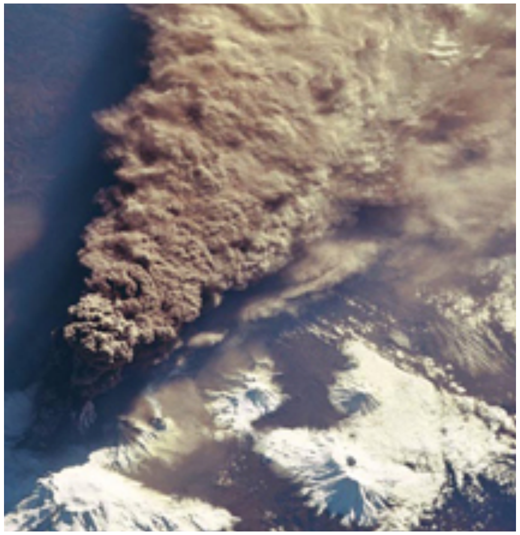
Lecture 3 – Climate Models



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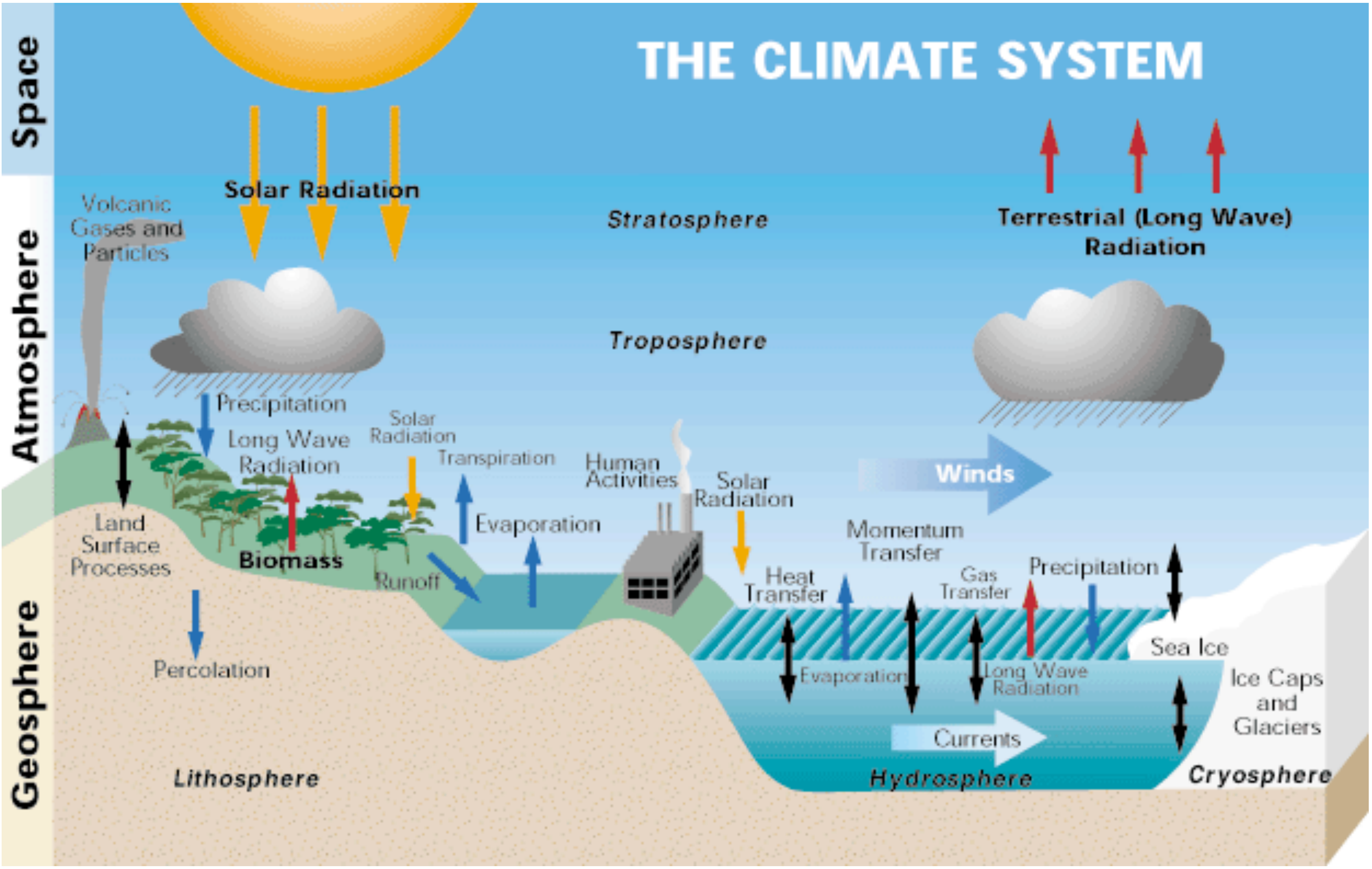
Climate Change Research Centre

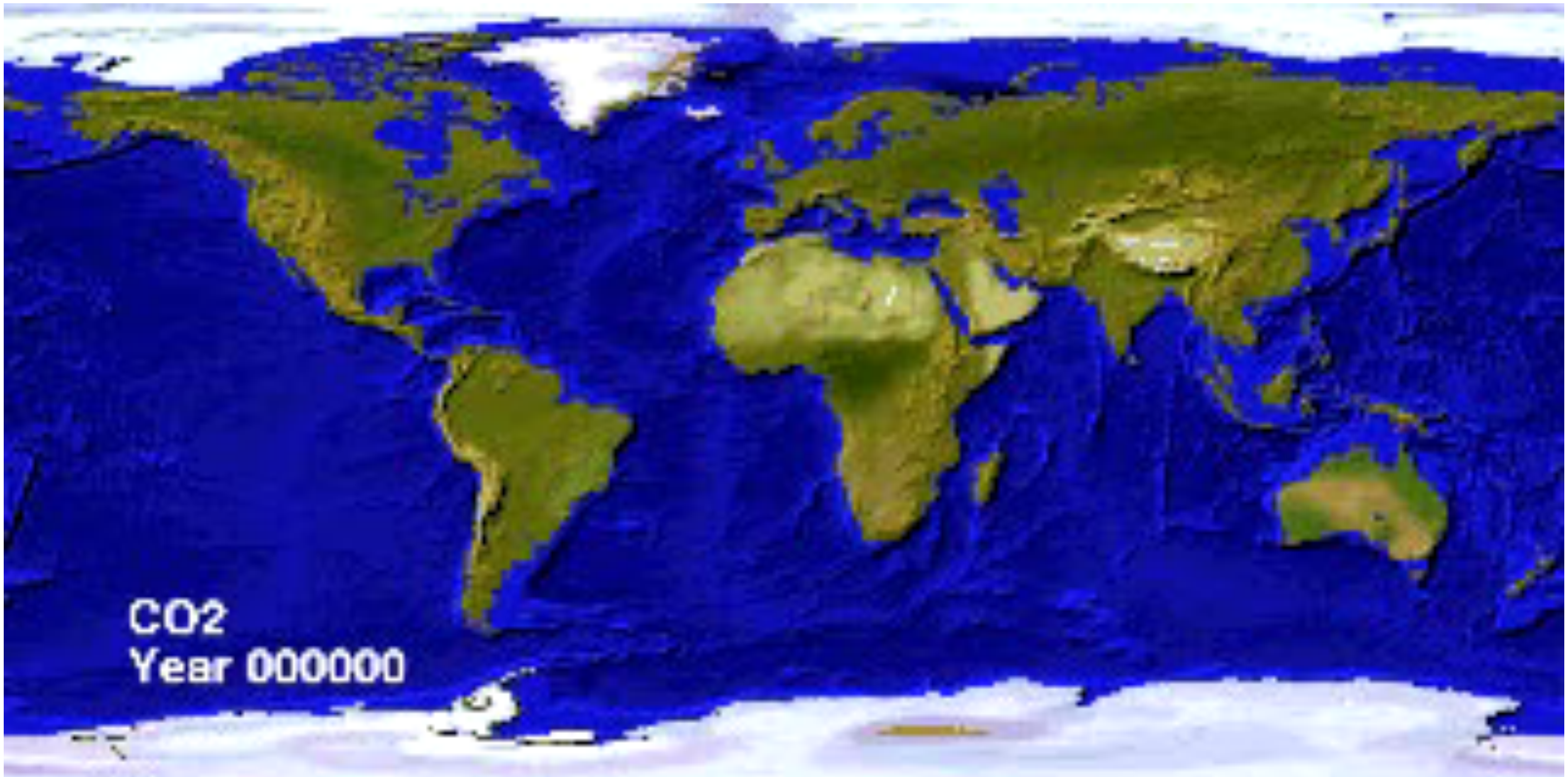
Outline

- Climate models – an introduction
- What is a model?
- Anatomy of a climate model
    - Atmosphere
    - Ocean
    - Land-surface
    - Cryosphere
    - Coupling
- Climate model evaluation
- Climate model projections



Schematic diagram of various components and interactions of the climate system.

Climate change simulation to year 2054



> 3 degs C warming

NCAR CCSM2

1. What is a model?

<u>1. What is a model?</u>

- A model is a **<u>representation of reality</u>**.

- **<u>Predictive</u>** models attempt to represent reality in the future

- **<u>Diagnostic</u>** models represent reality in the past.

Types of models

Iconic models

- A physical (scaled-down) version of the system

Analogue models

- Different physical appearance, but reproduces behaviour of system

Mathematical models

- Use mathematical or analytical relationships that represent the physical laws governing behaviour of the system
- Must understand these relationships
- Can collect data to use in the model

Nowadays the most important models for environmental management are mathematical / computational models.

Model Development

Model development generally follows the scientific method:

1. Observation - An observation is made that requires an explanation

2. Hypothesis - A reason is proposed to describe the observation

3. Experiments - An experiment to test the theory is designed, and a model is used to test it

4. Theory - After running the experiment and (dis)proving the hypothesis, the hypothesis is either refined, discounted or embraced.

Before Building a Model

- **Identify** the process to be modelled
- Decide on the required model **variables** needed
- Identify **qualitative or quantitative** relationships

Computational models

Easy to …

- run **multiple experiments**

- ***sensitivity analyses*** (to find out how sensitive the model is to any unknown inputs)

- ***parameter tuning*** (where appropriate, to adjust unknown input values to improve a model's performance)

Advantages of computer models

- Relatively inexpensive
- Comprehensiveness - keeps track of multiple relationships
- Logic - able to replicate logic consistently
- Accessibility - subject to explicit critique and examination (e.g., testing assumptions)
- Flexibility - capable of examining (cost-efficiently) a large number of conditions

Properties of a computer model

- *accepts input*
- *stores and retrieves information from memory*
- *follows instructions of an algorithm*
- *usually an iteration in time*
- *makes choices depending on current state*
- *obeys physical laws of system*
- *produces output*

Verification, Validation and Assessment of Models

- **Verification** - process of ensuring that the model is "doing what the builder intended" - in transformation of input to output, and so on.

- **Validation** - process of testing the model to ensure that the model offers a viable alternative to actual experimentation

- **Assessment** - process of testing the model to see whether it can simulate the real system within reasonable levels of accuracy

- *impossible if the reality being modelled has never before been experienced before (e.g., climate change)*

Benefits of Mathematical Models

• Cost is lower than experimentation with real system

• Enables compression of time
- e.g., paleoclimate models, climate change models

• Easy to manipulate variables

• Allows hypothetical questions to be addressed ("What if….?")

• Allows risks to be evaluated in an uncertain environment

• Allows evaluation of many different alternatives
-e.g., different CO_2 emissions scenarios

• Leads to deeper understanding of the real system

When to use a model?

- *The cost of observing systems is prohibitive*
- *Observations are impossible to make*
- *A model captures the real system within reasonable levels of accuracy*

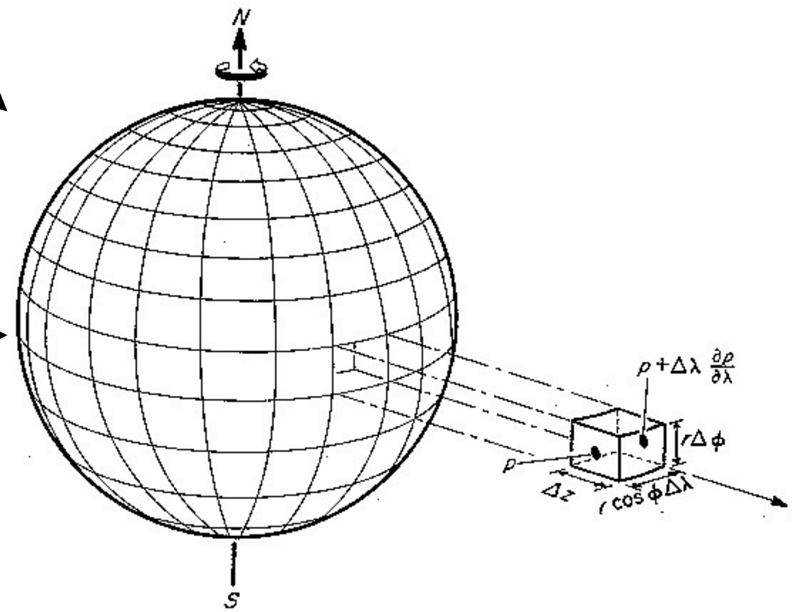
2. Climate models

Climate Modelling

Governing equations

Forcing conditions

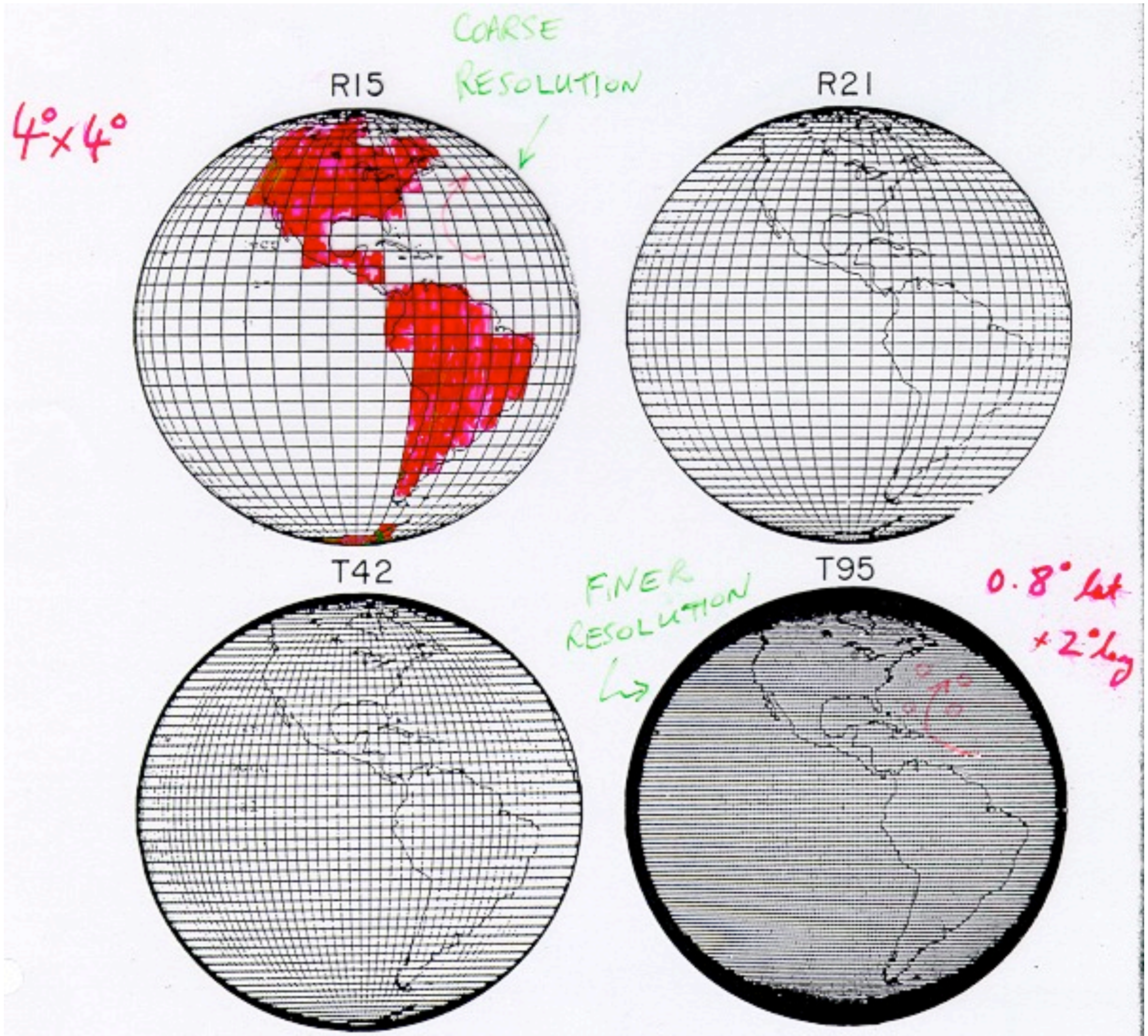
Initial conditions



Model output

Models of the ocean and atmosphere

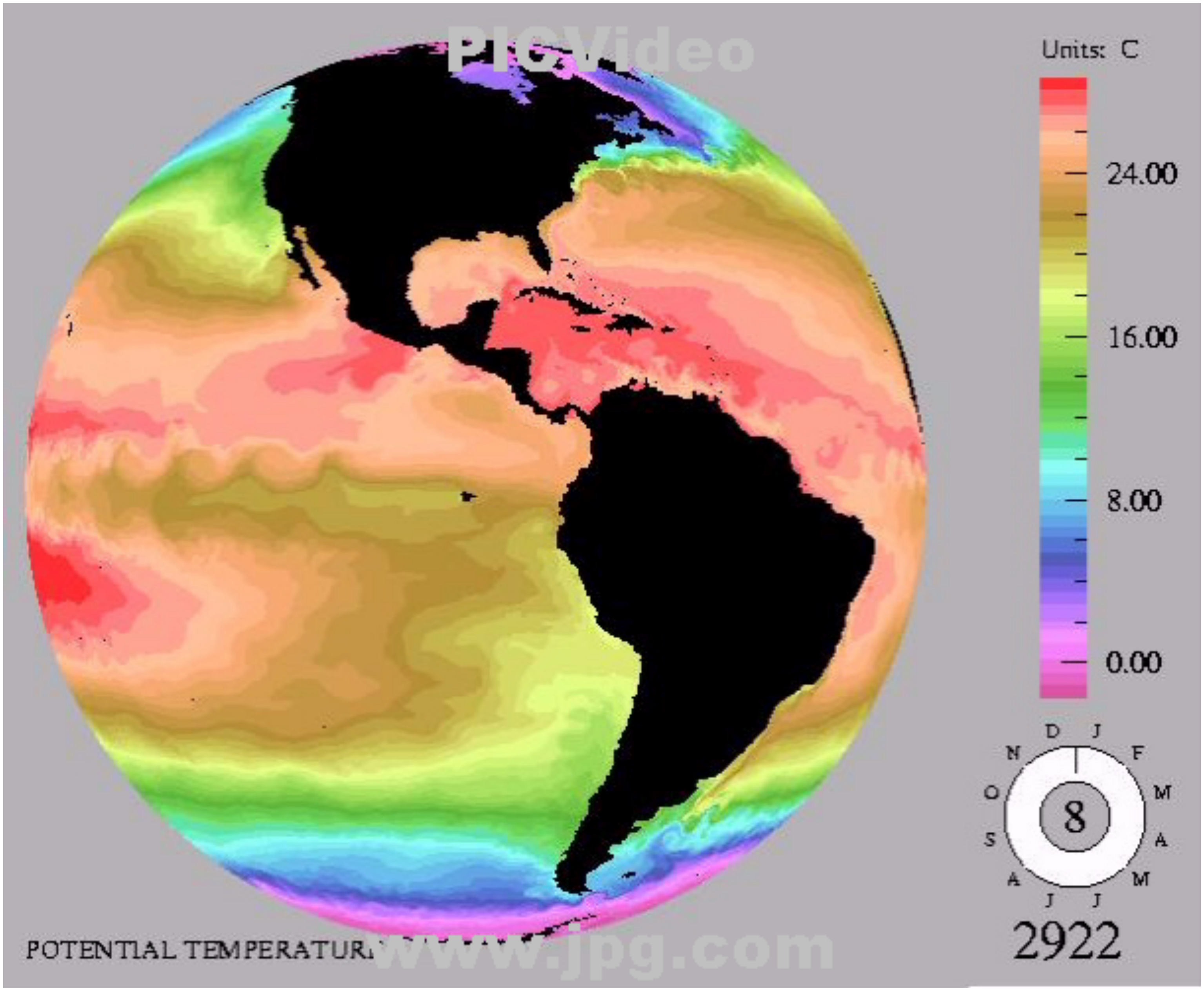
- Solve governing equations over a discrete grid
- Use (sparse) observations in forcing functions
- Integrate solutions forward in time
- Assess simulation vs. observed fields



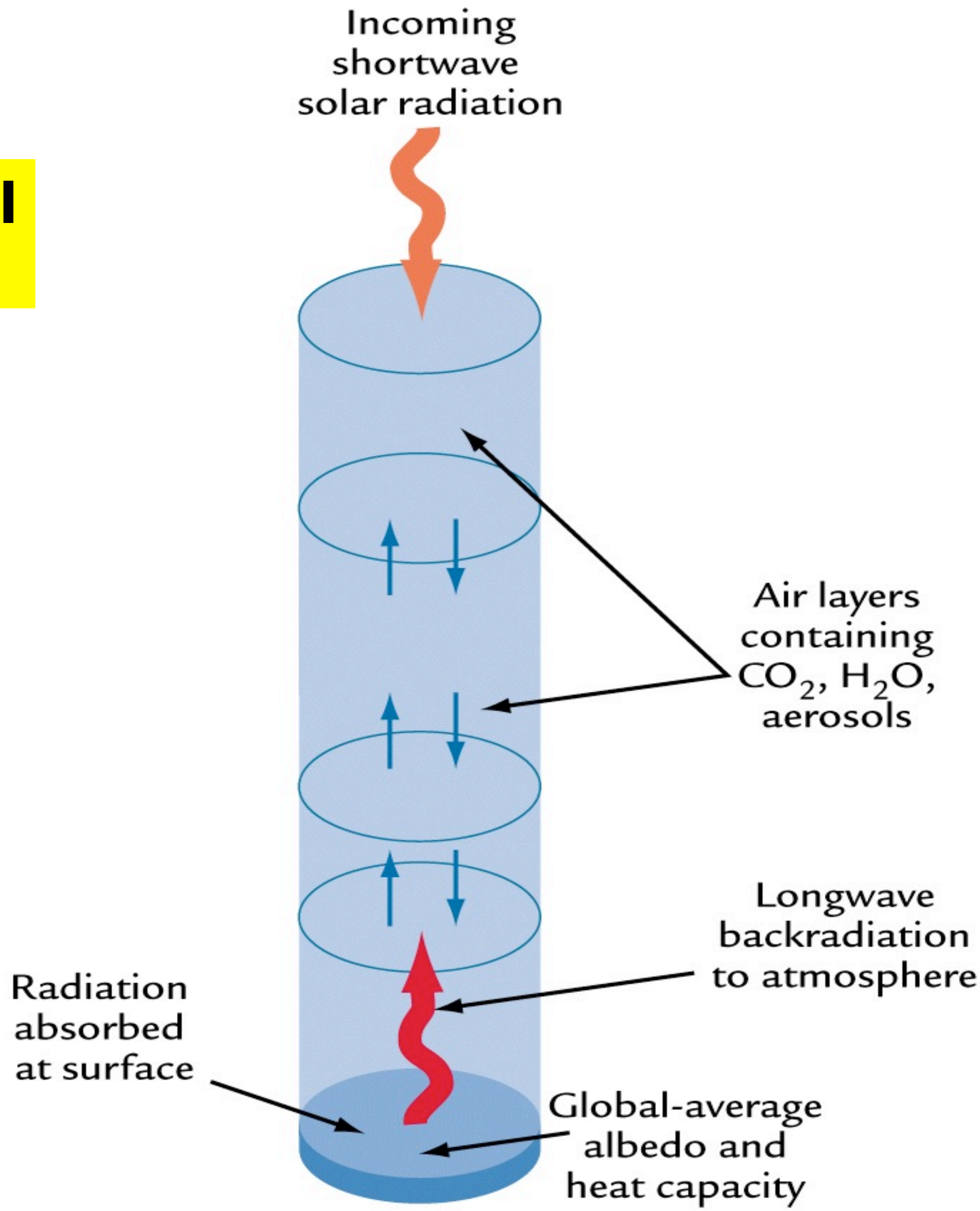
	LAT.	LONG.	TOTAL
R15	40	48	1920
R21	54	64	3456
T42	64	128	8192
T95	144	288	41472

Fig. 4.12 Gaussian grid on the globe for various resolutions: rhomboidal, R15 and R21, and triangular, T42 and T95. [David Williamson, personal communication.]

