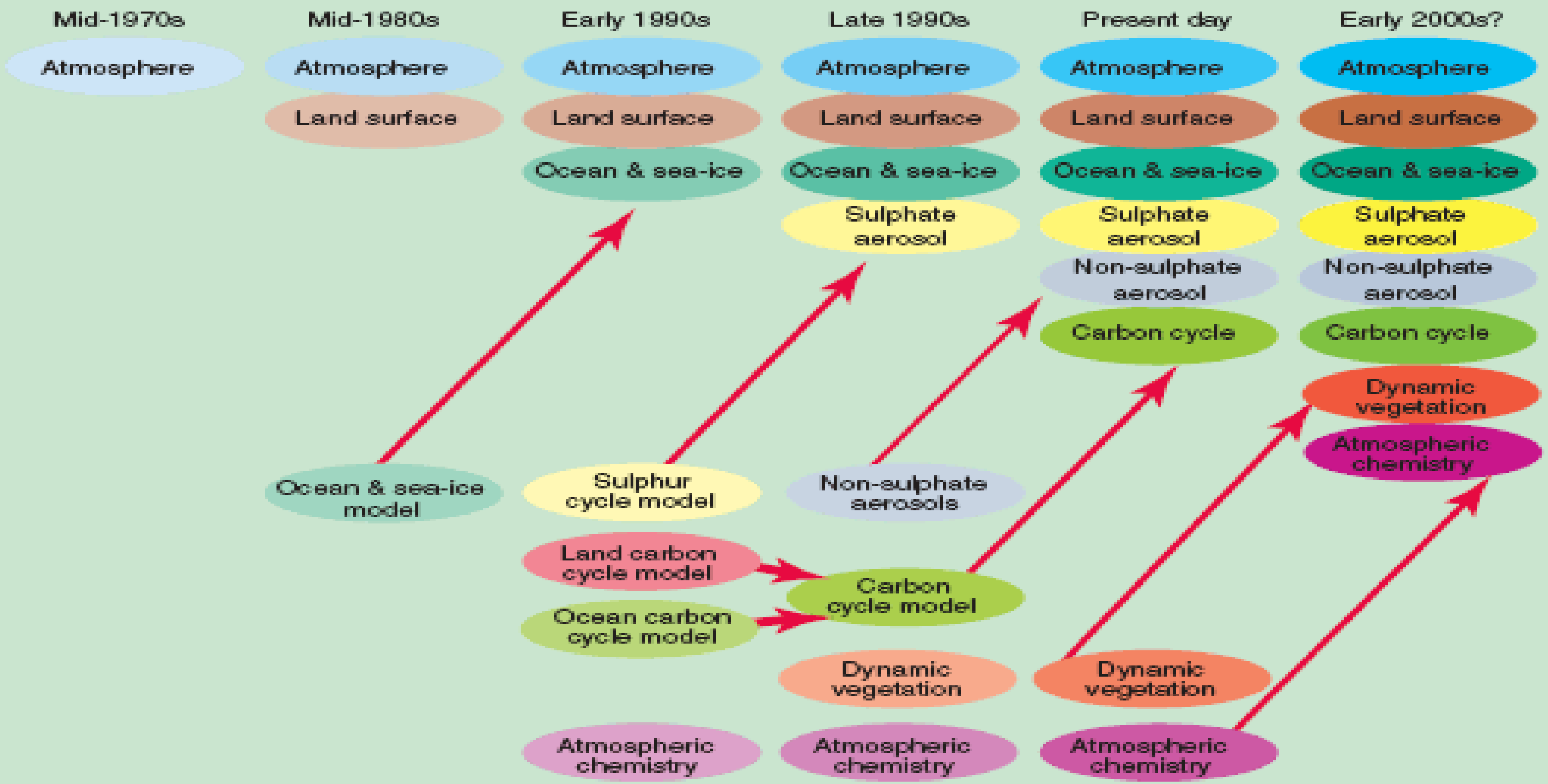


Fig. 2. The climate modeling pyramid. Adapted from Henderson-Sellers and McGuffie (1987)

