Principles of GCMs

Global Climate Models
actually
Global Circulation Models

Steven W. Running
3 March 2009

What is a GCM?

- A GCM is a three-dimensional global climate model
  - Models run for thousands of years
- Models are derived from **fundamental physical laws** which are modified to approximate the large-scale climate system.
  - 23 models were used in the AR4
  - Notable progress in recent years

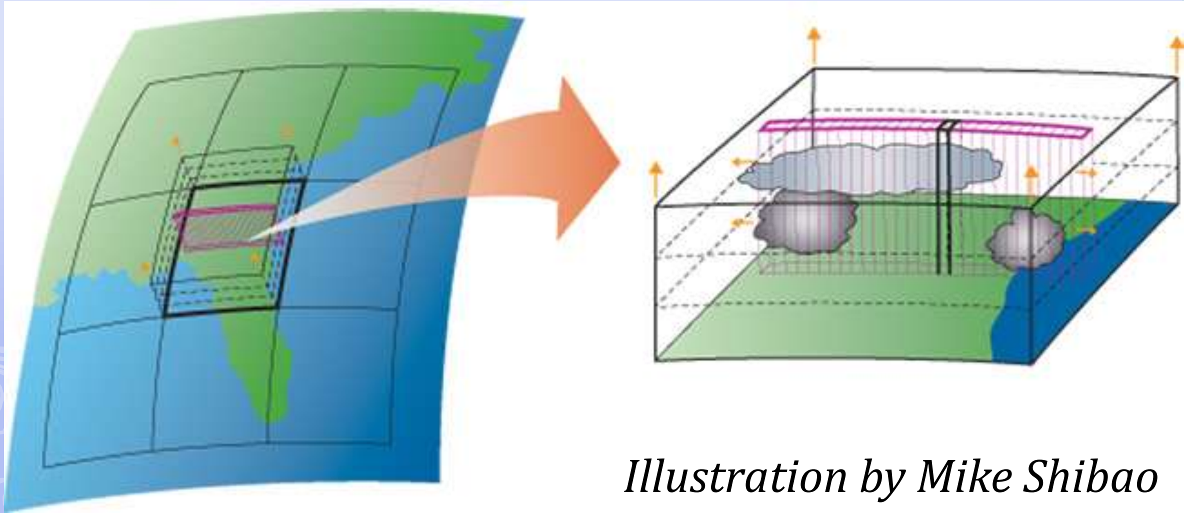


Illustration by Mike Shibao

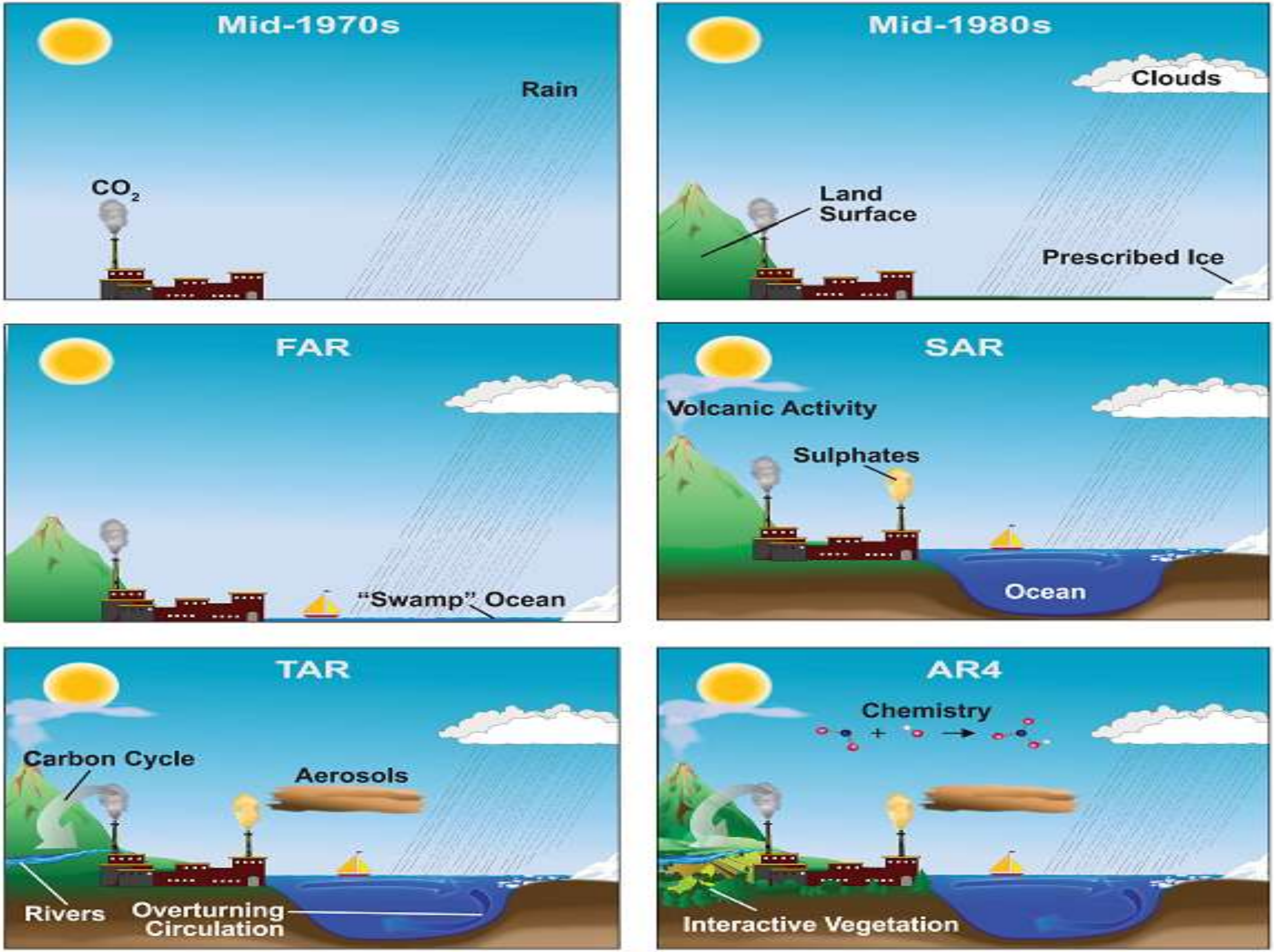
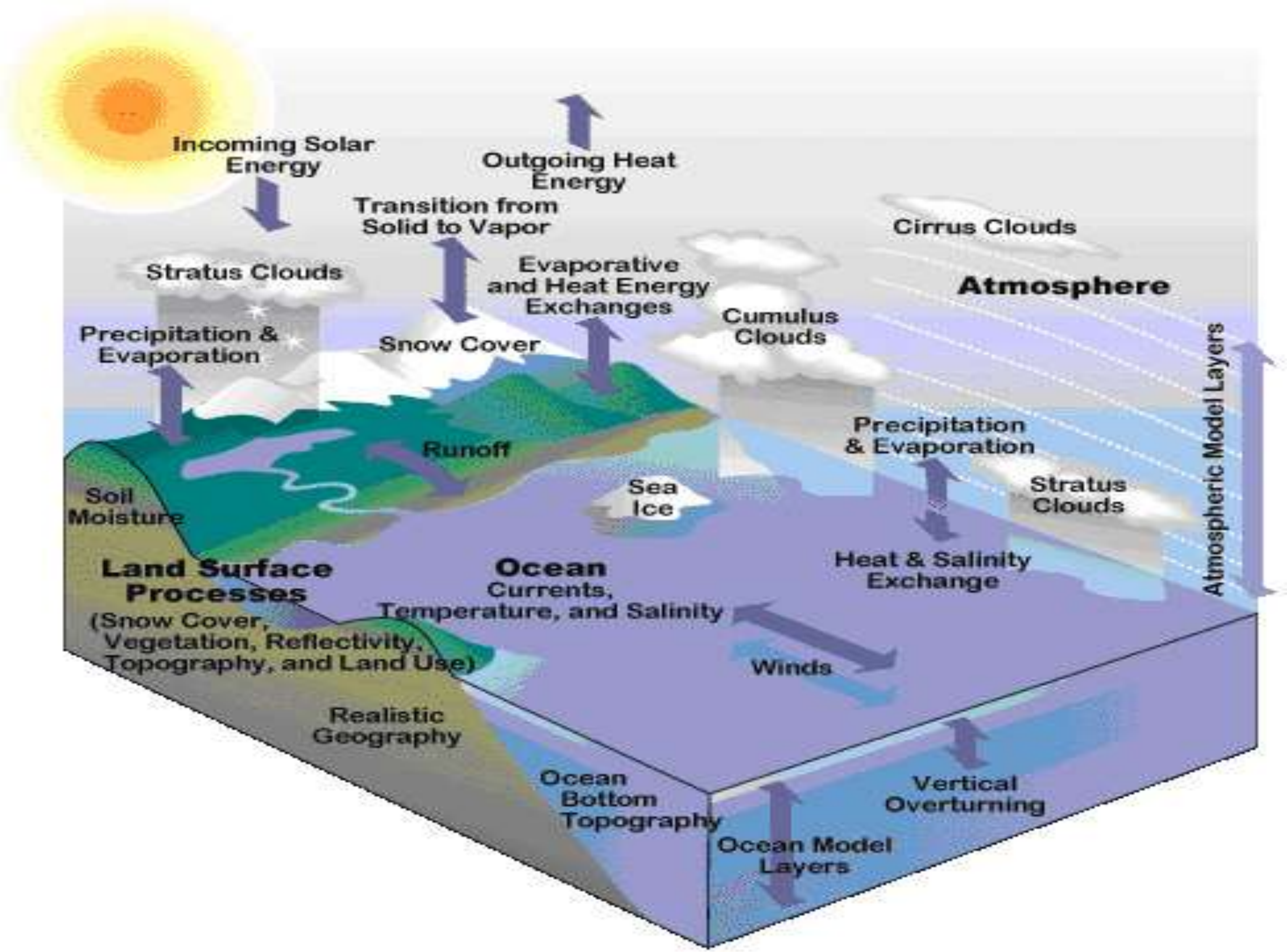
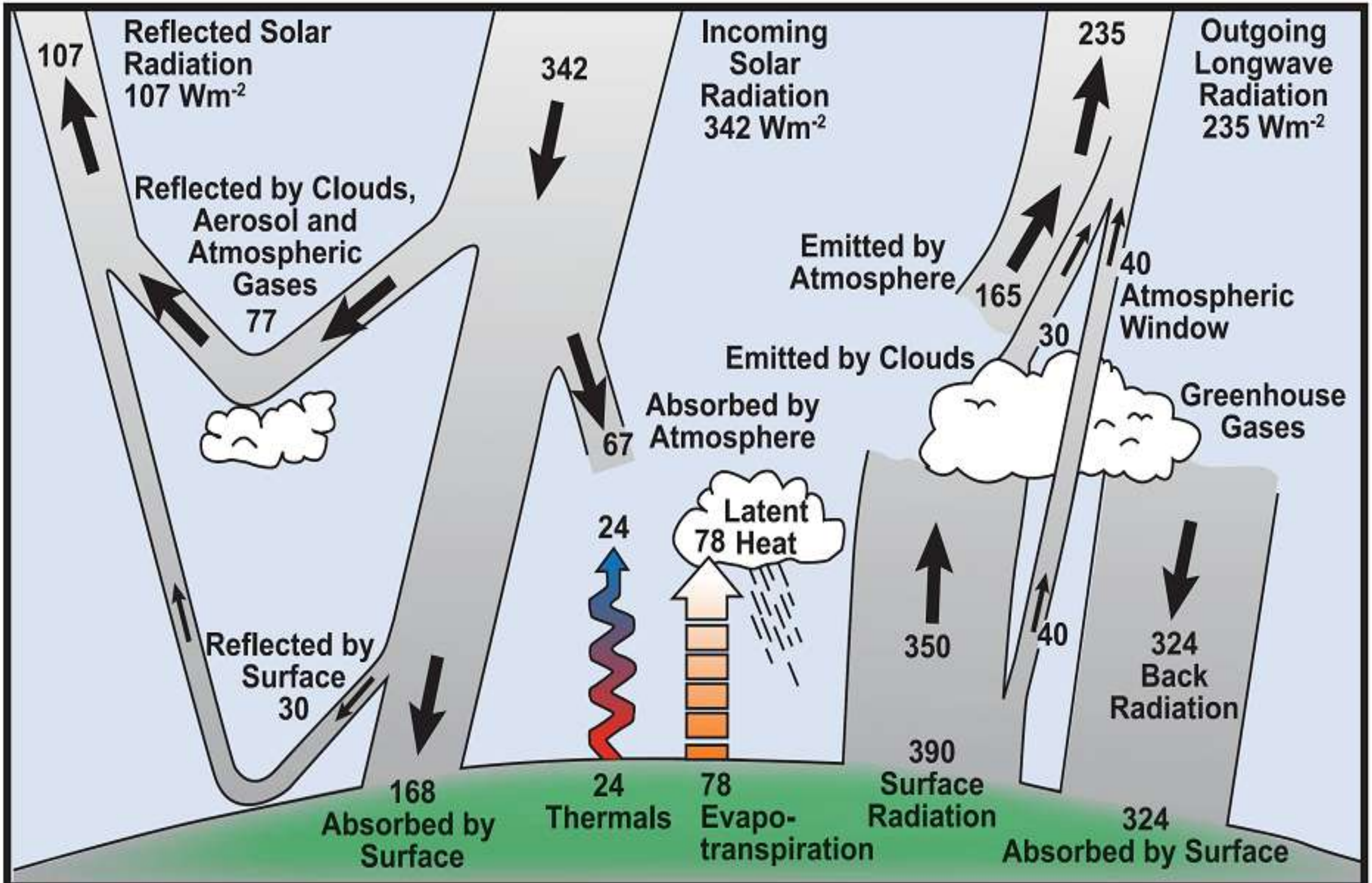