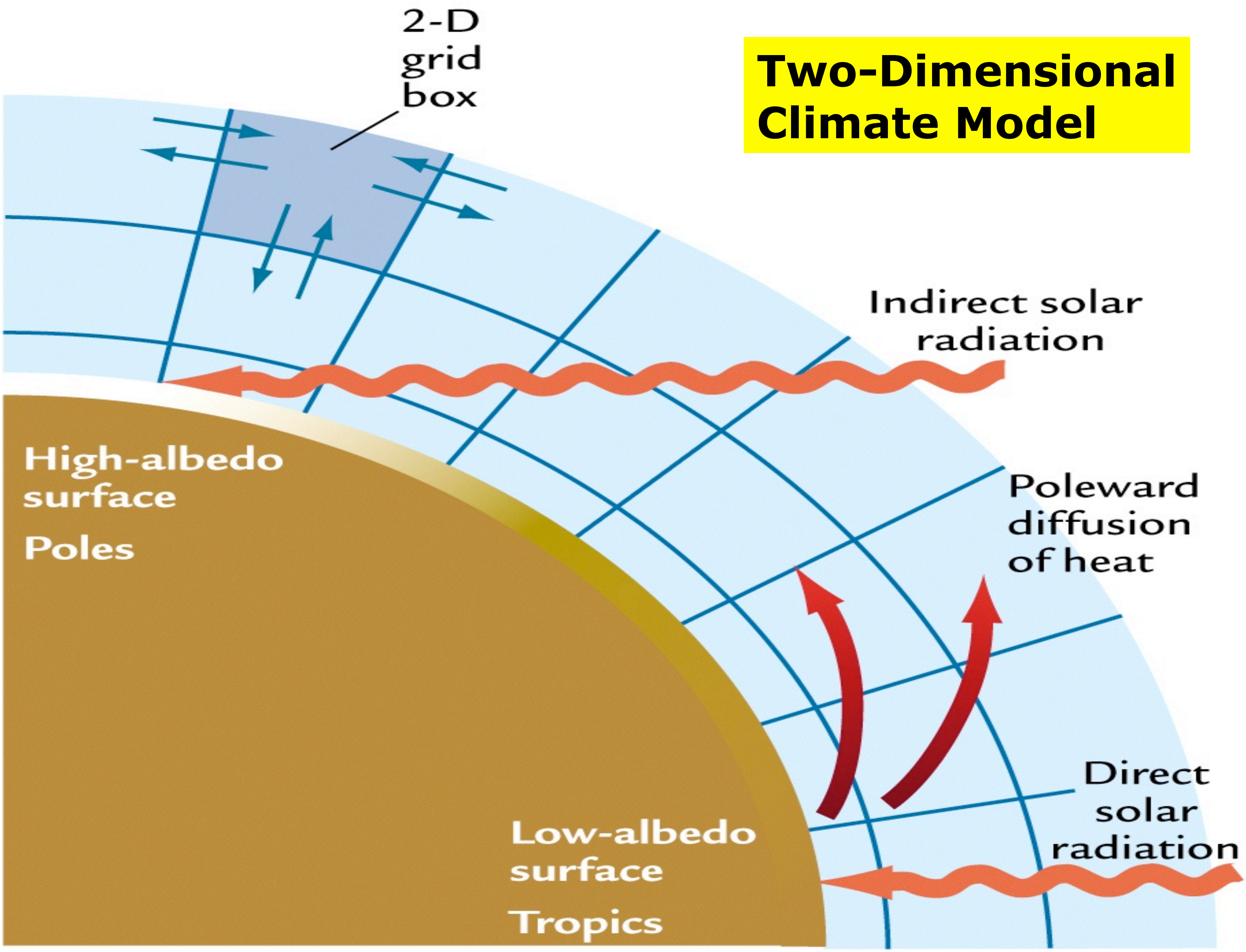
Sea surface temperature over the global ocean

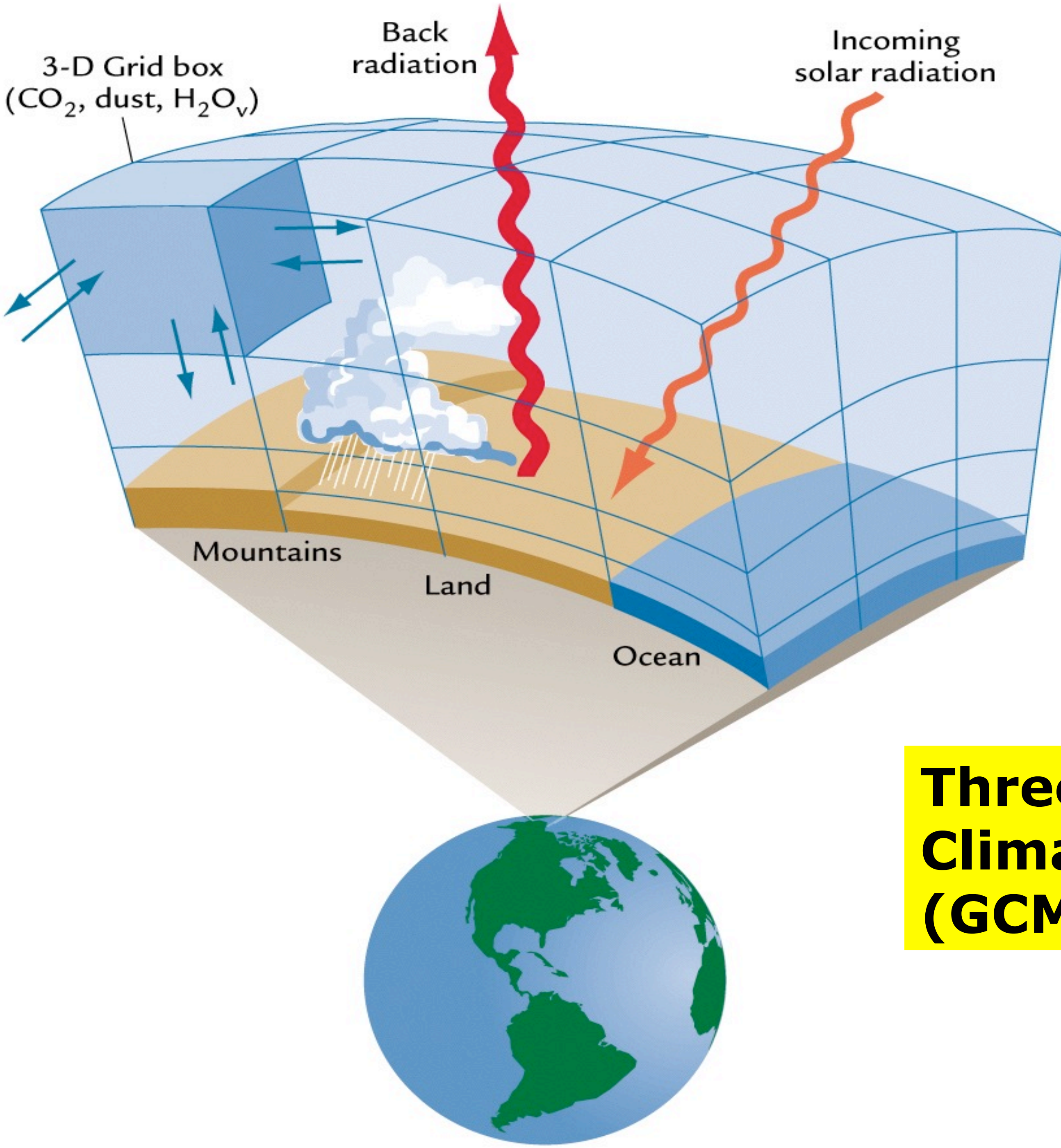


One-Dimensional Climate Model



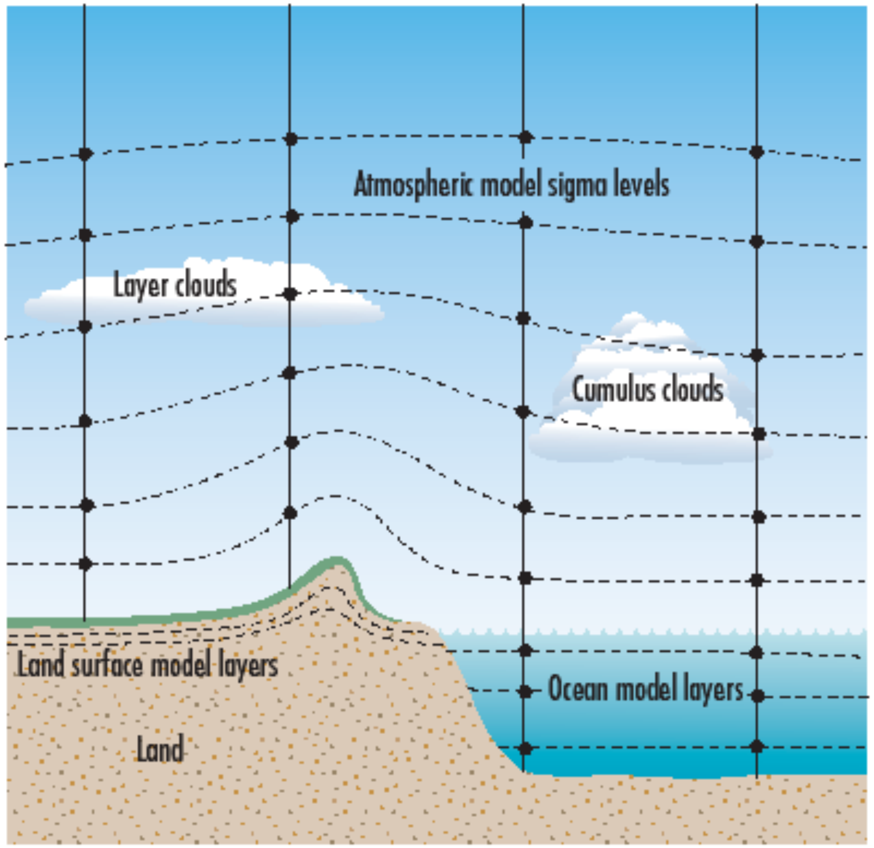
Two-Dimensional Climate Model



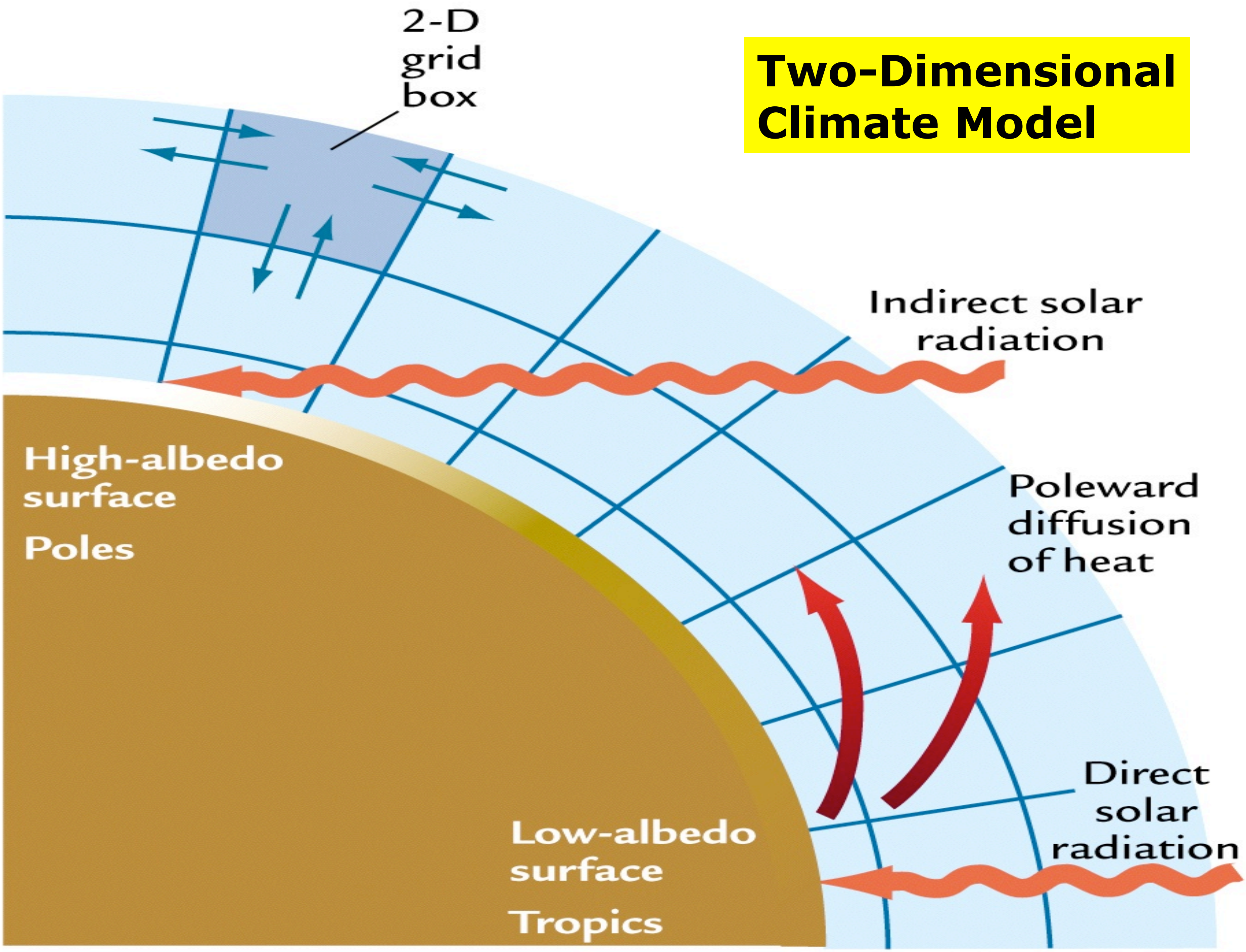


Three-Dimensional Climate Models (GCM)

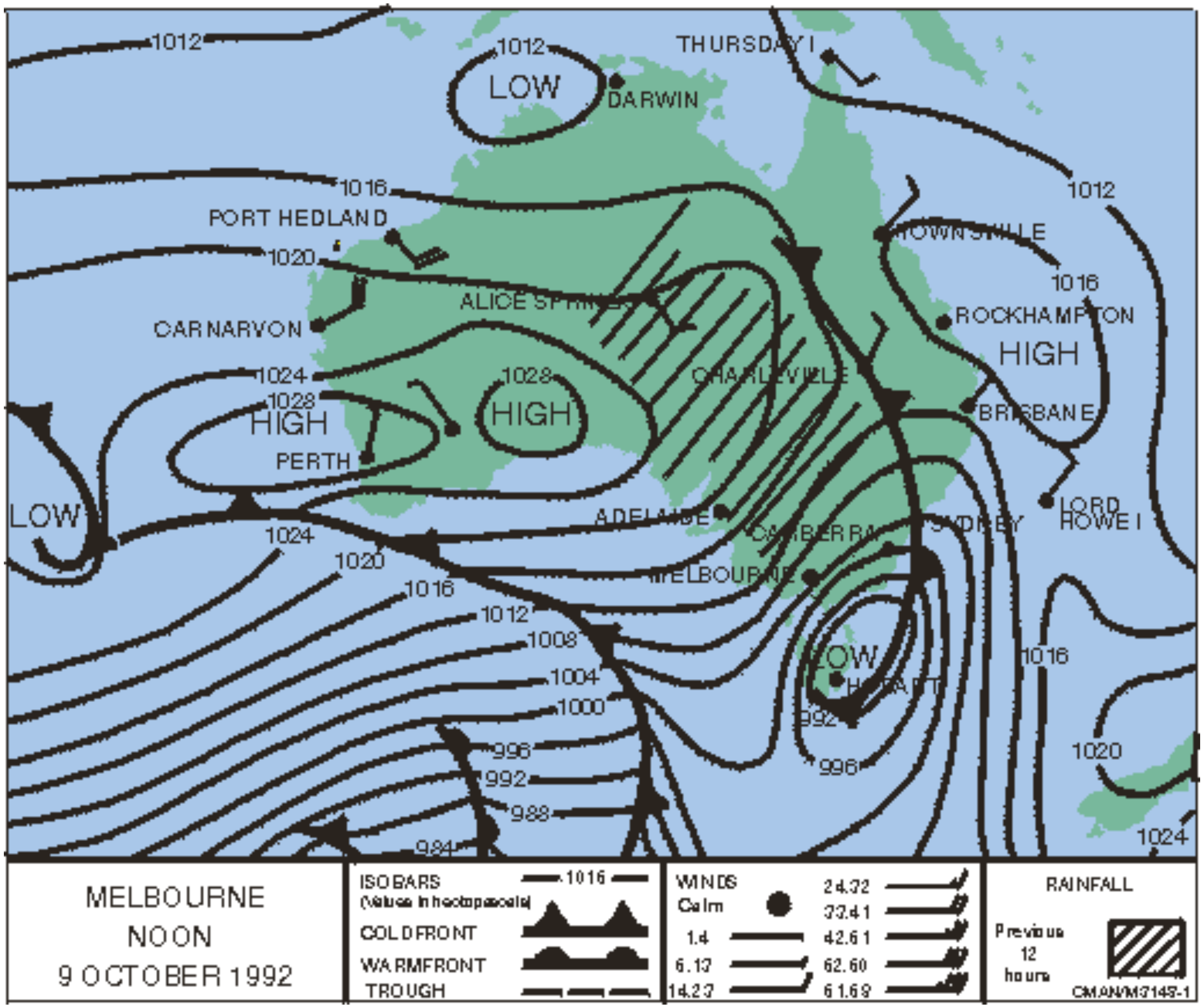
(i) Atmospheric models



Two-Dimensional Climate Model



Atmospheric models underpin weather prediction systems….



Nesting higher resolution models…

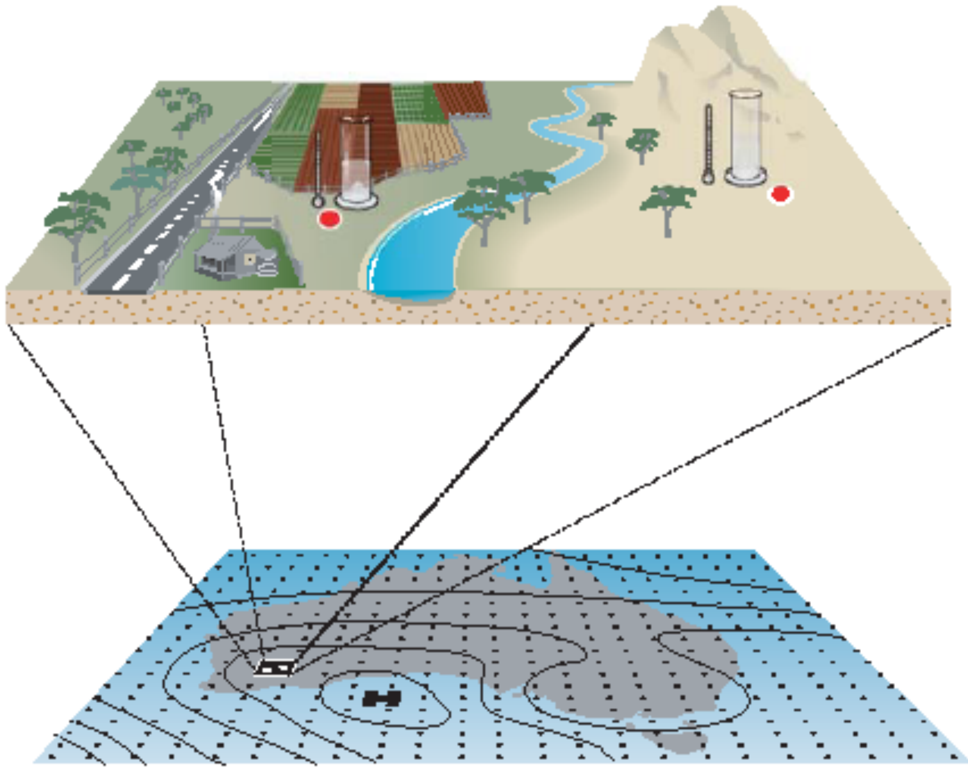
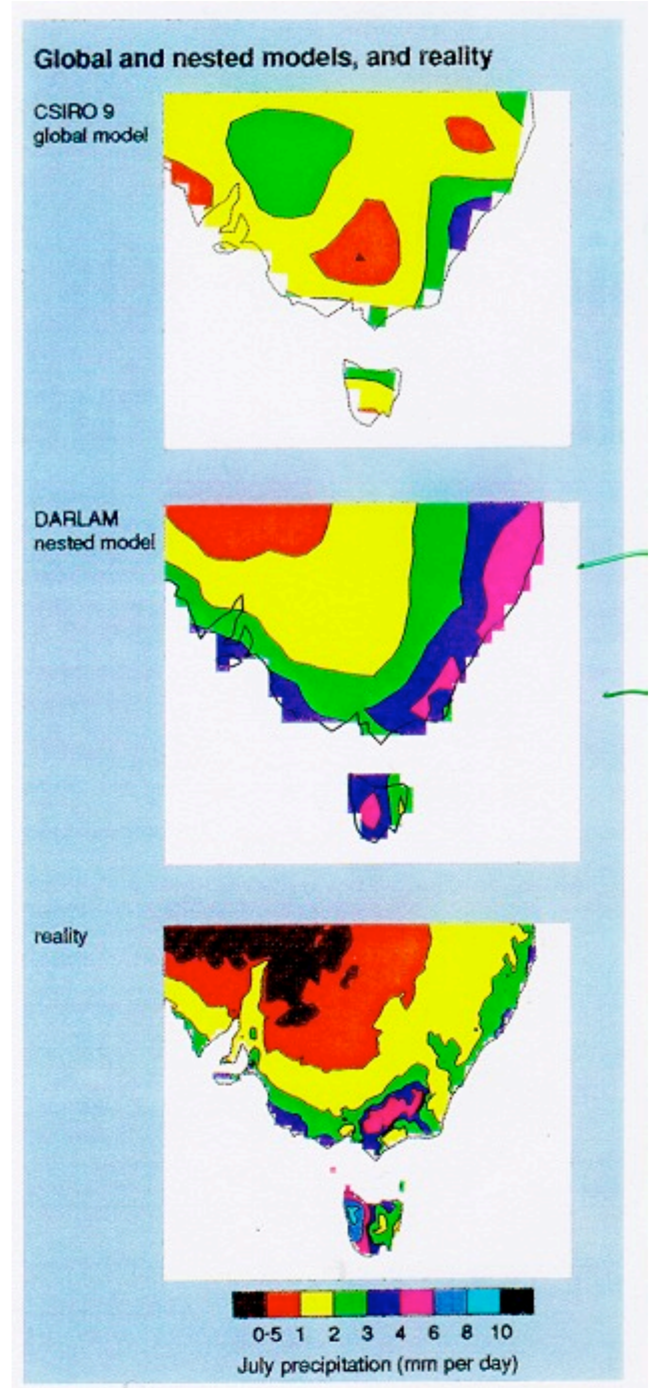


Figure 65. A schematic diagram describing the statistical downscaling approach. GCMs provide useful predictions for large-scale atmospheric patterns (lower part). Details contained within a grid box (upper part) are influenced by local features beyond the resolution of current global climate models.