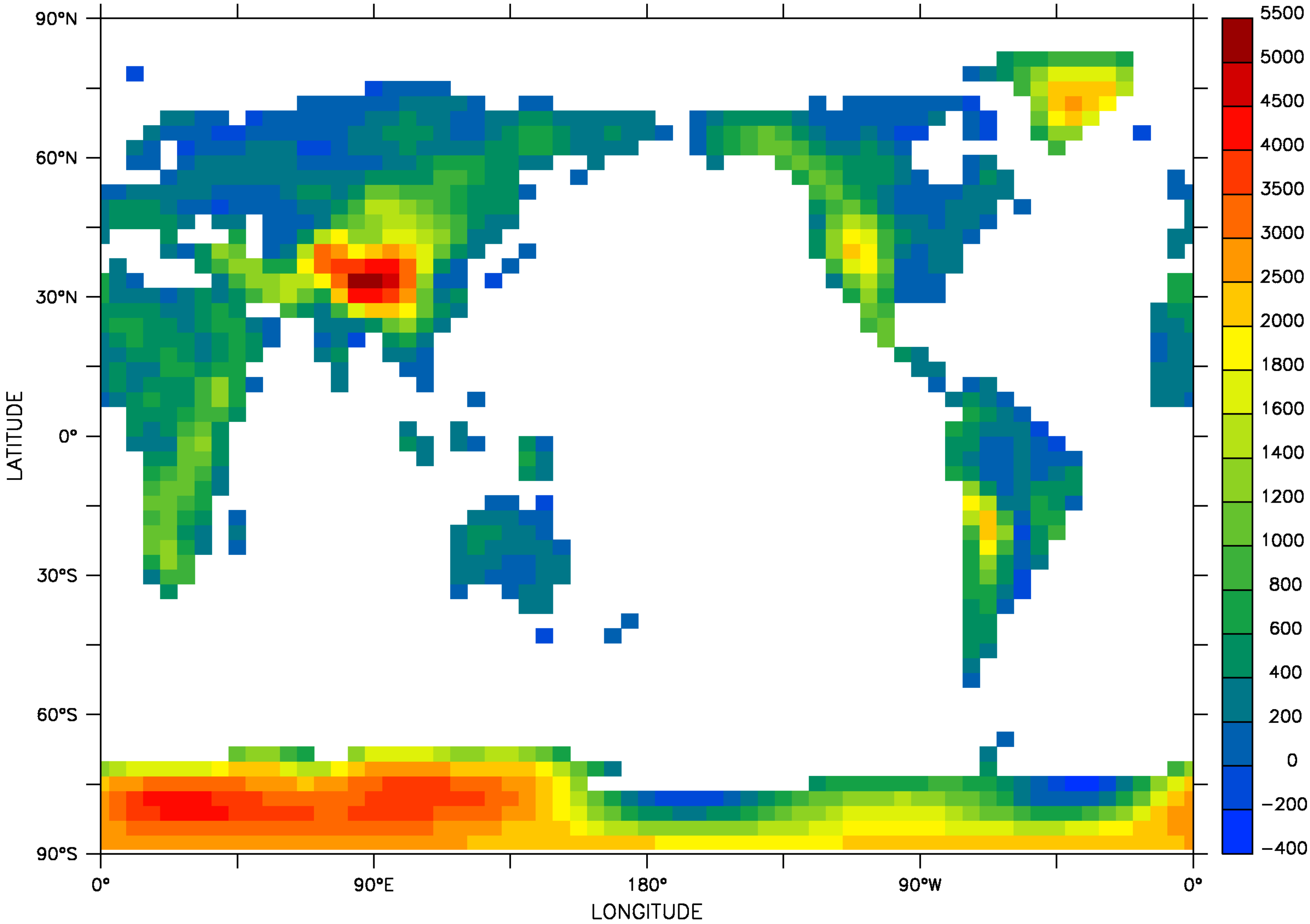
The Development of Climate models, Past, Present and Future



Box 3, Figure 1: The development of climate models over the last 25 years showing how the different components are first developed separately and later coupled into comprehensive climate models.

Limitations on the accuracy of climate models

- Lack of understanding of physical processes: if we don't understand a process, we can't describe it within a model
- Computational limitations:
  - It's impossible to include all physical processes in a single model, so some processes are always missing
  - Limited spatial resolution
- Essential to comprehensively evaluate a model before trusting the output