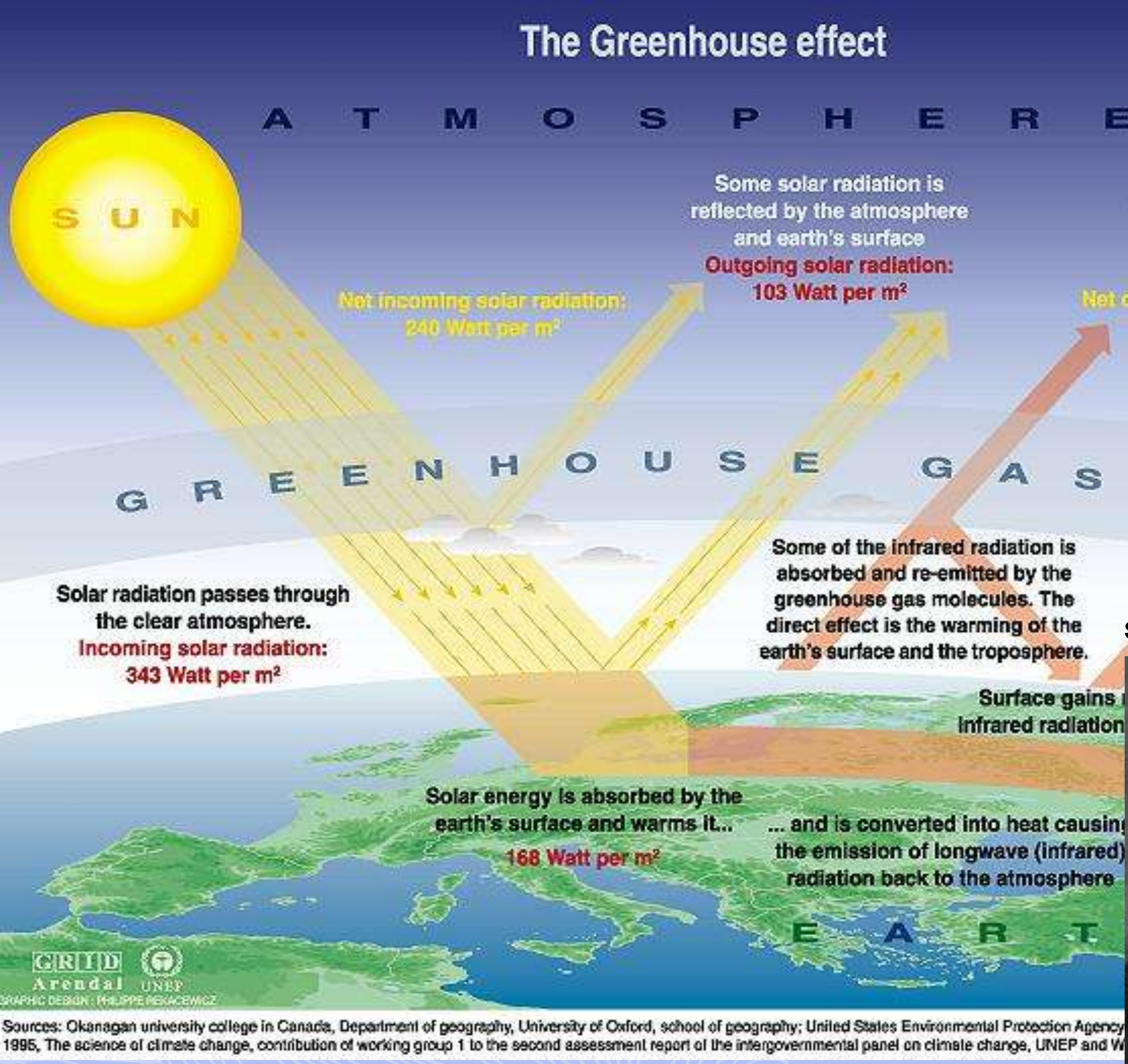
Figure 1.2. *The complexity of climate models has increased over the last few decades. The additional physics incorporated in the models are shown pictorially by the different features of the modelled world.*


Incoming Solar Energy
Outgoing Heat Energy
Transition from Solid to Vapor
Cirrus Clouds
Stratus Clouds
Evaporative and Heat Energy Exchanges
Atmosphere
Cumulus Clouds
Precipitation & Evaporation
Snow Cover
Atmospheric Model Layers
Precipitation & Evaporation
Runoff
Sea Ice
Stratus Clouds
Soil Moisture
Heat & Salinity Exchange
Land Surface Processes
(Snow Cover, Vegetation, Reflectivity, Topography, and Land Use)
Ocean
Currents, Temperature, and Salinity
Winds
Realistic Geography
Ocean Bottom Topography
Vertical Overturning
Ocean Model Layers

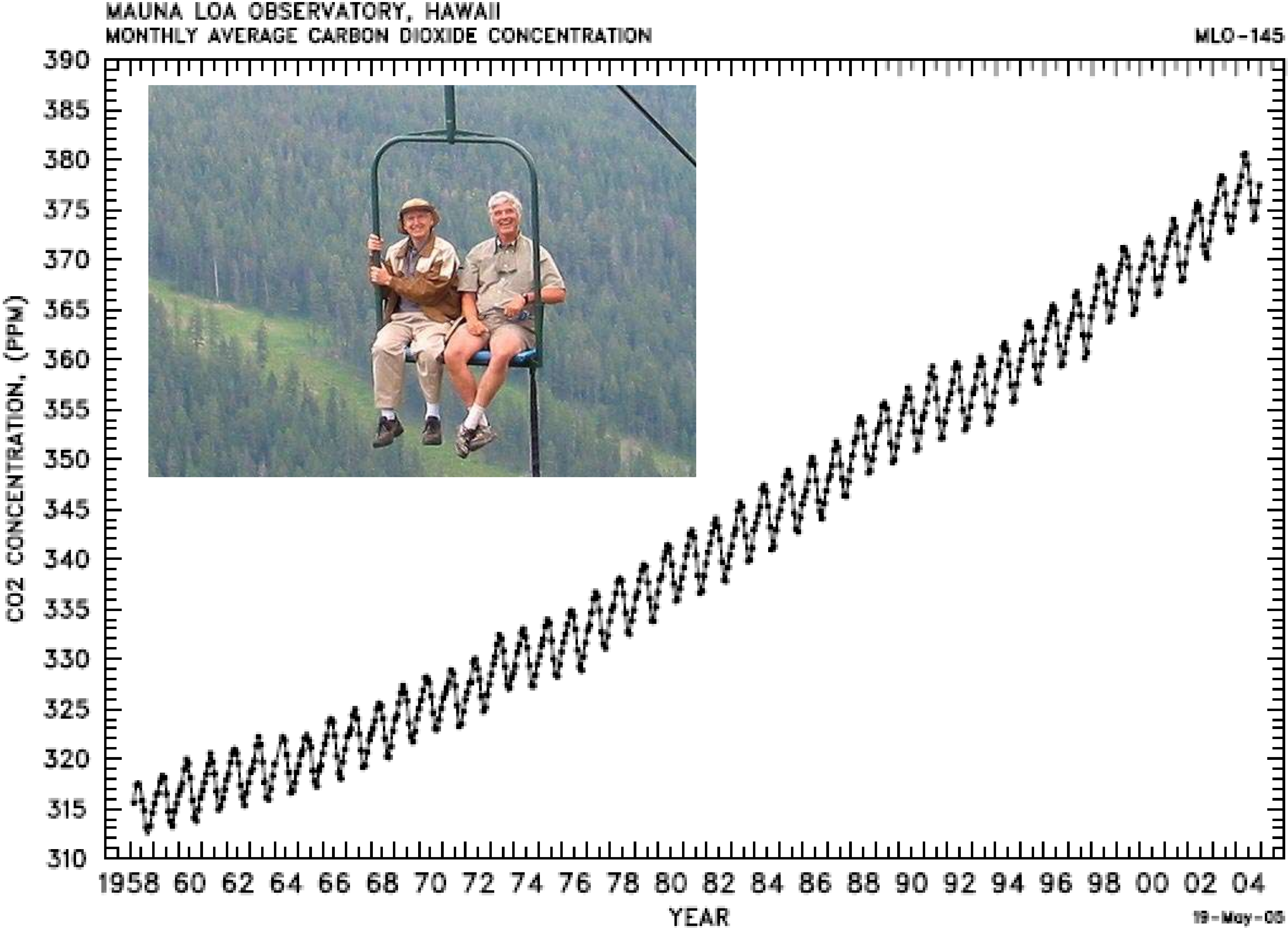

The Earth Simulator Center



FAQ 1.1, Figure 1. *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space. Source: Kiehl and Trenberth (1997).*



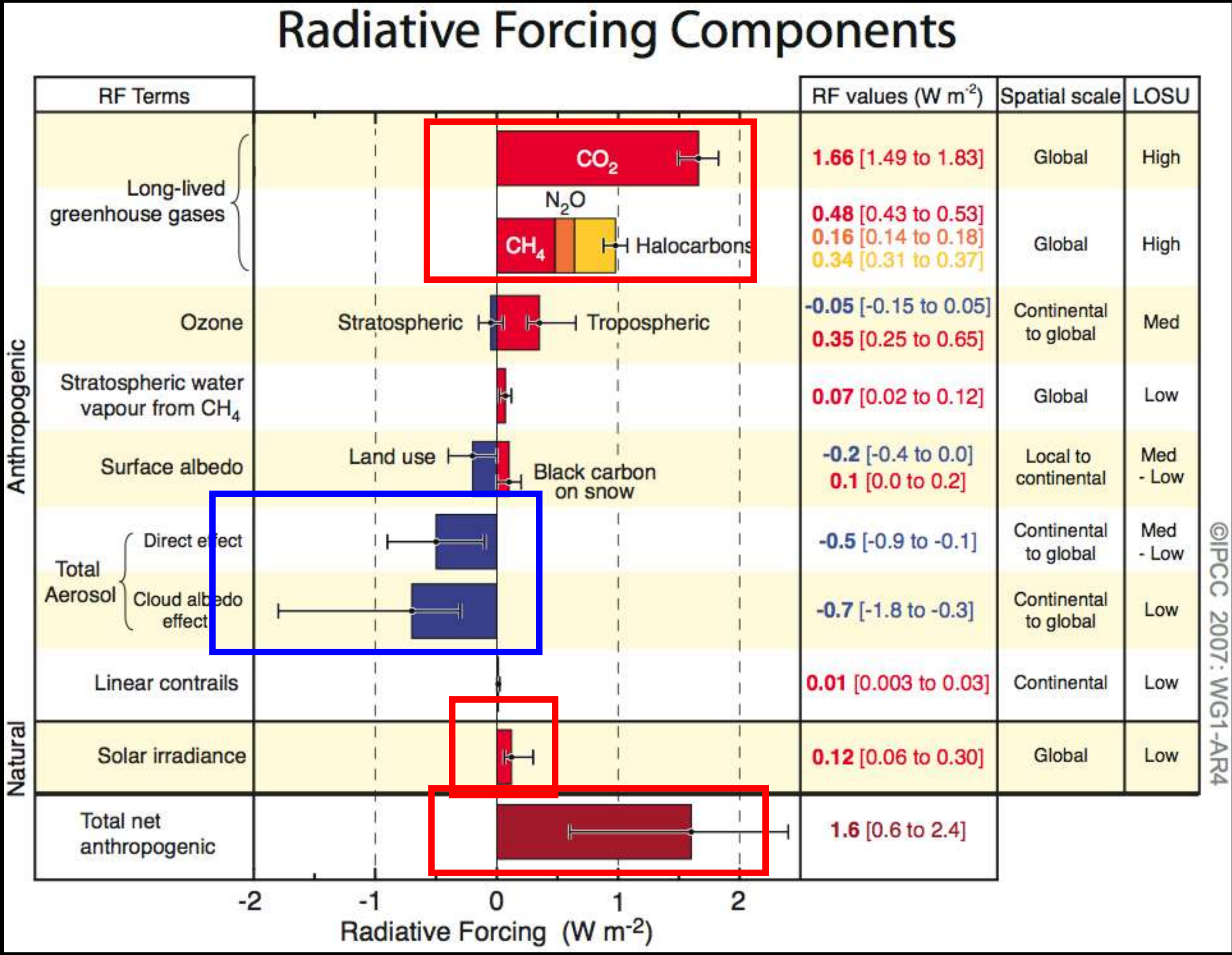
Svant Arrhenius, 1896


MAUNA LOA OBSERVATORY, HAWAII
MONTHLY AVERAGE CARBON DIOXIDE CONCENTRATION
MLO-145
CO2 CONCENTRATION, (PPM)
390
385
380
375
370
365
360
355
350
345
340
335
330
325
320
315
310
1958 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00 02 04
YEAR
19-May-05