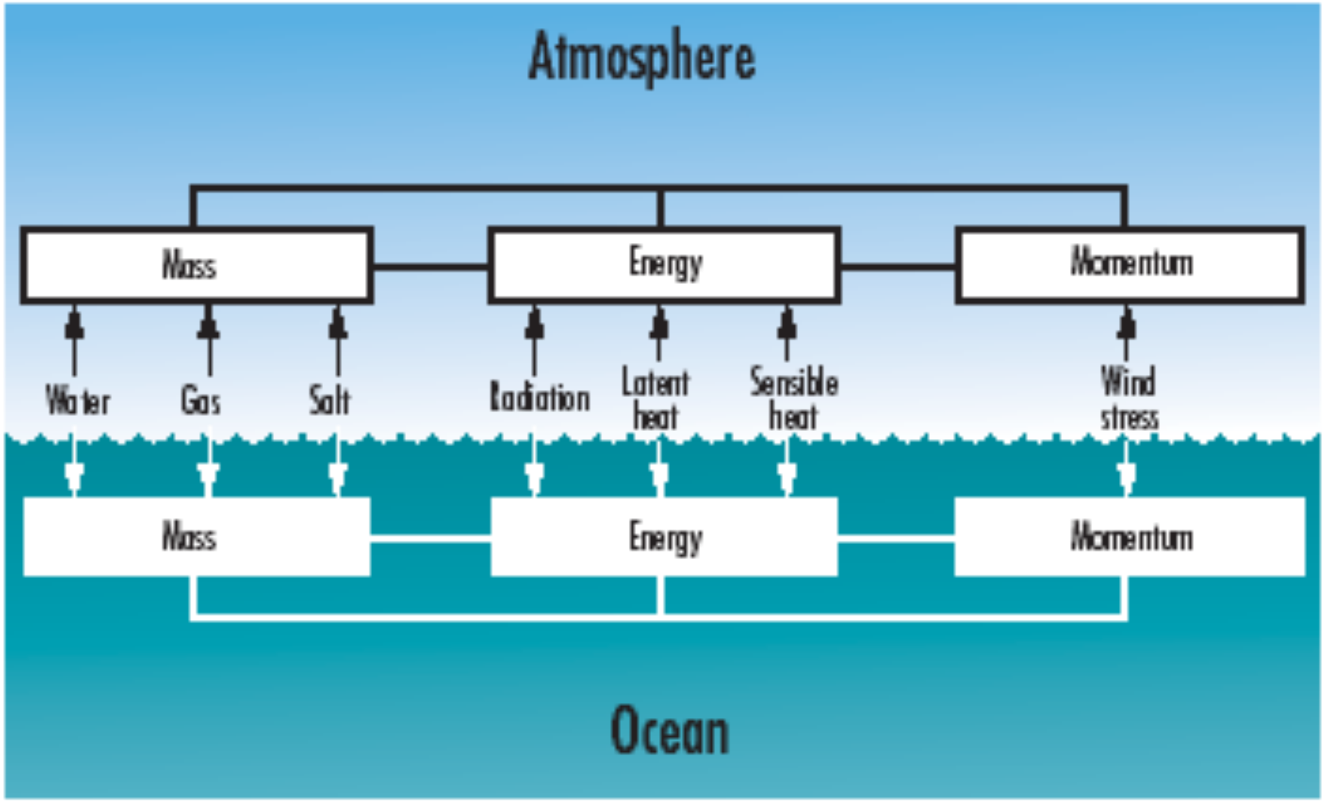
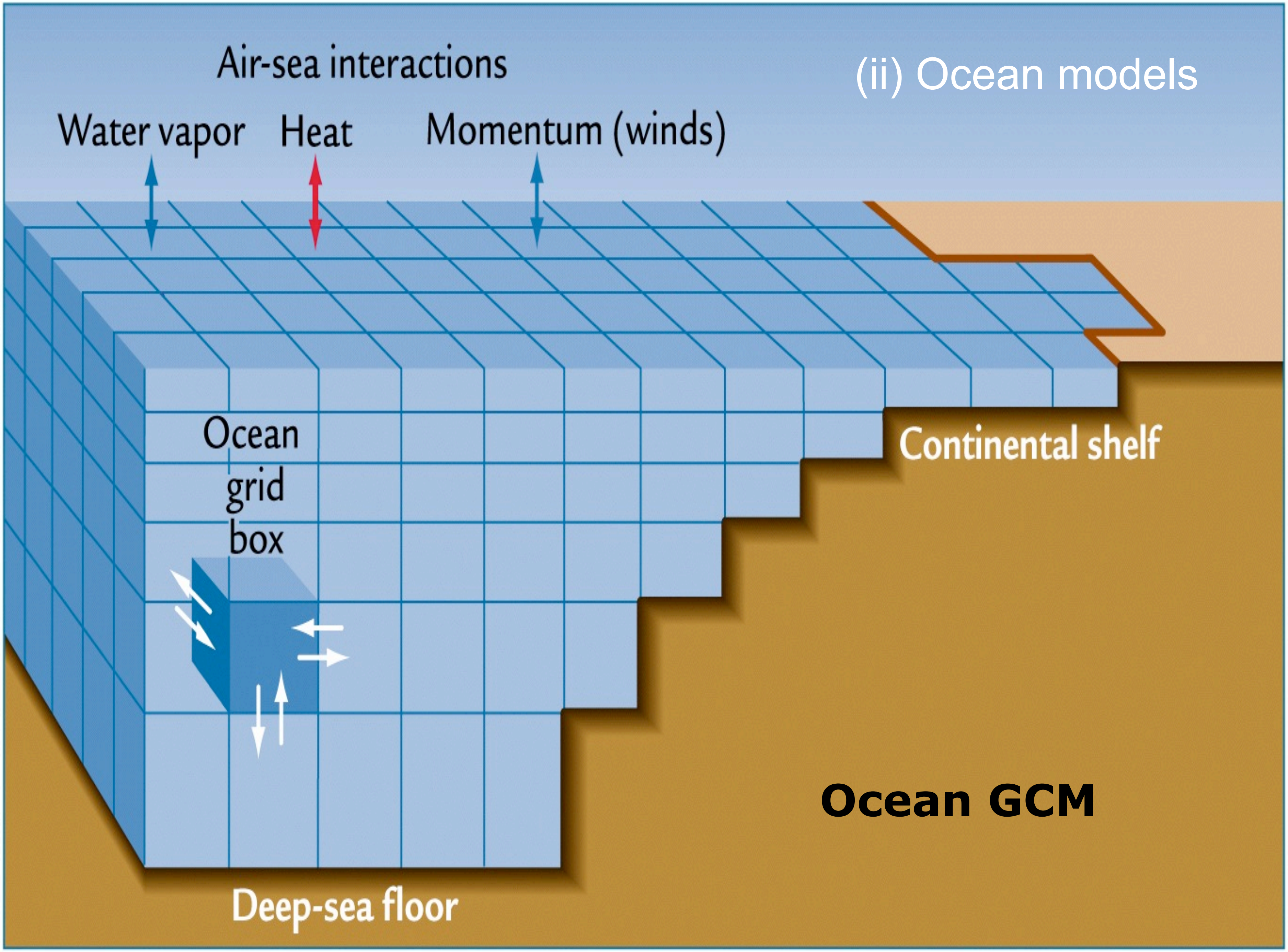
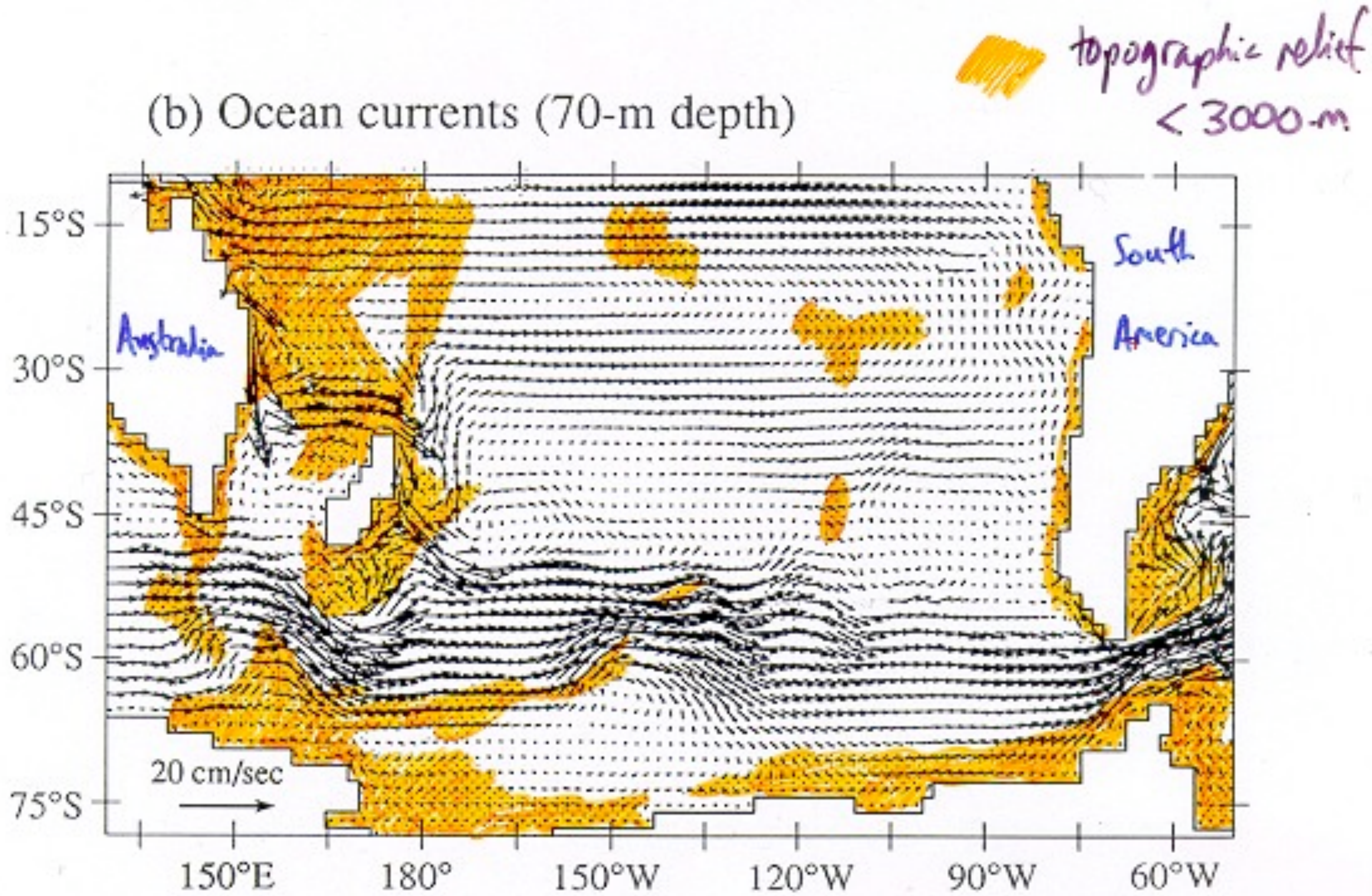


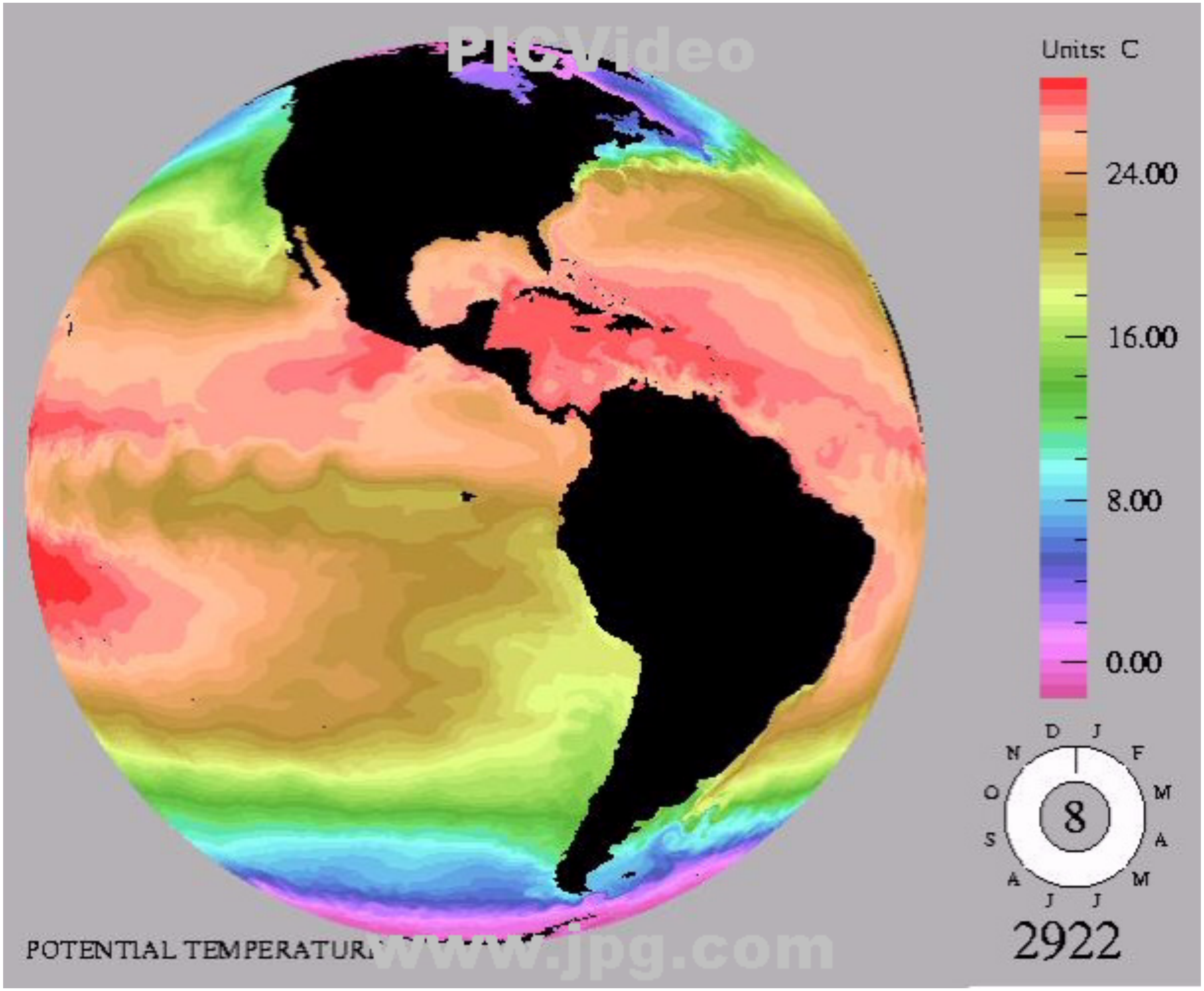
Figure 53. A schematic representation of the essential components of a fully coupled general circulation model, based on the conservation of mass, energy and momentum in the atmosphere and ocean, and the physical processes involved in the coupling between them.



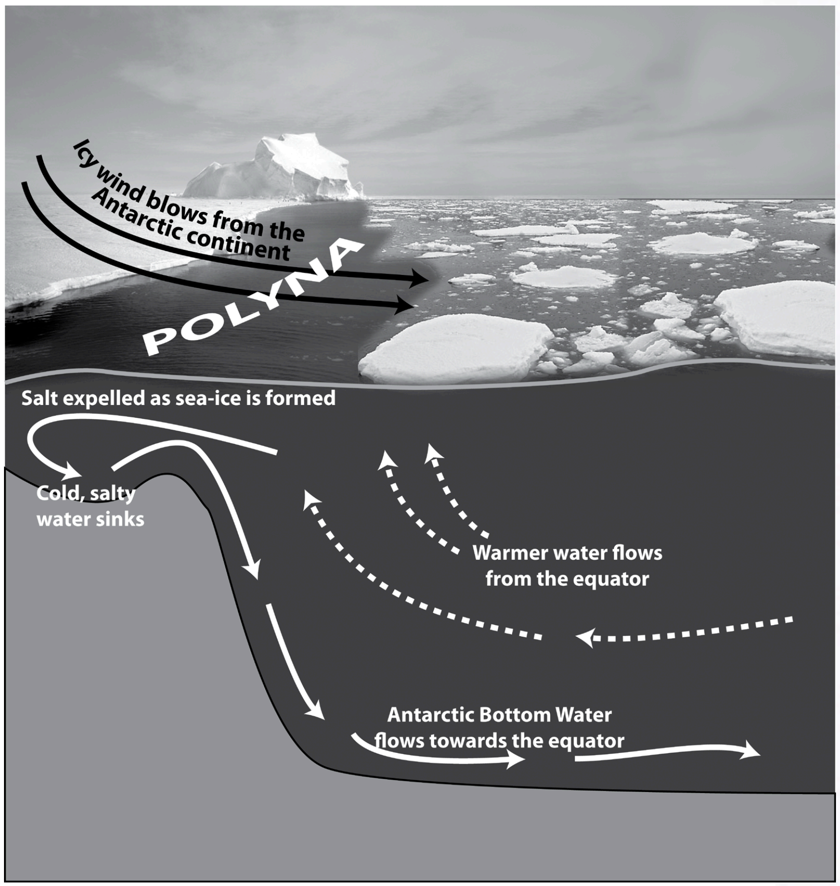
(ii) Ocean models
Air-sea interactions
Water vapor
Heat
Momentum (winds)
Ocean grid box
Continental shelf
Deep-sea floor
Ocean GCM

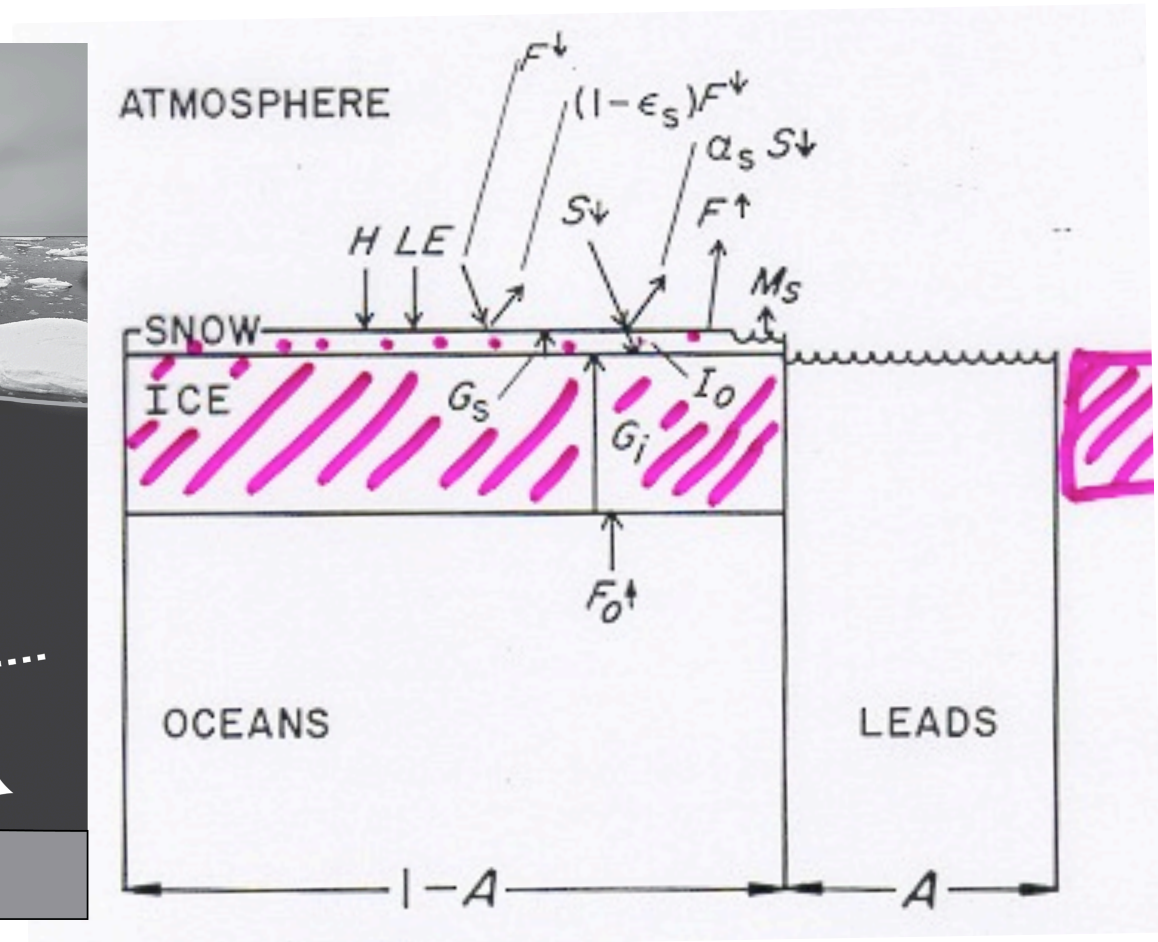

topographic relief
< 3000 m
(b) Ocean currents (70-m depth)
15°S
30°S
45°S
60°S
75°S
150°E
180°
150°W
120°W
90°W
60°W
Australia
South
America
20 cm/sec