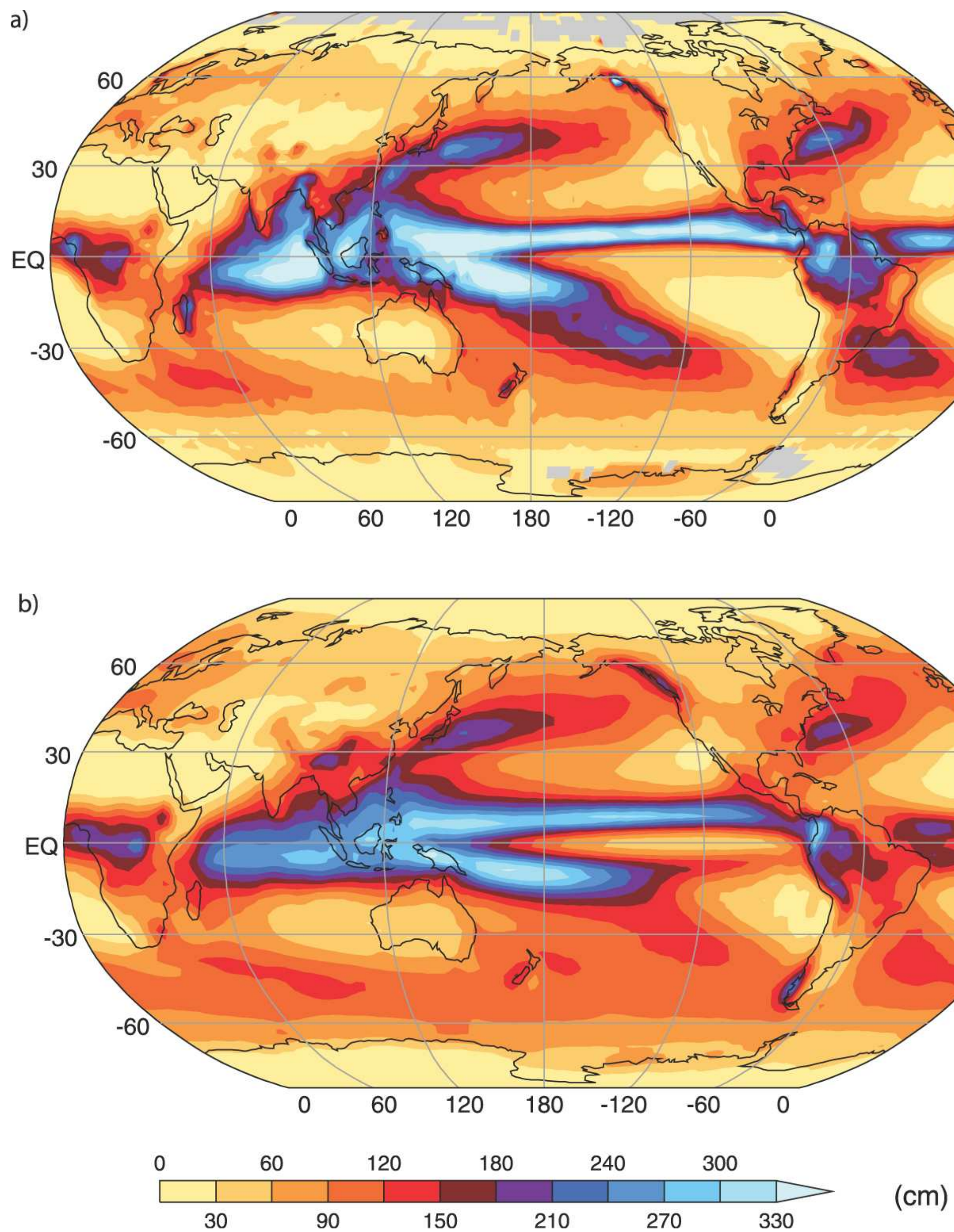


90°N
60°N
30°N
0°
30°S
60°S
90°S
LATITUDE
0°
90°E
180°
90°W
0°
LONGITUDE
5500
5000
4500
4000
3500
3000
2500
2000
1800
1600
1400
1200
1000
800
600
400
200
0
−200
−400

Models work!

- The figures on the right show annual rainfall

- Which is observed and which is modelled?



3. How does a climate model work?

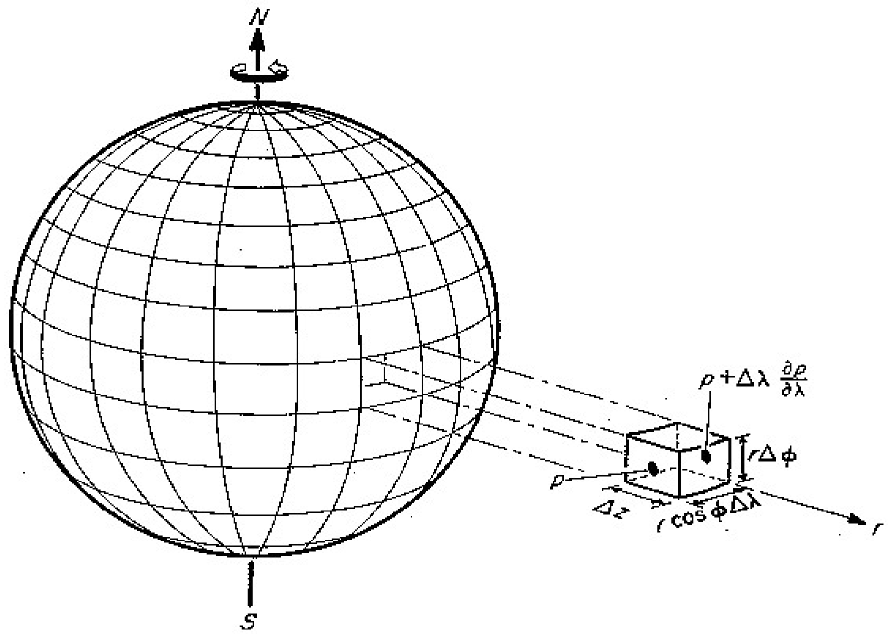
- A climate model accepts input data:
  - Initial conditions
  - Boundary conditions
- Iterates forwards in time, typically using an interval of 15 minutes to 1 hour
- Starting from the initial state of the climate system, applies physical laws to calculate the state of the climate system at the next time interval
- Repeats this process for as long as necessary
- Generates output data (lots!)