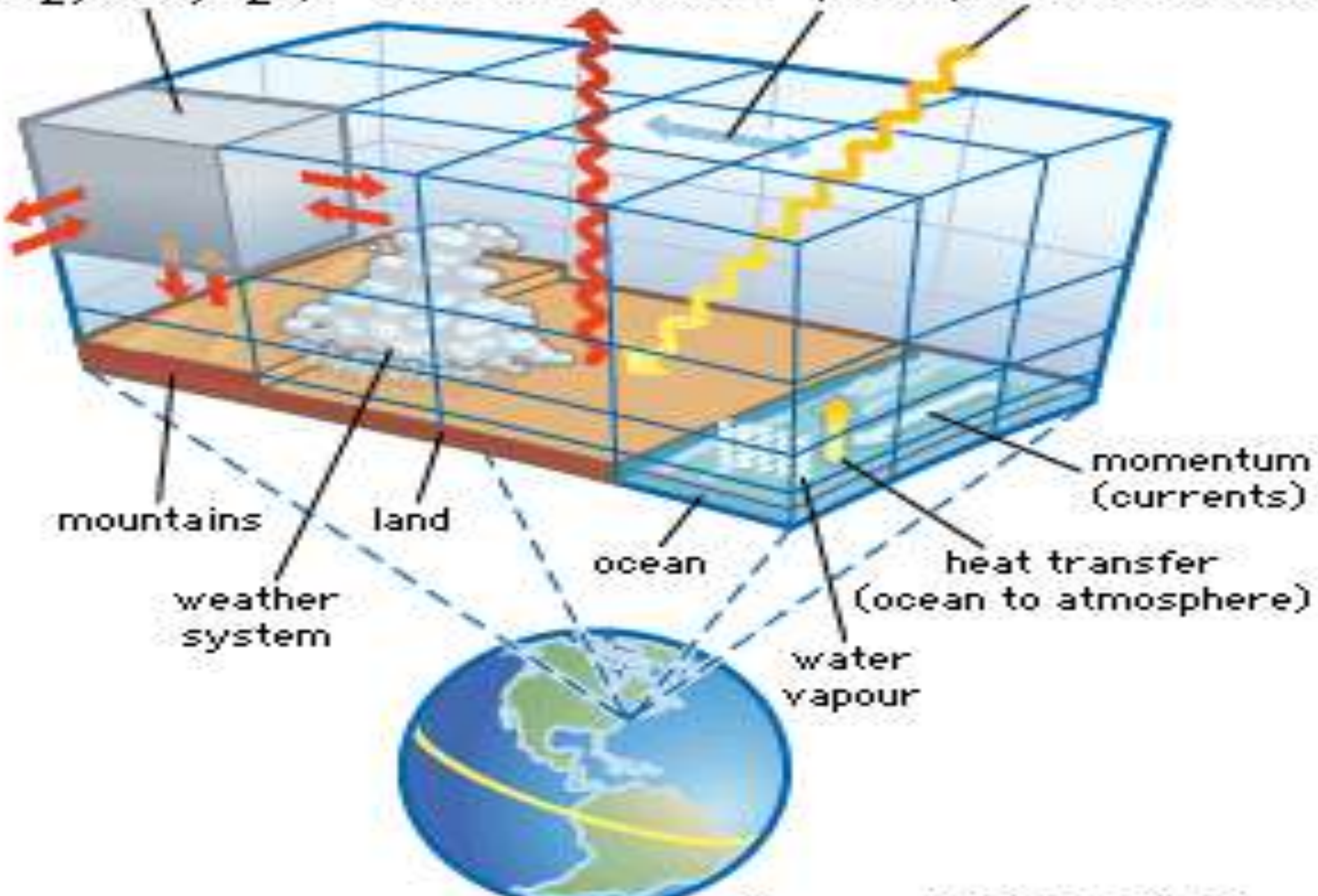
Human and Natural Drivers of Climate Change

1.6 W m^{-2} warms like 1.6 xmas tree lights over every m^2 on Earth.

Carbon dioxide is causing the bulk of the forcing, and it lives a long time in our atmosphere so every year of emission means commitments to climate change for future generations.



Concept diagram of climate modeling



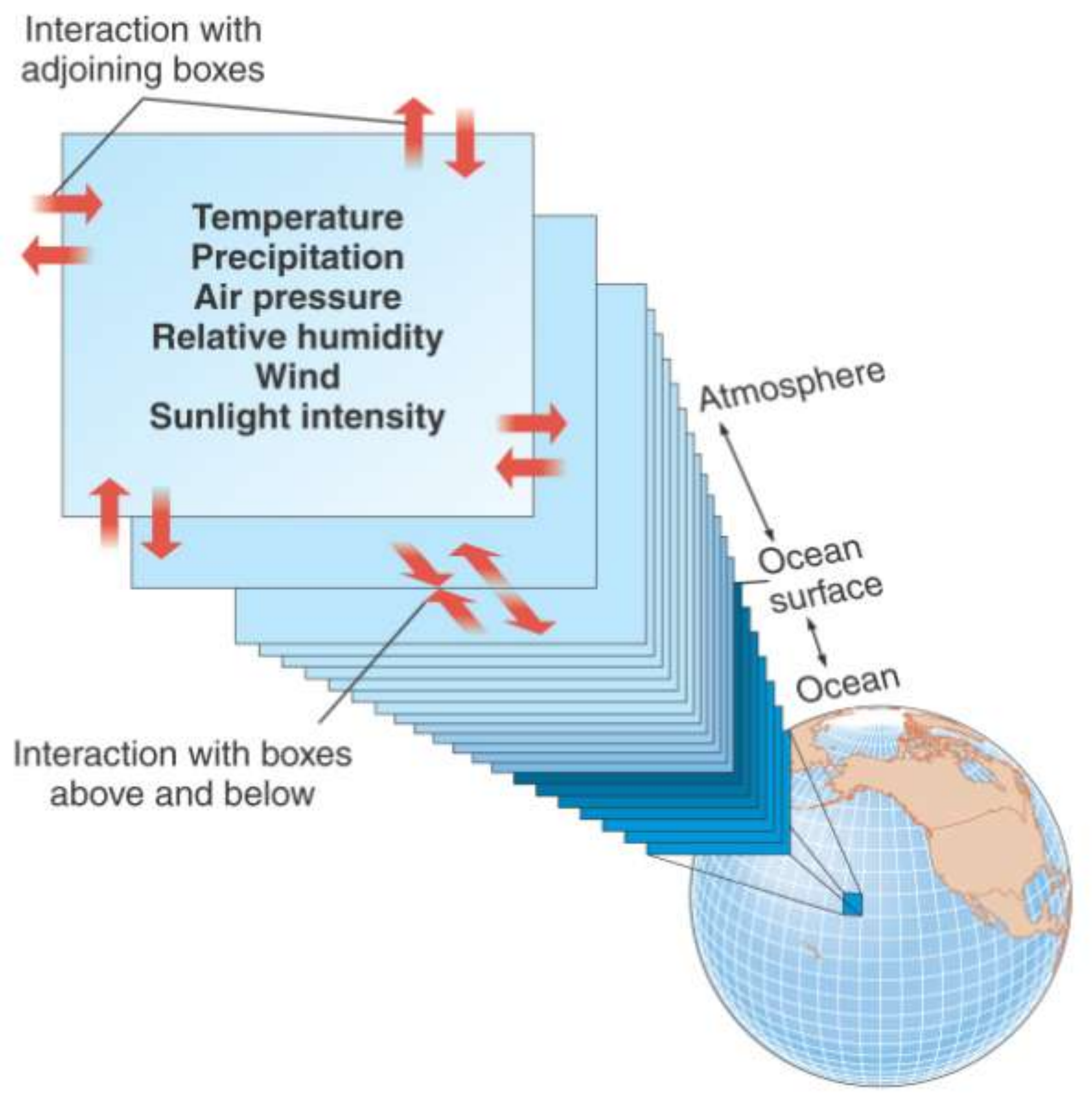
Source : 2000 W.F. Ruddiman

Basic Equations of a GCM (Hansen et al., 1983)

- Conservation of momentum
  $$\frac{\partial \vec{V}}{\partial t} = -(\vec{V}\cdot\nabla)\vec{V} - \frac{1}{\rho}\nabla p - \vec{g} - 2\vec{\Omega}\times\vec{V} + \nabla\cdot(k_m\nabla\vec{V}) - \vec{F}_d$$
- Conservation of energy
  $$\rho c_{\vec{V}}\frac{\partial T}{\partial t} = -\rho c_{\vec{V}}(\vec{V}\cdot\nabla)T - \nabla\cdot\vec{R} + \nabla\cdot(k_T\nabla T) + C + S$$
- Conservation of mass
  $$\frac{\partial \rho}{\partial t} = -(\vec{V}\cdot\nabla)\rho - \rho(\nabla\cdot\vec{V})$$
- Conservation of H_2O (vapor, liquid, solid)
  $$\frac{\partial q}{\partial t} = -(\vec{V}\cdot\nabla)q + \nabla\cdot(k_q\nabla q) + S_q + E$$
- Equation of state
  $$p = \rho R_d T$$

What about resolution?

- **Computational constraints** limit the resolution that is possible in model equations.
- three-dimensional models
  - Atmosphere: 2° x 2°, on average
  - Ocean: 1.5° x 1.5°, on average



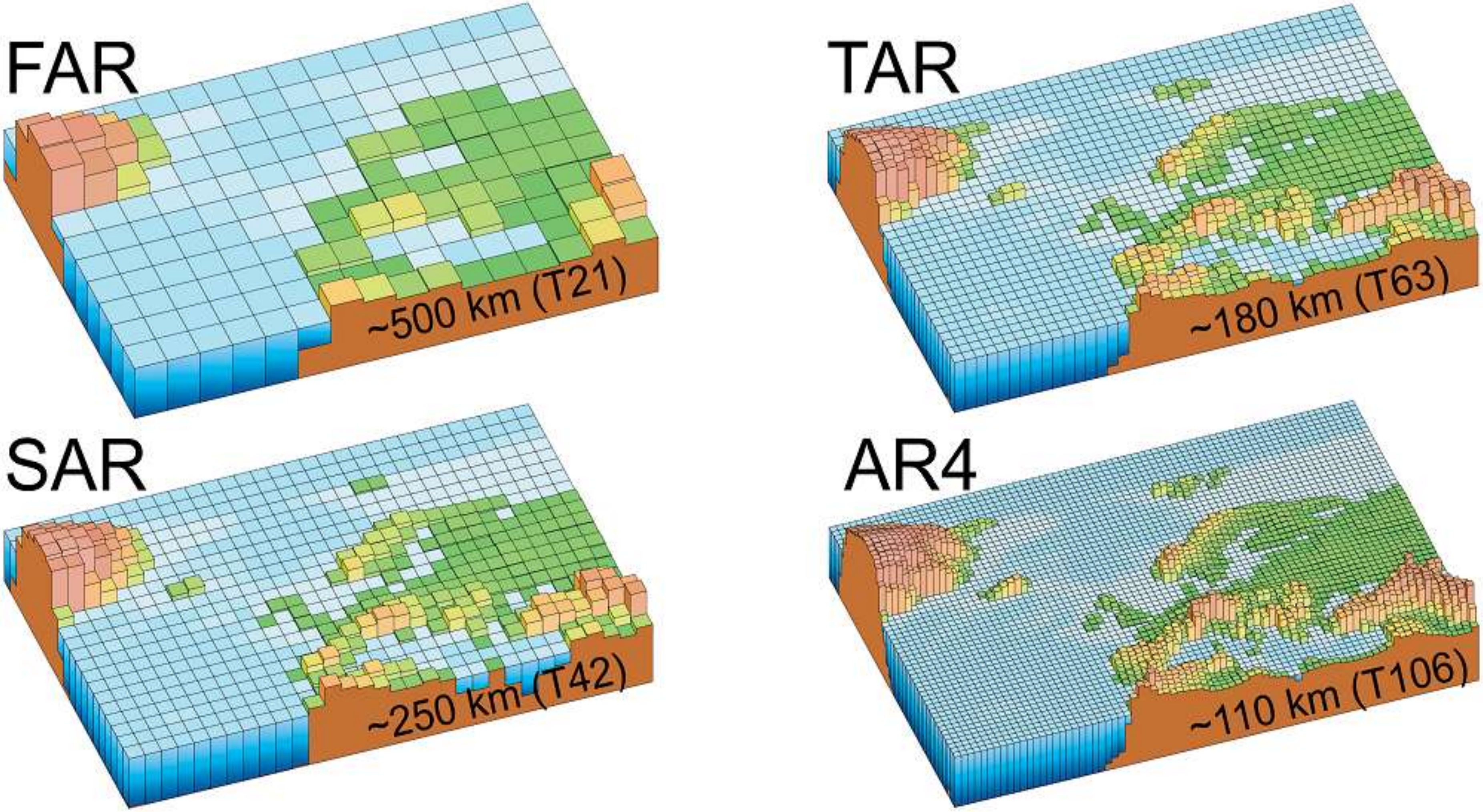
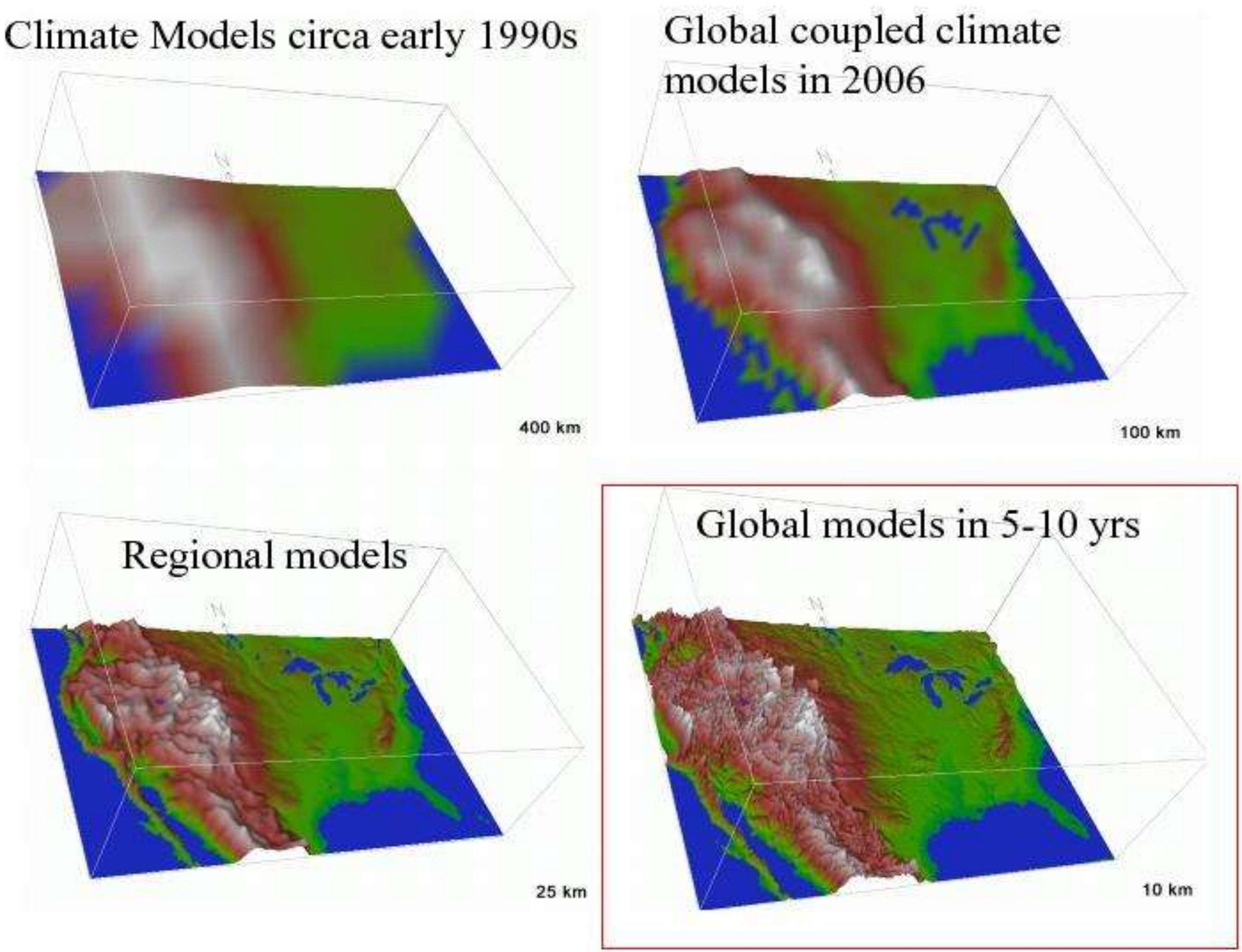
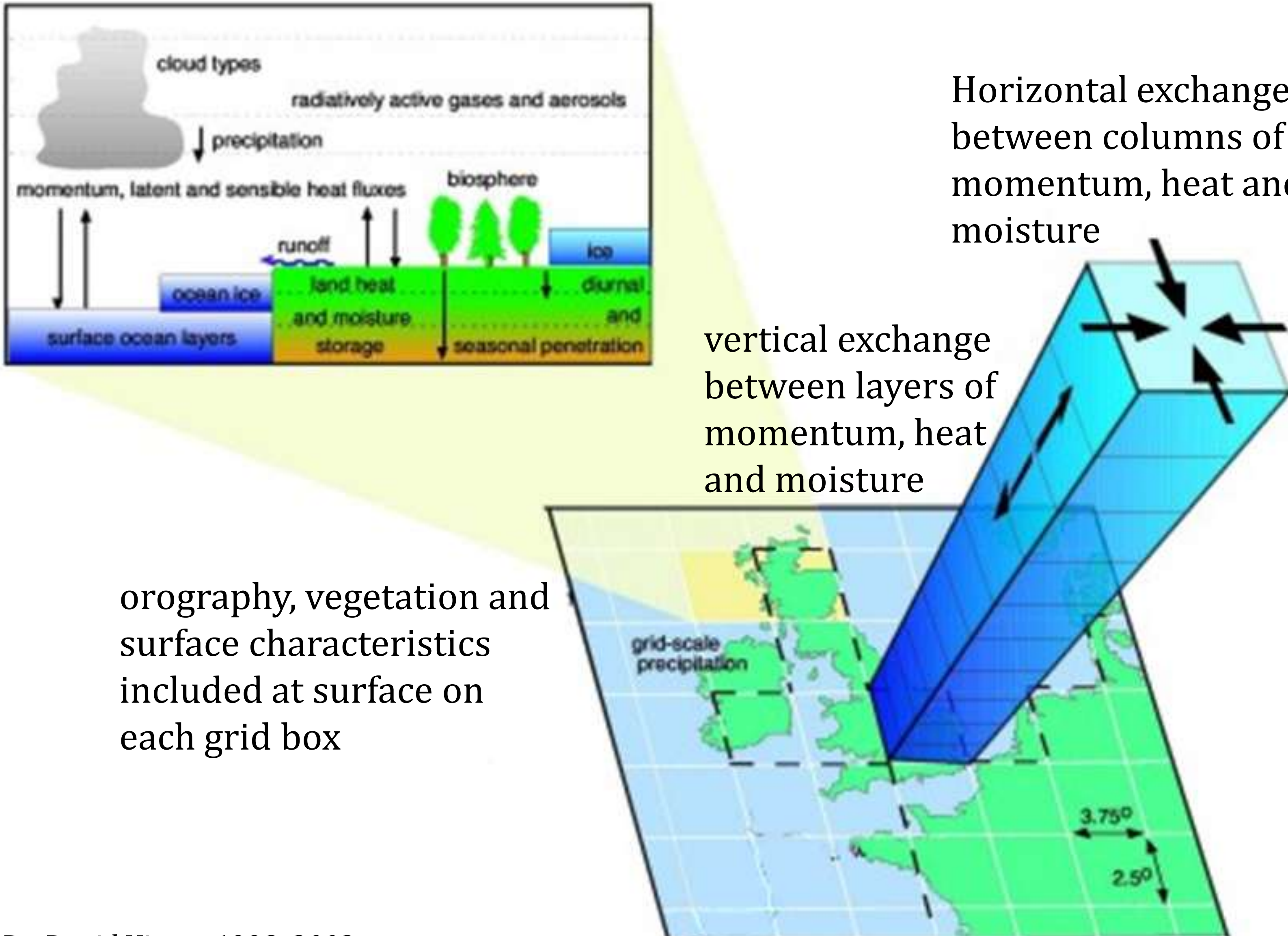