Sea surface temperature over the global ocean

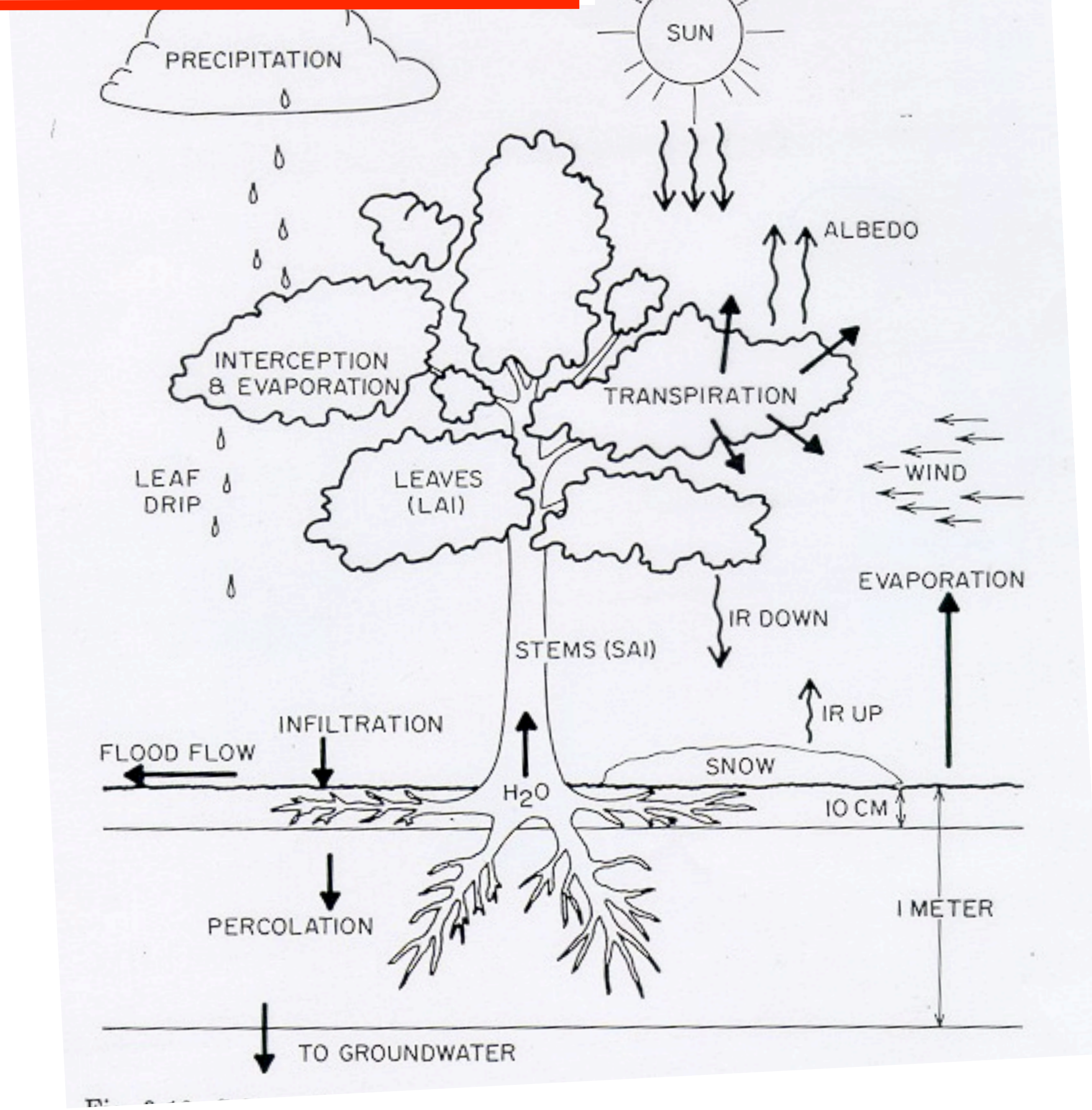


(iii) Sea-ice models

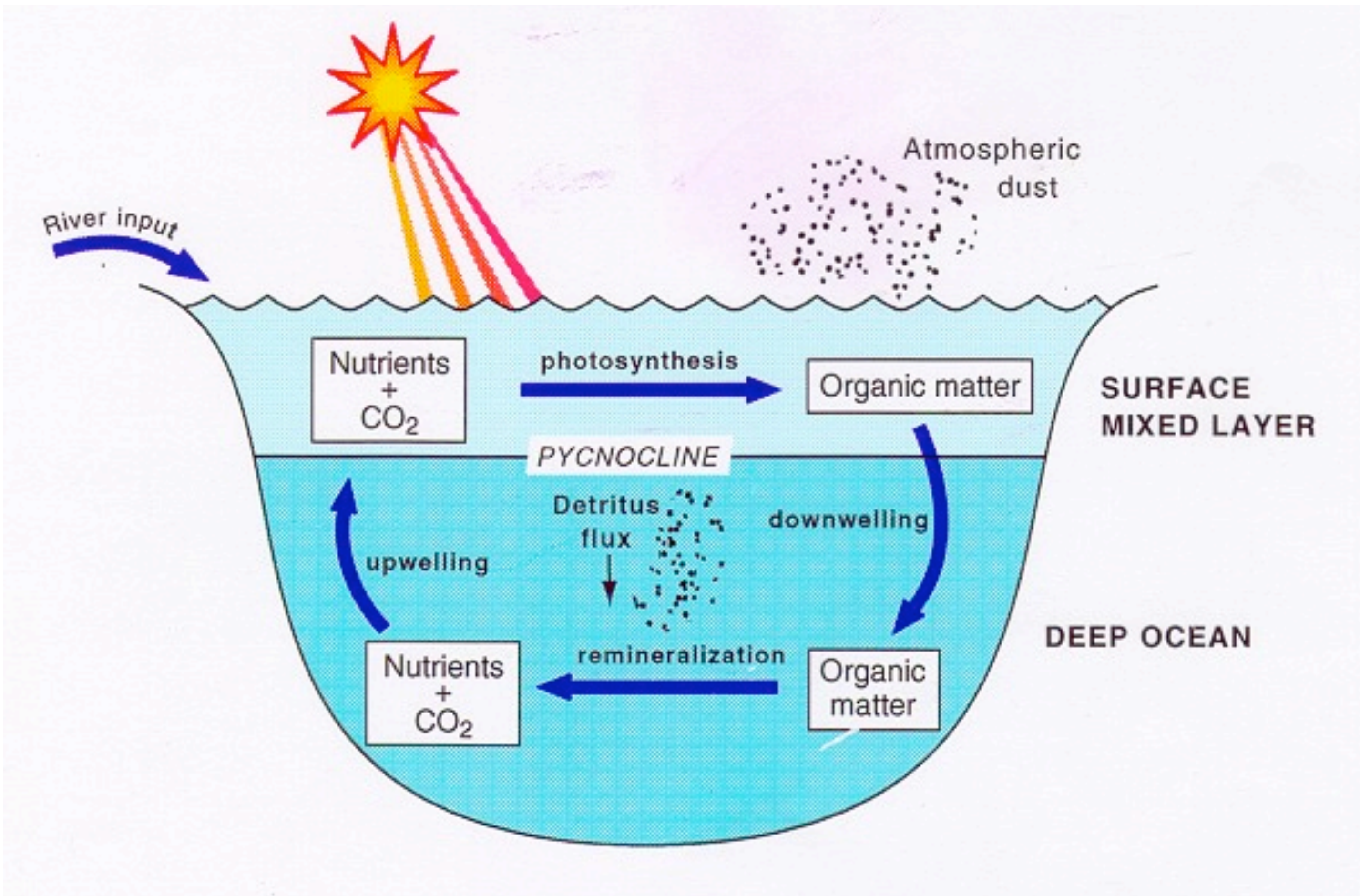


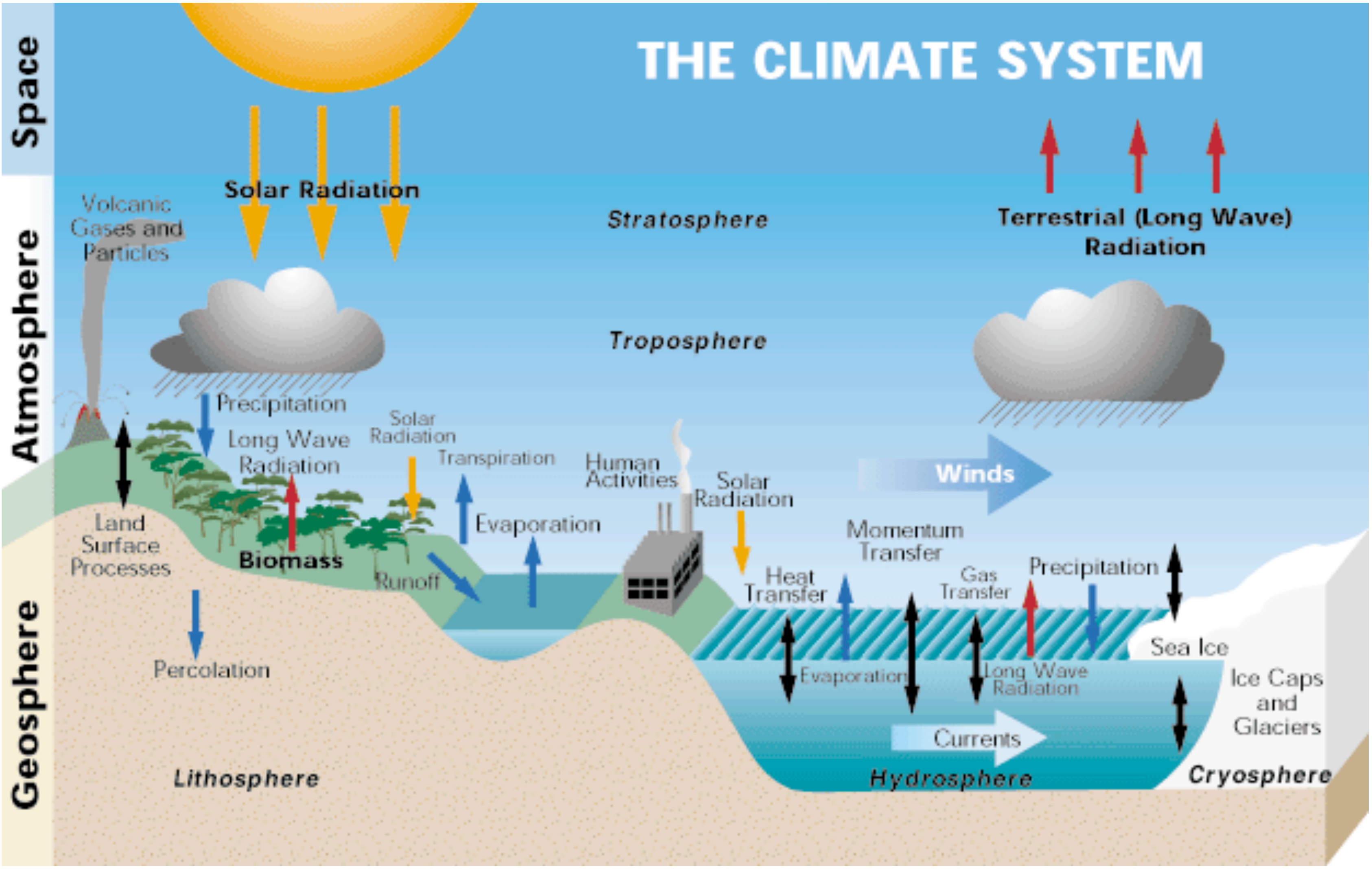


(iv) Land-surface models



(v) Coupled carbon cycle models




THE CLIMATE SYSTEM
Space
Atmosphere
Geosphere
Solar Radiation
Volcanic Gases and Particles
Stratosphere
Terrestrial (Long Wave) Radiation
Troposphere
Precipitation
Long Wave Radiation
Solar Radiation
Transpiration
Human Activities
Solar Radiation
Winds
Evaporation
Land Surface Processes
Biomass
Runoff
Momentum Transfer
Heat Transfer
Gas Transfer
Precipitation
Sea Ice
Evaporation
Long Wave Radiation
Ice Caps and Glaciers
Percolation
Currents
Lithosphere
Hydrosphere
Cryosphere

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.

Model assessment

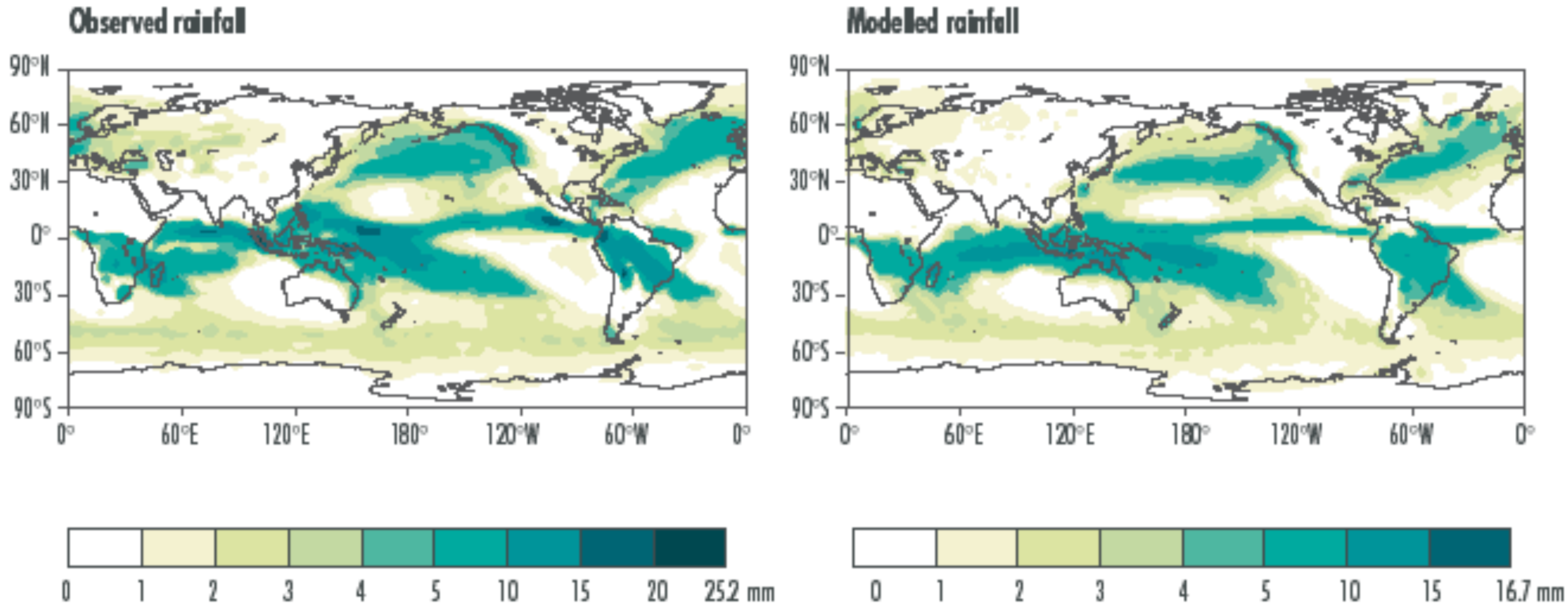
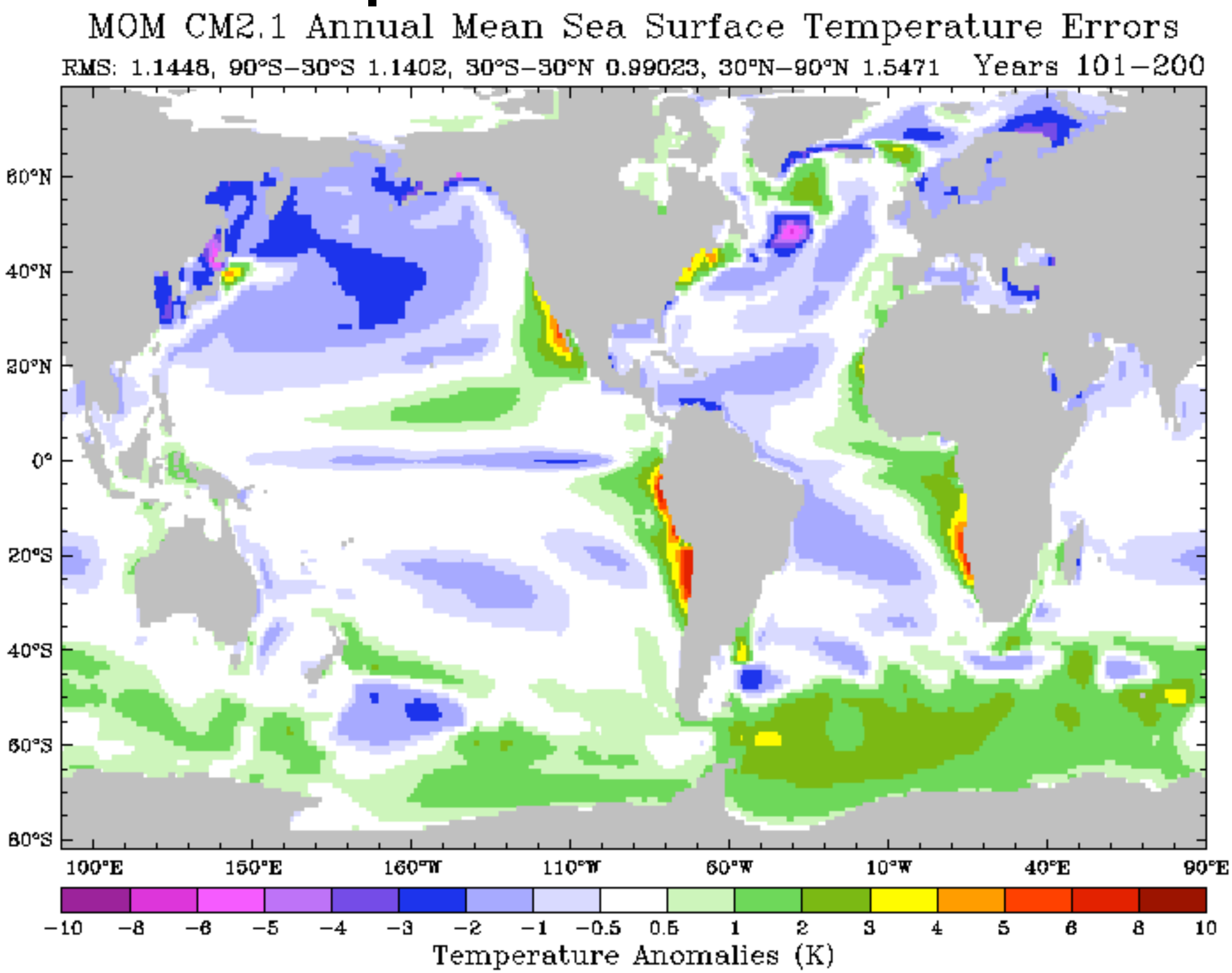
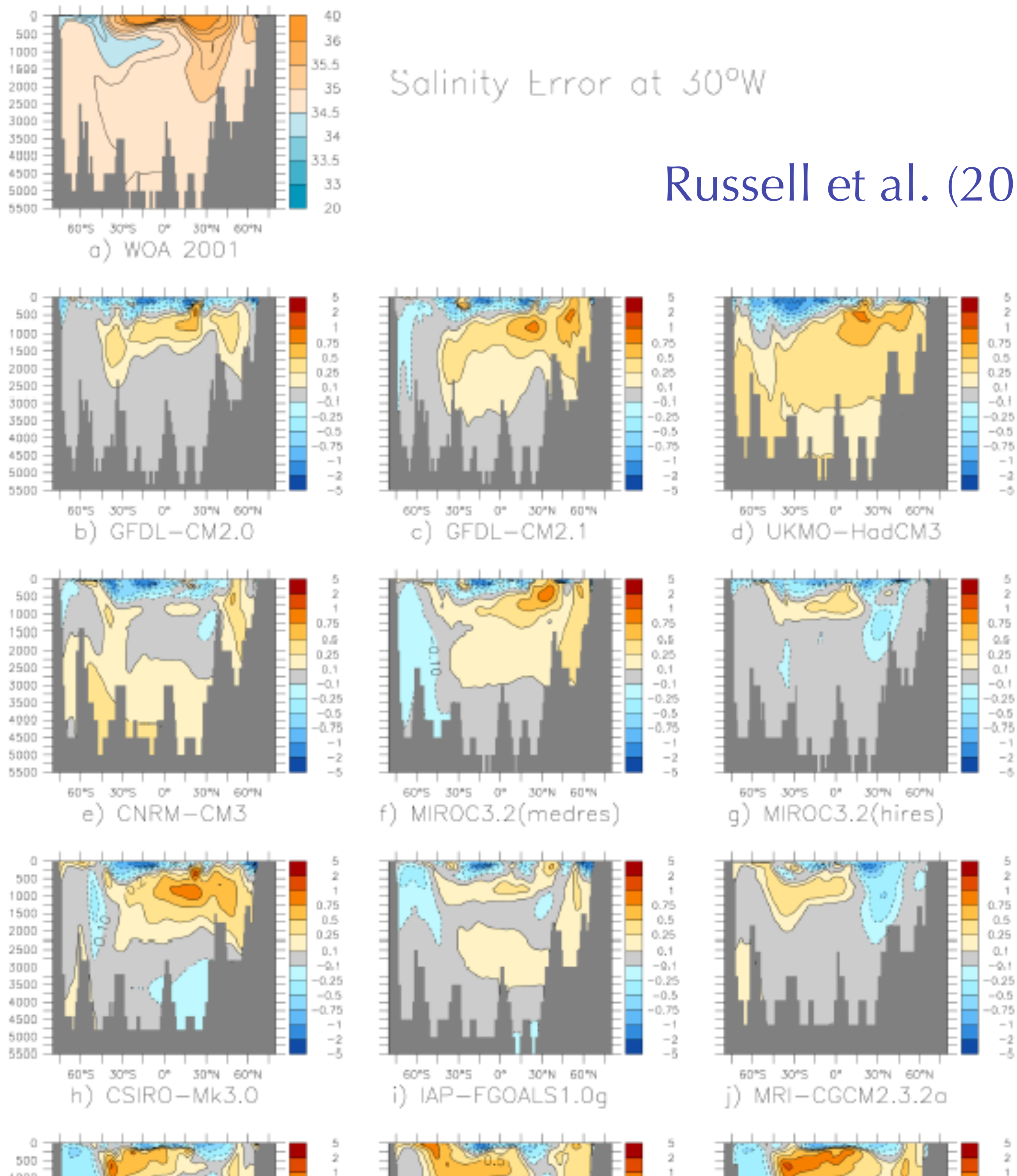


Figure 59. Comparison between (left) the observed climatological pattern of global precipitation and (right) the simulated pattern produced by the BMRC climate model.

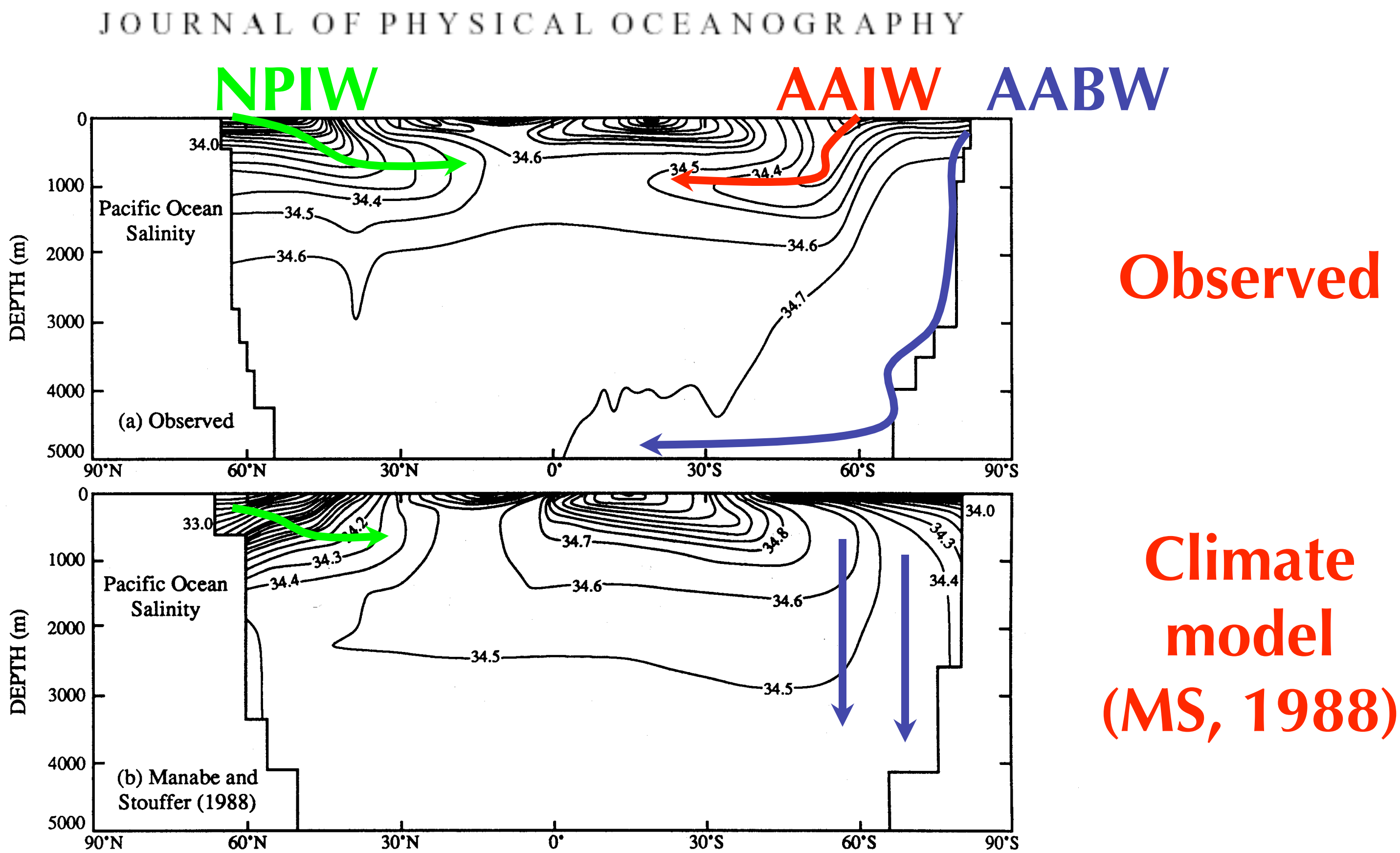
100-year-mean SST Biases in GFDL's CM2.1 Coupled Climate Model





