

Principles of GCMs

Global Climate Models

actually

Global Circulation Models

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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

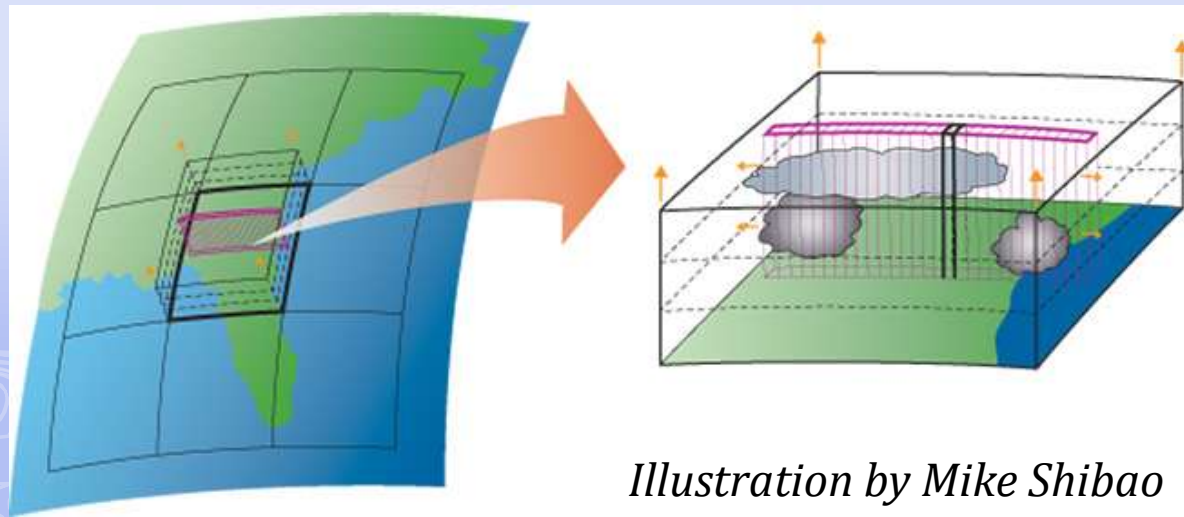


Illustration by Mike Shibao

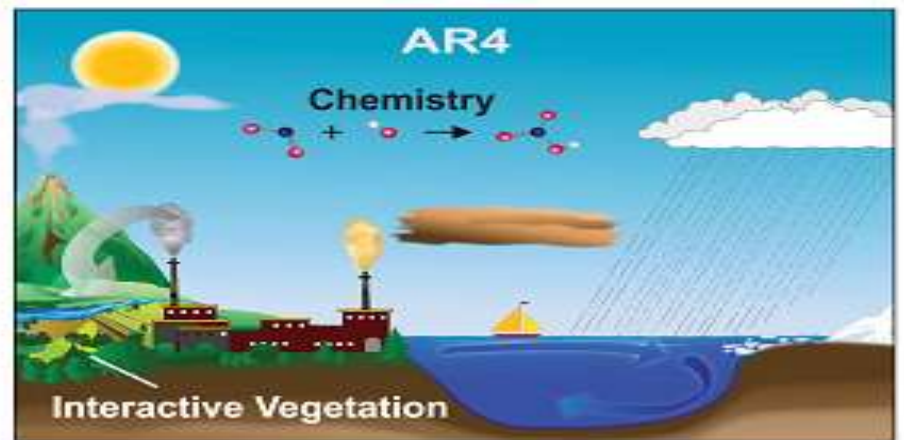
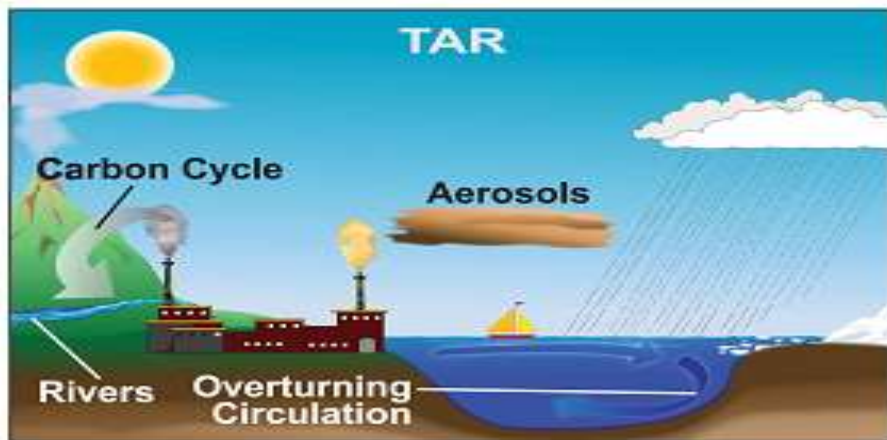
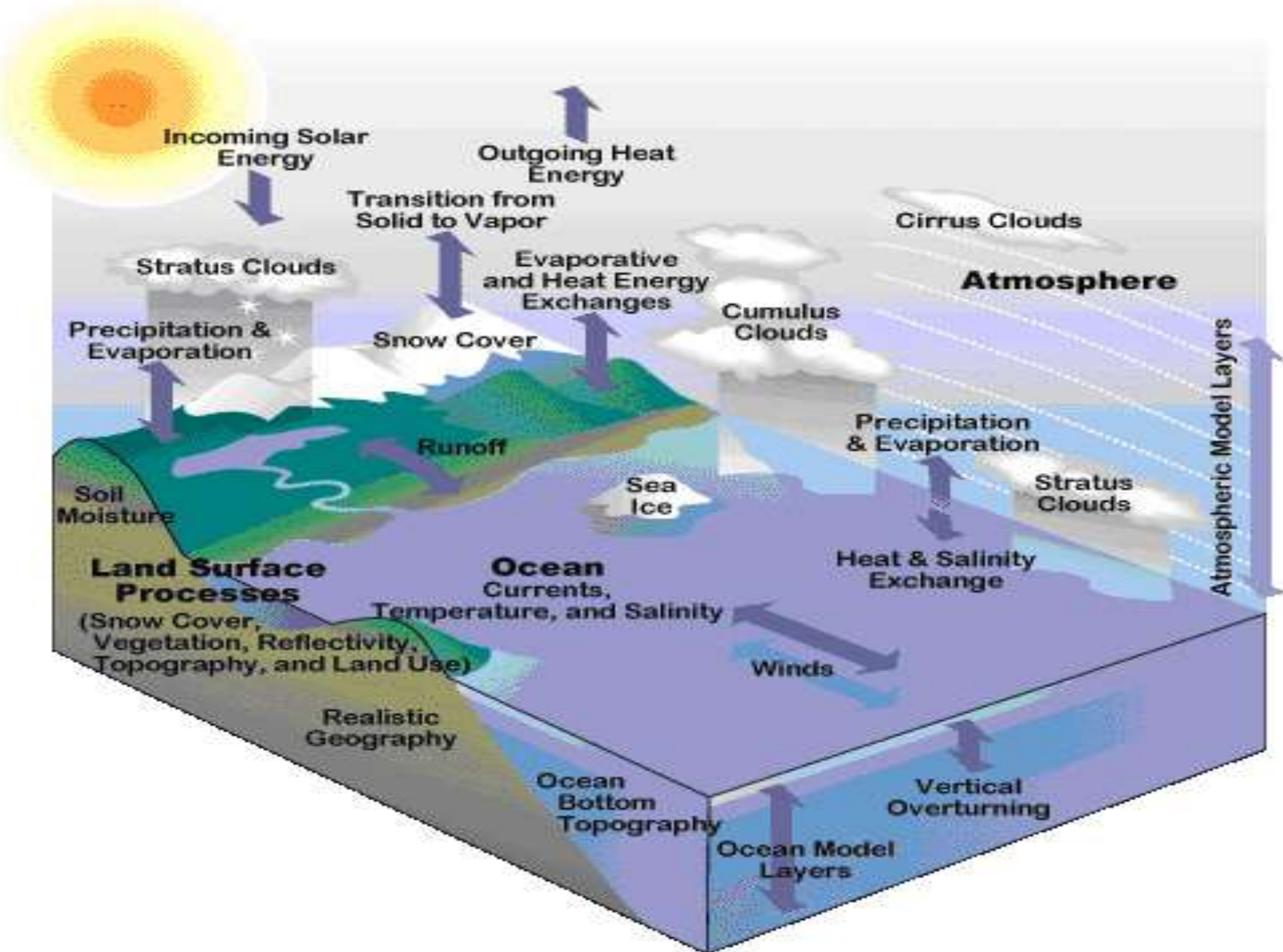


Figure 1.2. The complexity of climate models has increased over the last few decades. The additional physics incorporated in the models are shown pictorially by the different features of the modelled world.



Incoming Solar Energy

Outgoing Heat Energy

Transition from Solid to Vapor

Stratus Clouds

Cirrus Clouds

Atmosphere

Precipitation & Evaporation

Evaporative and Heat Energy Exchanges

Cumulus Clouds

Snow Cover

Precipitation & Evaporation

Stratus Clouds

Atmospheric Model Layers

Runoff

Sea Ice

Heat & Salinity Exchange

Soil Moisture

Land Surface Processes

Ocean

Currents, Temperature, and Salinity

(Snow Cover, Vegetation, Reflectivity, Topography, and Land Use)