Figure 1.4. *Geographic resolution characteristic of the generations of climate models used in the IPCC Assessment Reports: FAR (IPCC, 1990), SAR (IPCC, 1996), TAR (IPCC, 2001a), and AR4 (2007). The figures above show how successive generations of these global models increasingly resolved northern Europe. These illustrations are representative of the most detailed horizontal resolution used for short-term climate simulations. The century-long simulations cited in IPCC Assessment Reports after the FAR were typically run with the previous generation's resolution. Vertical resolution in both atmosphere and ocean models is not shown, but it has increased comparably with the horizontal resolution, beginning typically with a single-layer slab ocean and ten atmospheric layers in the FAR and progressing to about thirty levels in both atmosphere and ocean.*



Optimistic view on model-developement

Atmospheric GCMs (AGCM)



Horizontal exchange between columns of momentum, heat and moisture

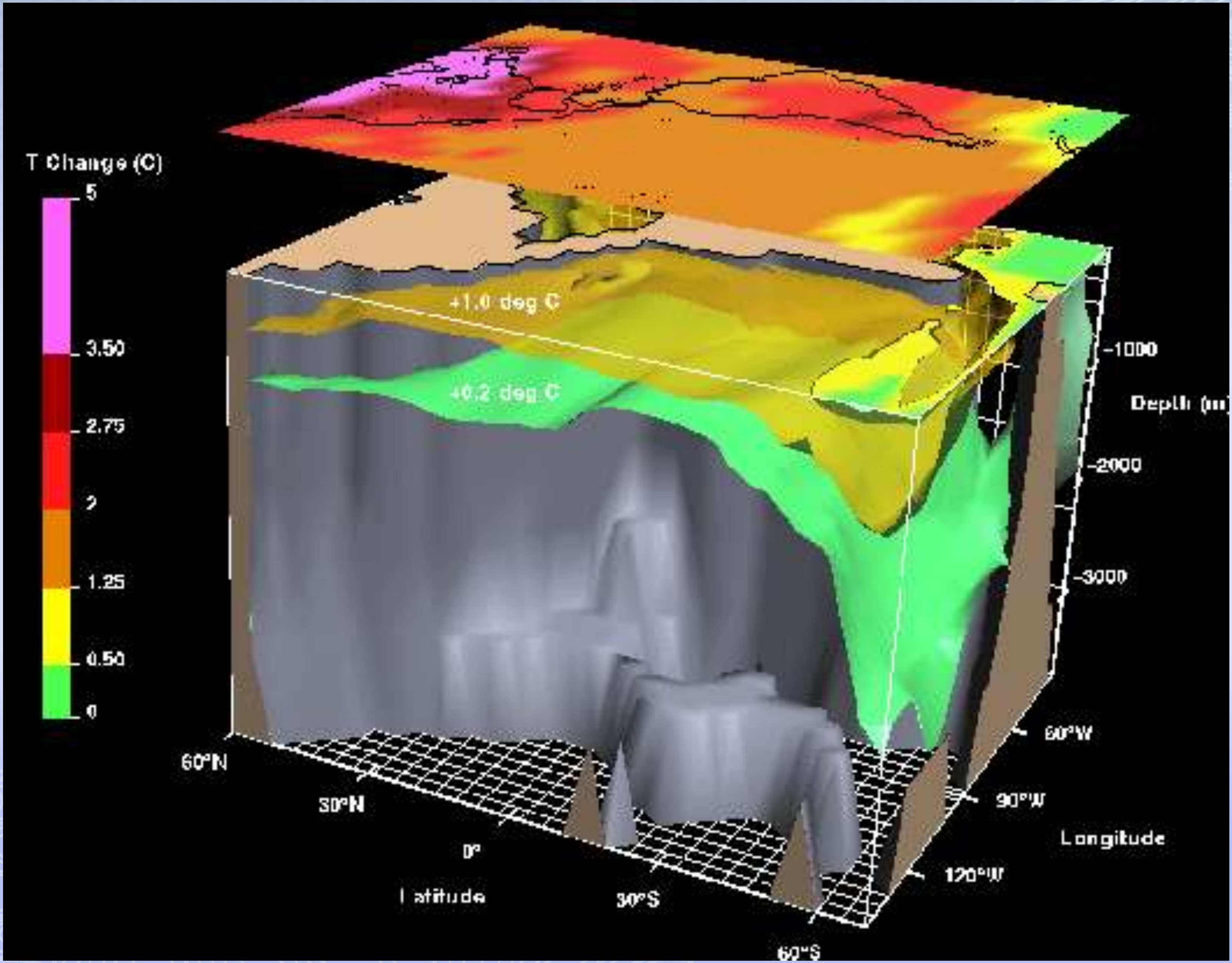
vertical exchange between layers of momentum, heat and moisture

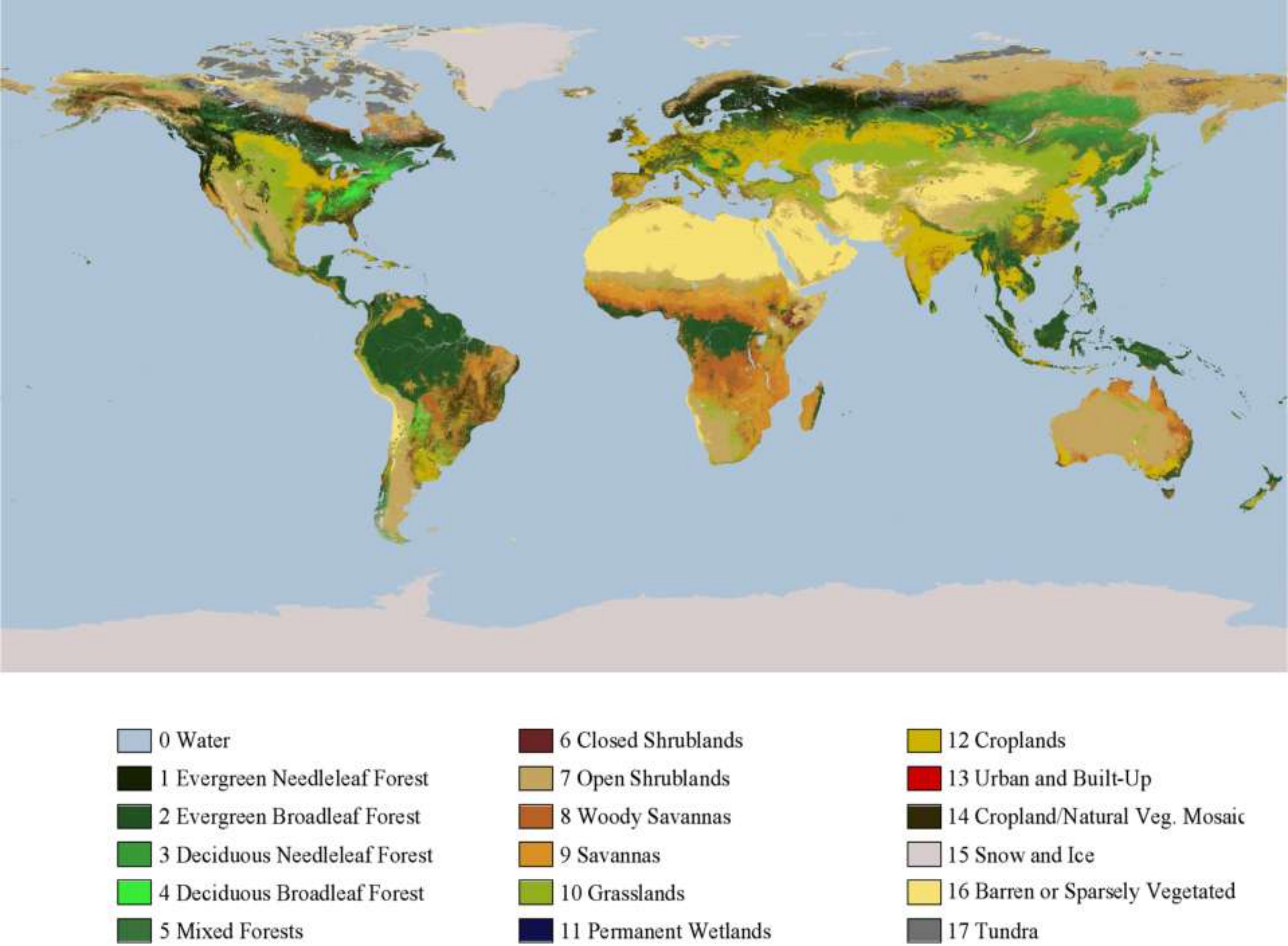
orography, vegetation and surface characteristics included at surface on each grid box