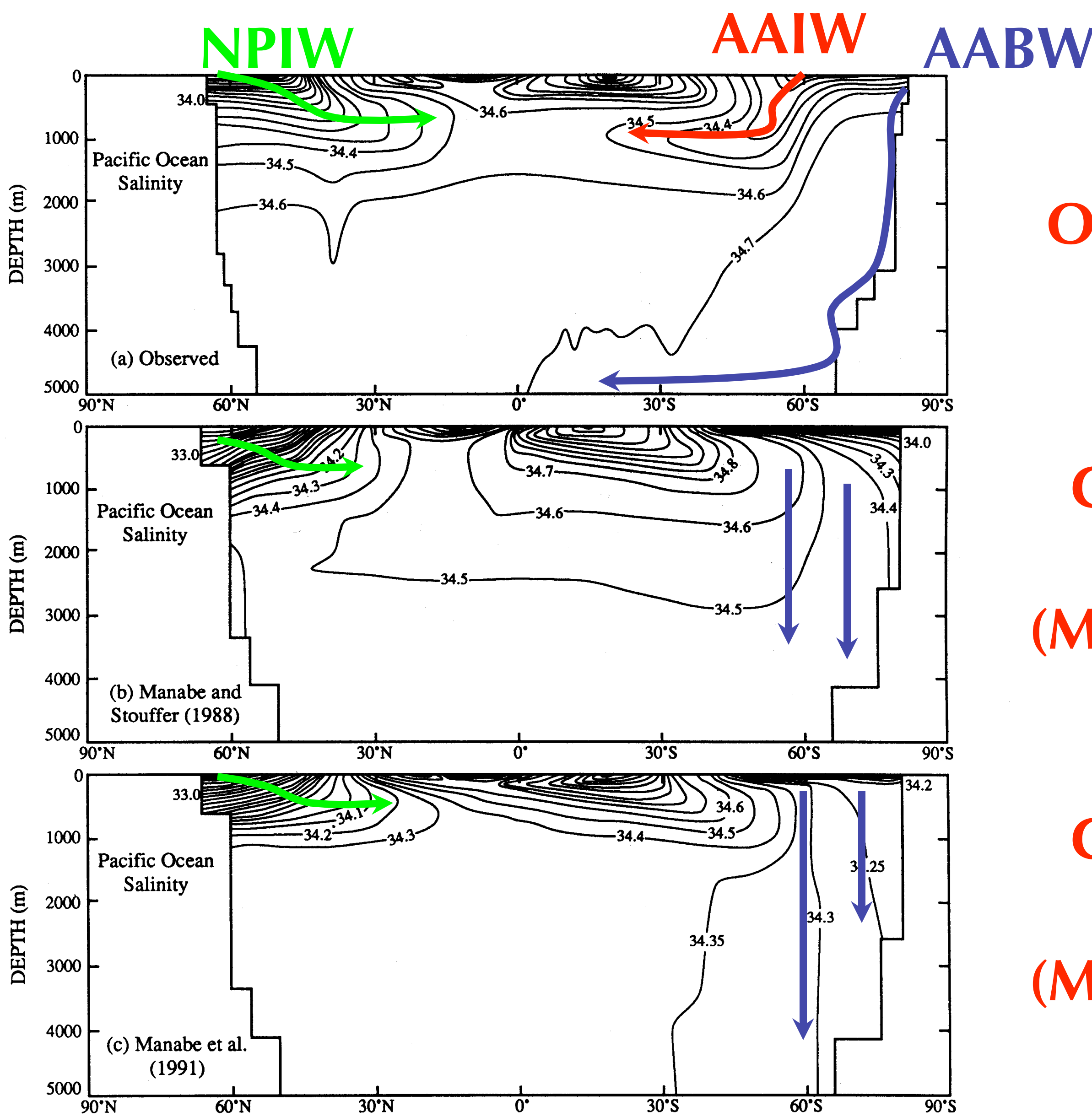
Russell et al. (2006)

Pacific Ocean Salinity



England, M.H., 1992: On the formation of Antarctic Intermediate and Bottom Water in ocean general circulation models. *J. Phys. Oceanogr.*, **22**, 918-926.

Pacific Ocean Salinity



Observed

Climate model (MS, 1988)

Climate model (MS, 1991)

FIG. 2. Zonally averaged and annually averaged latitude–depth sections of salinity in the Pacific Ocean. (a) Observed (redrafted from Levitus 1982), (b) in the Manabe and Stouffer (1988) climate model (their experiment I), and (c) in the Manabe et al. (1991) seasonally insulated climate model.

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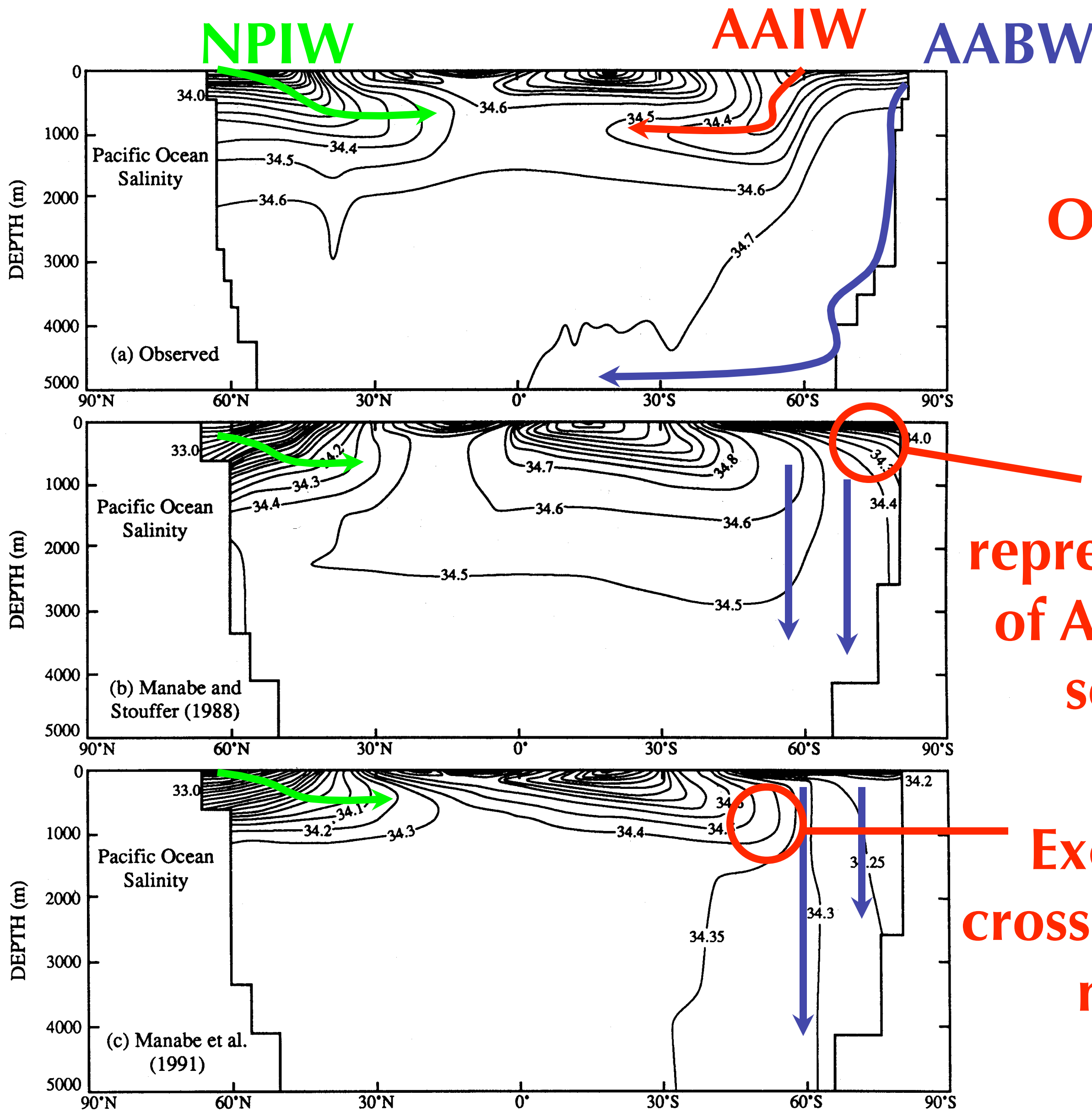
Pacific Ocean Salinity



Observed

Poor representation of Antarctic sea-ice

Excessive cross-isopycnal mixing

FIG. 2. Zonally averaged and annually averaged latitude–depth sections of salinity in the Pacific Ocean. (a) Observed (redrafted from Levitus 1982), (b) in the Manabe and Stouffer (1988) climate model (their experiment I), and (c) in the Manabe et al. (1991) seasonally insulated climate model.

England, M.H., 1992: *J. Phys. Oceanogr.*, **22**, 918-926.

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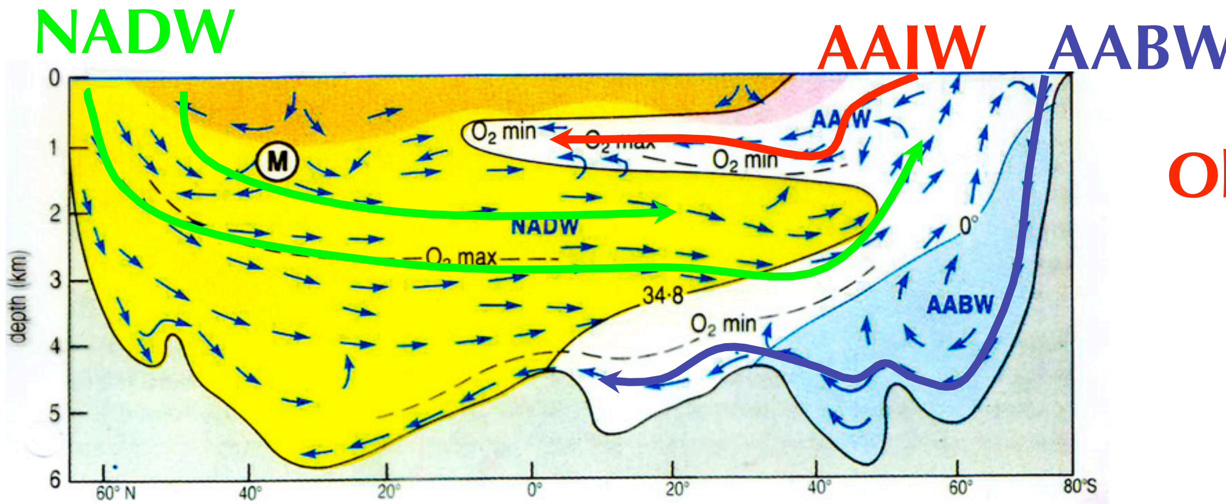
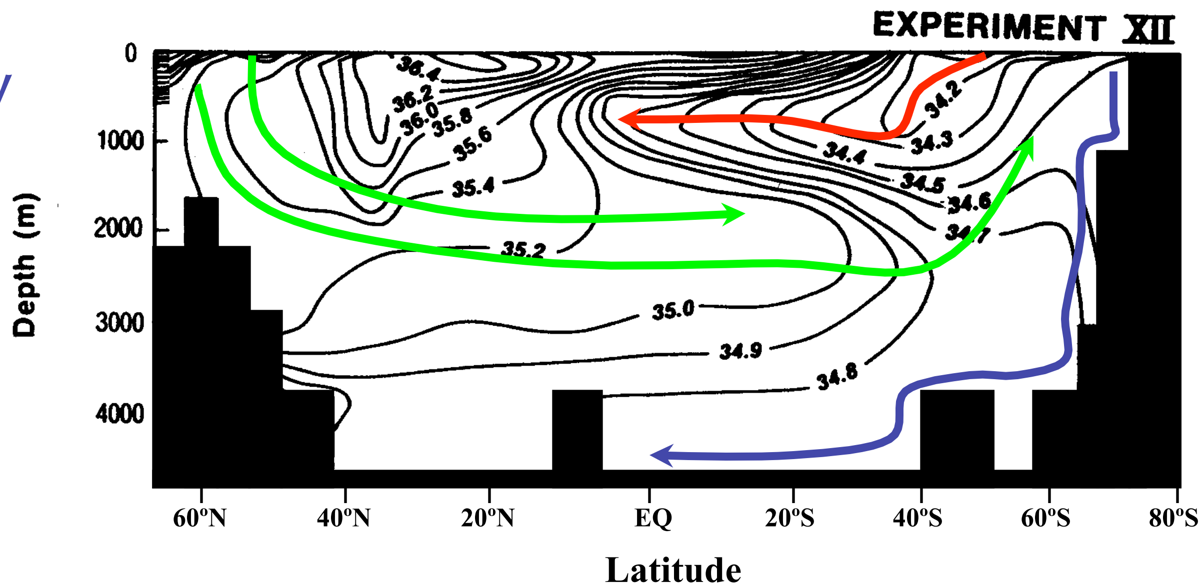
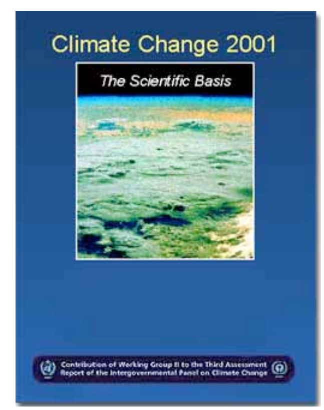
Atlantic Ocean Salinity



Observed

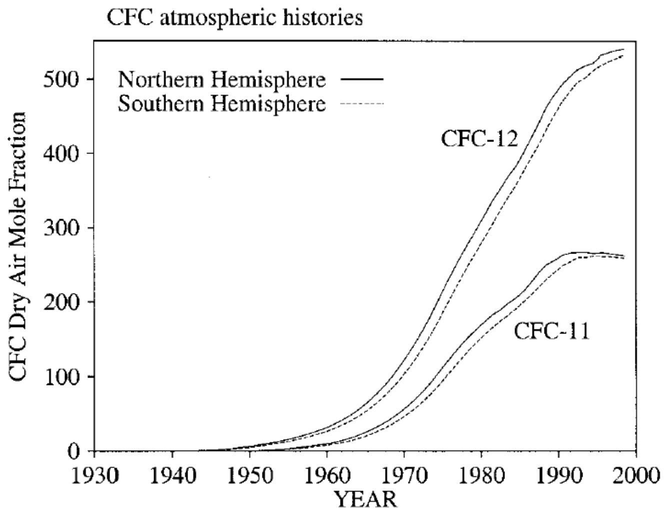


Modelled

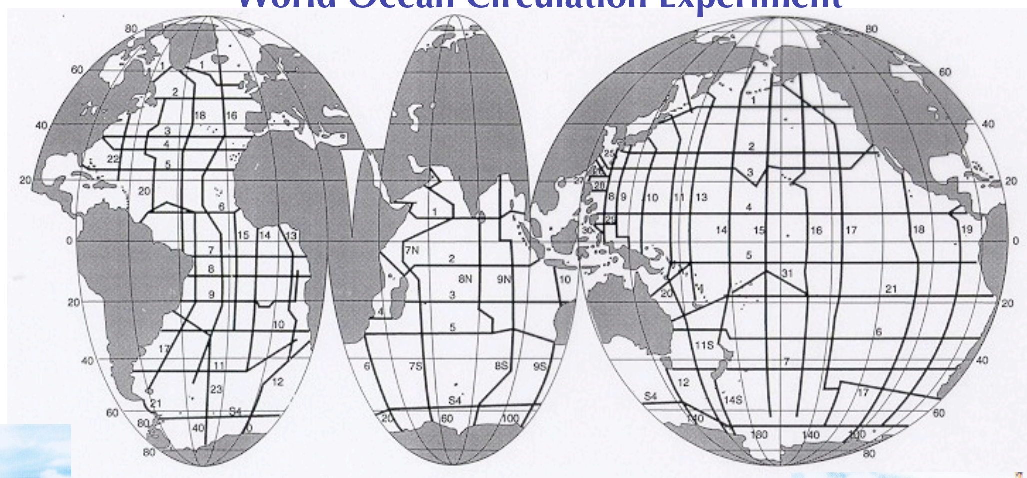


England, M. H., 1993: Representing the global-scale water masses in ocean general circulation models. *J. Phys. Oceanogr.*, **23**, 1523–1552.

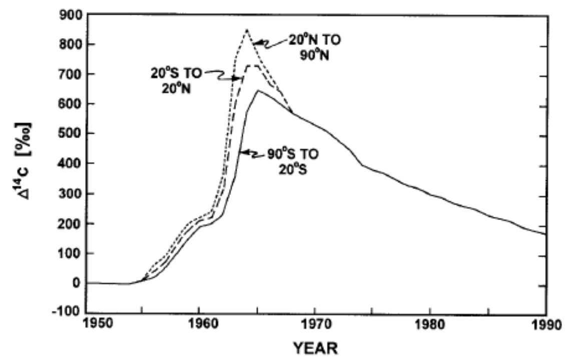
Geochemical tracers in ocean models



World Ocean Circulation Experiment



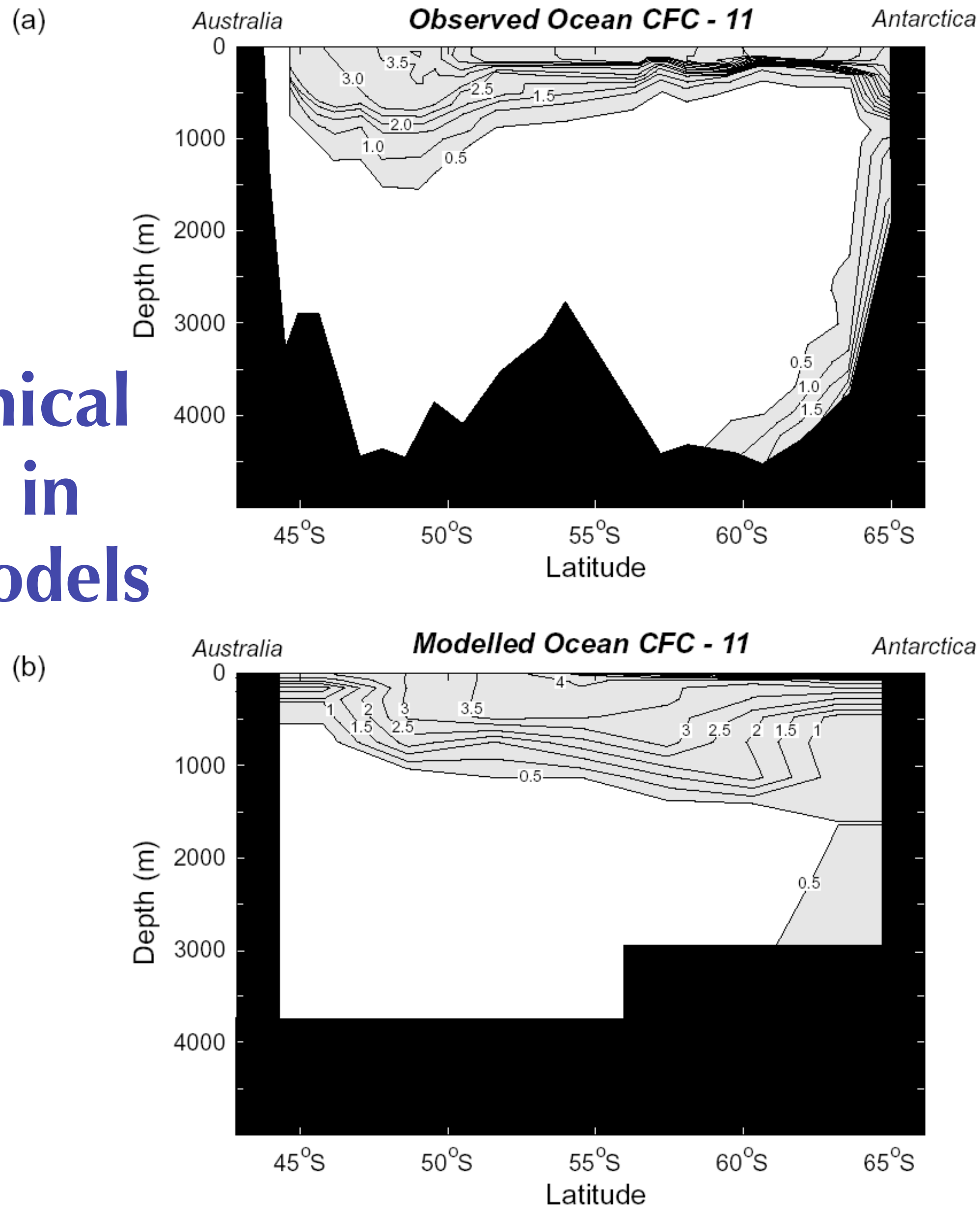
Bomb Radiocarbon



England and Maier-Reimer: TRACERS IN OCEAN MODELS

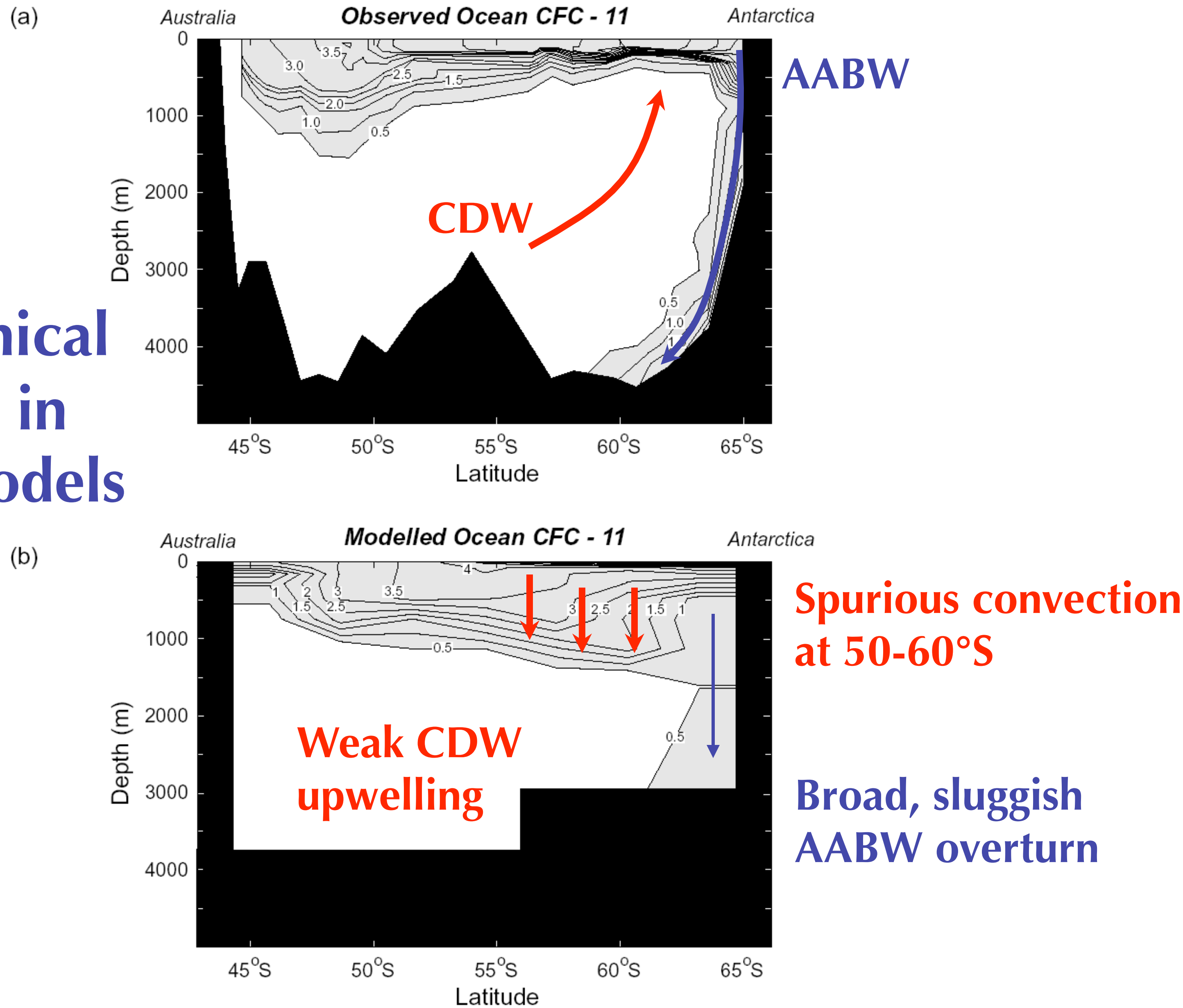
Reviews of Geophysics, 39, 1 / *February 2001*
pages 29–70

Geochemical tracers in ocean models



England, M. H., Using chlorofluorocarbons to assess ocean climate models, *Geophys. Res. Lett.*, *22*, 3051–3054, 1995.