Winds

Realistic Geography

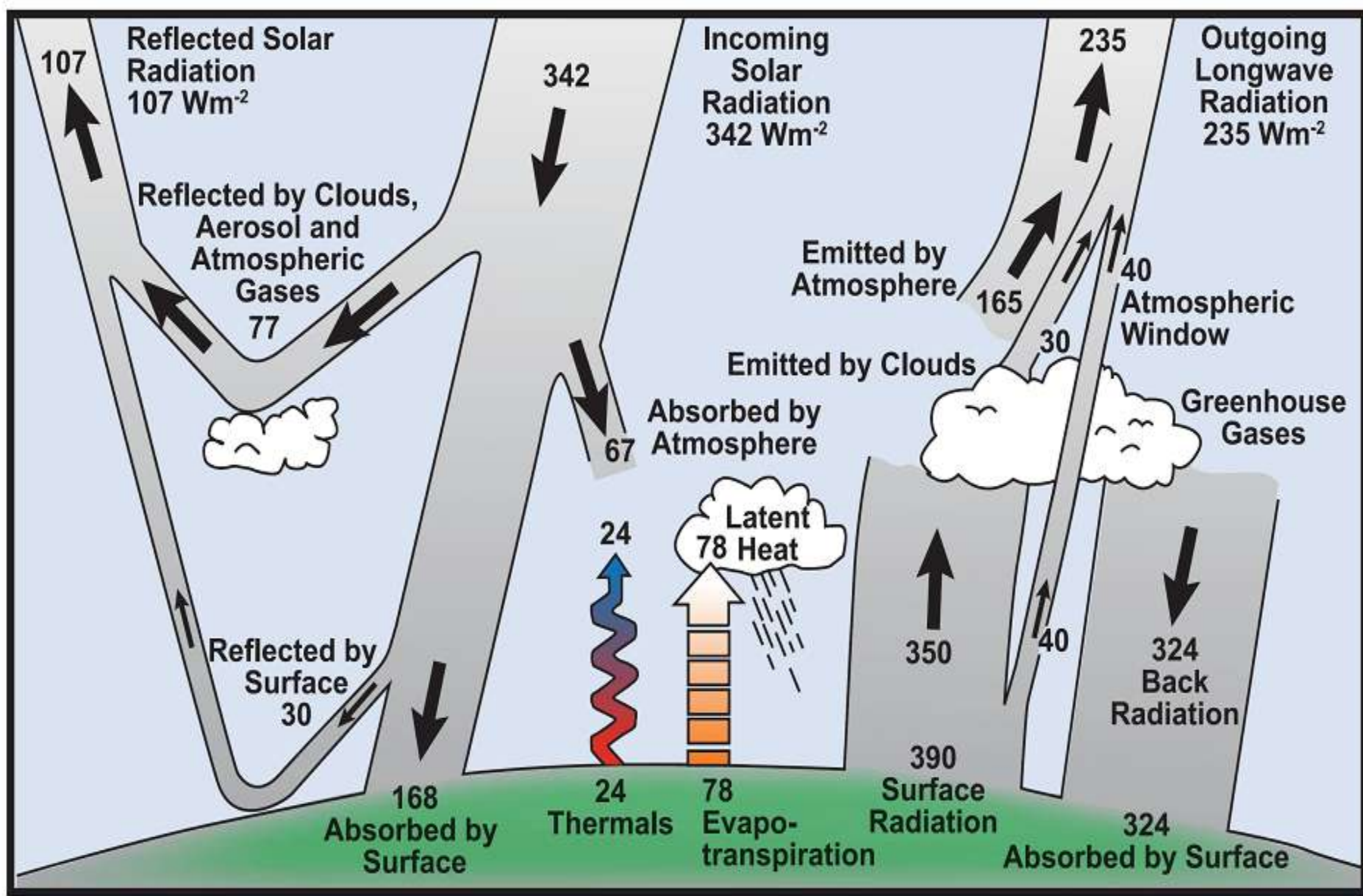
Vertical Overturning

Ocean Bottom Topography

Ocean Model Layers

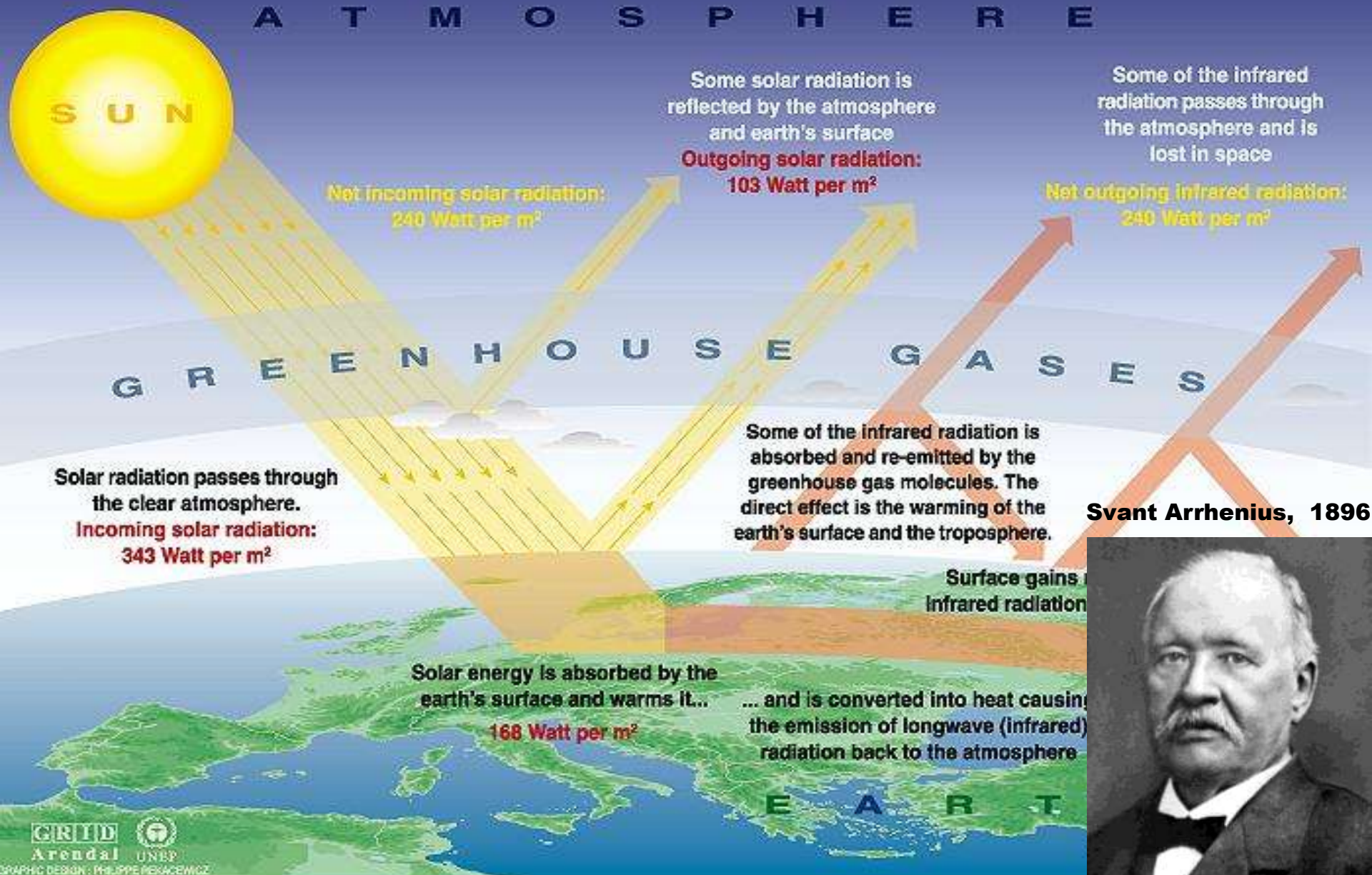


The Earth Simulator Center

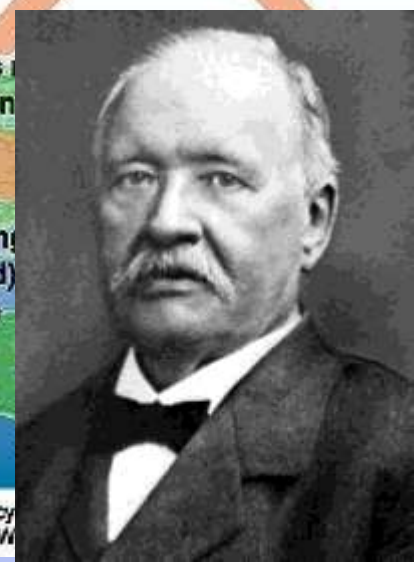


FAQ 1.1, Figure 1. Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming 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).

The Greenhouse effect



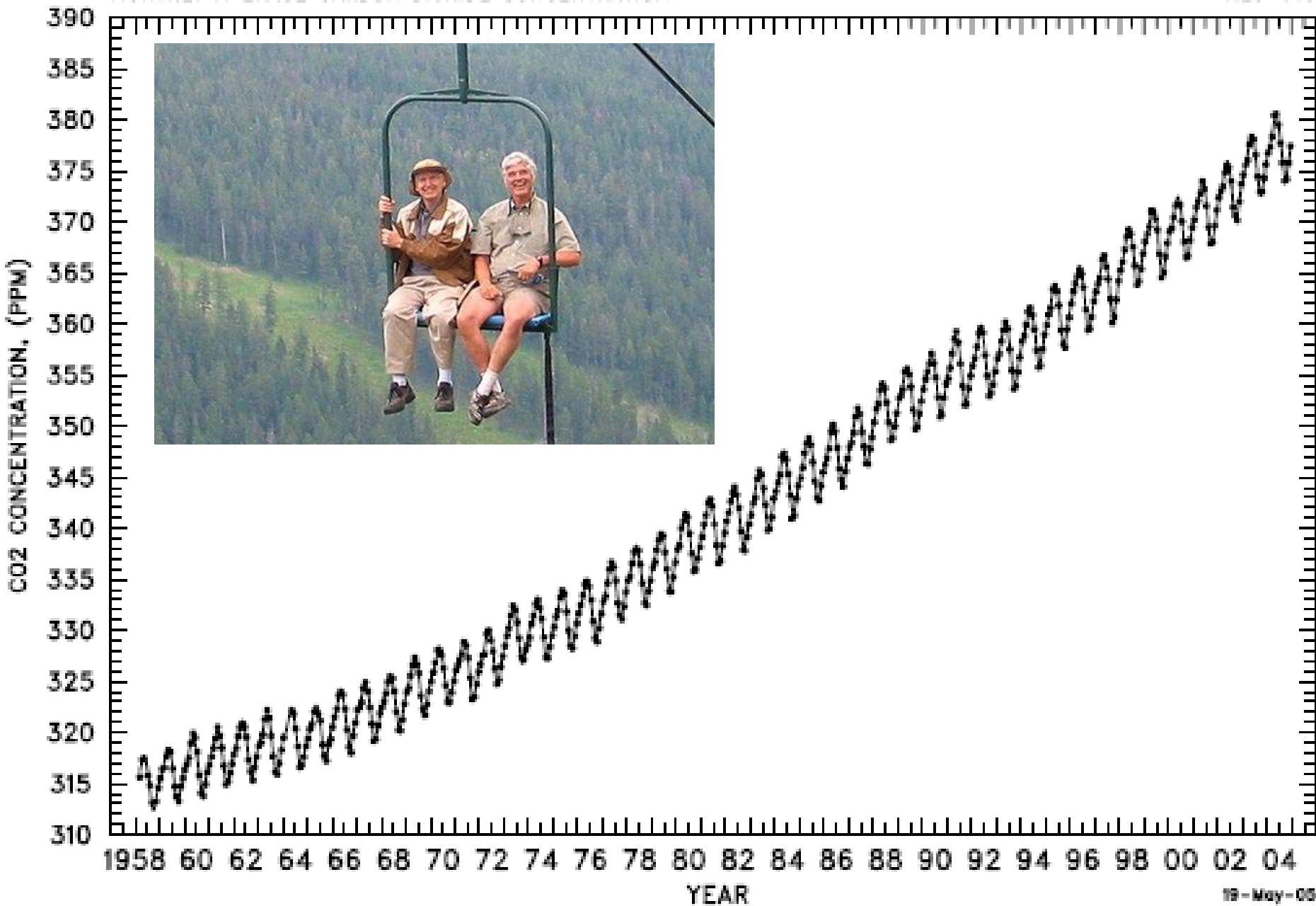
Svant Arrhenius, 1896



Sources: Okanagan university college in Canada, Department of geography, University of Oxford, school of geography; United States Environmental Protection Agency 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 W

MAUNA LOA OBSERVATORY, HAWAII
MONTHLY AVERAGE CARBON DIOXIDE CONCENTRATION

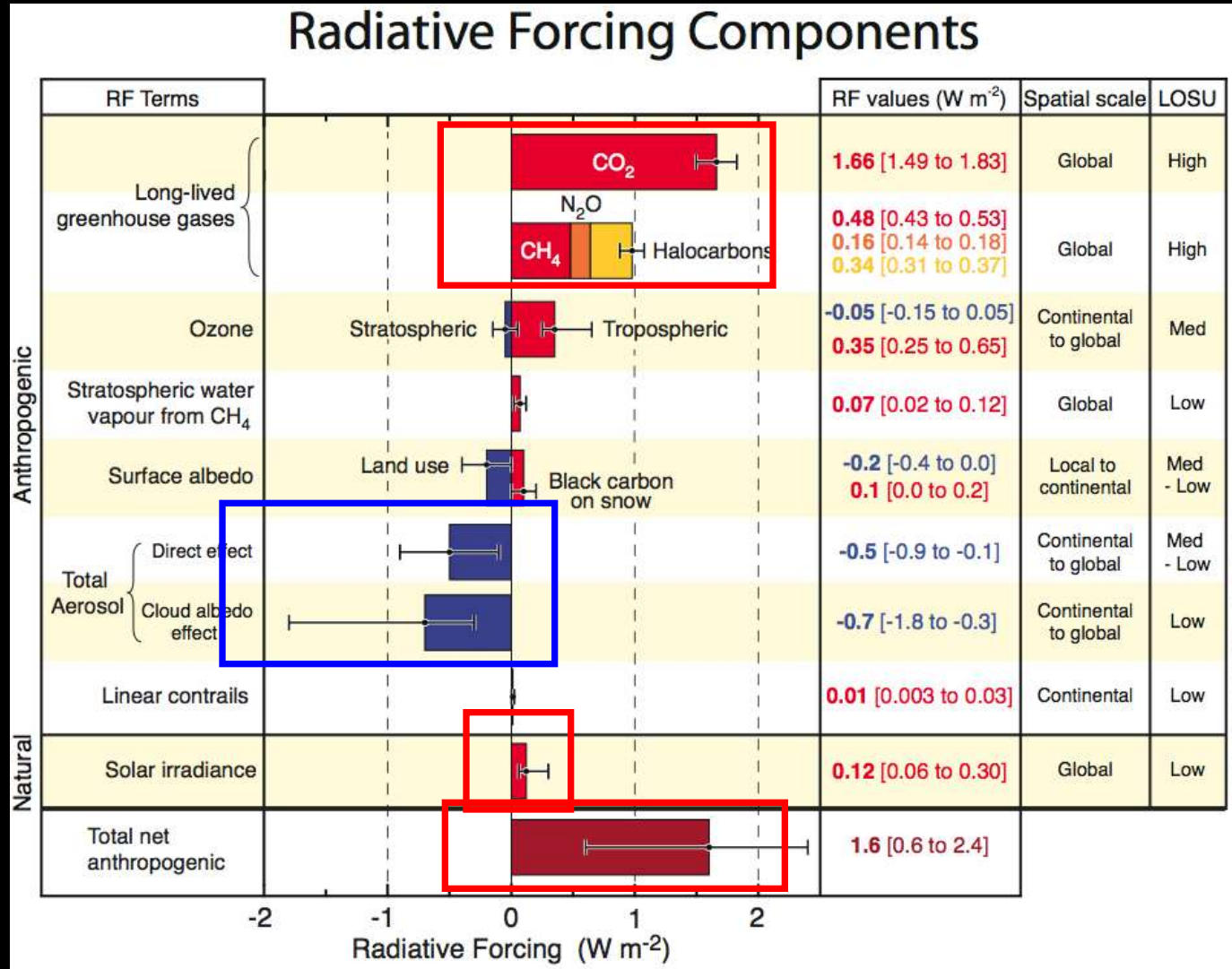
MLO-145



Human and Natural Drivers of Climate Change

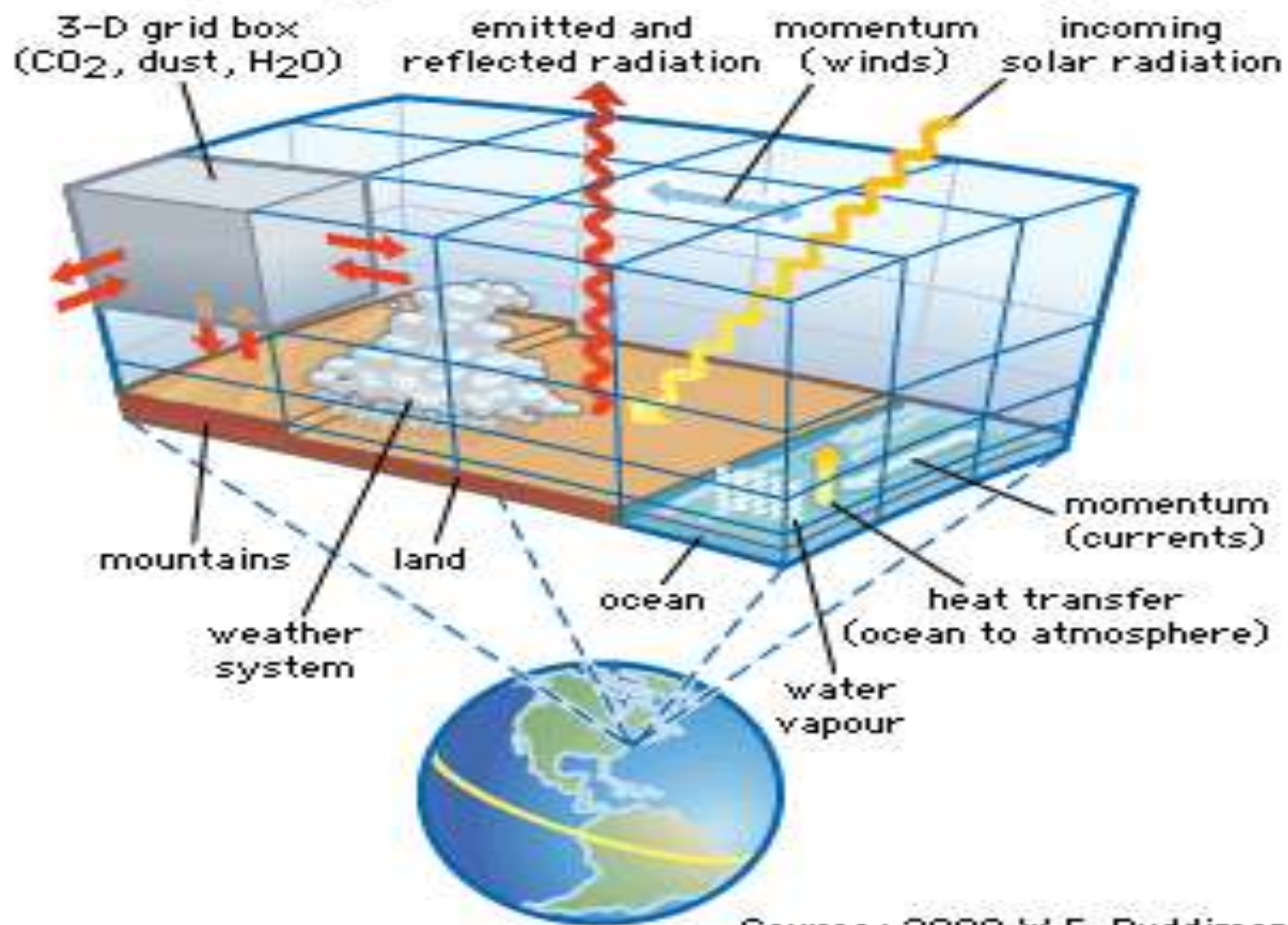
1.6 W m⁻² warms like 1.6 xmas tree lights over every m² on Earth.