Dr. David Vinter, 1998, 2002


The Atmosphere is very
small

Combined GCMs (AOGCM)




0 Water
1 Evergreen Needleleaf Forest
2 Evergreen Broadleaf Forest
3 Deciduous Needleleaf Forest
4 Deciduous Broadleaf Forest
5 Mixed Forests
6 Closed Shrublands
7 Open Shrublands
8 Woody Savannas
9 Savannas
10 Grasslands
11 Permanent Wetlands
12 Croplands
13 Urban and Built-Up
14 Cropland/Natural Veg. Mosaic
15 Snow and Ice
16 Barren or Sparsely Vegetated
17 Tundra

Fate of Anthropogenic CO_2 Emissions (2000-2007)

1.5 Pg C y^{-1}

+

7.5 Pg C y^{-1}

4.2 Pg y^{-1}

Atmosphere

46%

2.6 Pg y^{-1}

Land

29%

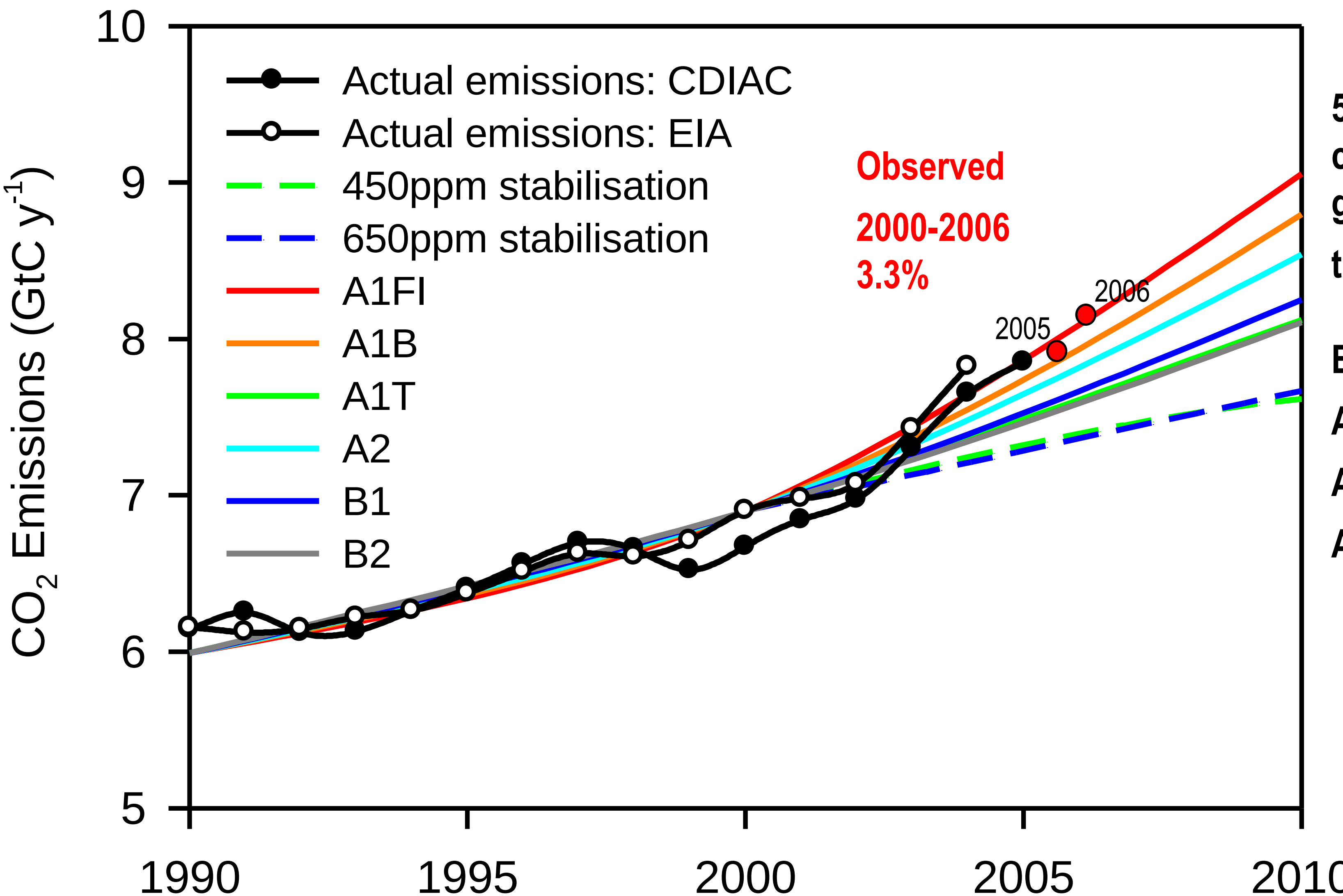
2.3 Pg y^{-1}

Oceans

26%

Canadell et al. 2007, PNAS (updated)

Trajectory of Global Fossil Fuel Emissions



50-year constant growth rates to 2050

B1 1.1%,
A1B 1.7%,
A2 1.8%
A1FI 2.4%

Raupach et al. 2007, PNAS

You can try it out for yourself with EdGCM!
http://edgcm.columbia.edu

Special Report on Emissions Scenarios (SRES)

- Available at http://www.grida.no/climate/ipcc/emission/
- 4 storylines
  - Consider future greenhouse gas pollution, land-use change, and other driving forces
  - Peak Oil is *not* discussed
  - *Do not* include additional climate initiatives (e.g., UNFCCC or Kyoto Protocol emissions targets
- 40 different scenarios, grouped by family into the storylines
  - These are not predictions or forecasts!
  - There is NO "best guess" scenario
  - Scenarios are NOT policy recommendations
- 6 scenario groups are considered equally sound and span a wide range of uncertainty

Special Report on Emissions Scenarios (SRES): Why storylines?

- To help the writing team to think more coherently about the complex interplay among scenario driving forces within each and across alternative scenarios;
- To make it easier to explain the scenarios to the various user communities by providing a narrative description of alternative futures that goes beyond quantitative scenario features;
- To make the scenarios more useful, in particular to analysts who contribute to IPCC WGII and WGIII;
  - The social, political, and technological context described in the scenario storylines is all-important in analyzing the effects of policies either to adapt to climate change or to reduce GHG emissions; and
- To provide a guide for additional assumptions to be made in detailed climate impact and mitigation analyses
  - At present no single model or scenario can possibly respond to the wide variety of informational and data needs of the different user communities of long-term emissions scenarios.

SRES: A1 Storyline – A more integrated world

- Rapid economic growth (~3%/year to 2100)
  - Strong commitment to market-based solutions
- Global population reaches 9 billion in 2050 and gradually declines
- Quick spread of new and efficient technologies
  - High rates of investment and innovation at national & international level
- Convergent world
  - Income and way of life converge between regions
  - Extensive social and cultural interactions worldwide

SRES: A1 Storyline Subsets

- A1F1
  - Emphasis on fossil fuels
- A1B
  - Balanced emphasis on all energy sources
- A1T
  - Emphasis on non-fossil energy sources

SRES: A2 Storyline – A more divided world

- World of independently operating, self-reliant nations (lower trade flow, less international cooperation)
- Continuously increasing population (15 billion by 2100)
- Regionally oriented economic development
  - Self-reliance and preservation of local identities
- Slower and more fragmented technological changes and improvements to per capita income
  - Primary changes in agricultural productivity to feed the 15 billion

SRES: B1 Storyline – A more integrated, more ecologically friendly world

- High level of environmental and social consciousness; globally coherent approach to more sustainable development

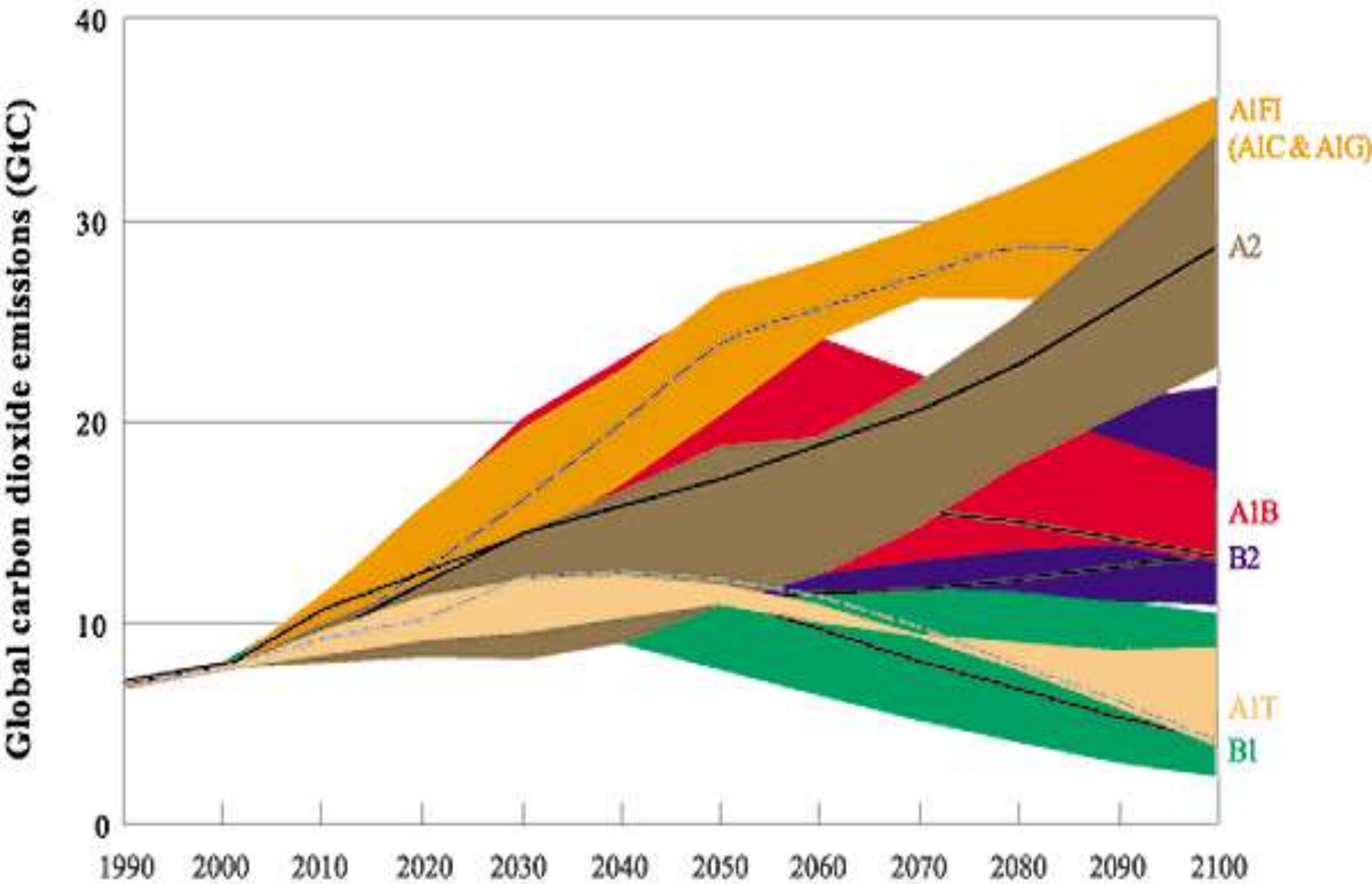
- Rapid economic growth as in A1, but with rapid changes towards a service and information economy
- Global population reaches 9 billion in 2050 and gradually declines as in A1
- Reductions in material intensity and the introduction of clean and resource efficient technologies
  - Smooth transition to alternative energy systems as conventional oil and gas resources decline
- Emphasis on <u>global</u> solutions to economic, social and environmental stability

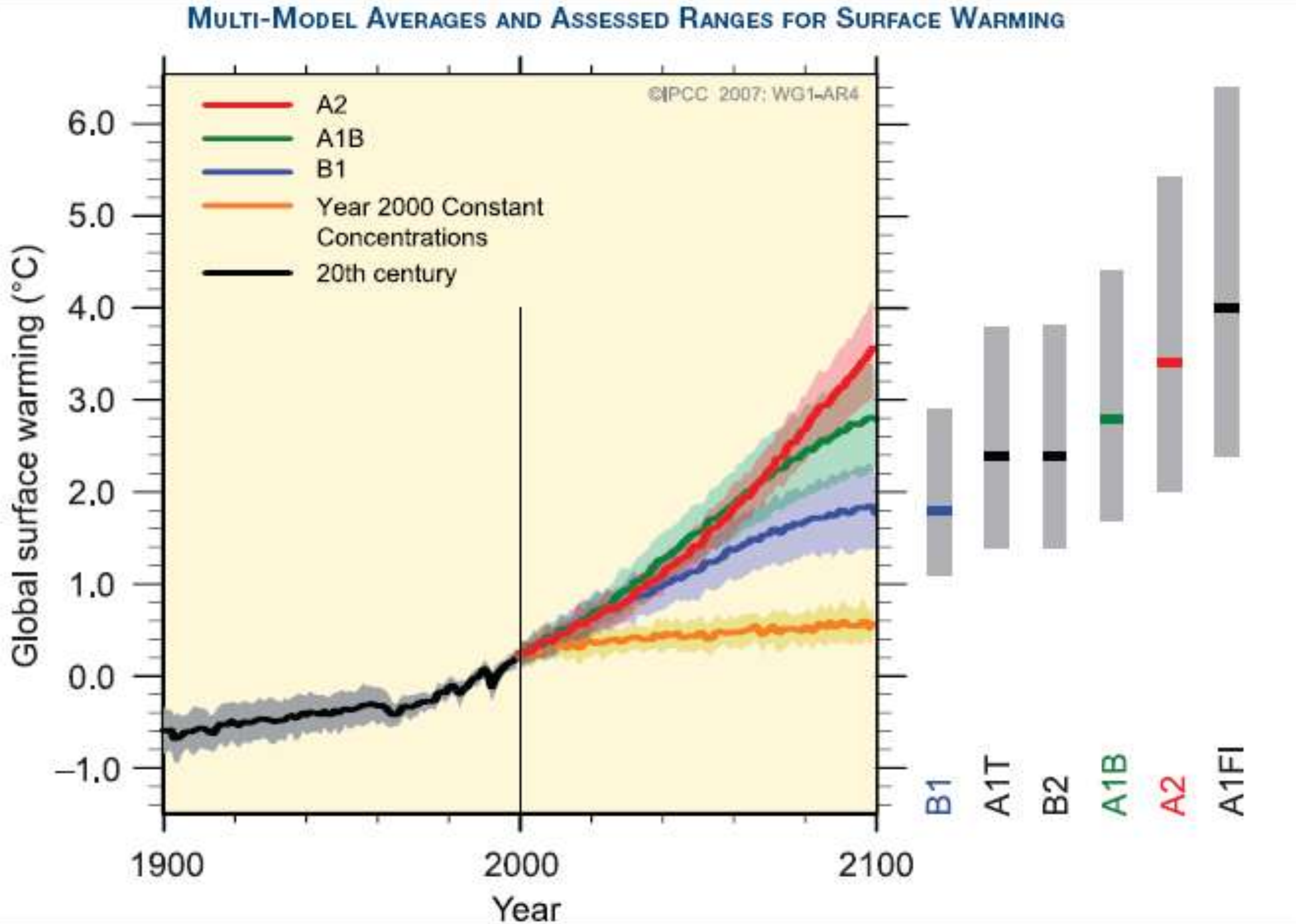
SRES: B2 Storyline – A more divided, but more ecologically friendly world

- Increased concern for environmental and social sustainability compared to A2, with shift to local and regional decisions

- Continuously increasing population, but at a slower rate than in A2
- Emphasis on local, rather than global, solutions to economic, social and environmental stability
- Intermediate levels of economic development
- Less rapid and more fragmented technological change than in B1 & A1.

