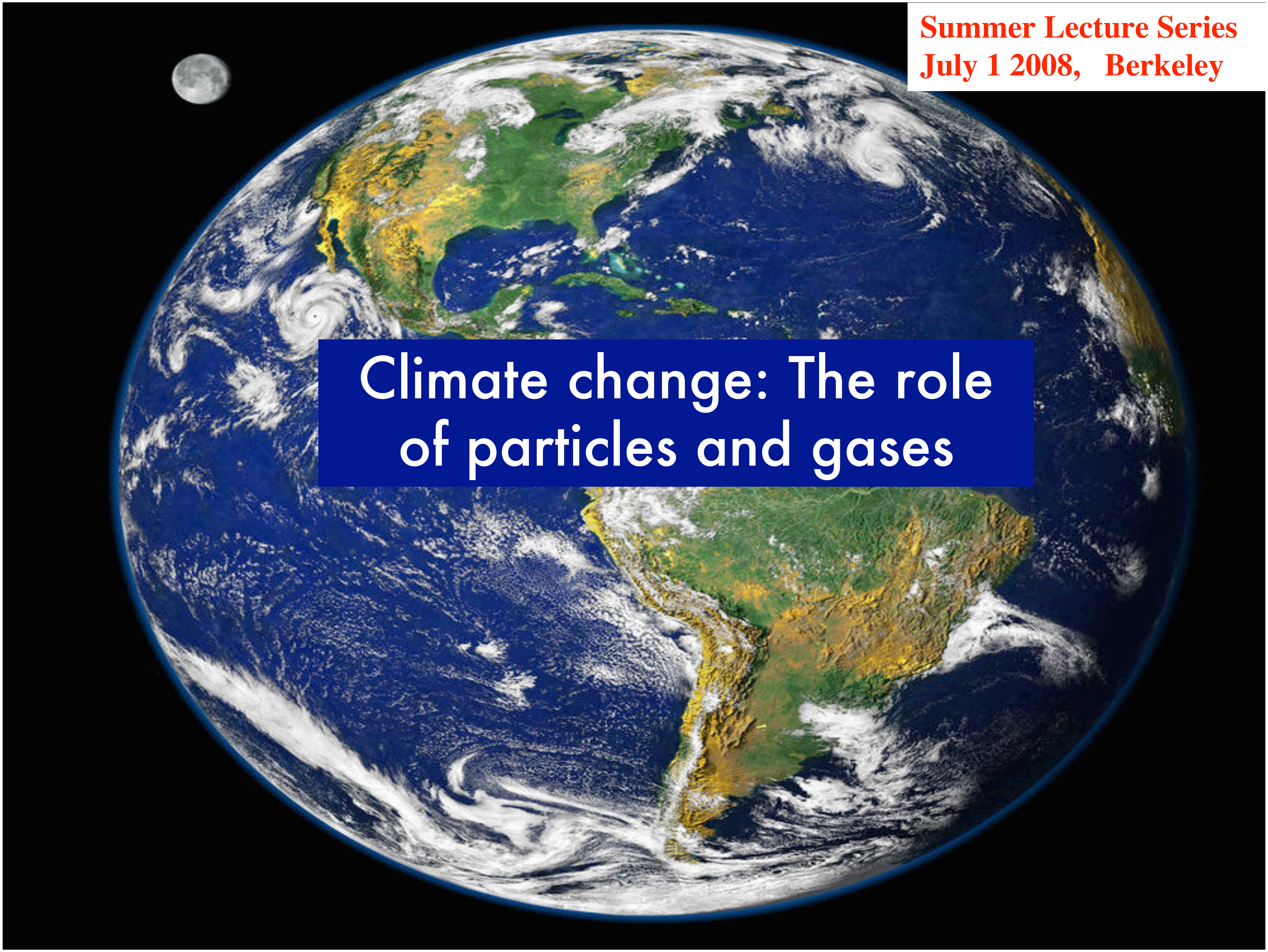
Summer Lecture Series
July 1 2008,   Berkeley

Climate change: The role of particles and gases



NORTH POLE ON THIN ICE

Exclusive: No ice at the North Pole

Polar scientists reveal dramatic new evidence of climate change
By Steve Connor, Science Editor

Scientists warn Arctic sea ice is melting at its fastest rate since records began ·
It seems unthinkable, but *for the first time in human history, ice is on course to disappear entirely from the North Pole this year.*

(Independent, UK, June 27, 2008)

Industry/economy and the environment appear to be headed on a collision course!