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.



© IPCC 2007: WG1-AR4

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

$$\rho c_V \frac{\partial T}{\partial t} = -\rho c_V (\vec{V} \cdot \nabla) T - \nabla \cdot \vec{R} + \nabla \cdot (k_T \nabla T) + C + S$$

- 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)

$$\frac{\partial q}{\partial t} = -(\vec{V} \cdot \nabla) q + \nabla \cdot (k_q \nabla q) + S_q + E$$

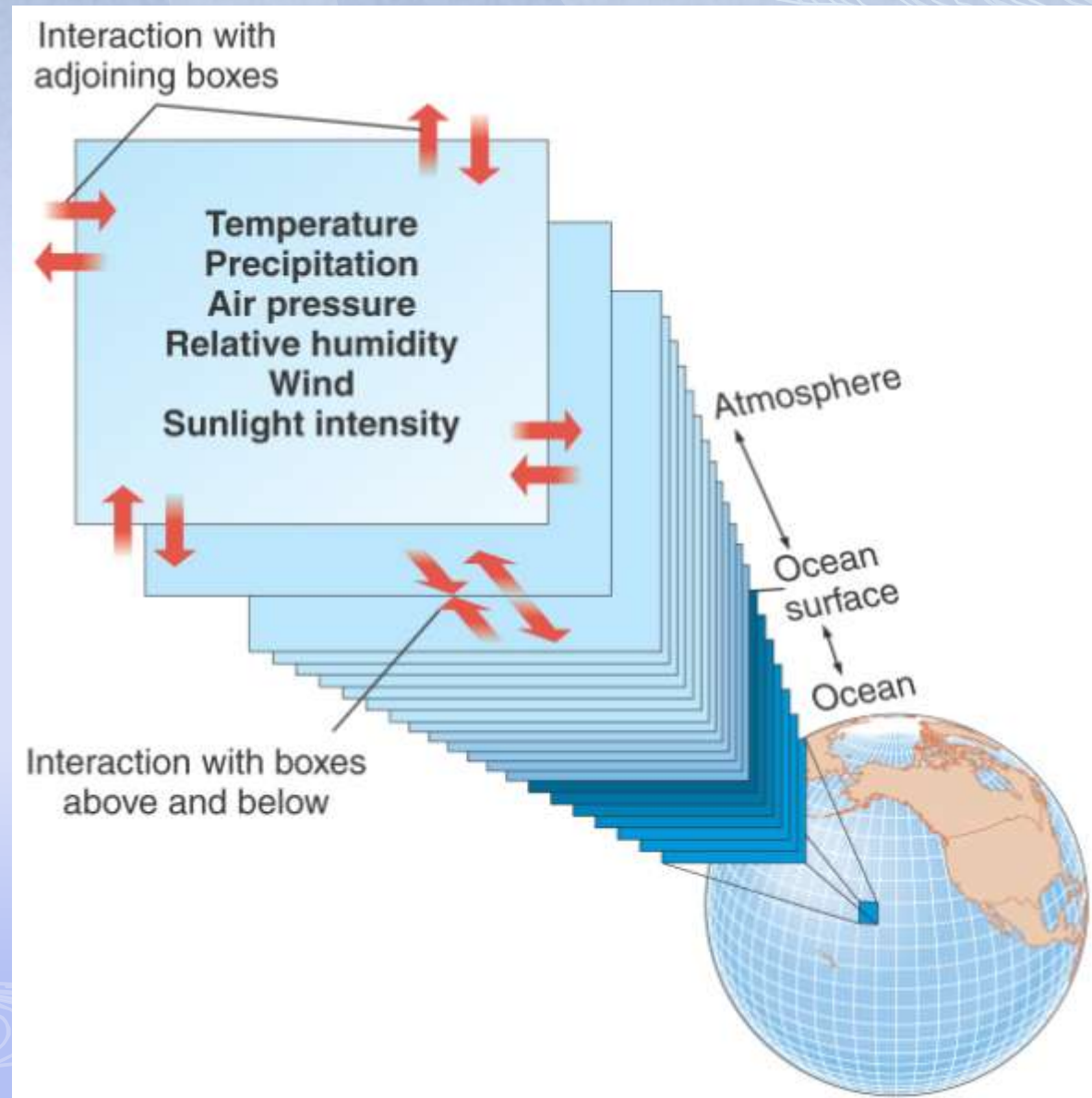
- Equation of state

$$\rho = \rho R_d T$$

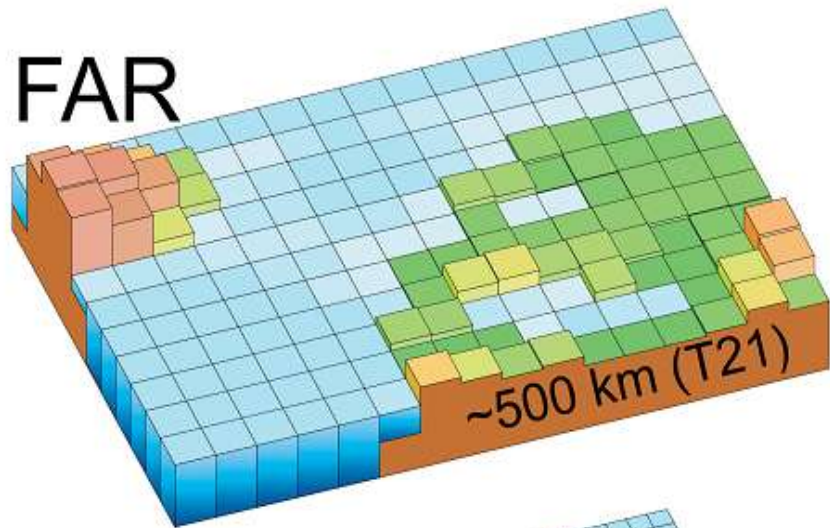
What about resolution?

□ **Computational constraints** limit the resolution that is possible in model equations. three-dimensional models

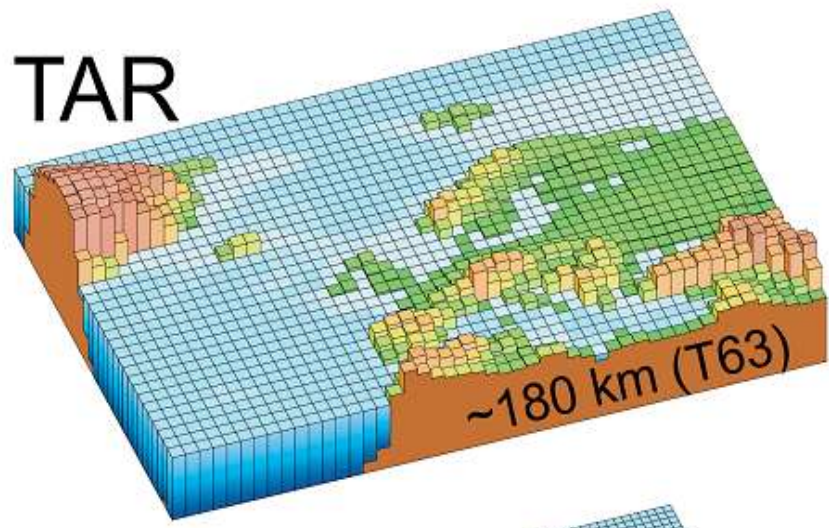
- Atmosphere:
 $2^{\circ} \times 2^{\circ}$, on average
- Ocean:
 $1.5^{\circ} \times 1.5^{\circ}$, on average



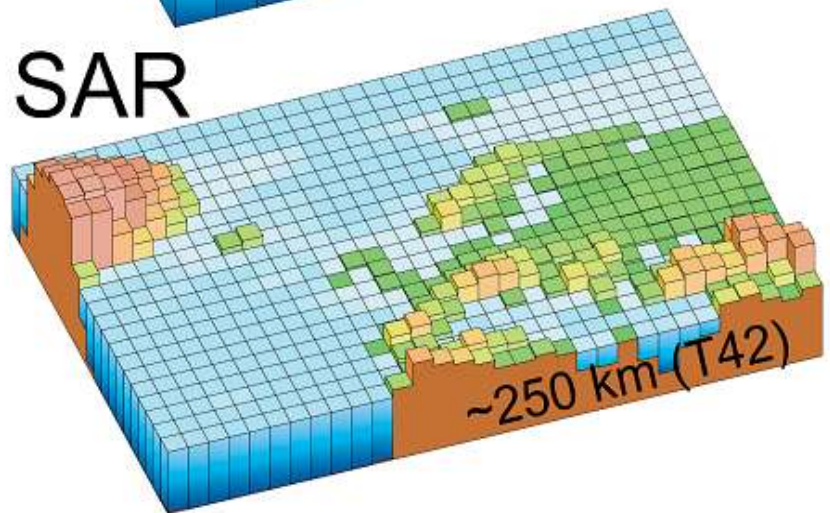
FAR



TAR



SAR



AR4

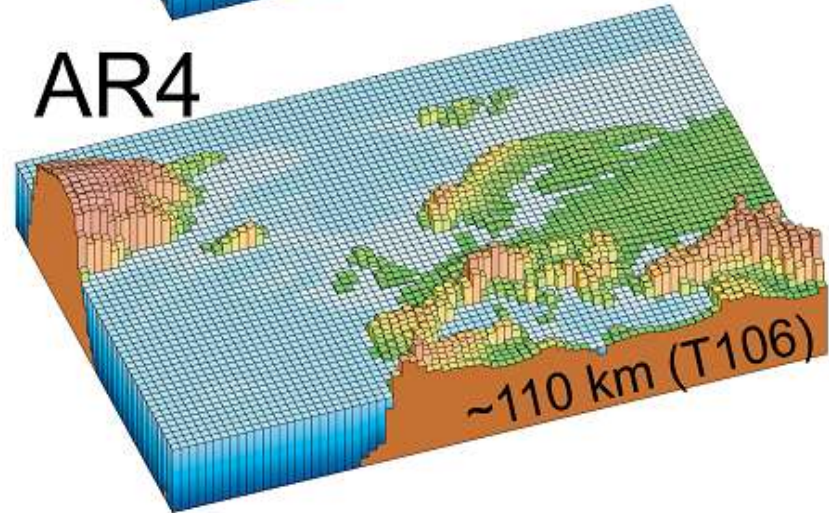
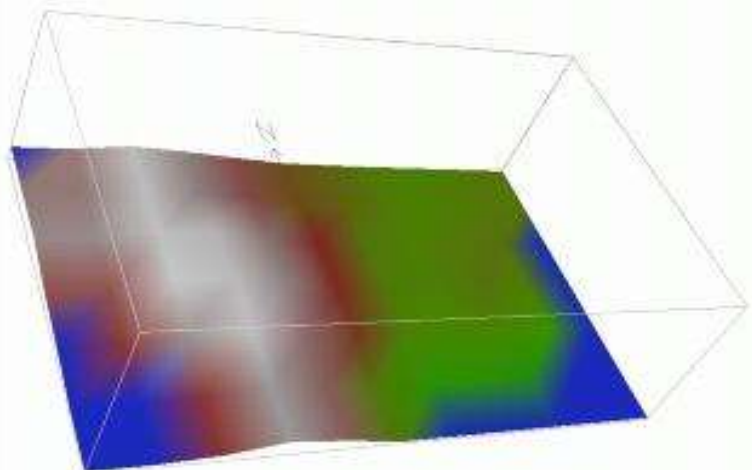


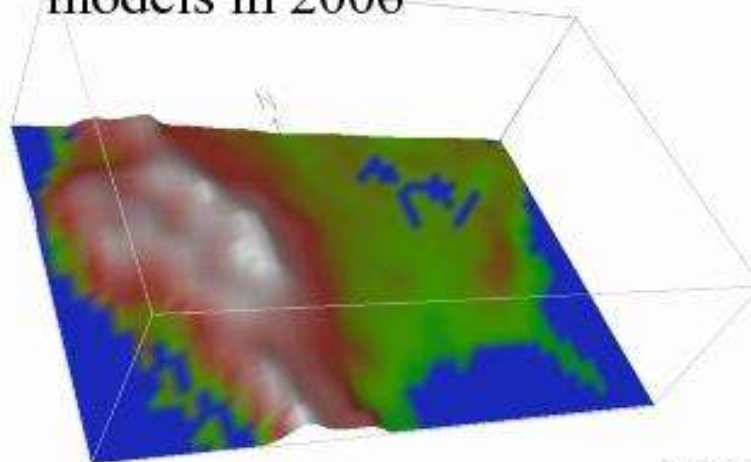
Figure 1.4. Geographic resolution characteristic of the generations of climate models used in the IPCC Assessment Reports: FAR (IPCC, 1990), SAR (IPCC, 1996), TAR (IPCC, 2001a), and AR4 (2007). The figures above show how successive generations of these global models increasingly resolved northern Europe. 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.