Global annual CO_2 emissions – all sources (6 scenario groups)





MULTI-MODEL AVERAGES AND ASSESSED RANGES FOR SURFACE WARMING
A2
A1B
B1
Year 2000 Constant Concentrations
20th century
©IPCC 2007: WG1-AR4
Global surface warming (°C)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
–1.0
1900
2000
2100
Year
B1
A1T
B2
A1B
A2
A1FI

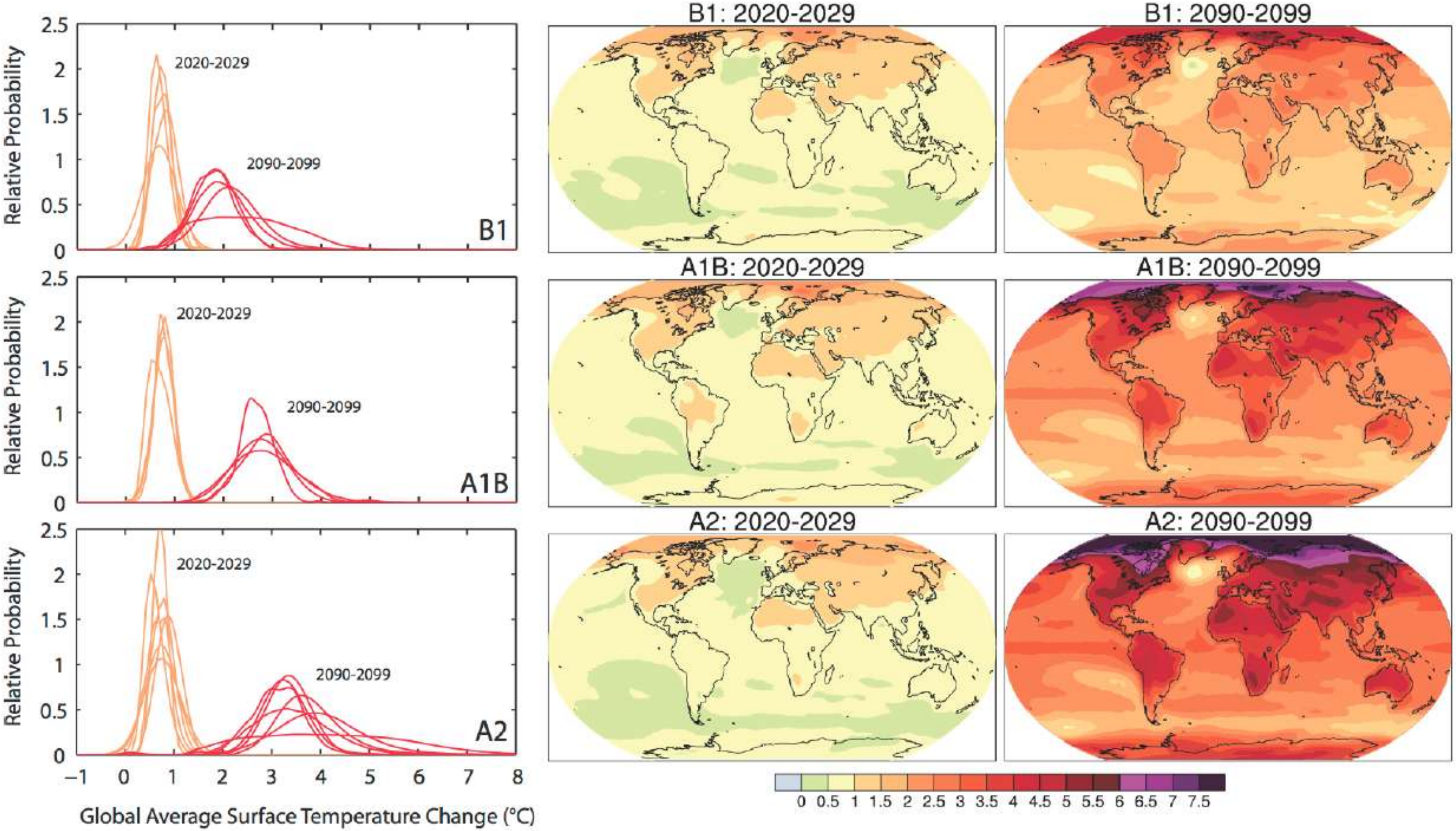
Projected Globally Averaged Surface Warming and Sea-Level Rise at the End of the 21st Century

	Temperature Change (°F at 2090–2099 relative to 1980–1999)		Sea-Level Rise (inches at 2090–2099 relative to 1980–1999)
Case	Best estimate	Likely range	Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations	1.1	0.5 – 1.6	NA
B1 scenario	3.2	2.0 – 5.2	7.1 – 15.0
A1T scenario	4.3	2.5 – 6.8	7.9 – 17.7
B2 scenario	4.3	2.5 – 6.8	7.9 – 16.9
A1B scenario	5.0	3.1 – 7.9	8.3 – 18.9
A2 scenario	6.1	3.6 – 9.7	9.1 – 20.1
A1FI scenario	7.2	4.3 – 11.5	10.2 – 23.2

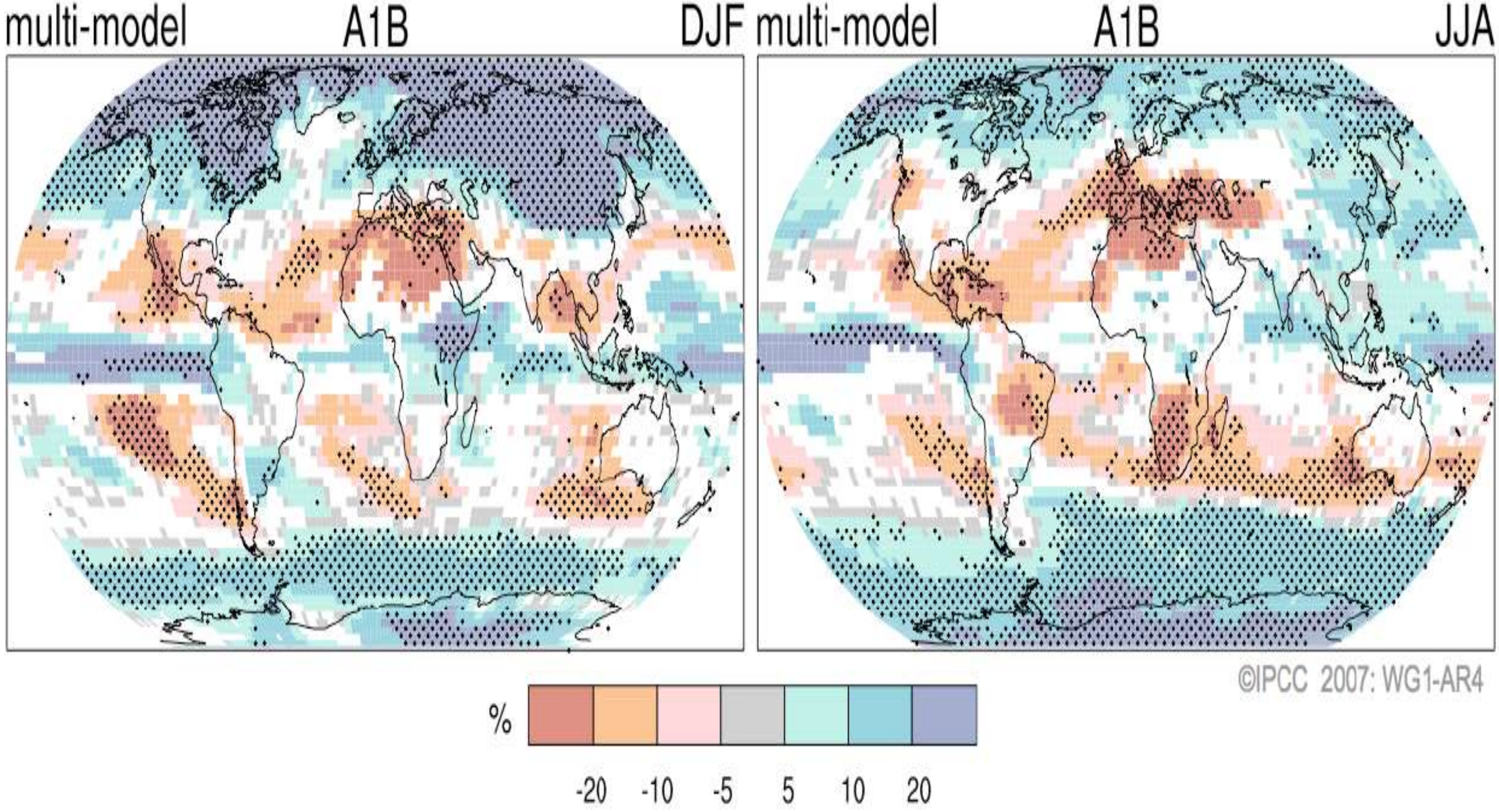
Source: Climate Change 2007: The Physical Science Basis—Summary for Policymakers.

Relative temperature change in °C is equal to °F / 1.8. 1” = 2.54 cm.
For example, the B2 Scenario has the best estimate of temperature change of 2.4 °C and a sea level rise of 20-43 cm by 2090-2099.