Geochemical tracers in ocean models



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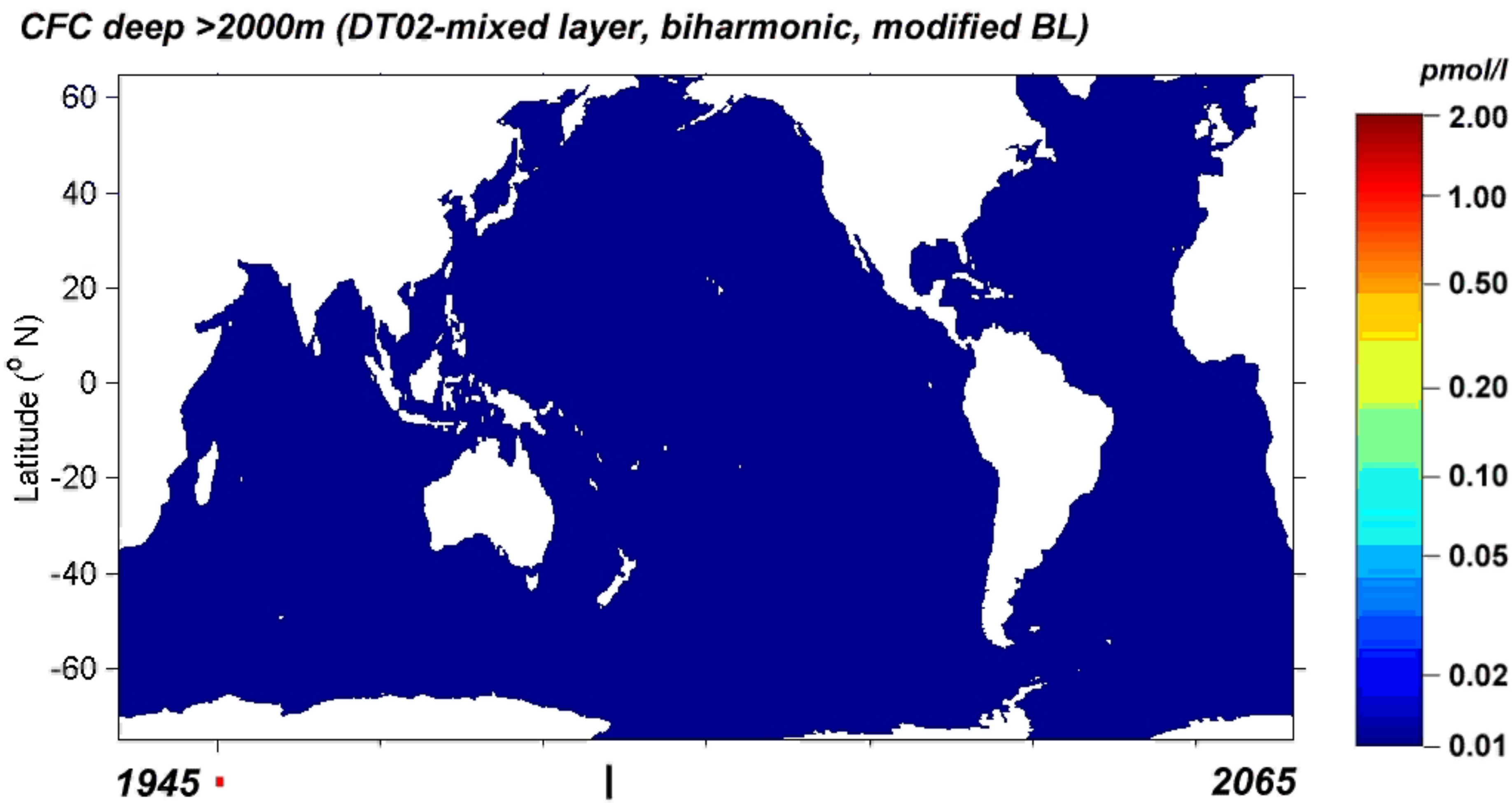


¼-degree global ocean model

Sen Gupta & England, JPO, 2003

NADW CFC content

Observed **Modelled**

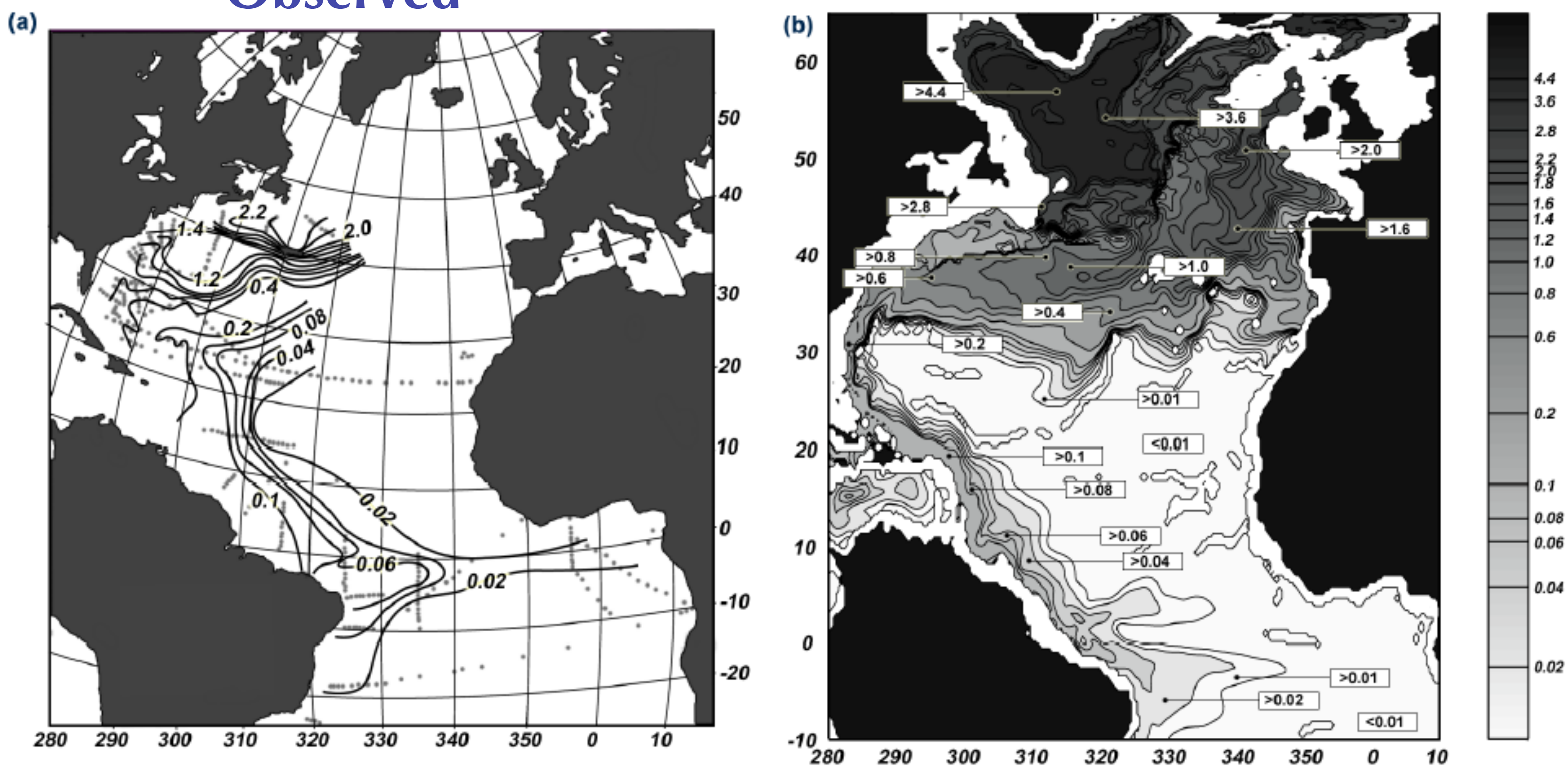
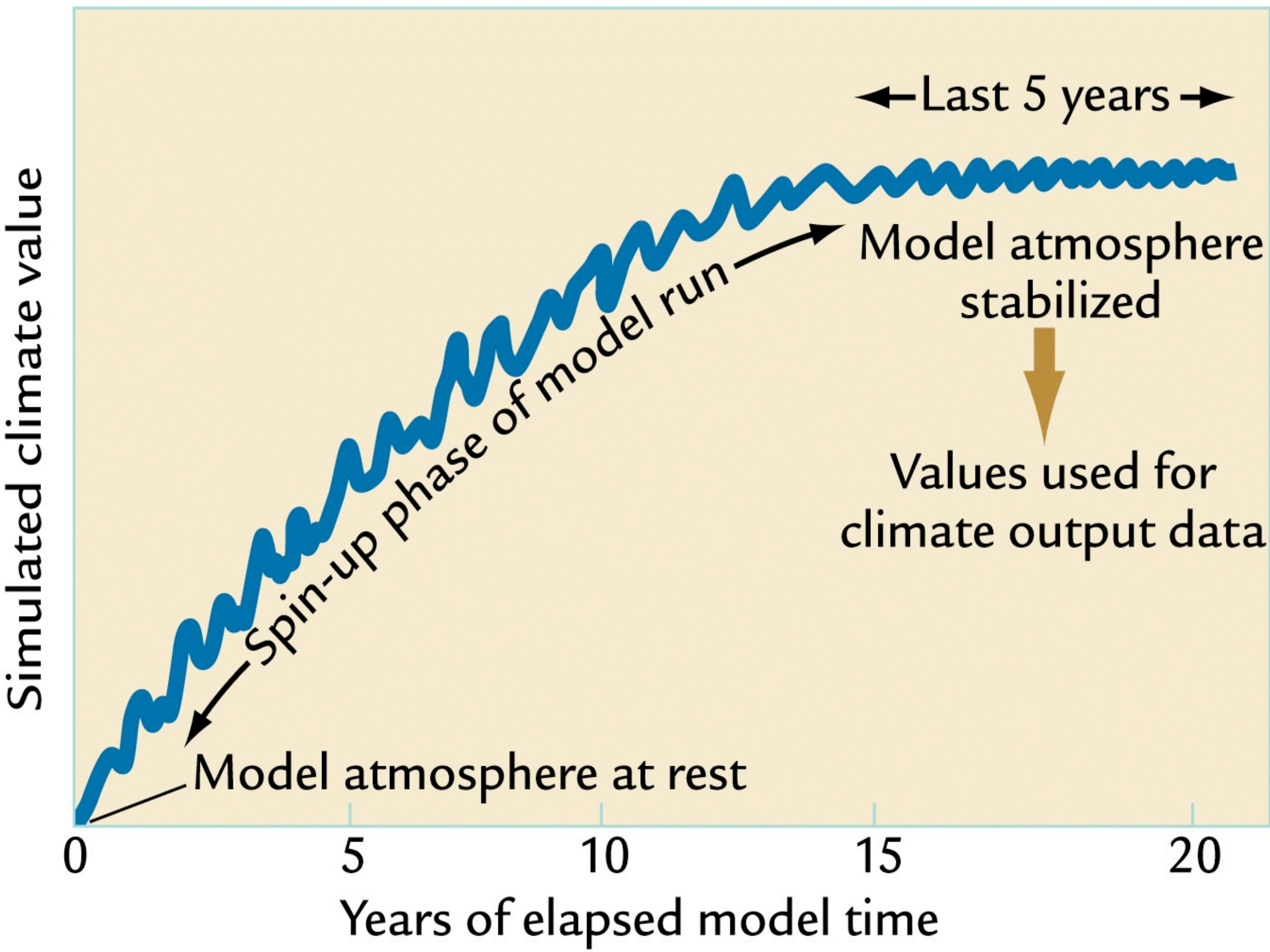
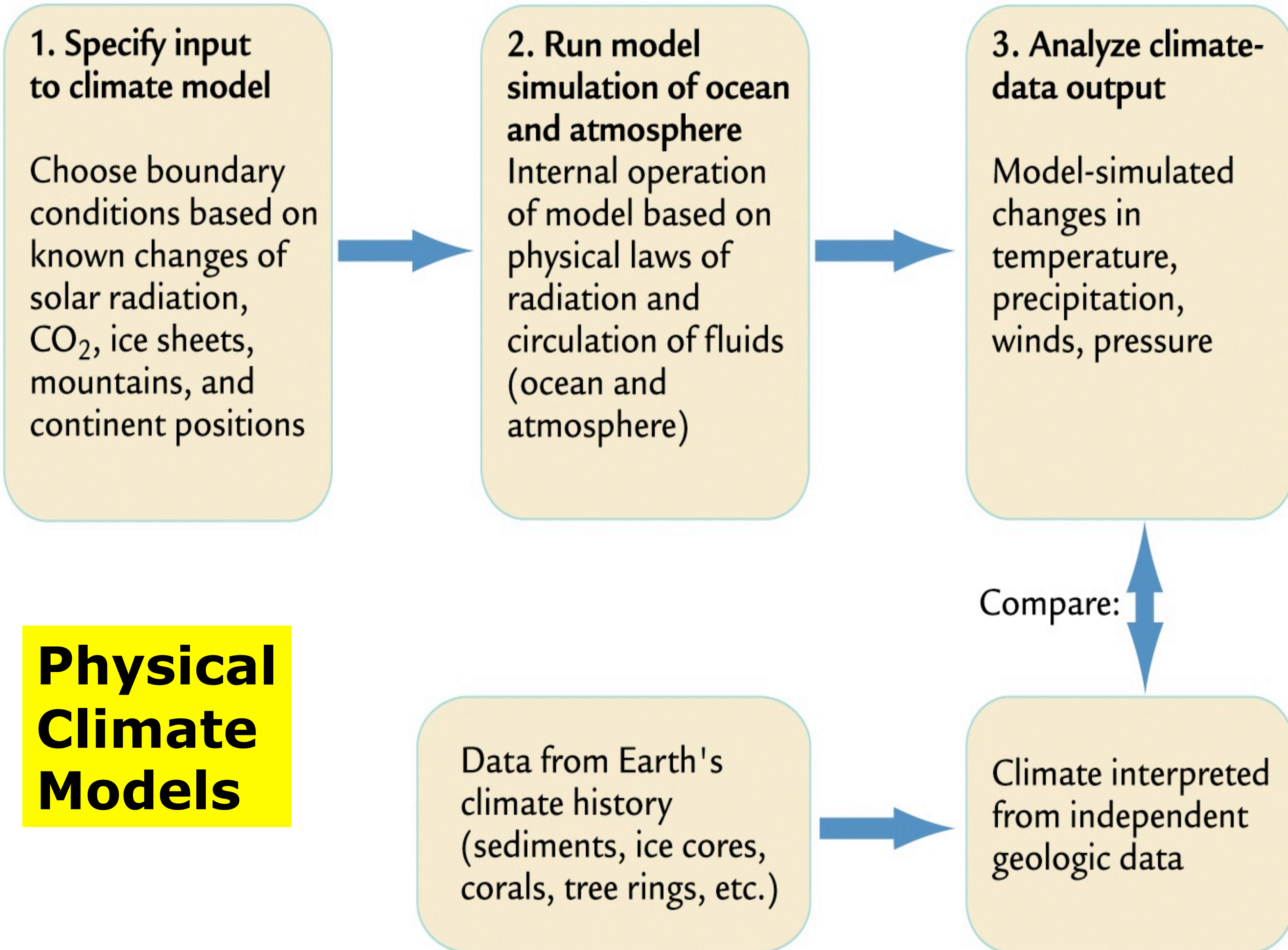


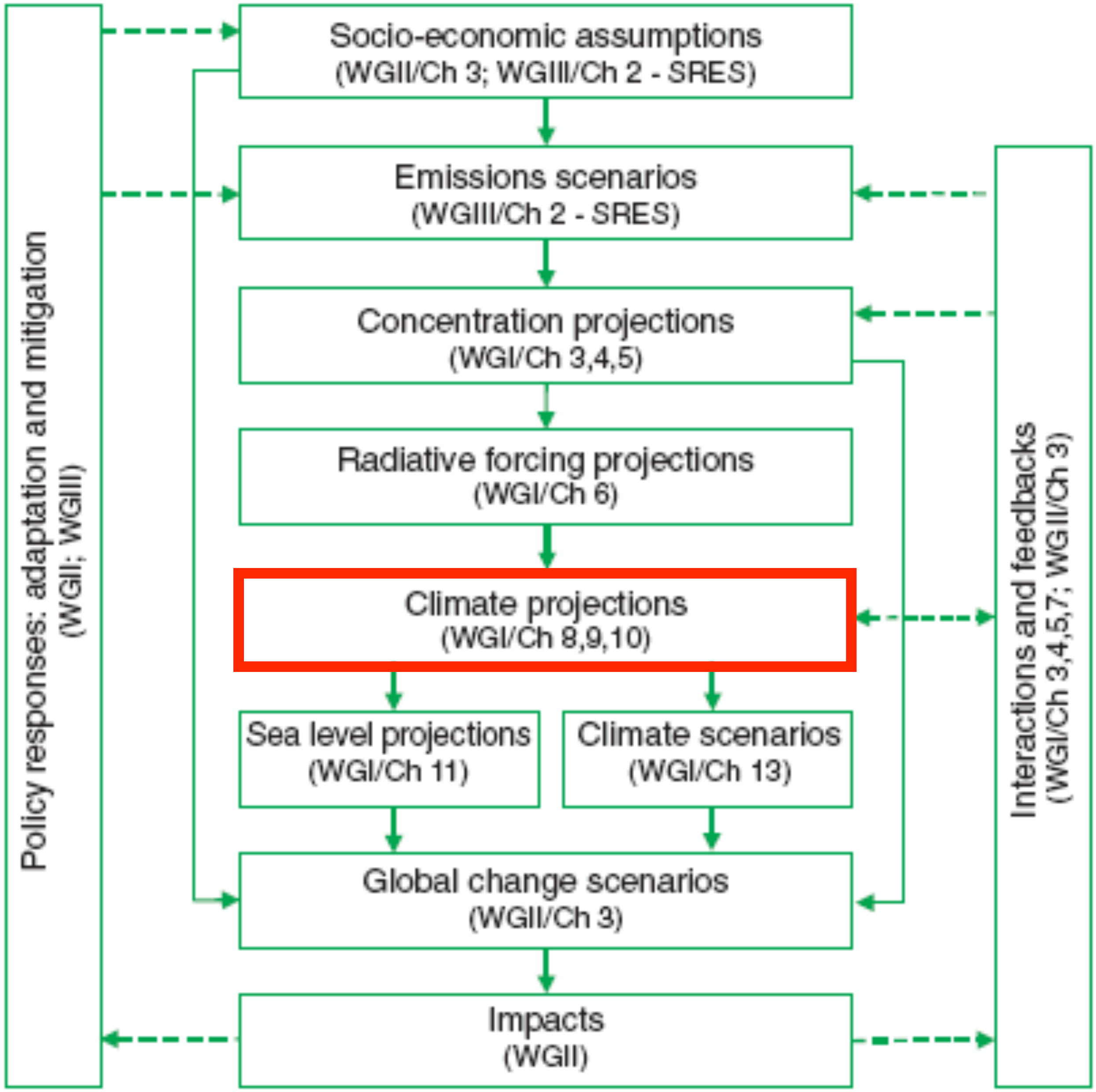
Figure 6. Lateral CFC-11 concentrations $[pmol kg^{-1}]$ for ULSW: (a) observed distribution from Smethie *et al.* (2000) (data normalised to a common date of 1990), (b) $CFC_{0.2}$ distribtion on $\sigma_{1.5} = 34.51 kg m^{-3}$ during June 1990.

Sen Gupta & England, JPO, 2003


Last 5 years
Model atmosphere stabilized
Values used for climate output data
Spin-up phase of model run
Model atmosphere at rest
Simulated climate value
0
5
10
15
20
Years of elapsed model time