Climate Models circa early 1990s



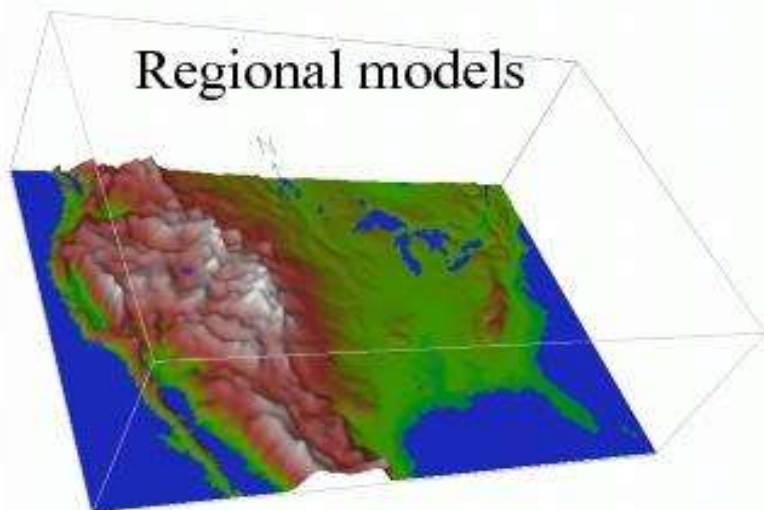
400 km

Global coupled climate models in 2006



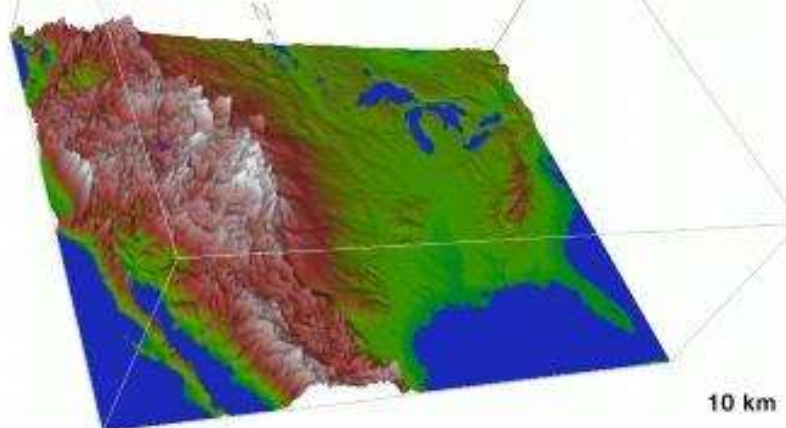
100 km

Regional models



25 km

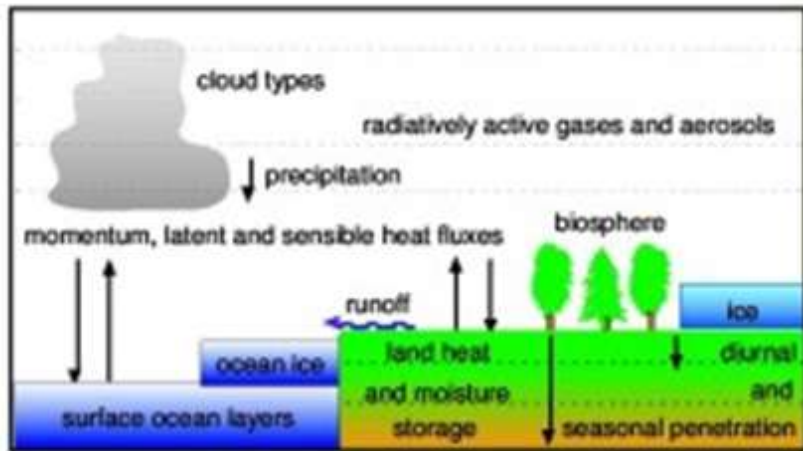
Global models in 5-10 yrs



10 km

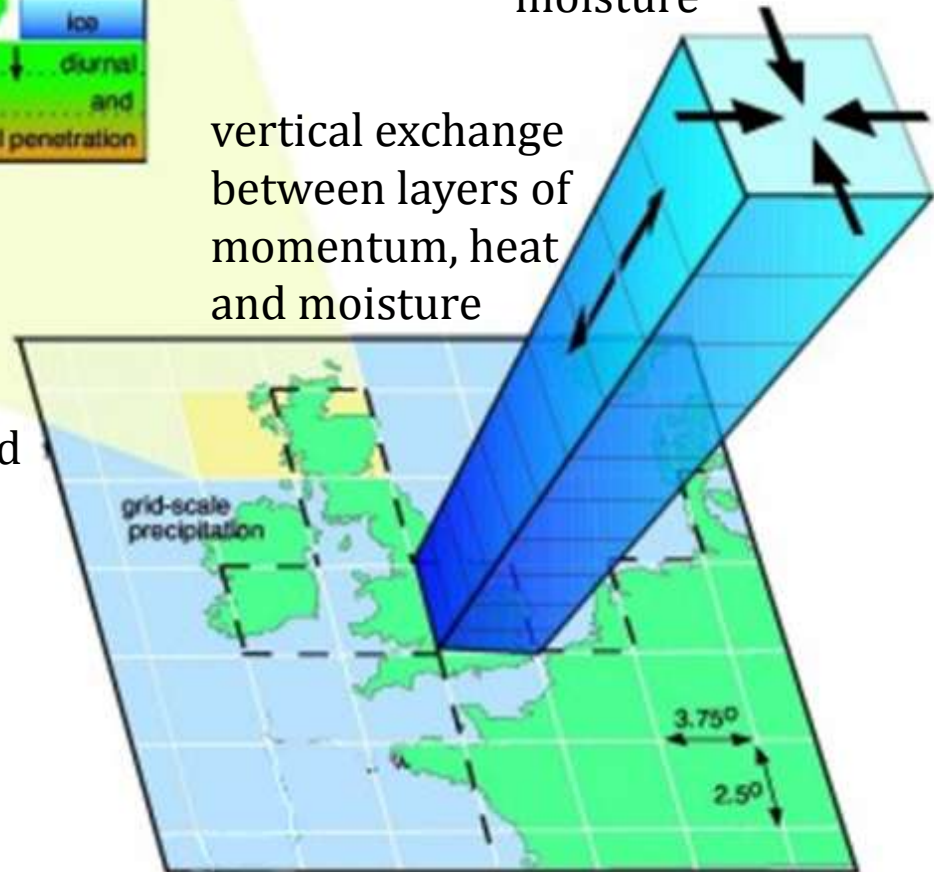
Optimistic view on model-development

Atmospheric GCMs (AGCM)



Horizontal exchange between columns of momentum, heat and moisture

vertical exchange between layers of momentum, heat and moisture

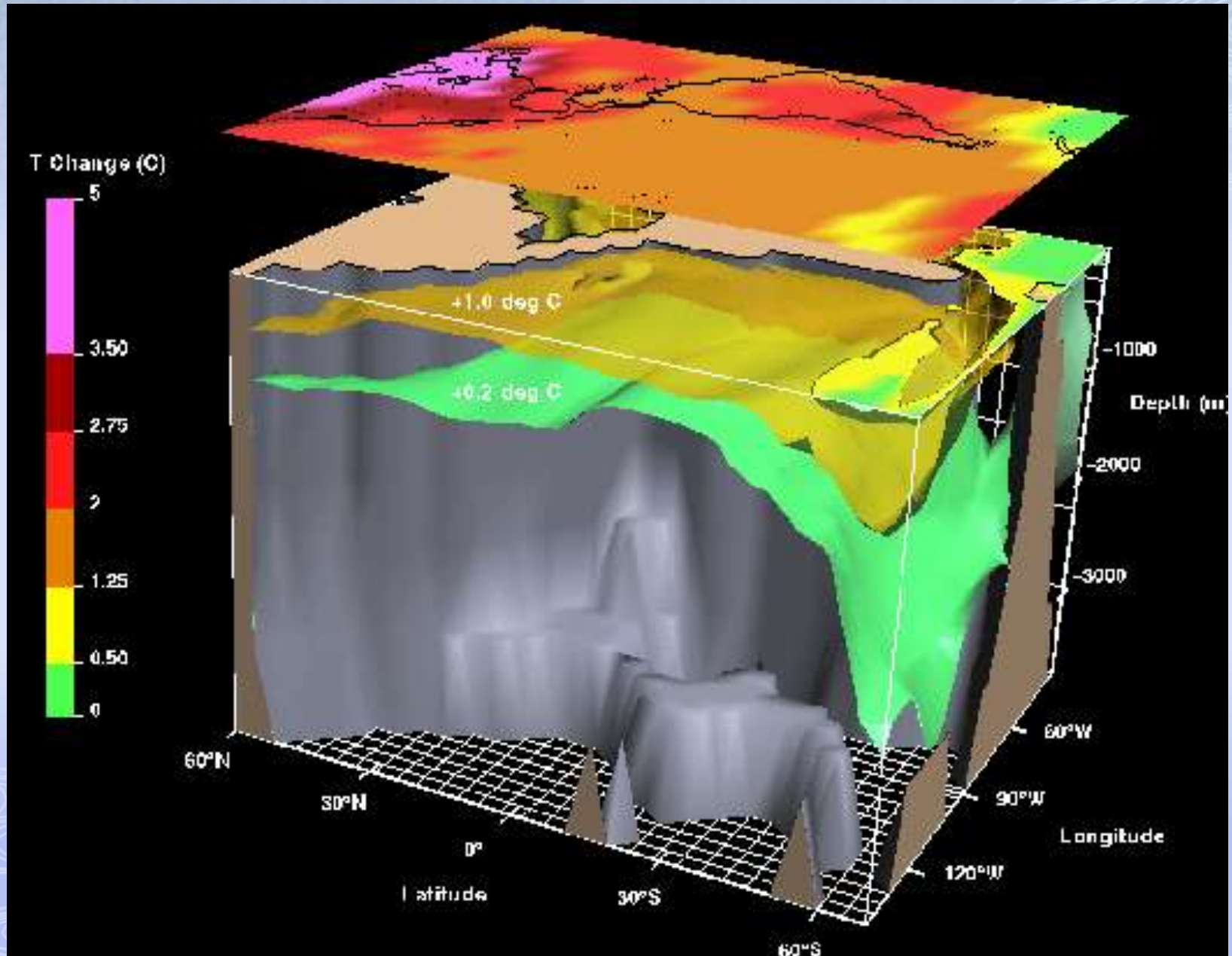


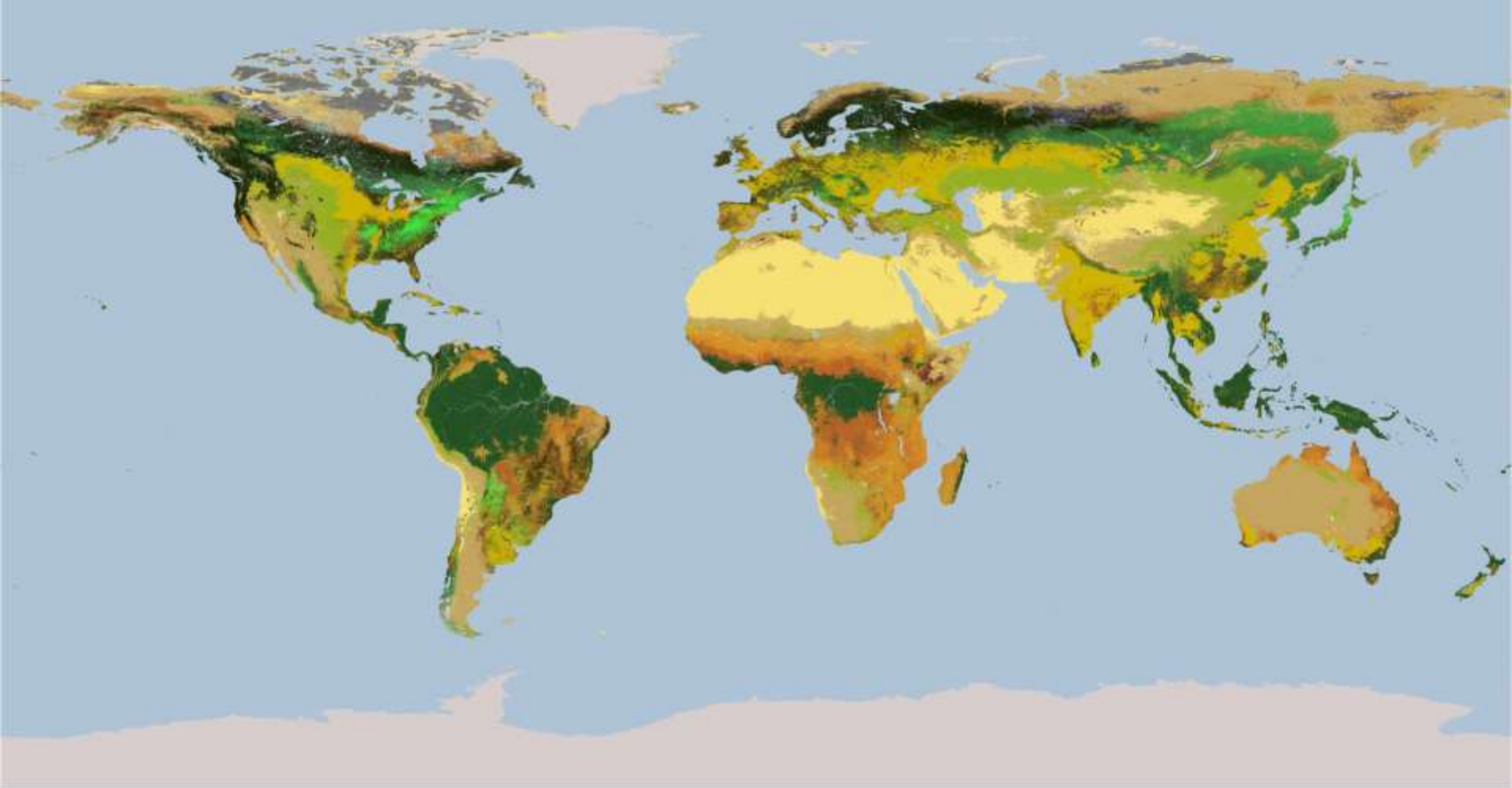
orography, vegetation and surface characteristics included at surface on each grid box

An aerial photograph of a large, dark blue lake situated in a mountainous region. The surrounding terrain is rugged and brownish, with numerous ridges and valleys. The sky is a clear, pale blue, and the horizon line is visible in the upper left corner, showing the curvature of the Earth.