AOGCM Projections of Surface Temperatures



Projected Patterns of Precipitation Changes



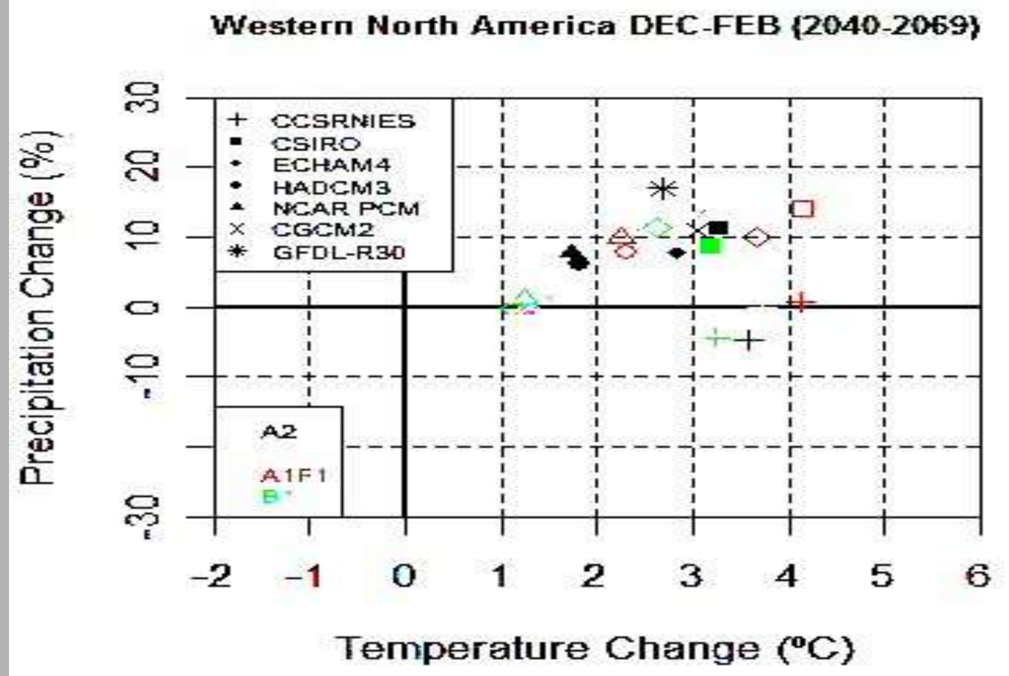
IPCC 4th Assessment GCMs

All Year

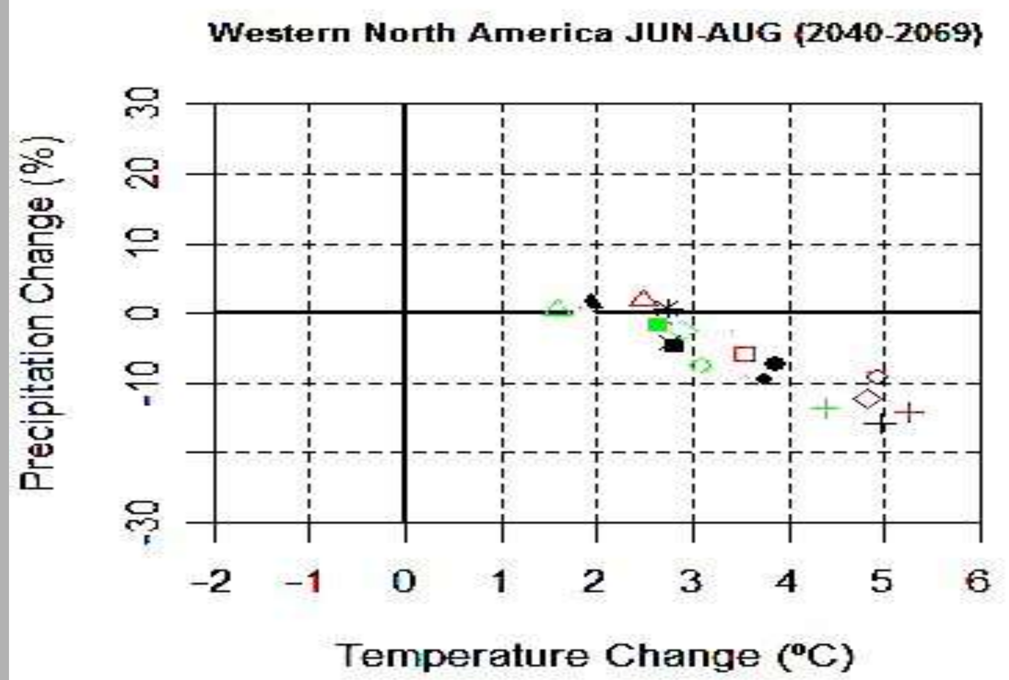
3°C (5.4°F) warmer

BUT

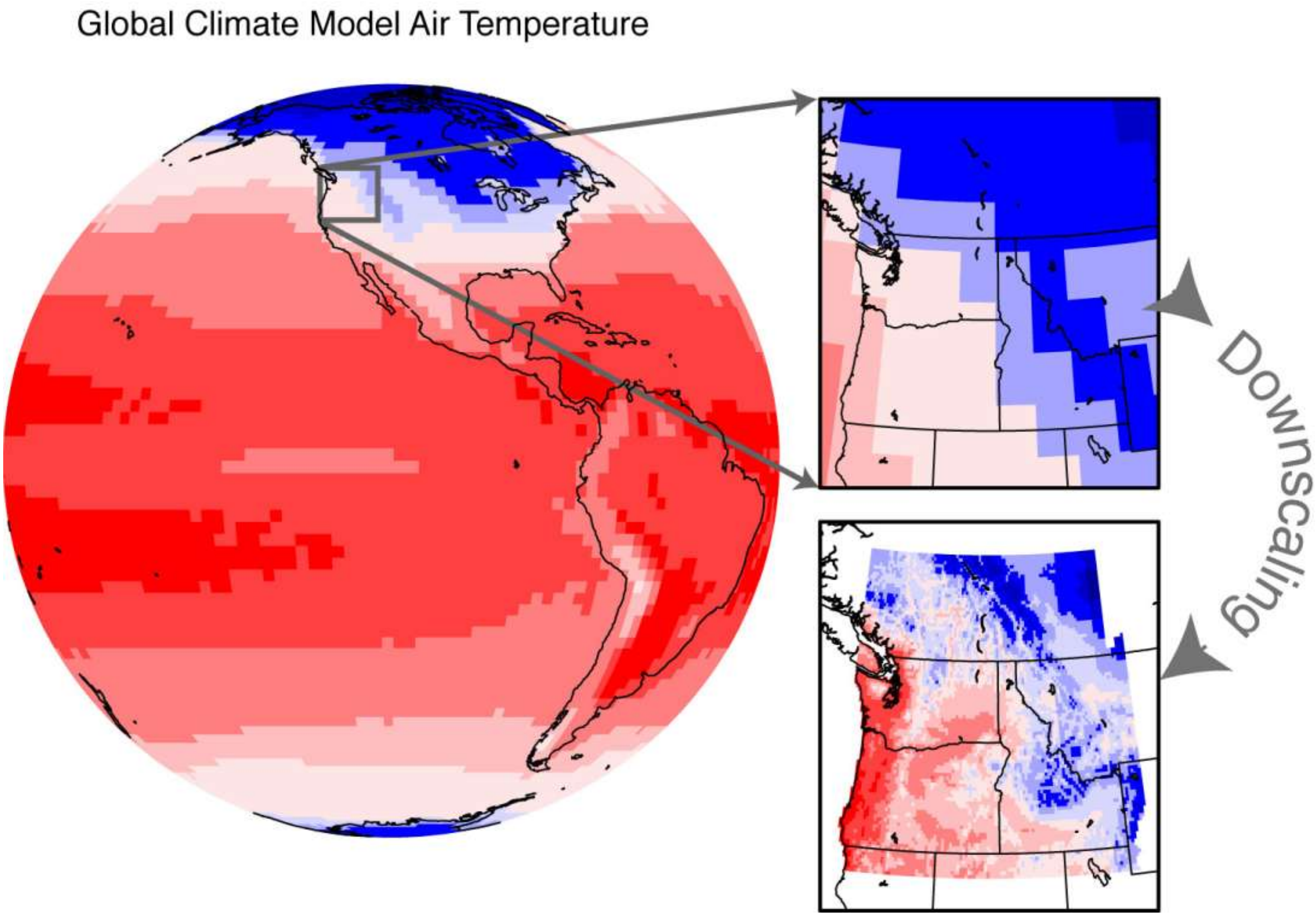
Winter – wetter



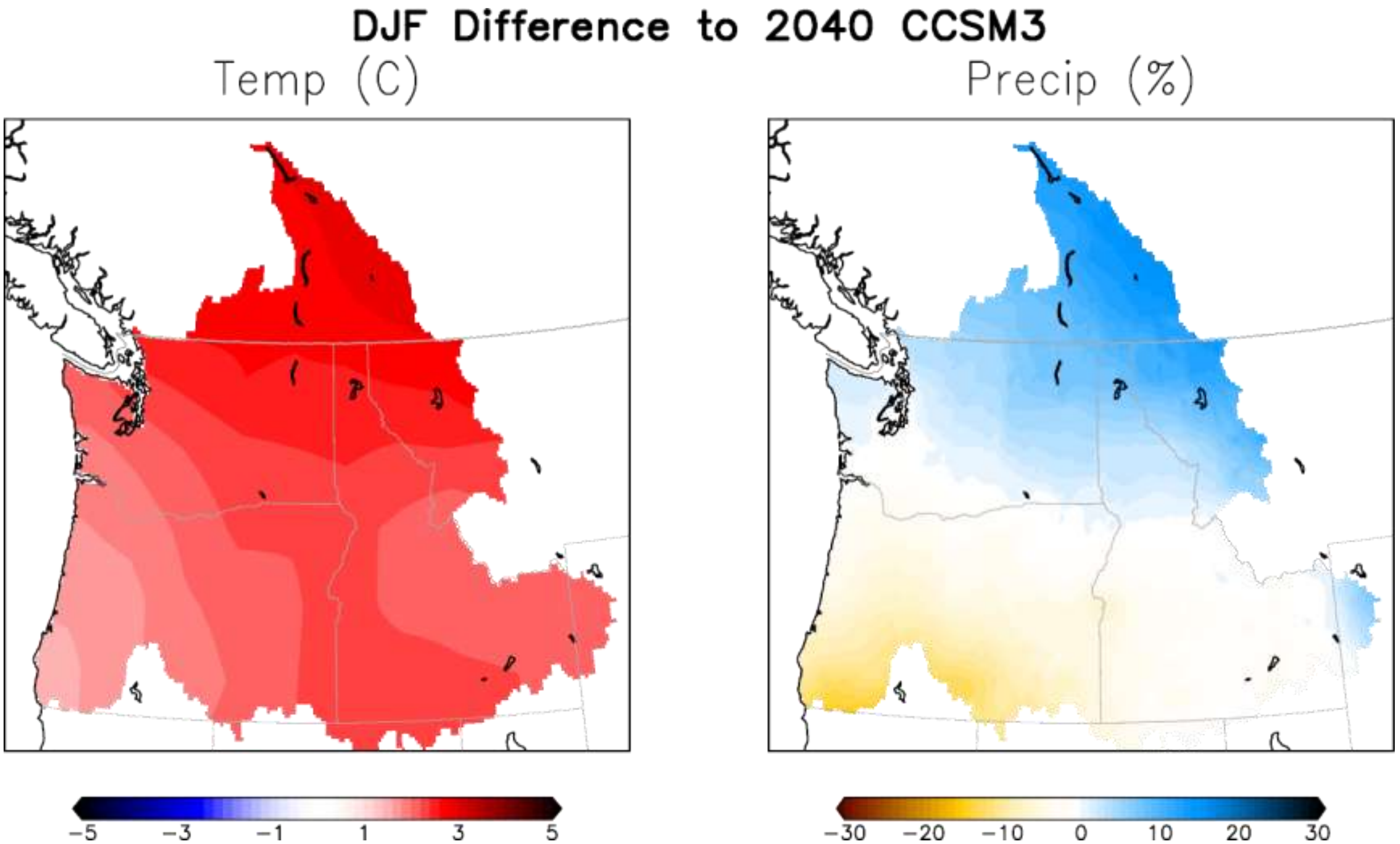
Summer – drier



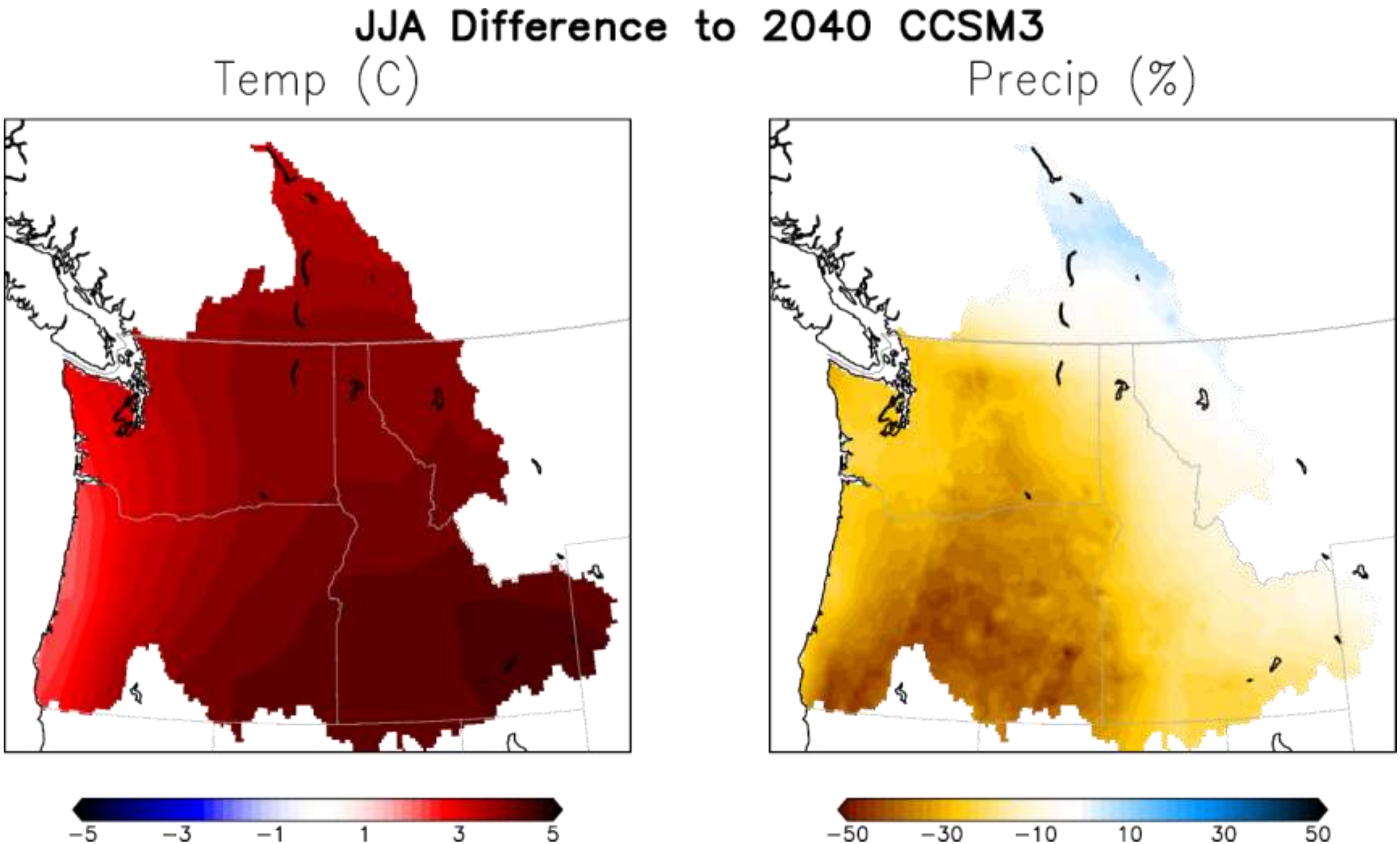
Downscaling global models for regional studies