Climate Modelling

Governing equations

Boundary conditions

Initial conditions



Output

4. How do you build a climate model?

- Identify the processes to be modelled
- Identify the quantities to be modelled
- Identify the relationships between these quantities
- Express these relationships mathematically
- Write computer code to solve these equations

How do you build a climate model?

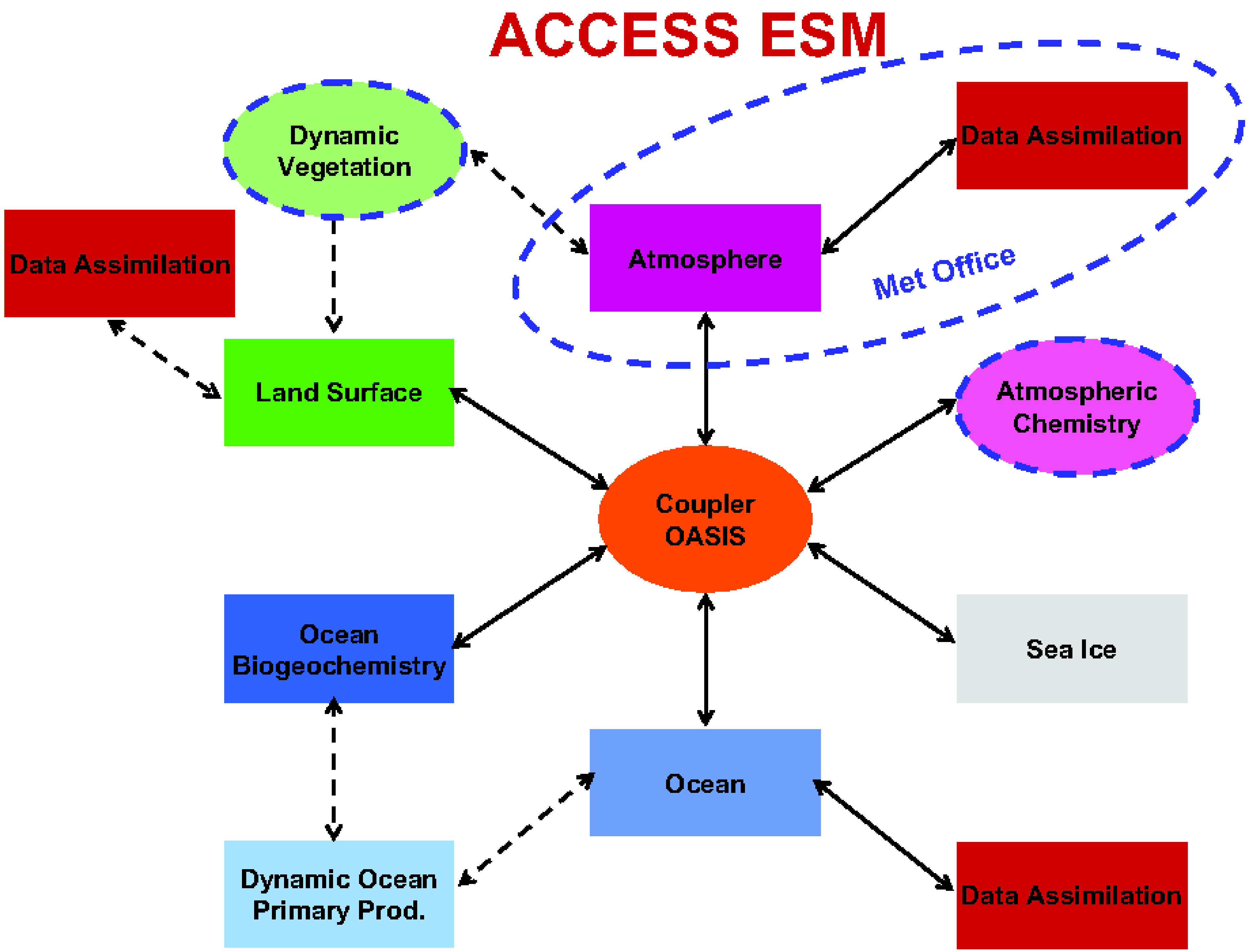
- Traditional approach:
  - Develop a computer program from scratch
- Modern approach:
  - Take existing components and combine them
- Test and debug
- Determine the optimal parameter settings (“tuning”)
- Evaluate, evaluate, evaluate...