**The Atmosphere is very
small**

Combined GCMs (AOGCM)





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

Fate of Anthropogenic CO₂ 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%



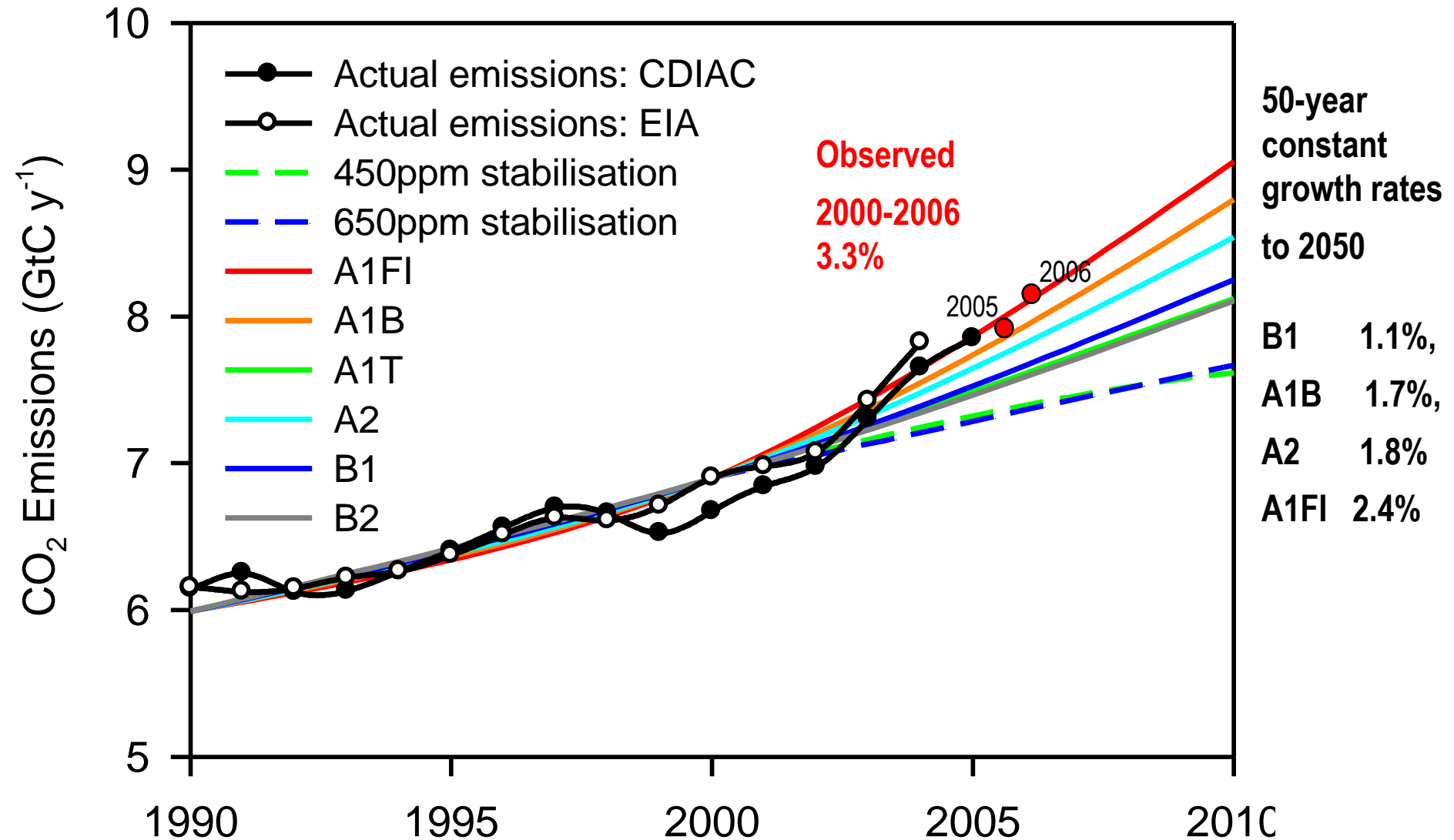
2.3 Pg y⁻¹

Oceans

26%



Trajectory of Global Fossil Fuel Emissions



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

The screenshot shows the EdGCM website in a Mozilla Firefox browser window. The browser's address bar displays <http://edgcm.columbia.edu/>. The website's header features the EdGCM logo and the text "Educational Global Climate Modeling".

Main Menu:

- Home
- Register
- About
- Software
- Download
- FAQ
- Support Forums
- Development
- Contacts
- Events Calendar

Outreach:

- Community Showcase
- Simulation Exchange
- Journal Exchange

Education:

- Education General
- Classroom Exercises
- Education Standards
- Student Projects
- Workshops / Training

Polls:

What interests you?

- Global Warming
- Paleoclimate
- Little Ice Age
- Catastrophic Events
- Climate Prediction
- Intl. Protocol
- Climate Modeling

EdGCM: The Project

The EdGCM Project develops and distributes a research-quality global climate model (GCM) with a [user-friendly interface](#) that runs on desktop computers. Anyone can explore the subject of climate change using the same methods and tools that scientists employ. The software allows users to experience the full scientific process including: designing experiments, setting up and running computer simulations, post-processing output, using [scientific visualization](#) to display results, and creating [scientific manuscripts](#) ready for publishing to the web.

[Read more...](#)

"Anthropocene" Greenhouse Gas Effects

[Outreach - Student Projects](#)

Written by Dominique Alhambra and Christine Iovitte
Wednesday, 09 May 2007
Submitted in partial fulfillment of: Course No. AOS 331, Prof. Jack Williams, Dept of Geography, Univ. of Wisconsin - Madison, Fall 2006.

The early anthropogenic hypothesis by William Ruddiman posits that human influence on climate may have actually begun thousands, not hundreds, of years ago. Increased greenhouse gas levels were not solely caused by greenhouse gas emissions from fossil fuel burning after the start of the Industrial Revolution, but also caused by our ancestors' first agricultural developments. The resultant rise in temperature then delayed the glacial onset that should have occurred naturally. Through climate simulations with the EdGCM model, we compared pre- and post-industrial levels to estimated natural levels for five greenhouse gases: carbon dioxide, methane, nitrous oxide, and two chlorofluorocarbons (CFCs). Our results put our model at, or very close to, an incipient glacial state, supporting the hypothesis of an overdue glaciation.

[Read more...](#)



Snowball Earth: Effect of Obliquity

[Outreach - Student Projects](#)

Written by John Swain and Jeremiah Marsicek
Wednesday, 09 May 2007



Geologic evidence suggests that during the Sturtian period (~750Ma) of the Neoproterozoic Era the Earth was blanketed by snow and ice. Glacial deposits are found on all continents, including regions that were at low latitudes.

Examining the Effects of Global Warming on Greenland

[Outreach - Exercises](#)

Written by Mark Chandler
Sunday, 11 December 2005



Tracking the changes in temperature and snowfall over Greenland is of great interest to scientists because of the concern that global warming could lead to a melting of the Greenland ice sheet and add to rising sea levels.

EdGCM in Antarctica

- [More Flooding to Elsewhere](#)
- [ANZILL in Google Earth](#)
- [Off the Ice](#)
- [Departure](#)
- [12 Hours at the South Pole](#)
- [Head, meet foot](#)
- [South Pole \(Yes?\)](#)

EdGCM Forum Posts

- [Google Earth](#)
- [Ocean albedo calculations](#)
- [source code for Modern File VRST0.vsp](#)
- [Terrain and initial conditions](#)
- [4d tools?](#)

Visitor Locations

Visitor locations



Click to see

Done

Now: Fair and 57°F Today: 73°F Fri: 78°F

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 ($\sim 3\%$ /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

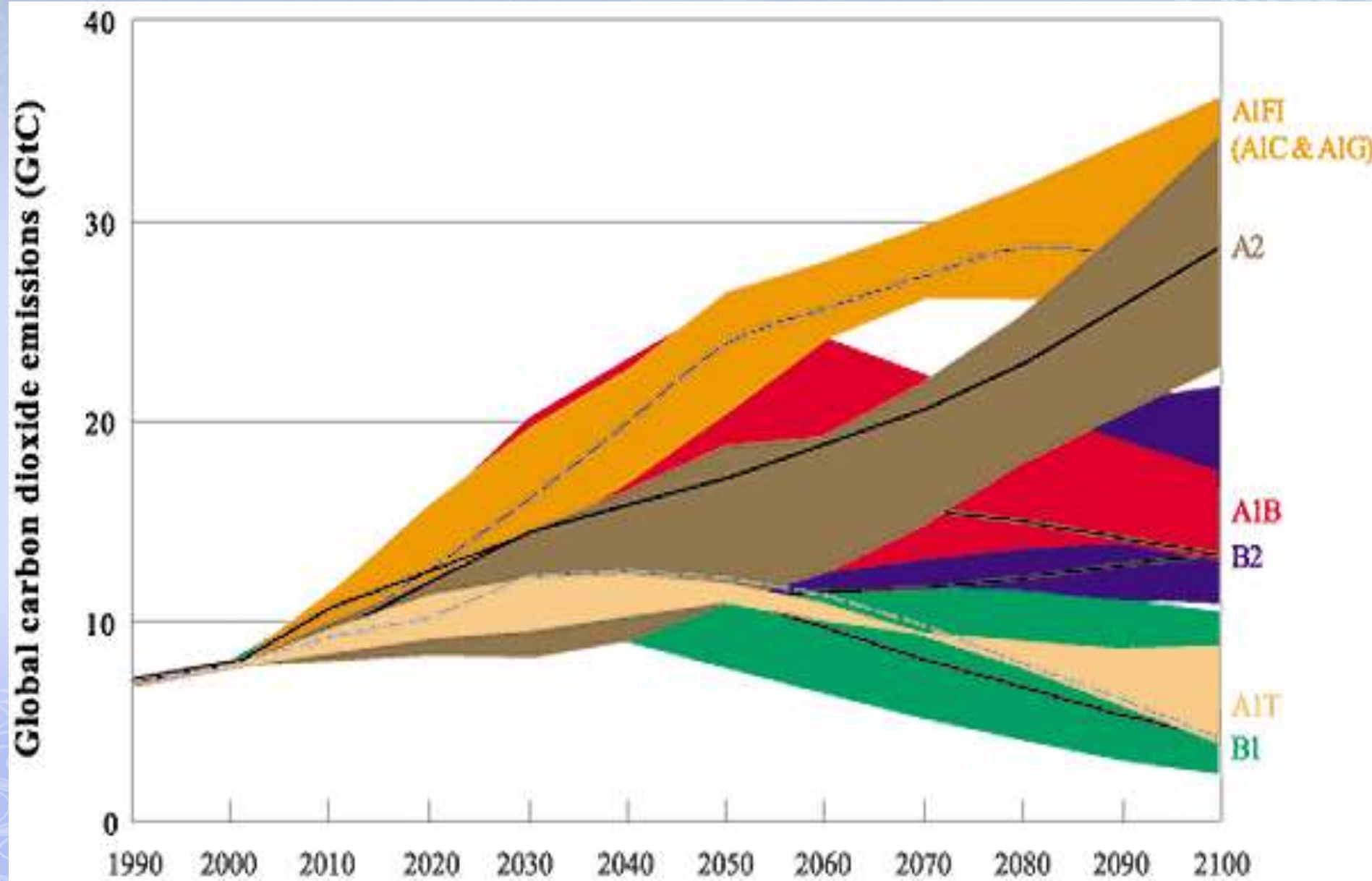
SRES: B1 Storyline – A more integrated, more ecologically friendly world

- ❑ 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 global solutions to economic, social and environmental stability

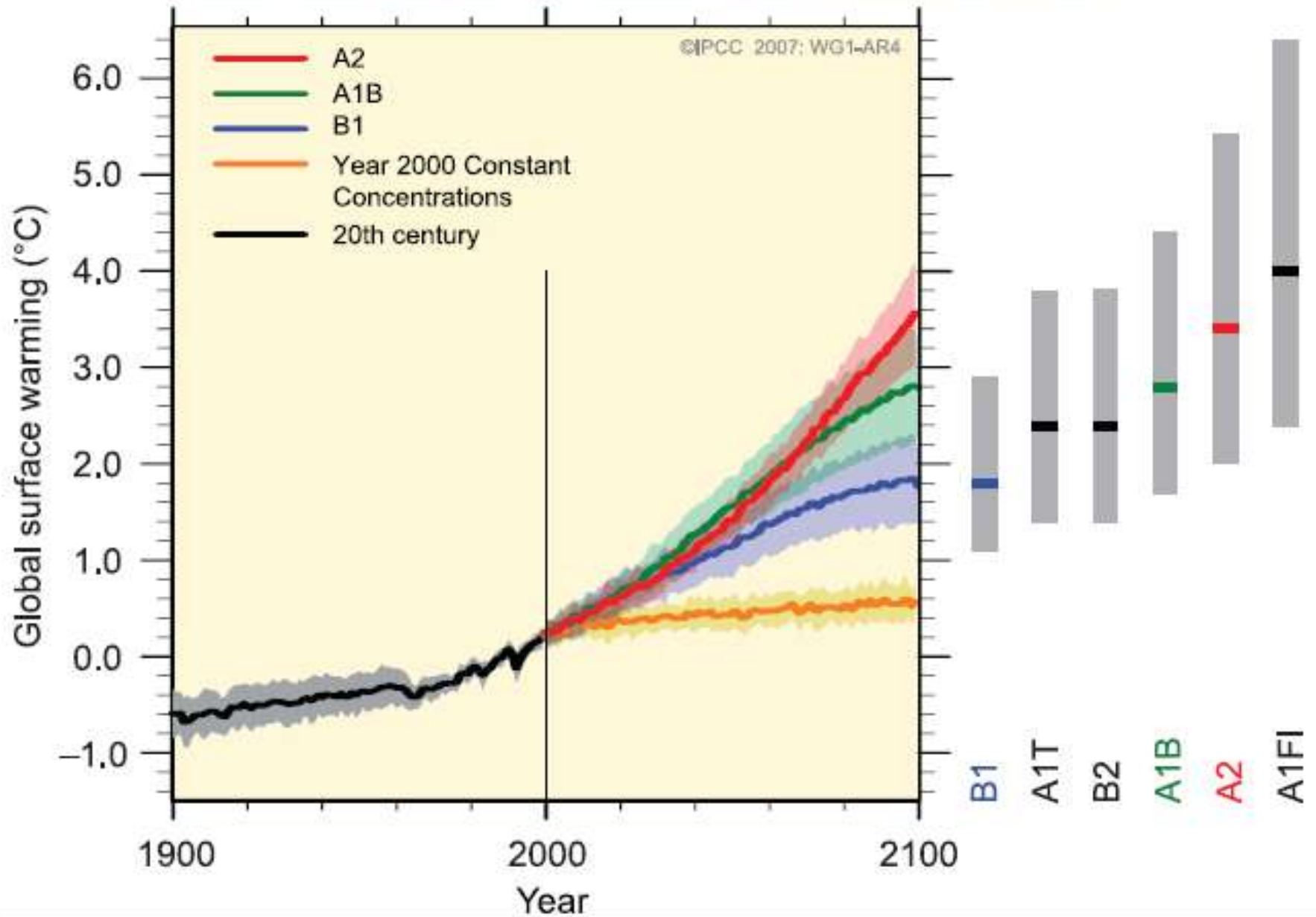
SRES: B2 Storyline – A more divided, but more ecologically friendly world