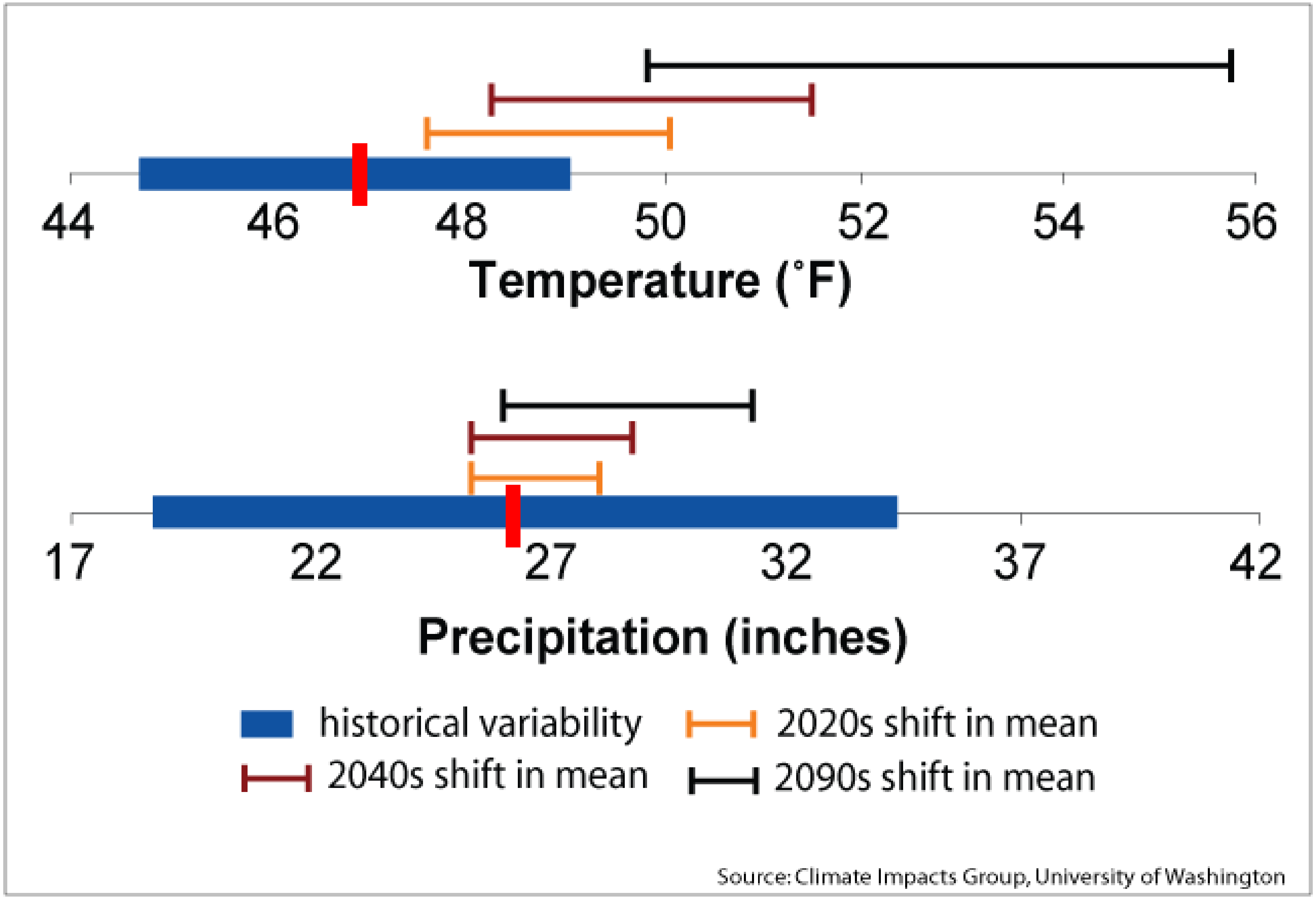
Downscaling -- Winter



Downscaling -- Summer



Comparing Projected Change in Mean with 20th Century Variability



IPCC 5th Assessment Scenario Planning

IPCC Expert Meeting Report: Towards New Scenarios

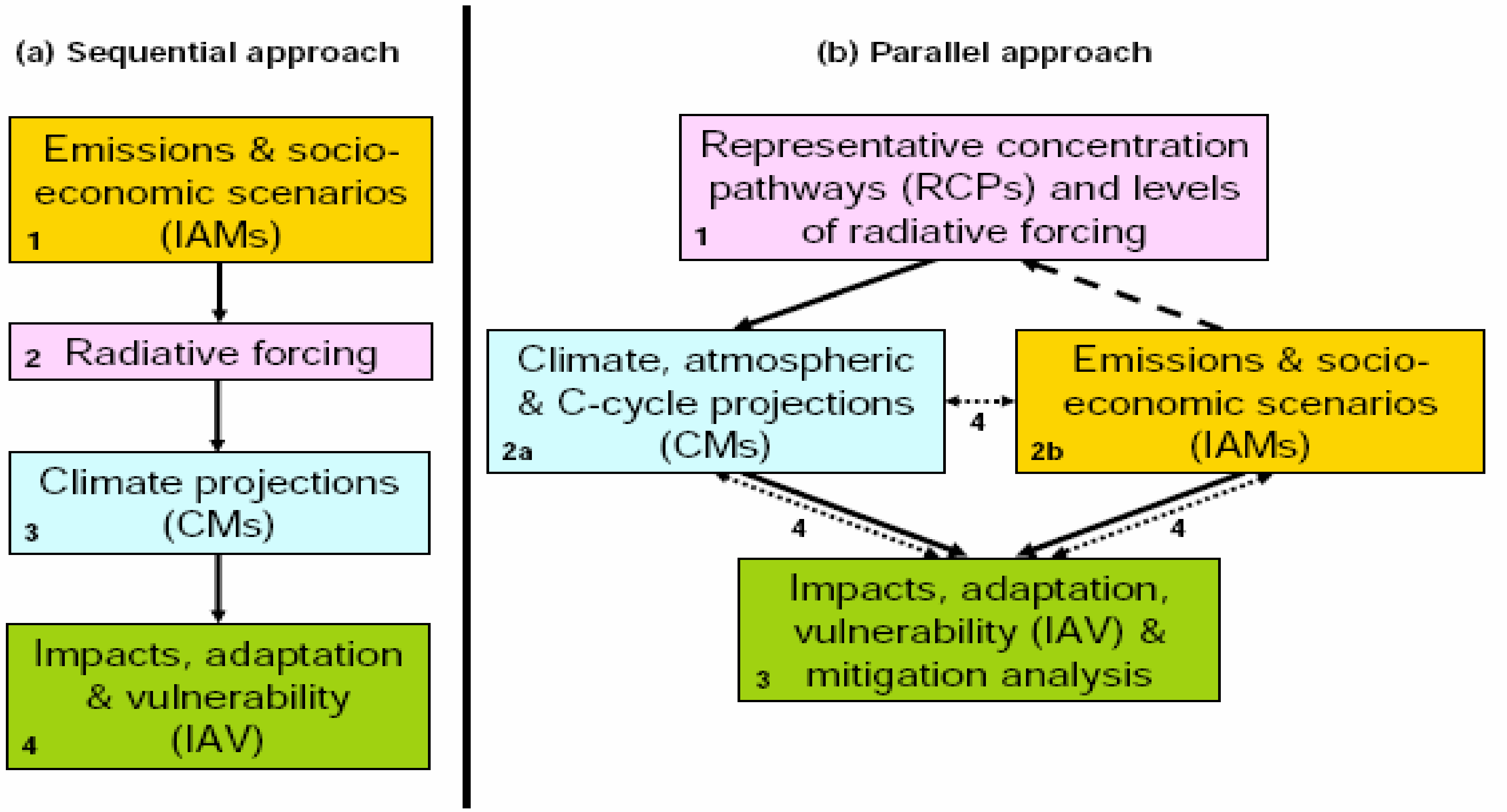


Figure 1. Approaches to the development of global scenarios: (a) previous sequential approach; (b) proposed parallel approach. Numbers indicate analytical steps (2a and 2b proceed concurrently). Arrows indicate transfers of information (solid), selection of RCPs (dashed), and integration of information and feedbacks (dotted).

Rising Temperatures

- Full range of projected temperature increase is 1.1-6.4°C (2-11.5°F)
- Best estimate range is 1.8-4.0 °C (1.8-4.0°F)
- Warming is expected to be greatest over land and at most high northern latitudes
  - Least over Southern Ocean and parts of North Atlantic Ocean

Source: IPCC *Climate Change 2007: The Physical Science Basis*—Summary for Policymakers.

Increasingly Severe Weather

Tropical cyclones (hurricanes and typhoons) are likely to become more intense, with higher peak wind speeds and heavier precipitation associated with warmer tropical seas.

Source: IPCC *Climate Change 2007: The Physical Science Basis*—Summary for Policymakers.

Increasingly Severe Weather

Associated Press

en.wikipedia.org/wiki/North_American_blizzard_of_2005

Increases in the amount of high latitude precipitation are very likely.

Source: IPCC *Climate Change 2007: The Physical Science Basis*—Summary for Policymakers.

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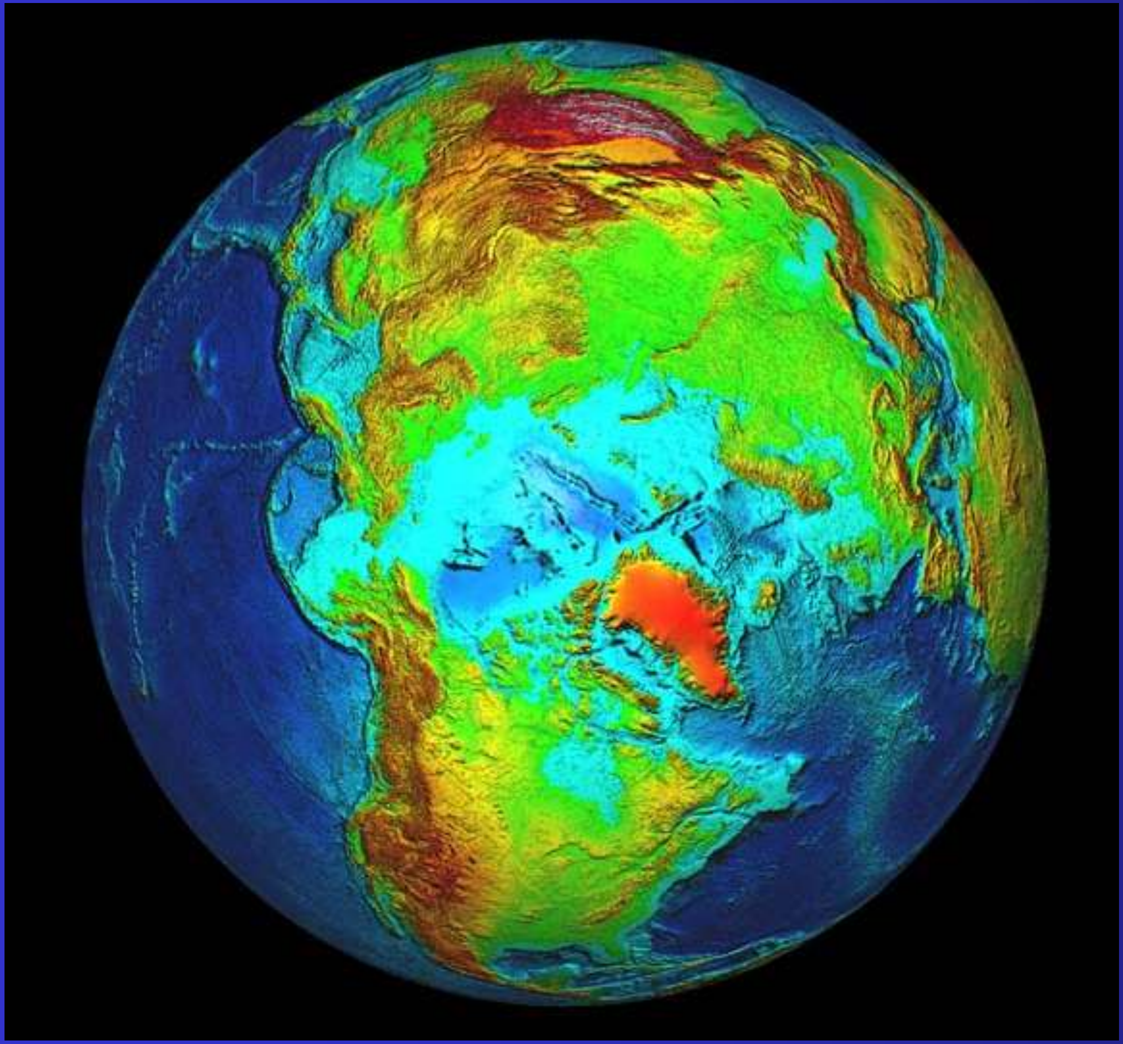
Drought

National Park Service

Decreases in precipitation are likely in most subtropical land regions

Source: IPCC *Climate Change 2007: The Physical Science Basis*—Summary for Policymakers.

Melting Ice


NOAA

•Sea ice is projected to shrink in both the Arctic and Antarctic under all model simulations.

•Some projections show that by the latter part of the century, late-summer Arctic sea ice will disappear almost entirely.

Source: IPCC *Climate Change 2007: The Physical Science Basis*—Summary for Policymakers.

Sea-level Rise Projections Include:

•ocean expansion resulting from increased water temperatures;

National Park Service

•meltwater runoff from mountain glaciers around the world; and

NASA

•a contribution due to increased ice flow from Greenland and Antarctica **at the rates observed for 1993-2003**.

Source: IPCC *Climate Change 2007: The Physical Science Basis*—Summary for Policymakers.

Sea-level Rise Projections DO NOT Include:


Photo Roger Braithwaite


iStockphoto.com

- Ice sheet instability

- Carbon dioxide uptake changes

IPCC: “Larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea-level rise.”

Source: IPCC *Climate Change 2007: The Physical Science Basis*—Summary for Policymakers.

Threshold risks:

Weiss and Overpeck U. Arizona

Some models do suggest that sustained warming between 2-7°F above today's global average temperature would initiate irreversible melting of the Greenland ice sheet—which could ultimately contribute about ***23 feet*** to sea-level rise.

Source: IPCC *Climate Change 2007: The Physical Science Basis*—Summary for Policymakers.


THE FUTURE

Wild New Technologies

- IFR – Integral Fast Reactor Nuclear Power Plants
- Boron nano-particle oxidation for vehicle fuels
- 30,000deg F Plasma incinerators for garbage