How do you build a climate model?

- *Very* specialised and time-consuming process
- The end result is a very large and complex computer program
- A typical state-of-the-art climate model:
  - represents *hundreds* of person-years of work
  - consists of hundreds of thousands, or even millions, of lines of computer code
  - is very computationally expensive
  - generates enormous amounts of data

Case study: ACCESS

- Australian Community Climate and Earth System Simulator
- Atmosphere: Unified Model (UK)
- Ocean: MOM4 (USA)
- Sea ice: CICE (USA)
- Land surface: CABLE (Australia)
- Coupler: OASIS (France)
- Around one million lines of source code
- Can simulate around 2-3 years per day
- Generates up to 50 GB of data for each year



ACCESS ESM
Dynamic Vegetation
Data Assimilation
Atmosphere
Data Assimilation
Met Office
Land Surface
Atmospheric Chemistry
Coupler OASIS
Ocean Biogeochemistry
Sea Ice
Ocean
Dynamic Ocean Primary Prod.
Data Assimilation

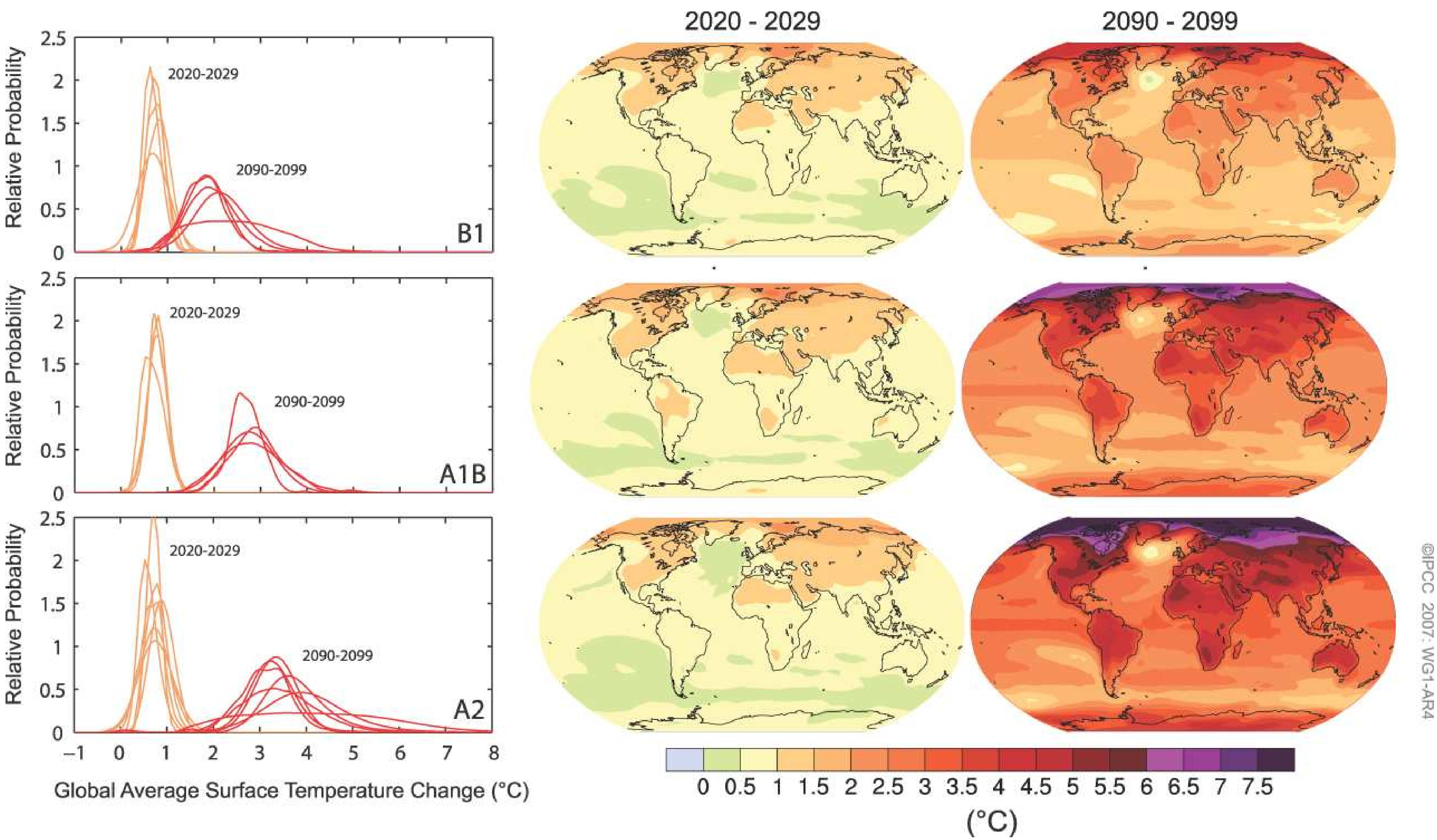
5. How do you use a climate model?