- ❑ 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 CO₂ emissions – all sources (6 scenario groups)



MULTI-MODEL AVERAGES AND ASSESSED RANGES FOR SURFACE WARMING



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

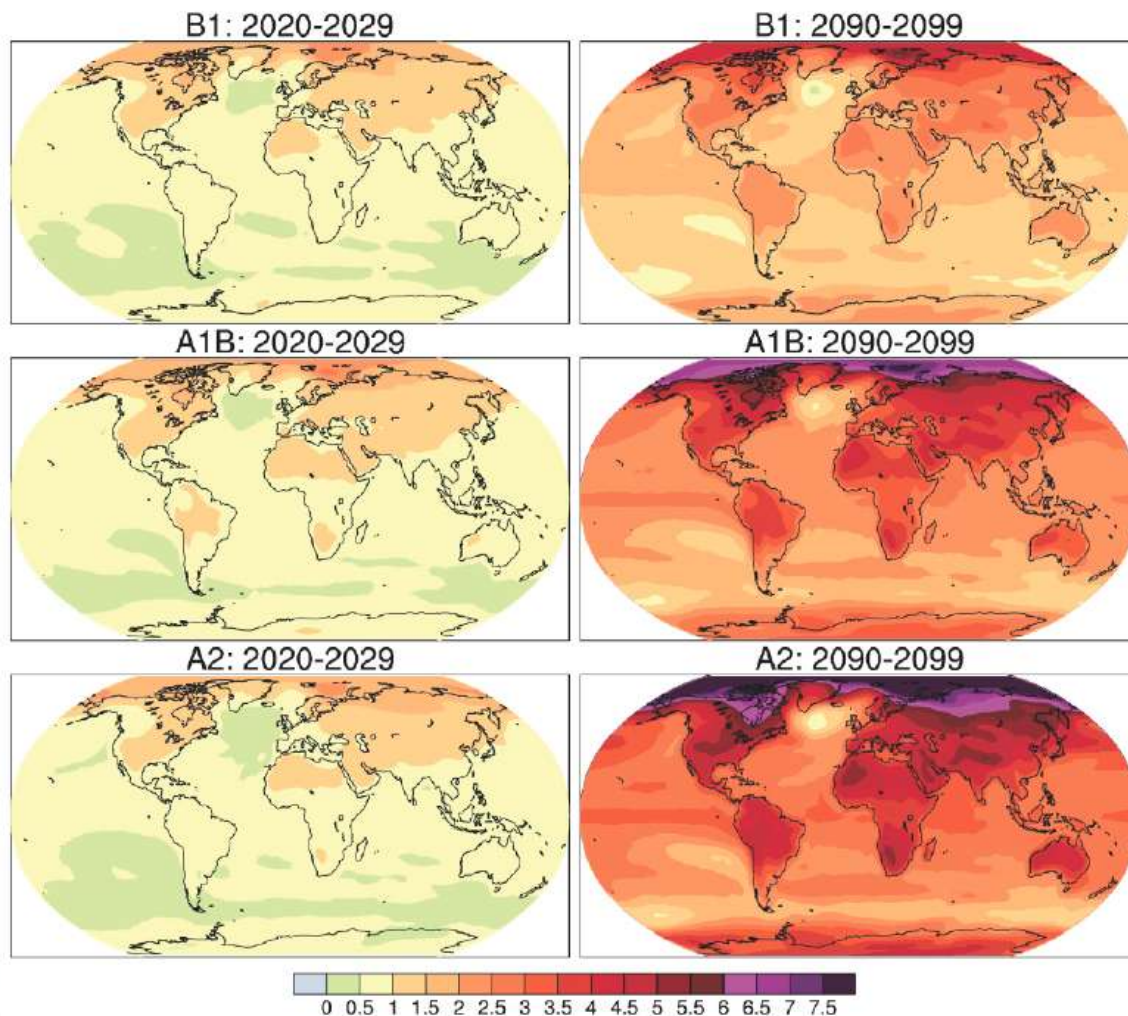
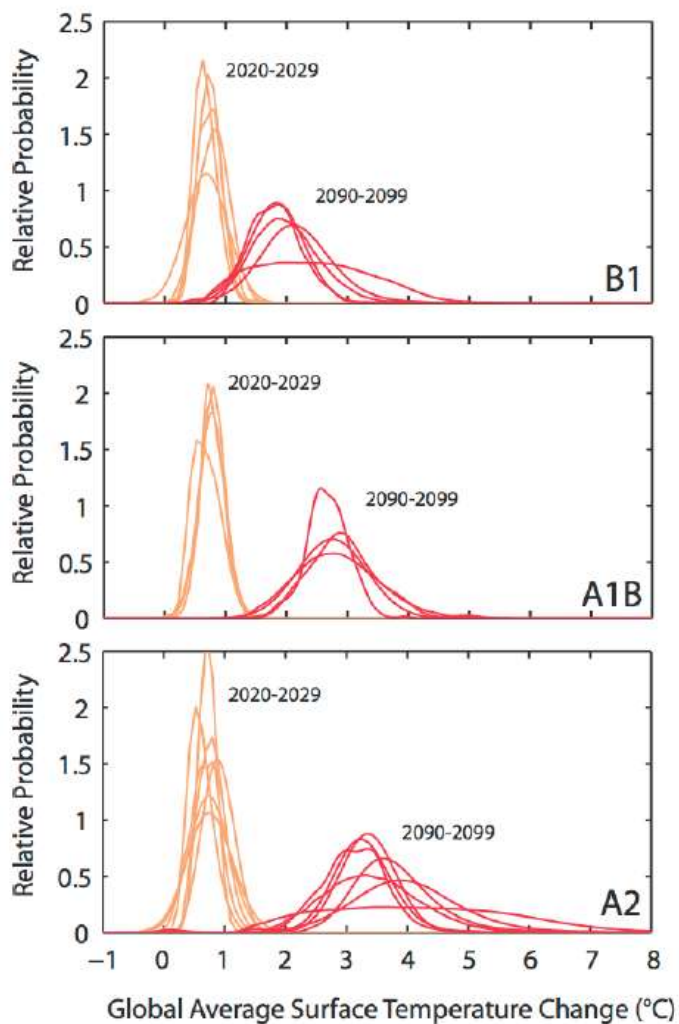
Case	Temperature Change (°F at 2090–2099 relative to 1980–1999)		Sea-Level Rise (inches at 2090–2099 relative to 1980–1999)
	Best estimate	Likely range	Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations	1.1	0.5 – 1.6	NA
B1 scenario	3.2	2.0 – 5.2	7.1 – 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

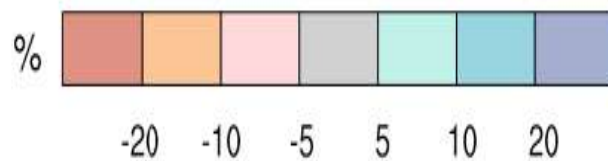
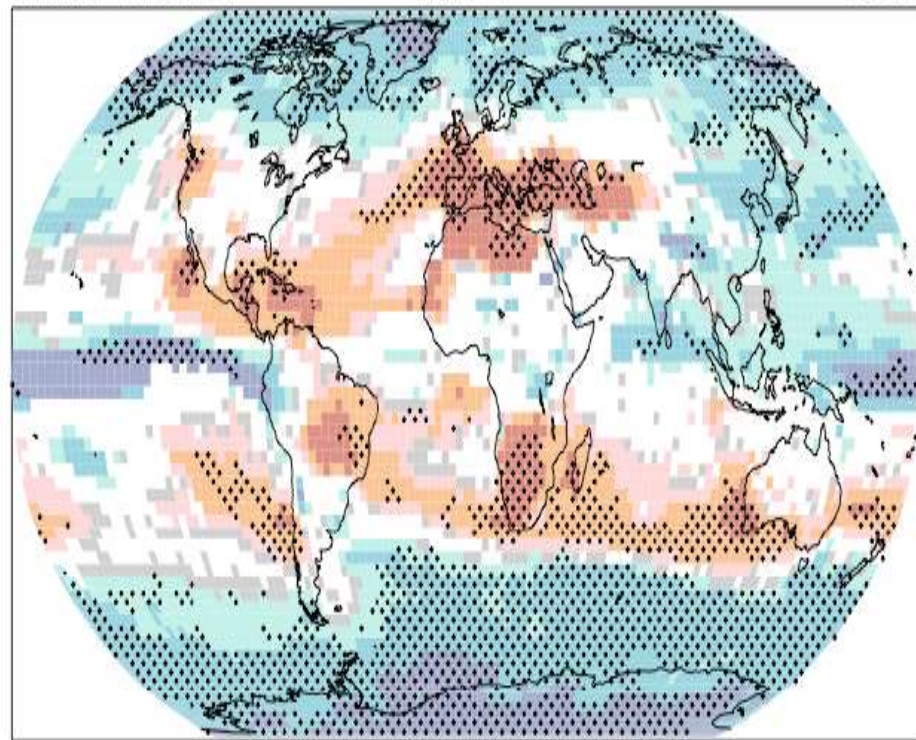
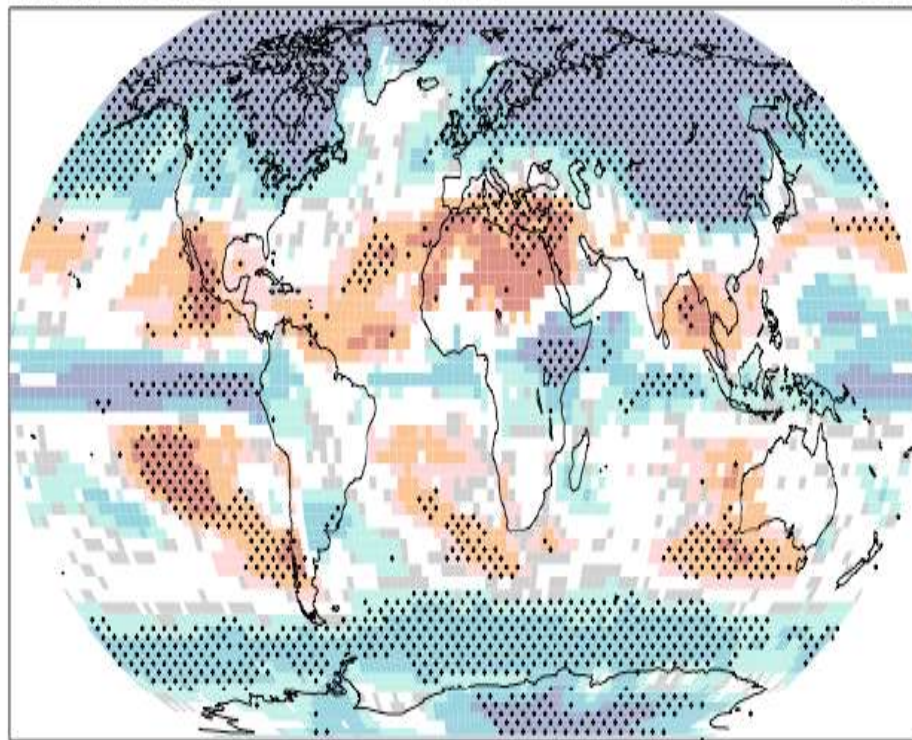
multi-model

A1B

DJF multi-model

A1B

JJA



©IPCC 2007: WG1-AR4

IPCC 4th

Assessment GCMs

All Year

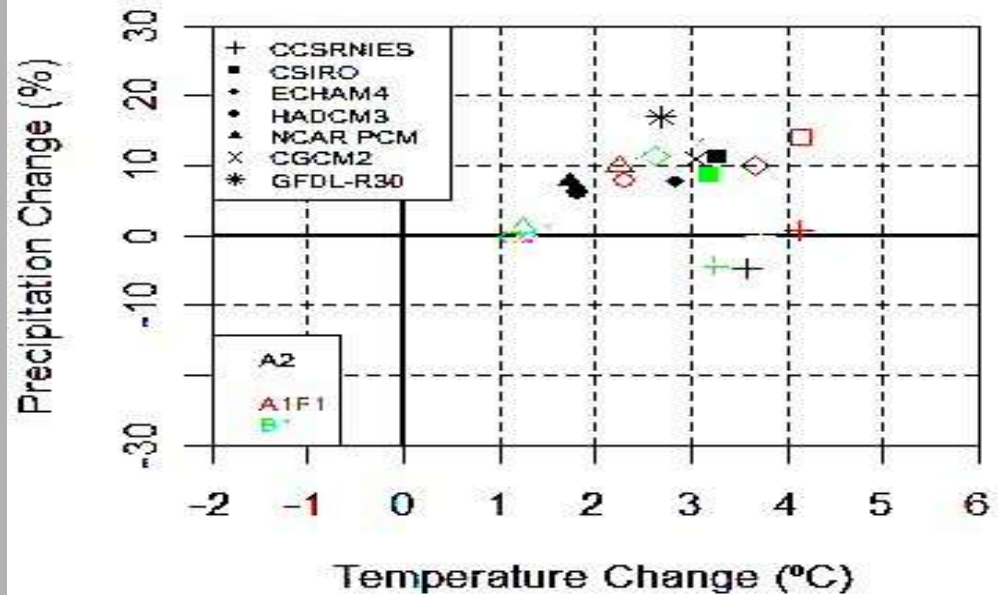
3°C (5.4°F) warmer

BUT

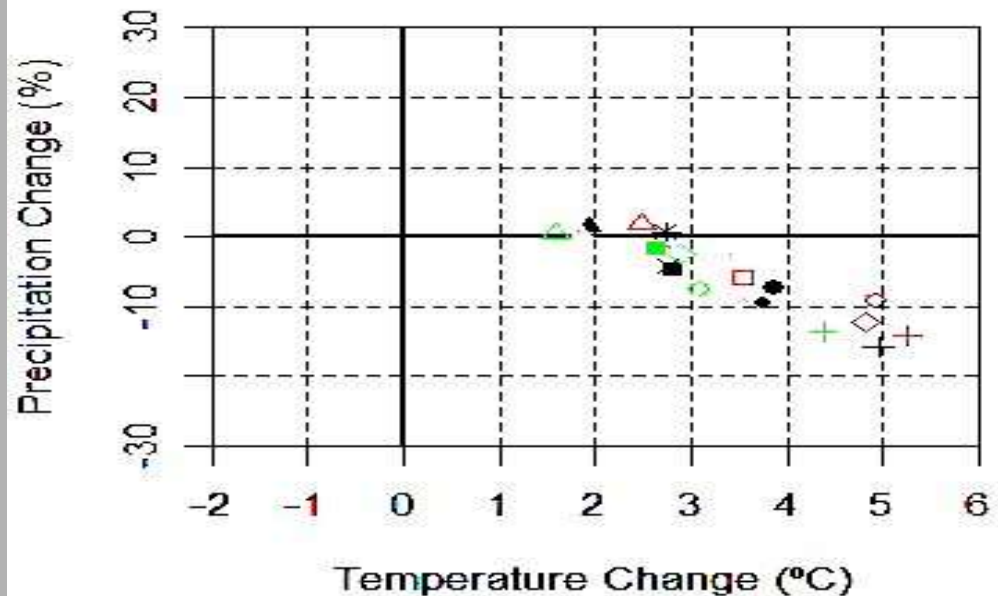
Winter – wetter

Summer – drier

Western North America DEC-FEB (2040-2069)