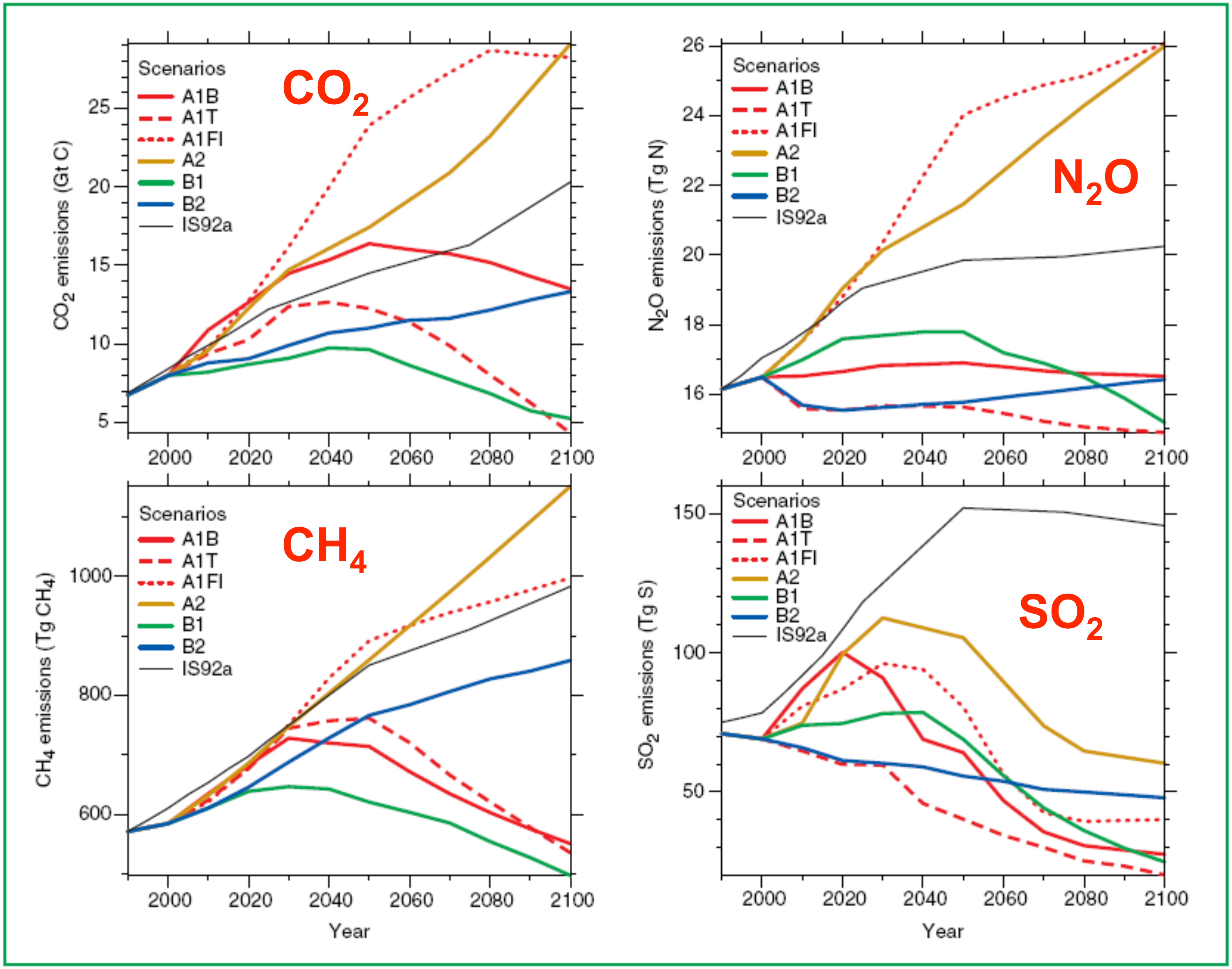
Physical Climate Models



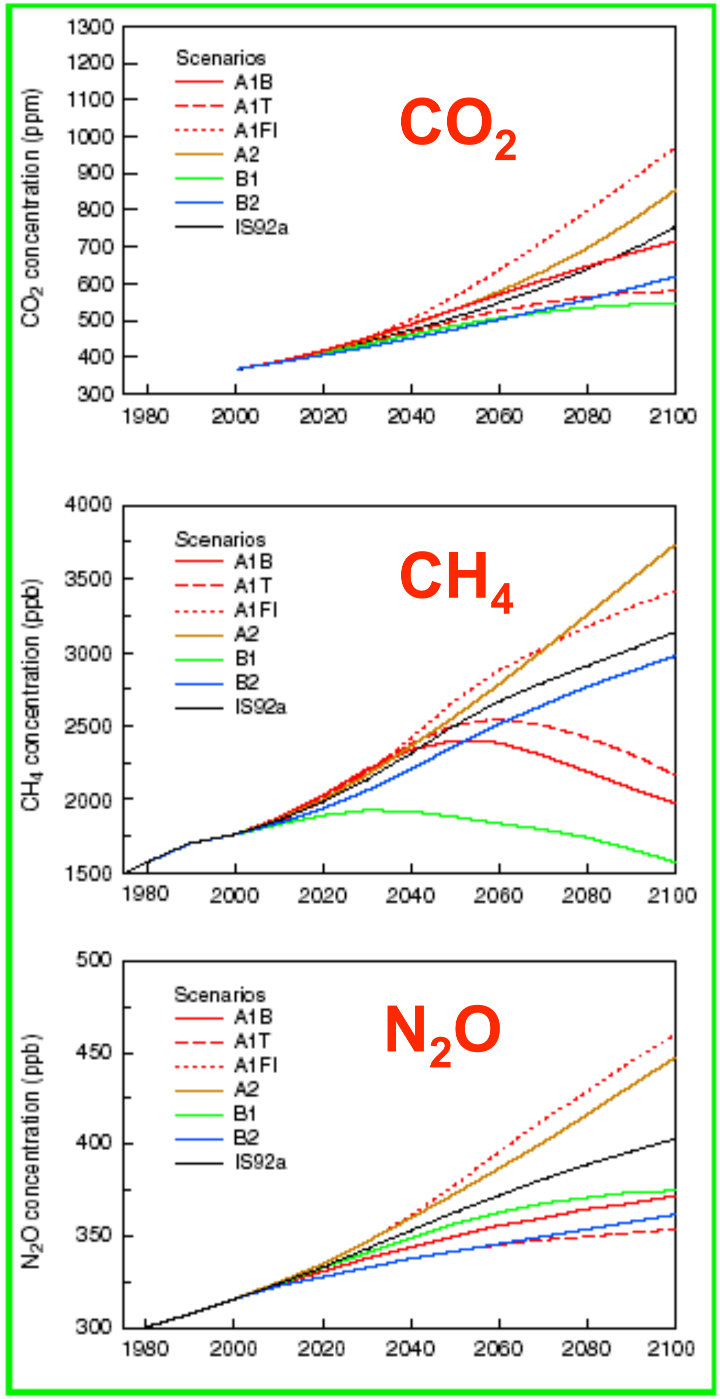


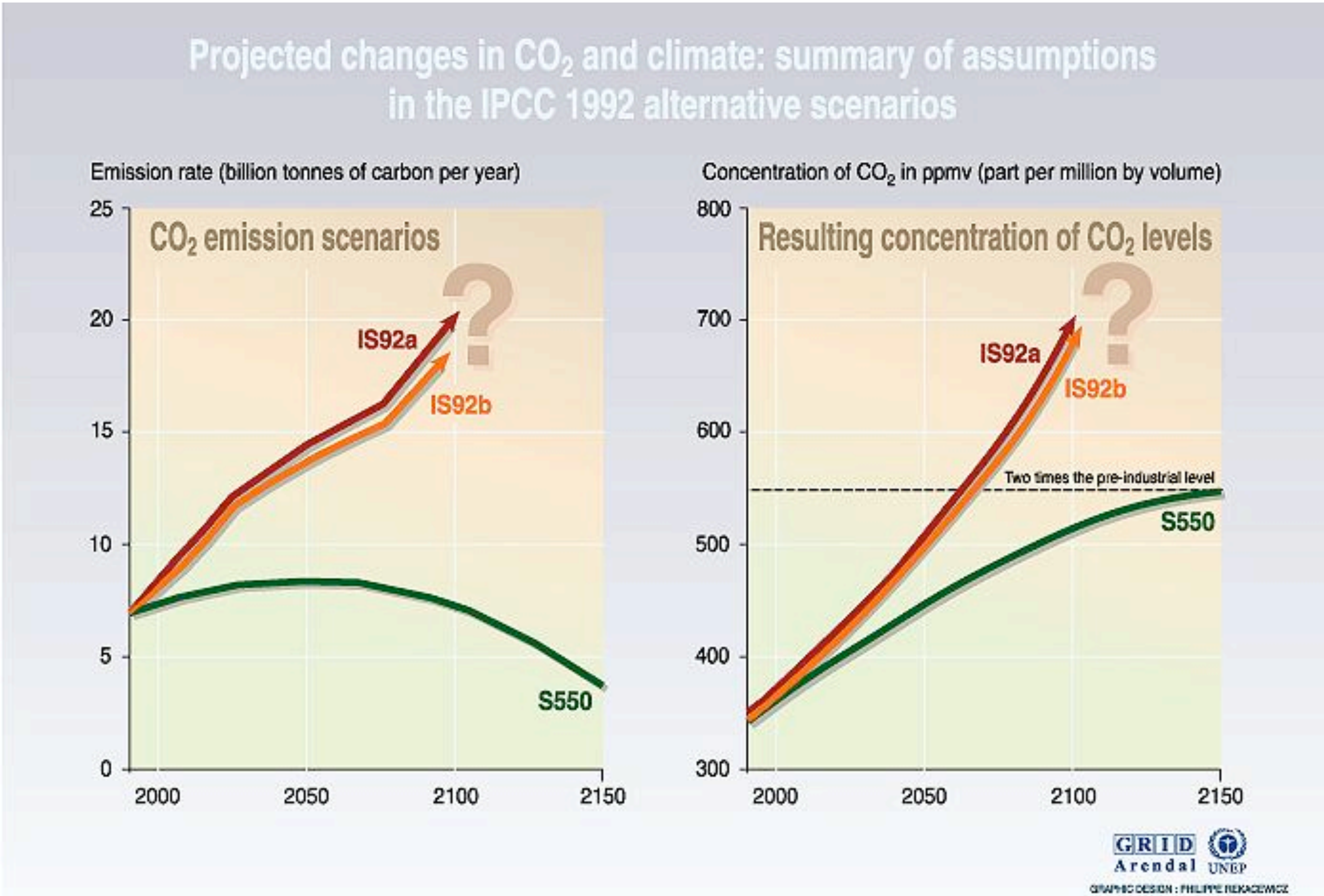
Socio-economic assumptions
(WGII/Ch 3; WGIII/Ch 2 - SRES)
Emissions scenarios
(WGIII/Ch 2 - SRES)
Concentration projections
(WGI/Ch 3,4,5)
Radiative forcing projections
(WGI/Ch 6)
Climate projections
(WGI/Ch 8,9,10)
Sea level projections
(WGI/Ch 11)
Climate scenarios
(WGI/Ch 13)
Global change scenarios
(WGII/Ch 3)
Impacts
(WGII)
Policy responses: adaptation and mitigation
(WGII; WGIII)
Interactions and feedbacks
(WGI/Ch 3,4,5,7; WGII/Ch 3)

EMISSIONS SCENARIOS

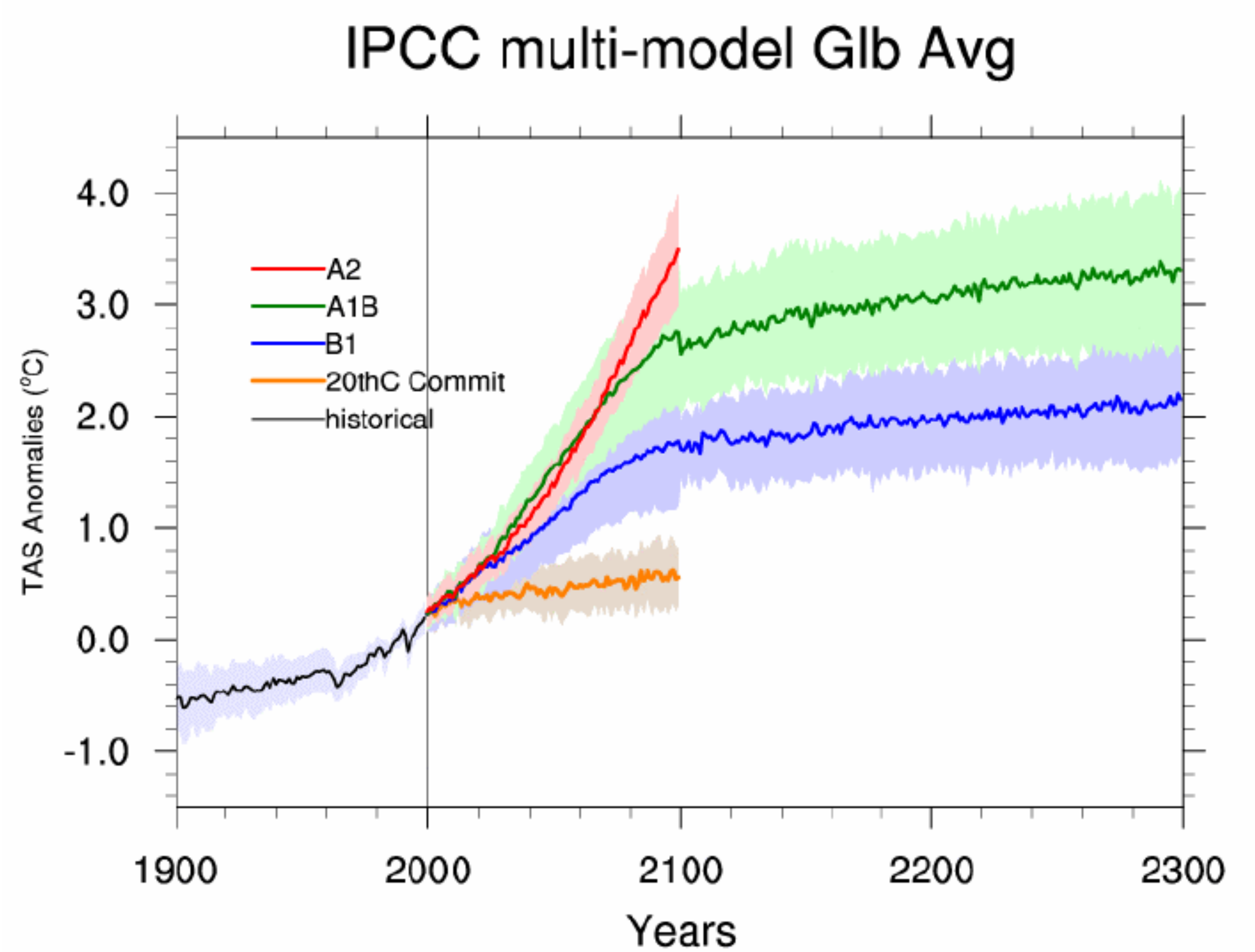


CONCENTRATIONS

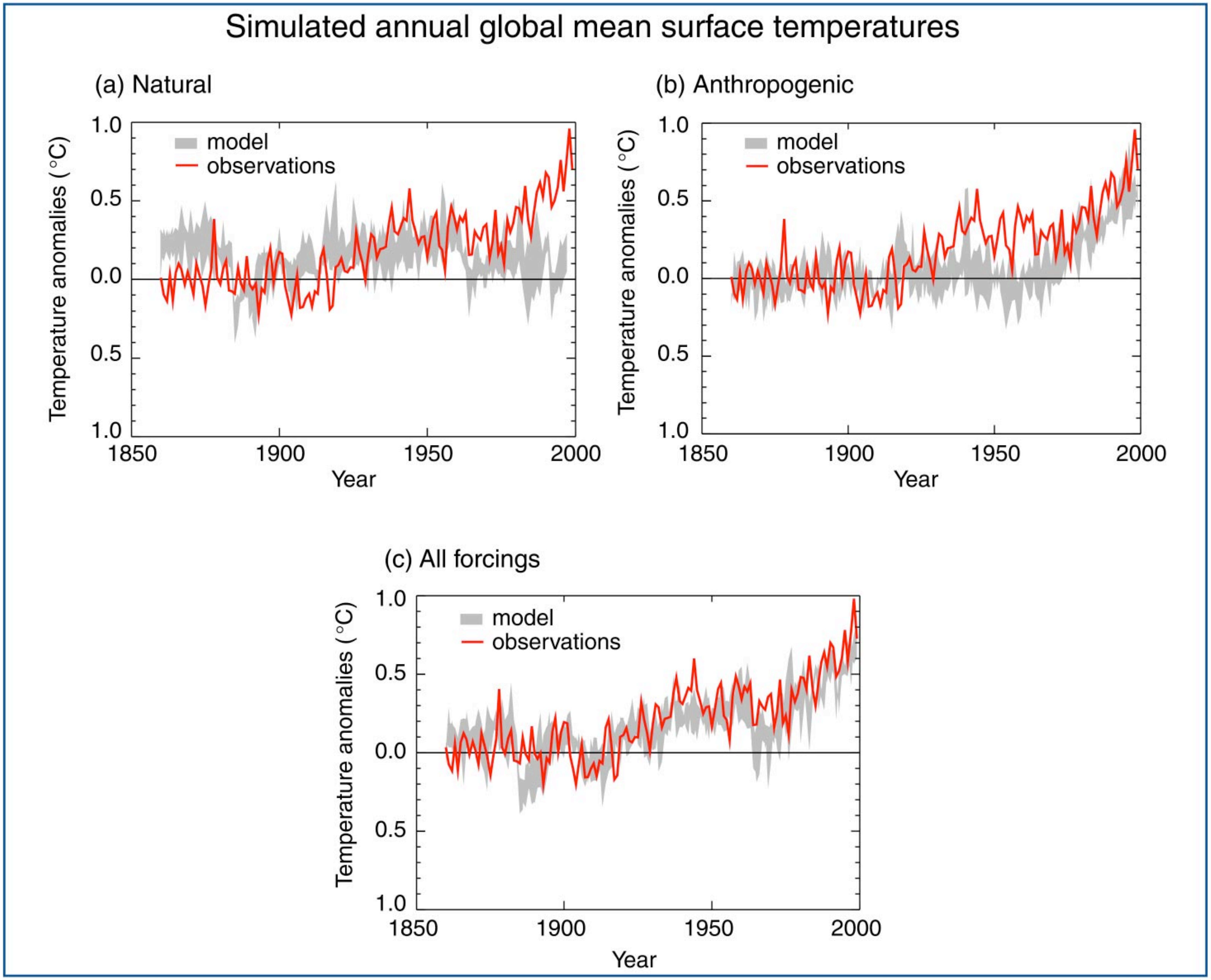




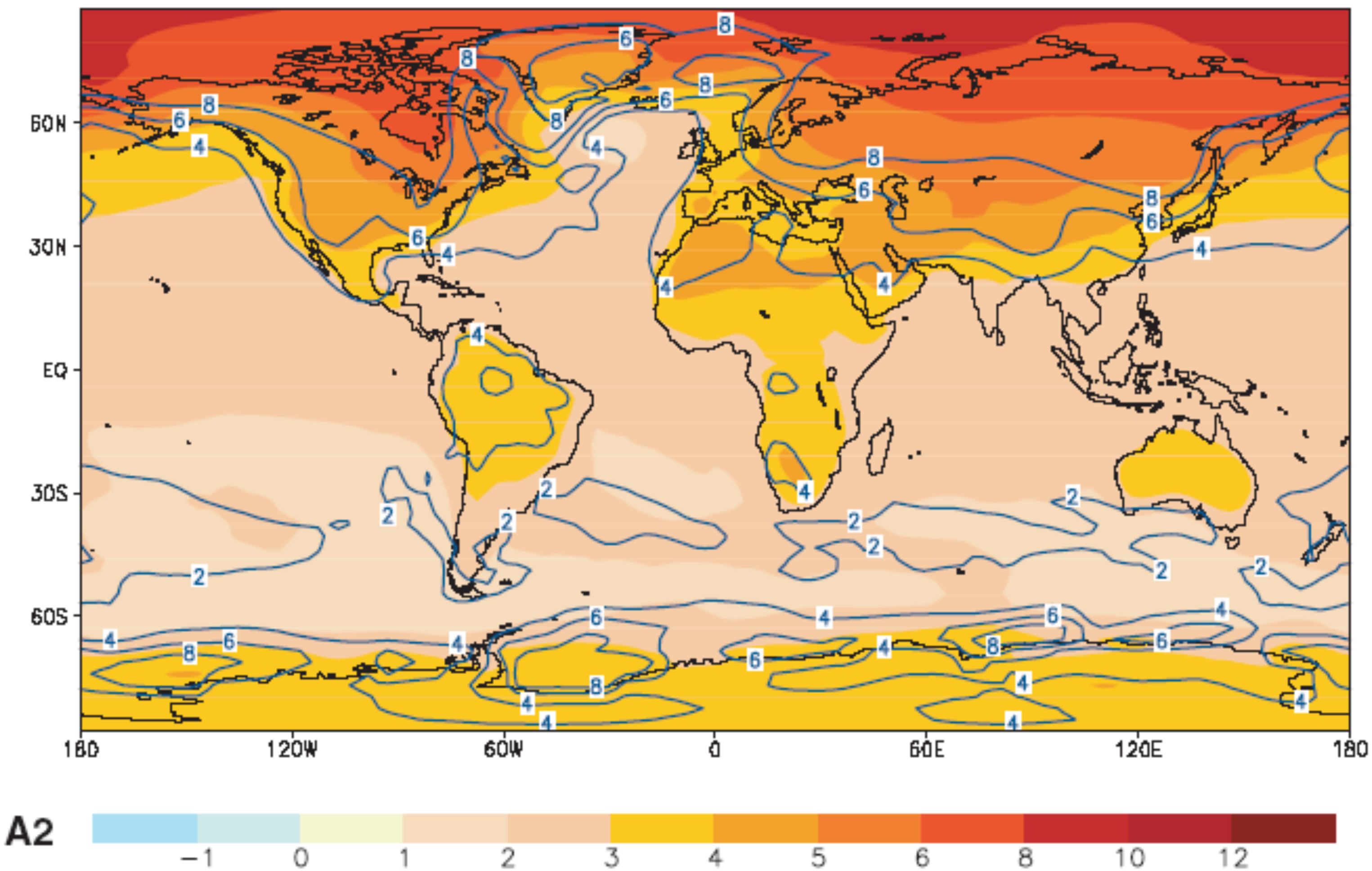
Sources: Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge press university, 199; Hadley center for climate prediction and research, United Kingdom, in Climate change information kit, Information unit for convention (IUC), UNEP, Geneva, 1997.



IPCC multi-model Glb Avg
A2
A1B
B1
20thC Commit
historical
TAS Anomalies (°C)
4.0
3.0
2.0
1.0
0.0
-1.0
1900
2000
2100
2200
2300
Years


Simulated annual global mean surface temperatures
(a) Natural
(b) Anthropogenic
(c) All forcings
model
observations
Temperature anomalies (°C)
1.0
0.5
0.0
0.5
1.0
1850
1900
1950
2000
Year

Annual-mean temperature change predicted for 2070-2100 in IPCC Third Assessment Report models



Annual mean change in temperature (colour shading) and its range (isolines) (Unit: °C) for the SRES scenario A2, showing the period 2071 to 2100 relative to the period 1961 to 1990.

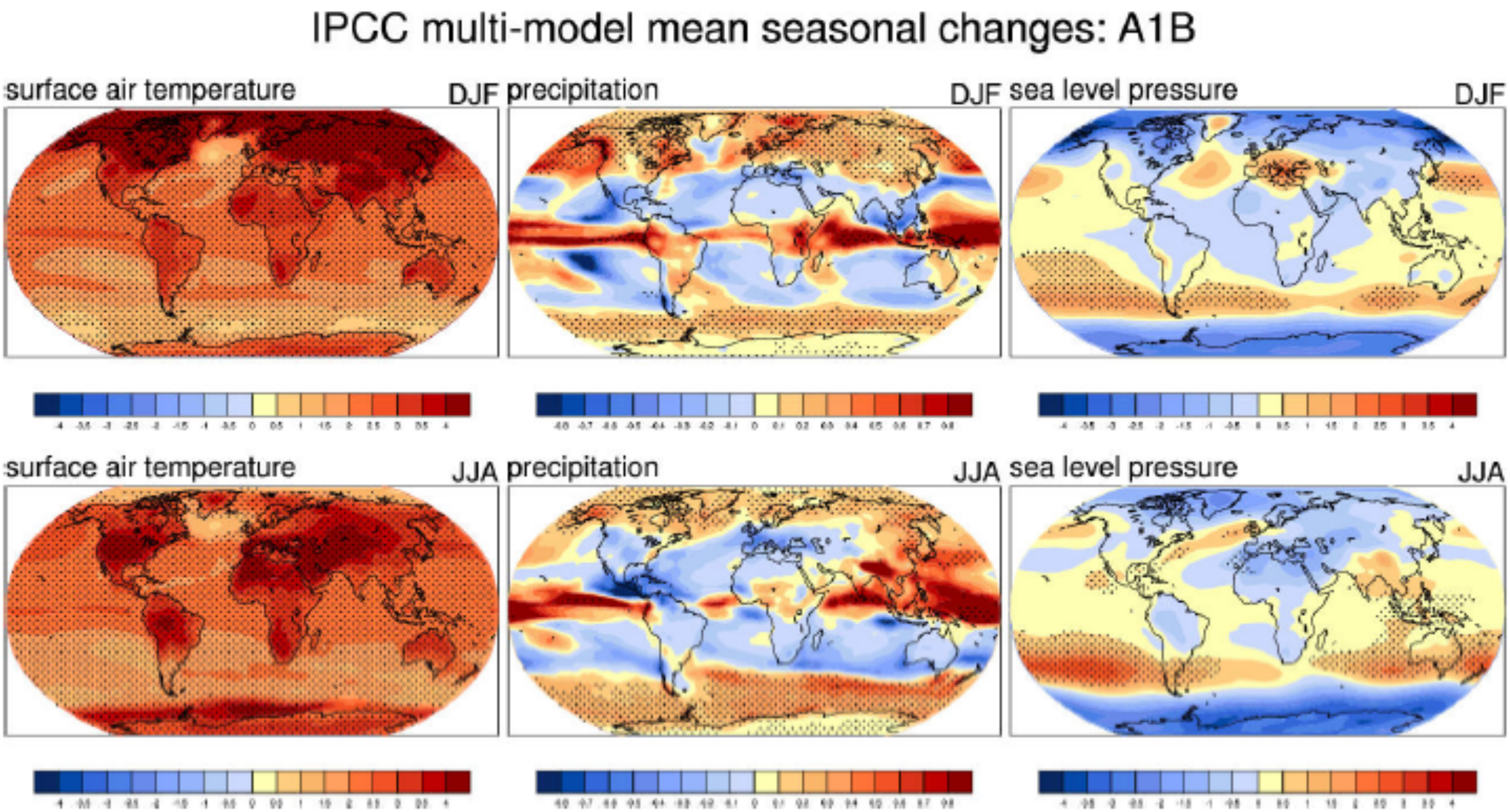


Figure 10.3.6. Multi-model mean change under the A1B scenario for 2080–2099 relative to 1980–1999, for DJF (top) and JJA (bottom). The variables are, from left to right, surface air temperature (°C), precipitation (mm/d), and sea level pressure (hPa). Stippling denotes areas where the magnitude of the multi-model ensemble mean exceeds the inter-model standard deviation.