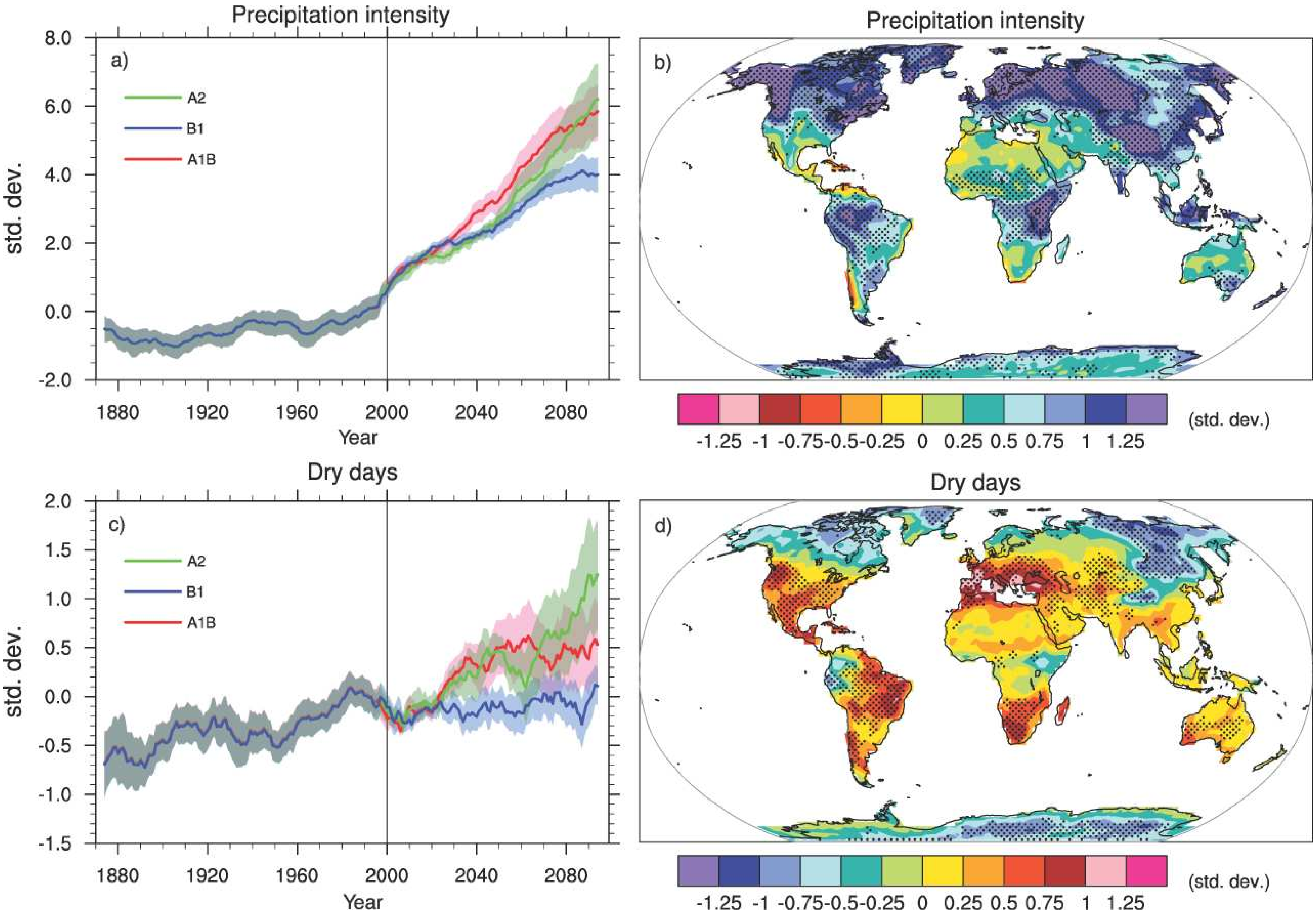
- Select the question that you want to answer
- Select an appropriate model
- Configure the model accordingly:
  - Initial conditions
  - Boundary conditions
- Find a big enough computer, and somewhere to store the data...