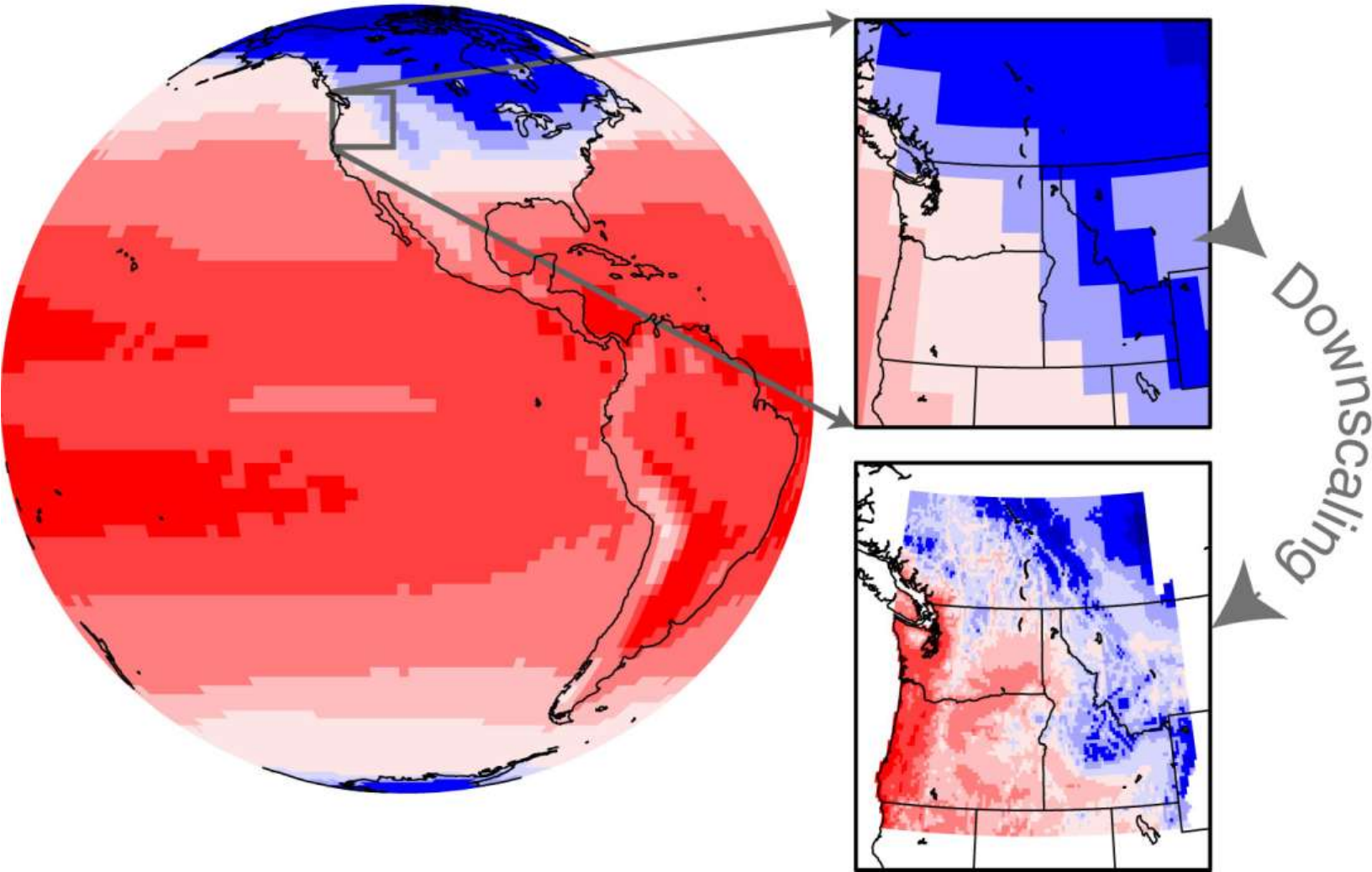


Western North America JUN-AUG (2040-2069)



Downscaling global models for regional studies

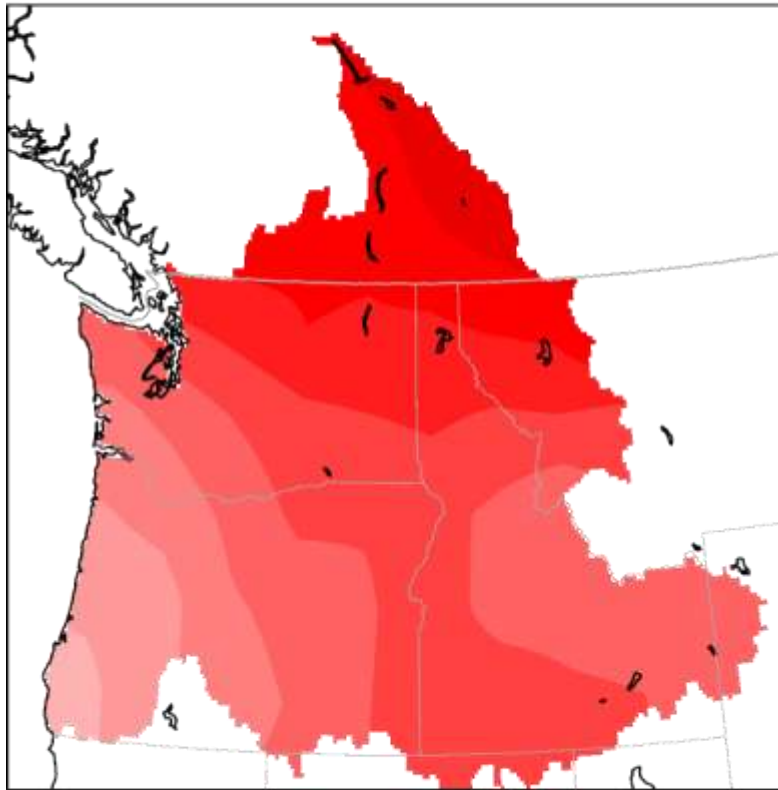
Global Climate Model Air Temperature



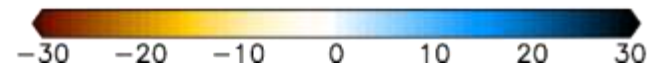
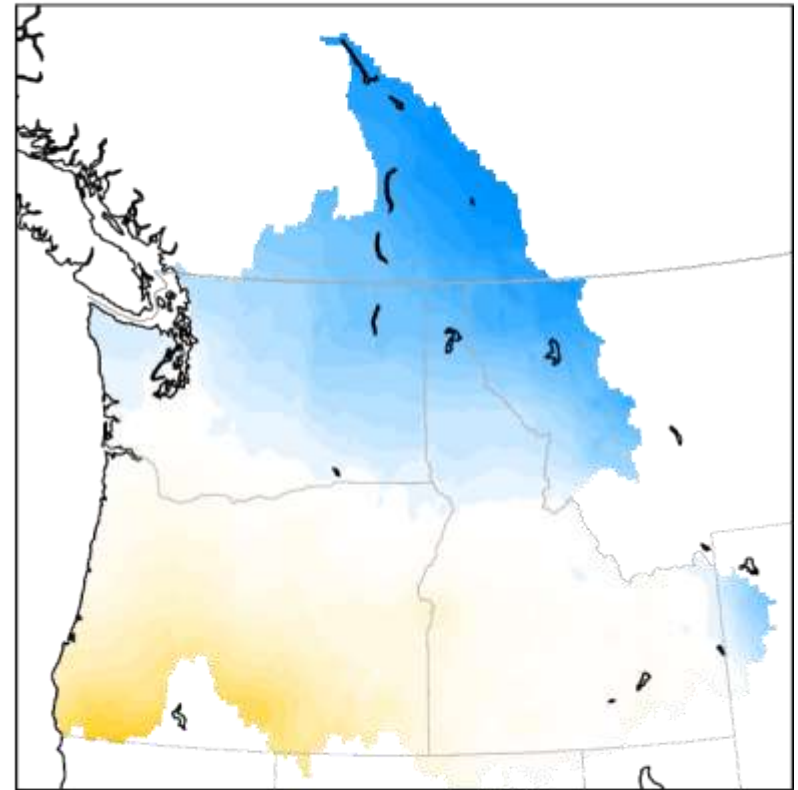
Downscaling -- Winter

DJF Difference to 2040 CCSM3

Temp (C)



Precip (%)

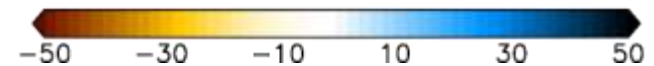
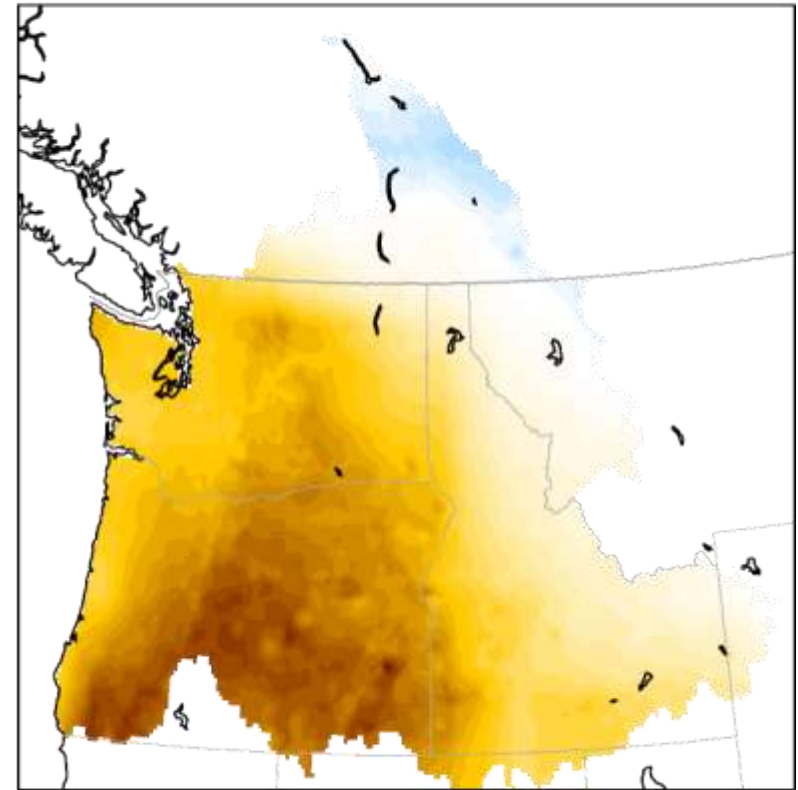
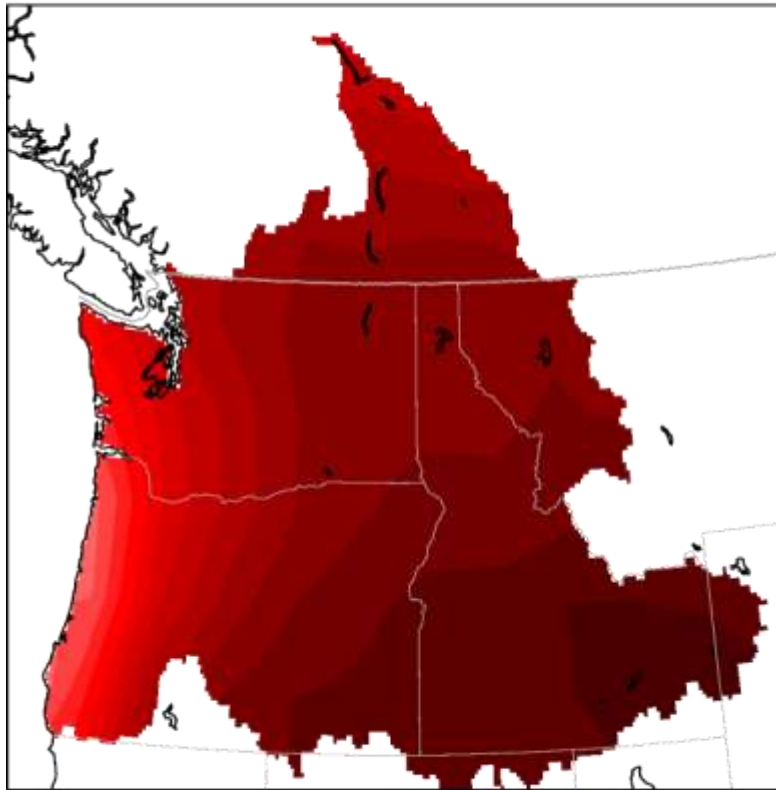