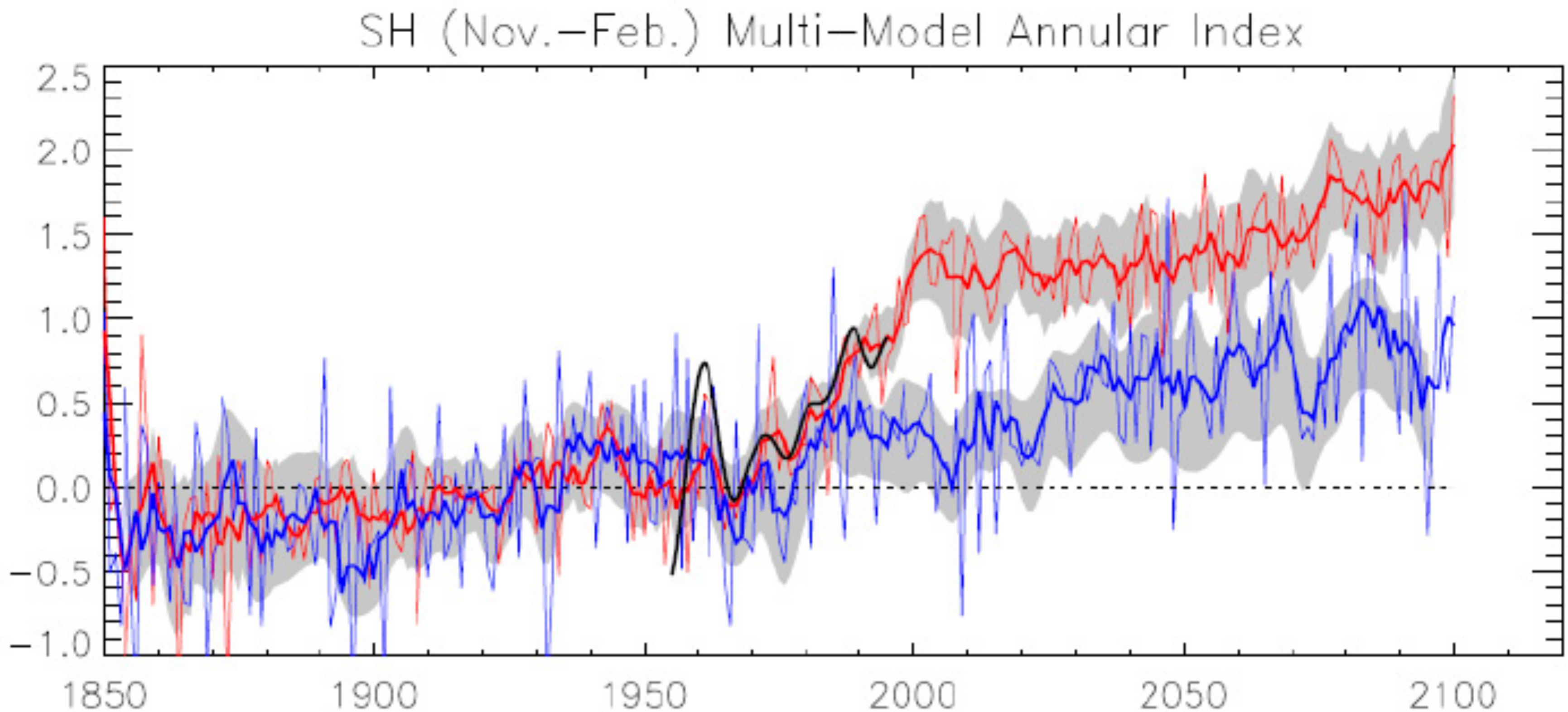
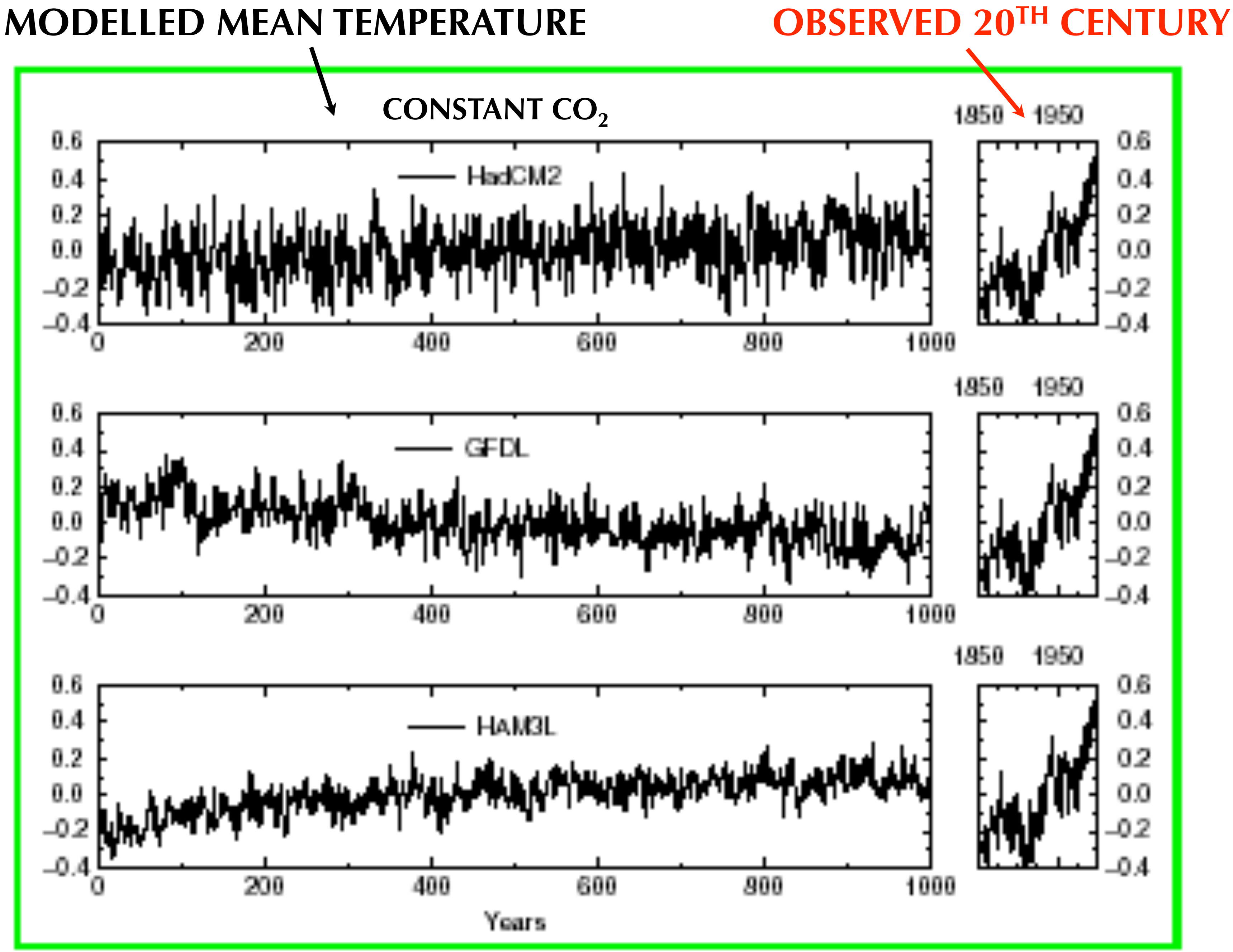
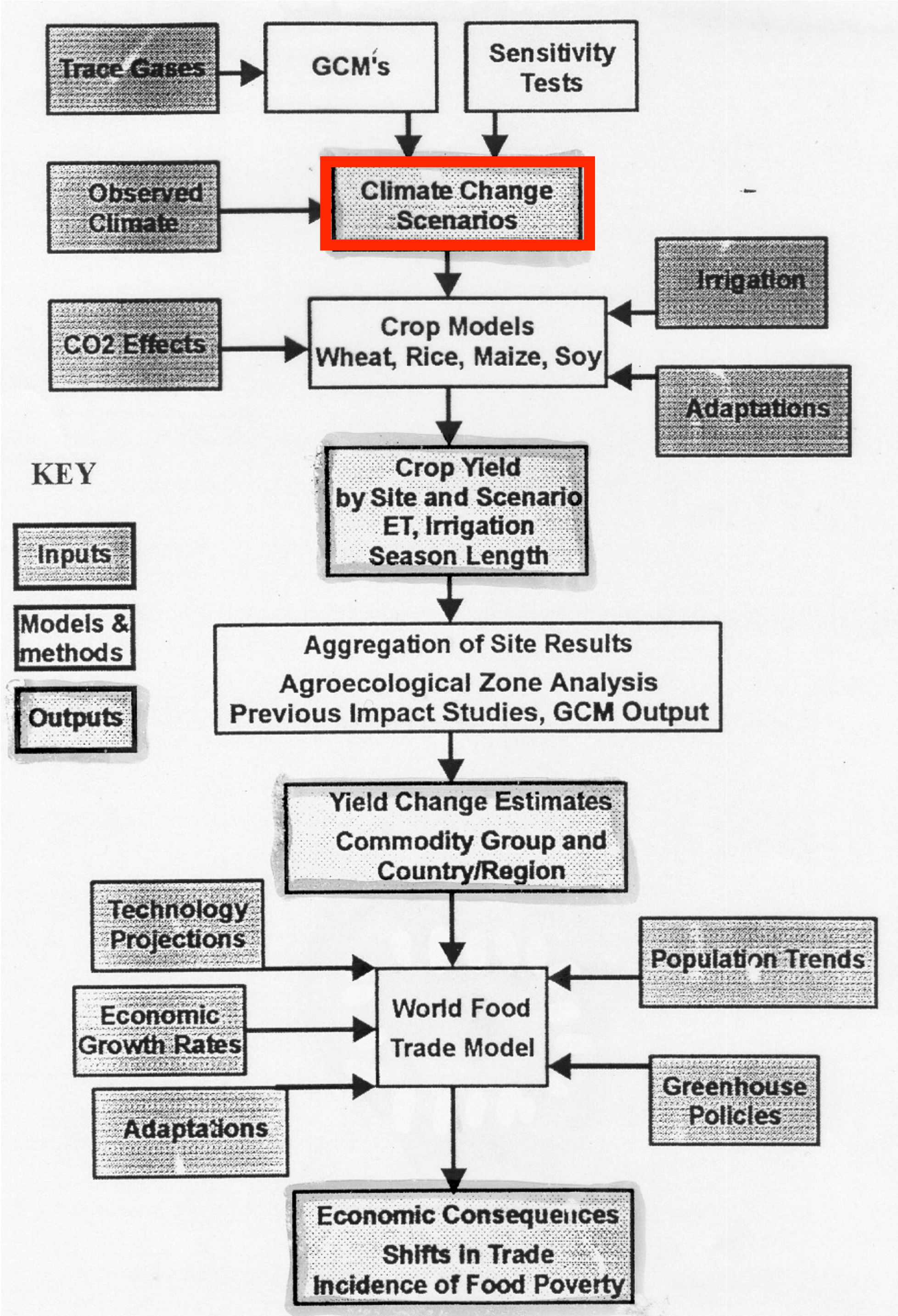


Figure 10.3.17. . Multi-model mean of the regression of the leading EOF of ensemble mean SH SLP with ensemble mean SLP for models with (red) and without (blue) ozone forcing. The time series of regression coefficients has zero mean between 1950 and 1999. The thick red and blue lines show a 5-year low-passed filtered version of the multi-model mean for models with and without ozone forcing, respectively. The gray shading represents the inter-model spread at the 95% level and is filtered. A filtered version of the regression coefficient for NCEP SLP is in black. From Miller et al. (2005).

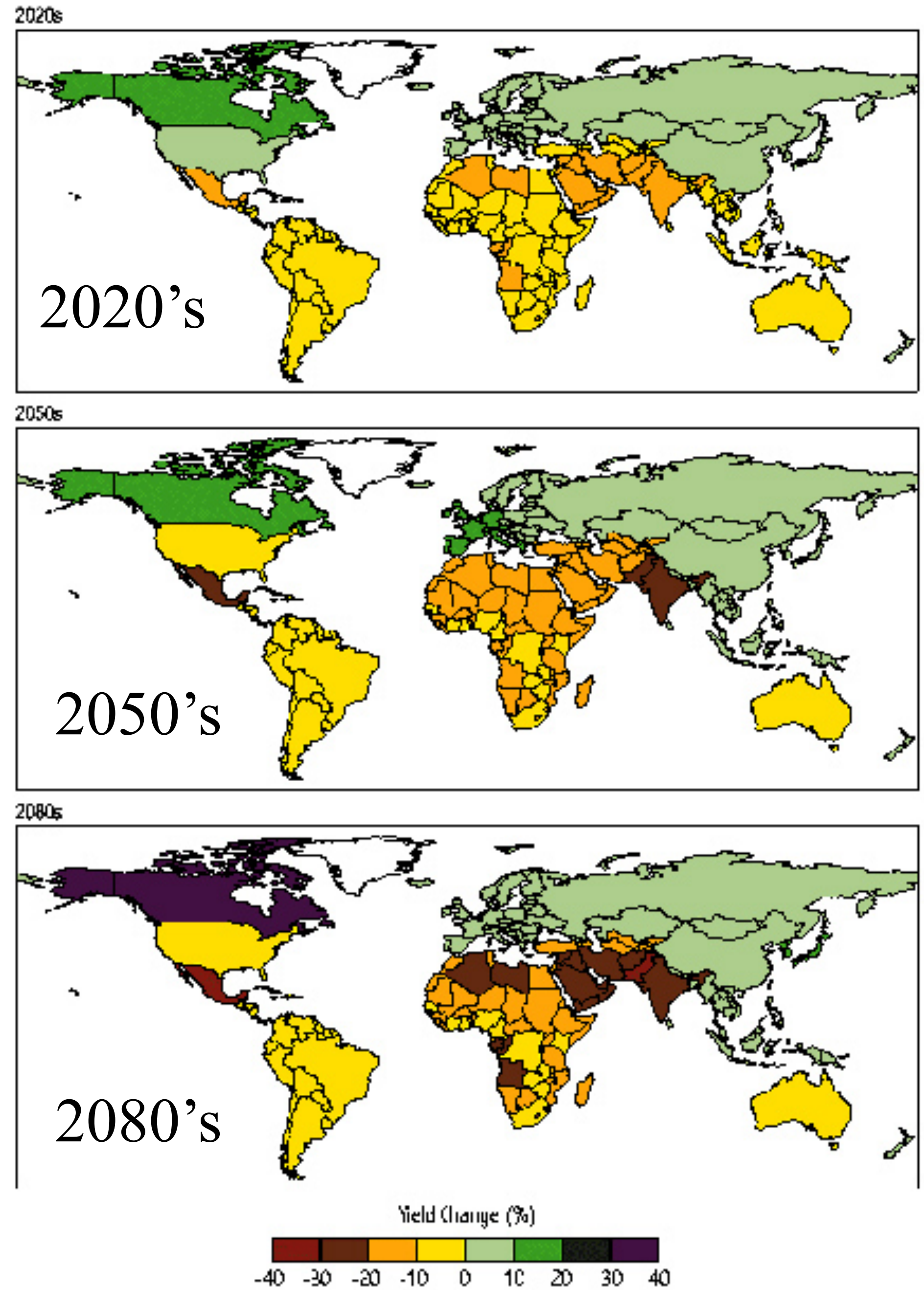


MODELLED MEAN TEMPERATURE
OBSERVED 20TH CENTURY
CONSTANT CO2
HadCM2
GFDL
HAM3L
1850
1950
0.6
0.4
0.2
0.0
−0.2
−0.4
0
200
400
600
800
1000
Years

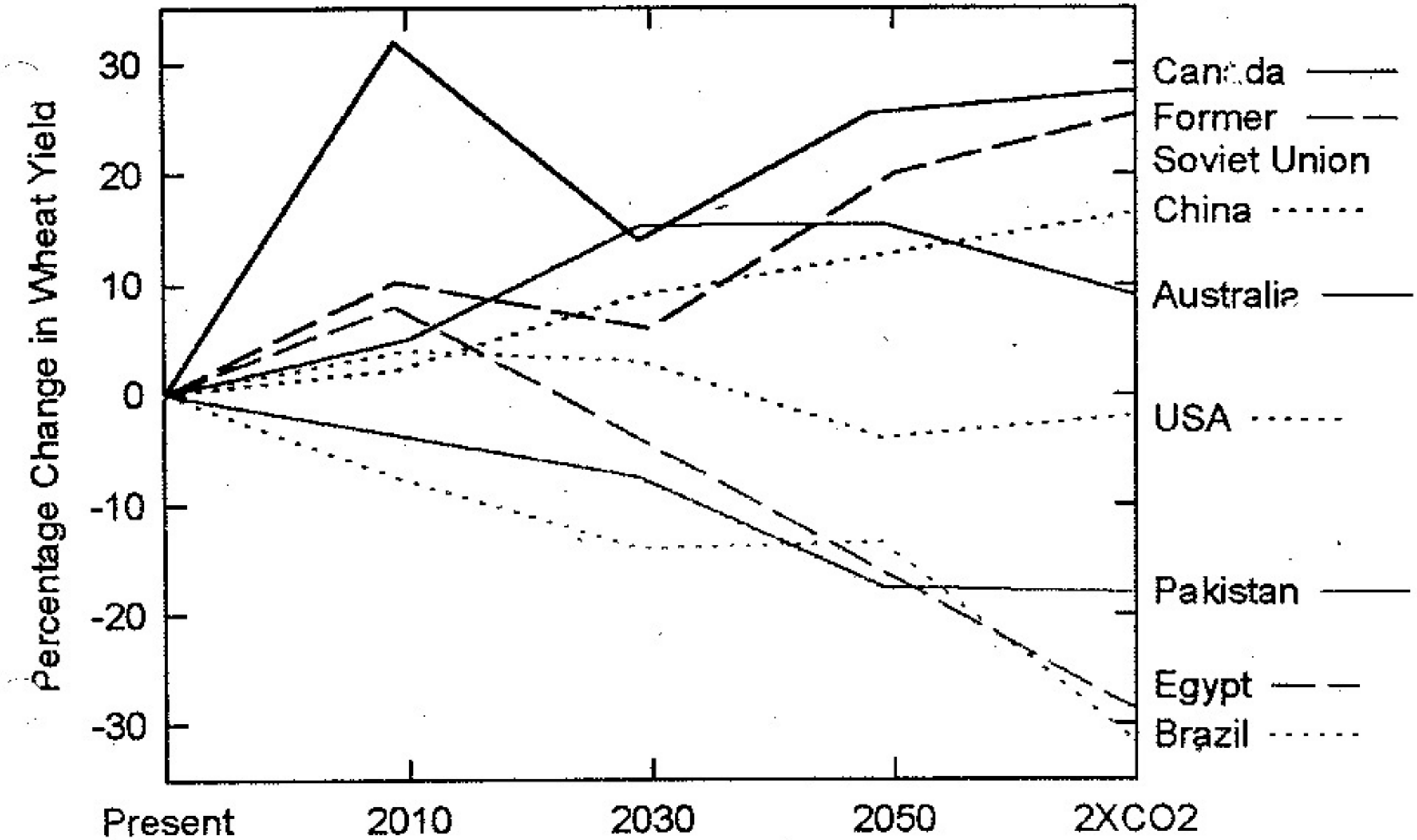
Integrated climate impacts assessment model



Crop yield changes projected relative to today aggregated by nation



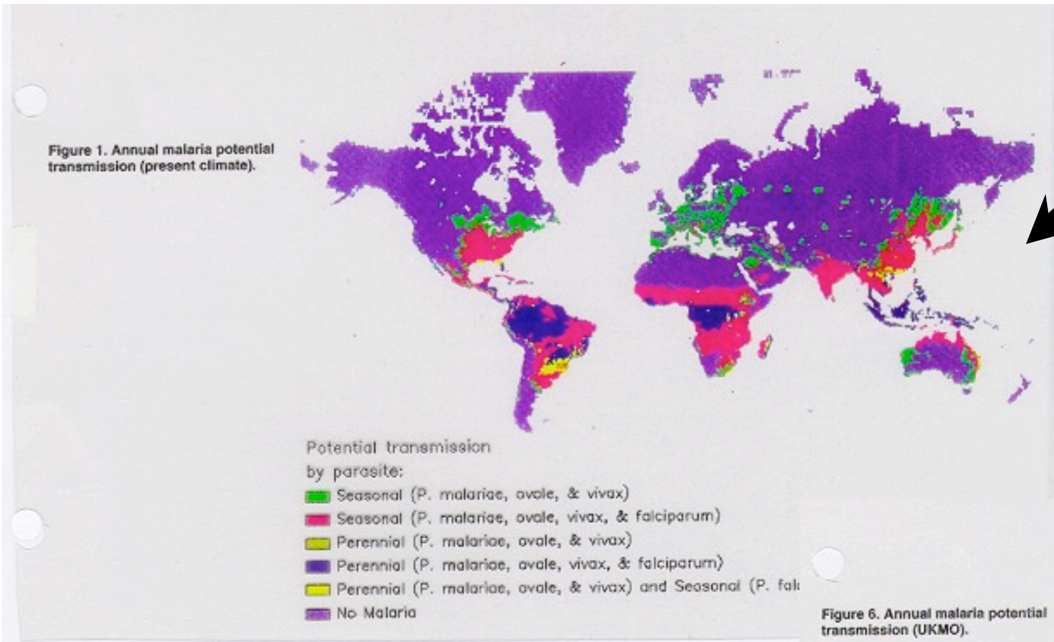
Source: Jackson Institute, University College London / Goddard Institute for Space Studies / International Institute for Applied Systems Analysis



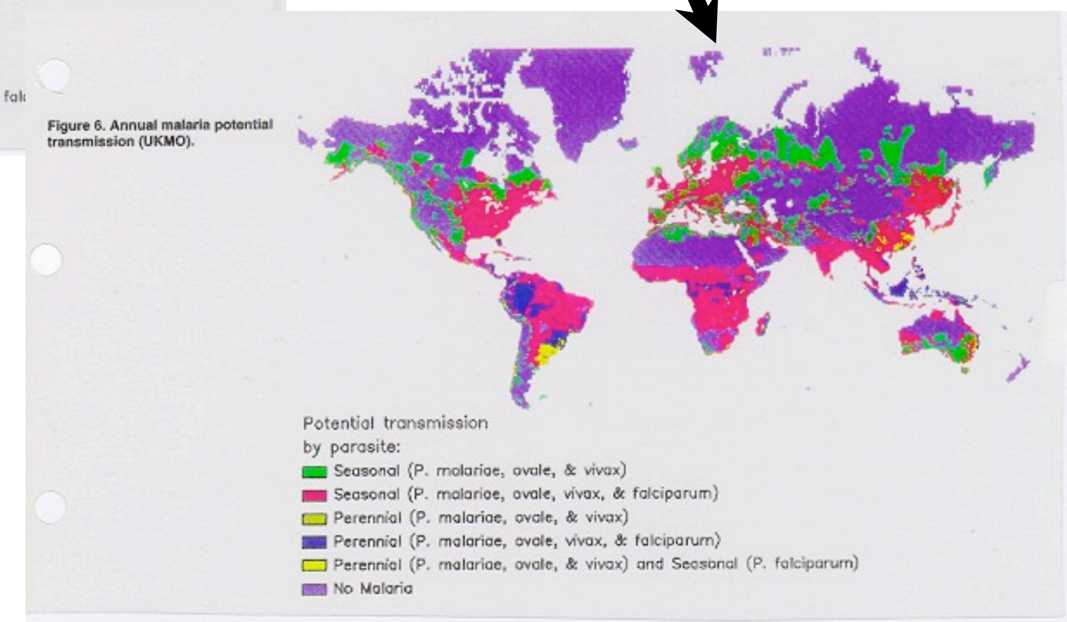
Predictions of national food supply to 2070

Malaria potential transmission

Today



2040



Conclusions

- **Climate system models comprise coupled sub-models of the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere.**

- The models are assessed rigorously against observations and are based – where possible – on fundamental laws of physics.

- The models are pretty good already, and are getting better all the time.

- Climate models provide a unique (the only!) tool for forecasting future climate change and its impacts

- Climate change will have far-reaching impacts over the next 50-100 years: on health, agriculture, biodiversity, built environment, freshwater supply, social, political, economic,….

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