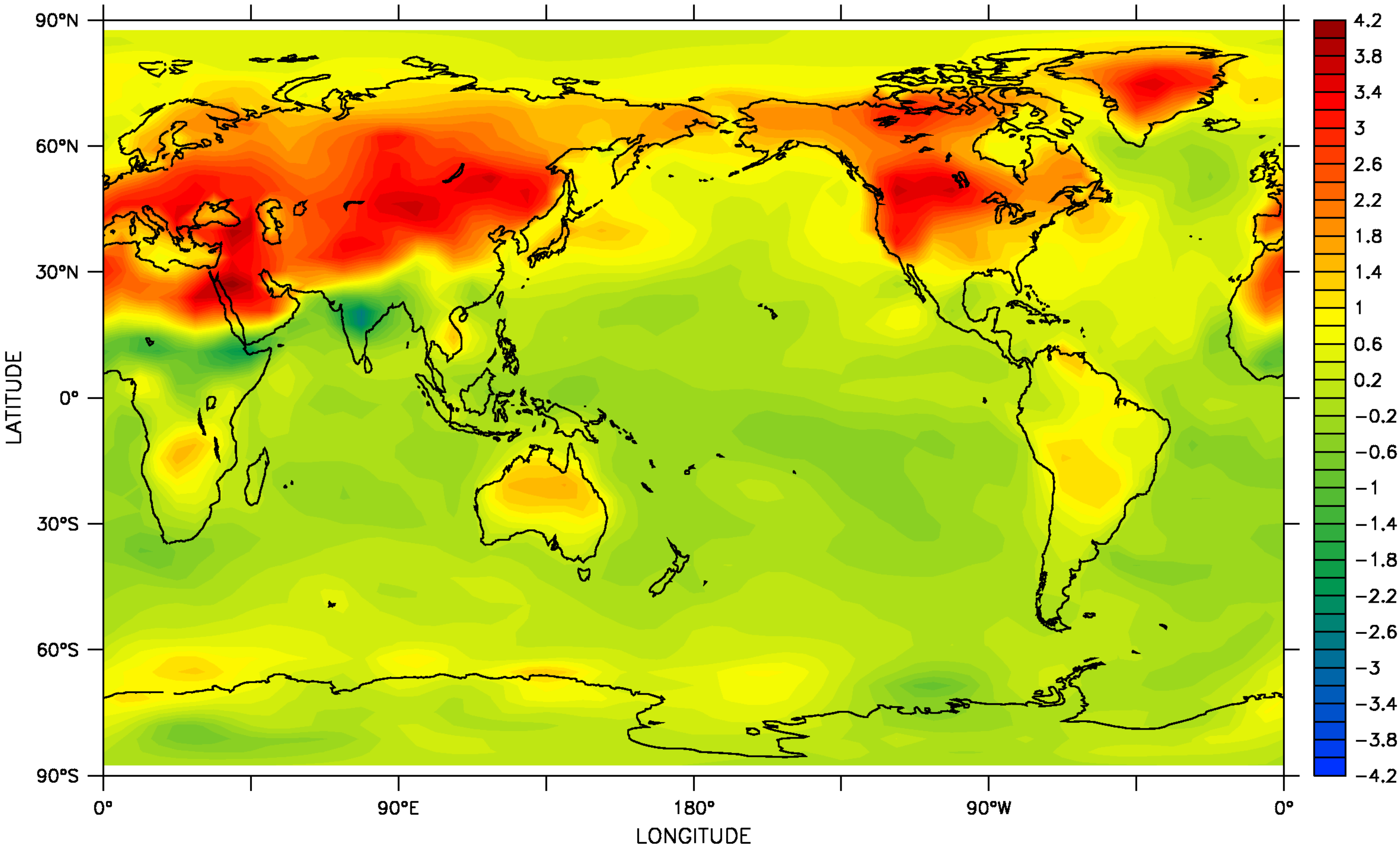
National Facility, Canberra

National Facility, Canberra

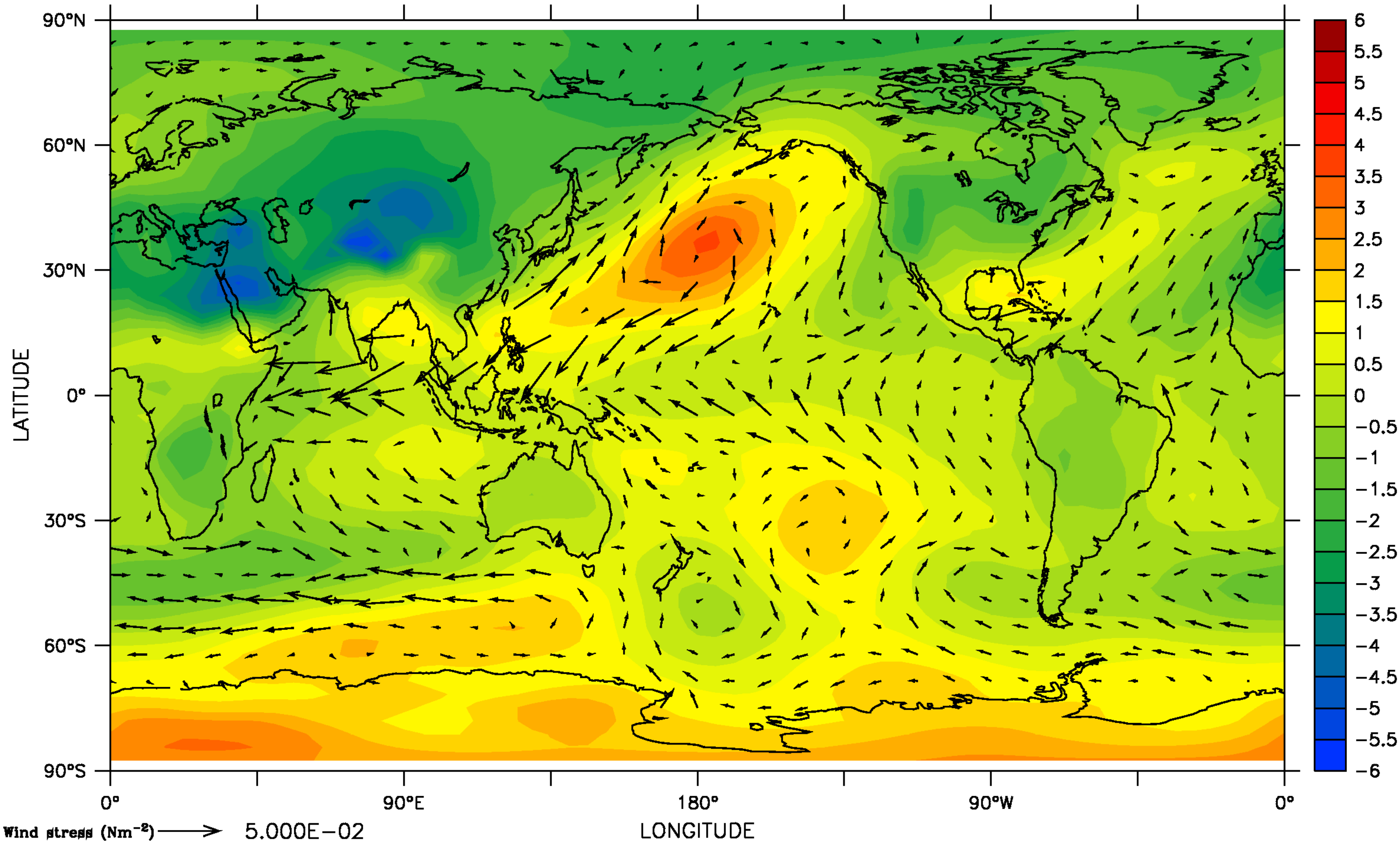
6. Examples of climate modelling




Precipitation intensity
a)
A2
B1
A1B
std. dev.
8.0
6.0
4.0
2.0
0.0
-2.0
1880
1920
1960
2000
2040
2080
Year
Precipitation intensity
b)
-1.25 -1 -0.75 -0.5 -0.25 0 0.25 0.5 0.75 1 1.25
(std. dev.)
Dry days
c)
A2
B1
A1B
std. dev.
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
1880
1920
1960
2000
2040
2080
Year
Dry days
d)
-1.25 -1 -0.75 -0.5 -0.25 0 0.25 0.5 0.75 1 1.25
(std. dev.)



June−July−August surface air temperature, 8ka minus 0ka BP (°C)



June−July−August mean sea level pressure, 8ka minus 0ka BP (hPa)