Downscaling -- Summer

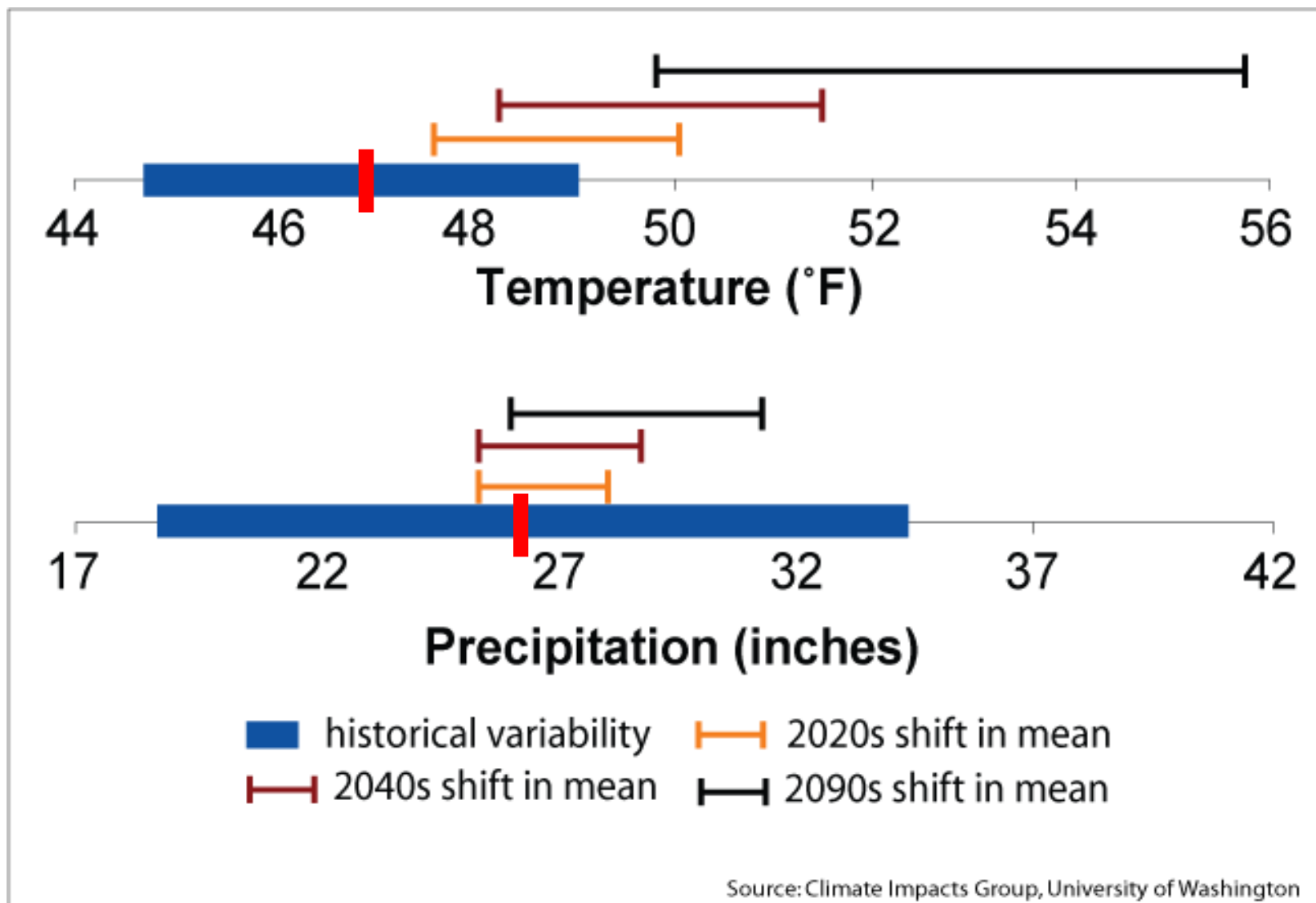
JJA Difference to 2040 CCSM3

Temp (C)

Precip (%)



Comparing Projected Change in Mean with 20th Century Variability



IPCC 5th Assessment Scenario Planning

IPCC Expert Meeting Report: Towards New Scenarios

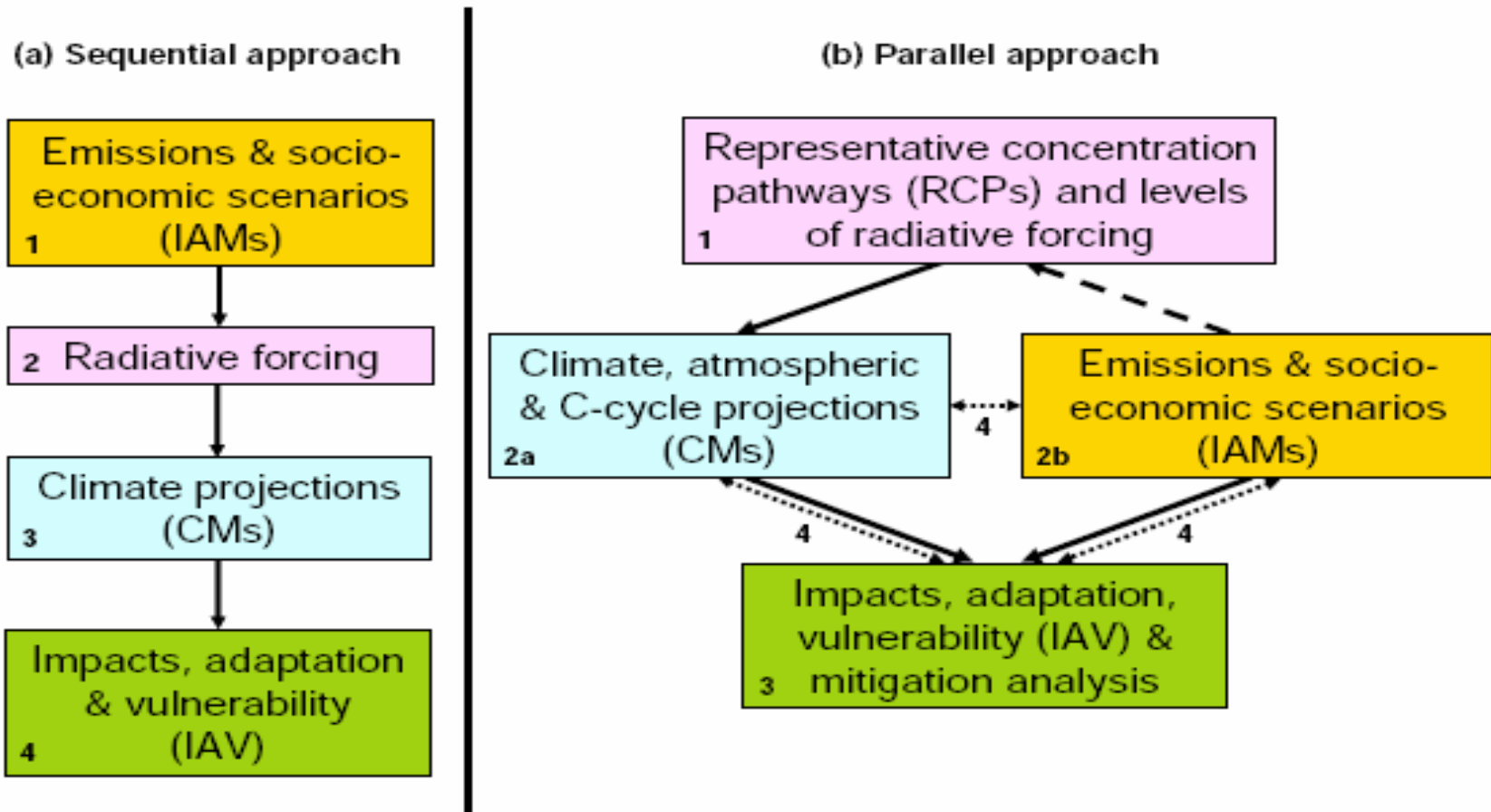


Figure 1. Approaches to the development of global scenarios: (a) previous sequential approach; (b) proposed parallel approach. Numbers indicate analytical steps (2a and 2b proceed concurrently). Arrows indicate transfers of information (solid), selection of RCPs (dashed), and integration of information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

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

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



Associated Press

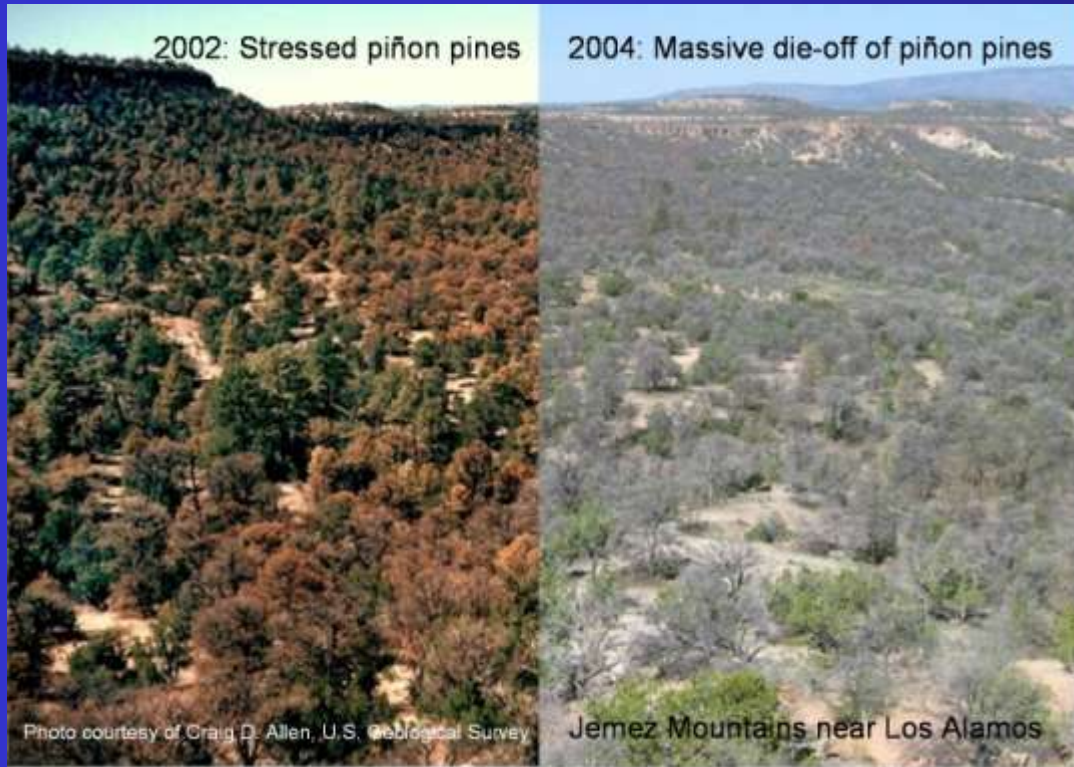
en.wikipedia.org/wiki/North_American_blizzard_of_2005



Drought



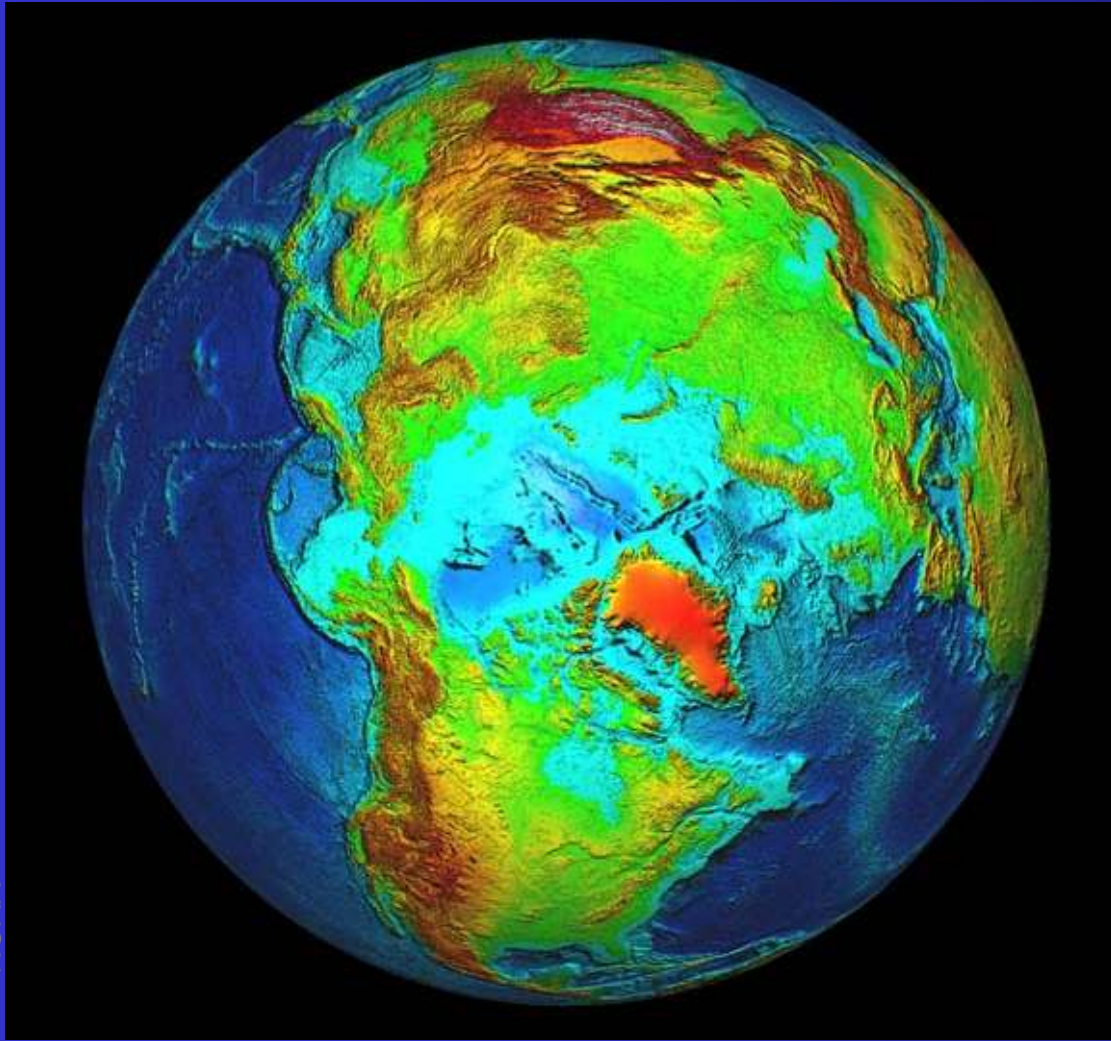
Decreases in precipitation are likely in most subtropical land regions



AP / Mustafa Quraishi

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

Melting Ice



- 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.

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:

- 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.”

Photo Roger Braithwaite



iStockphoto.com



Threshold risks:

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.

Weiss and Overpeck U. Arizona



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