OUTLINE

Climate record - ~1 M yrs to present-day

Drivers of climate change

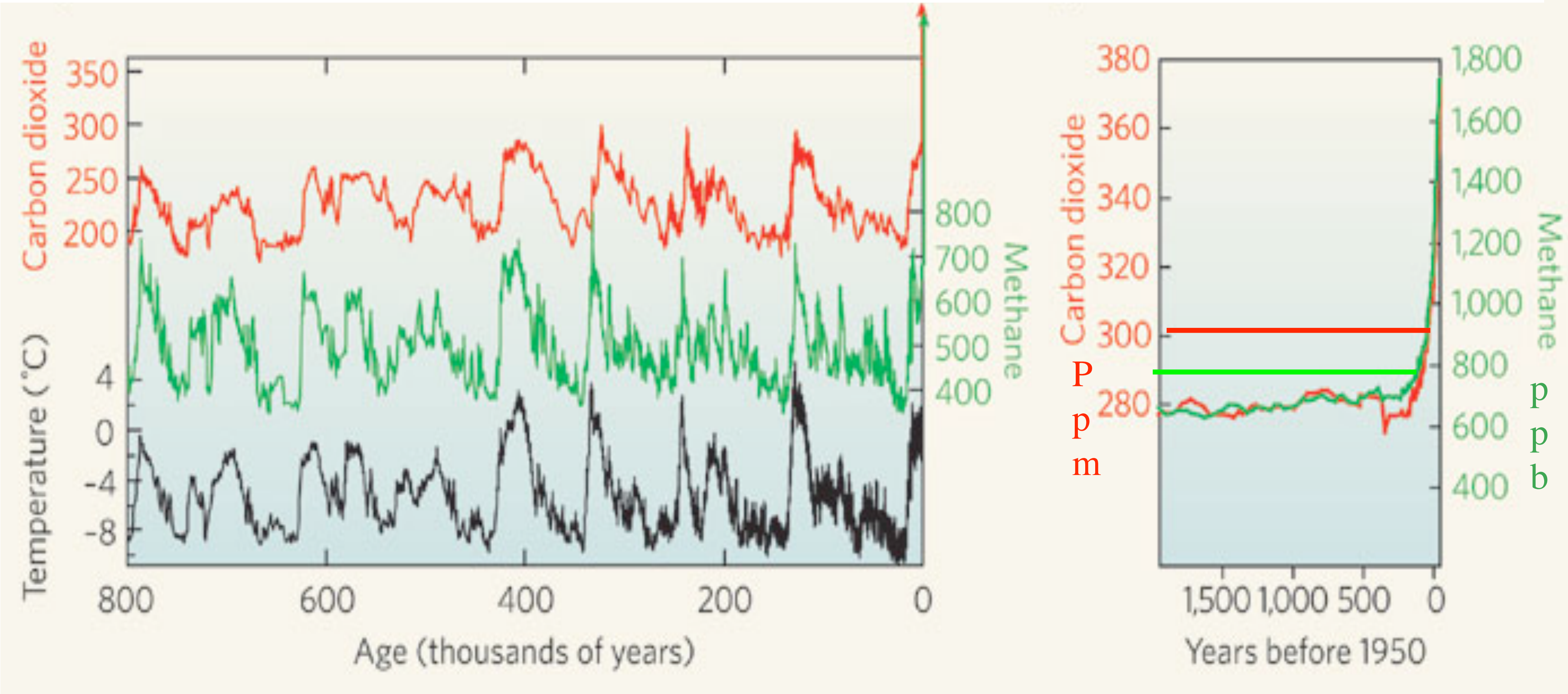
Understanding climate change

Global and Regional Signals - Industrial age

Future Climate

Earth's climate history

EPICA Dome C ice core records with a temperature reconstruction (relative to the average of the past millennium).

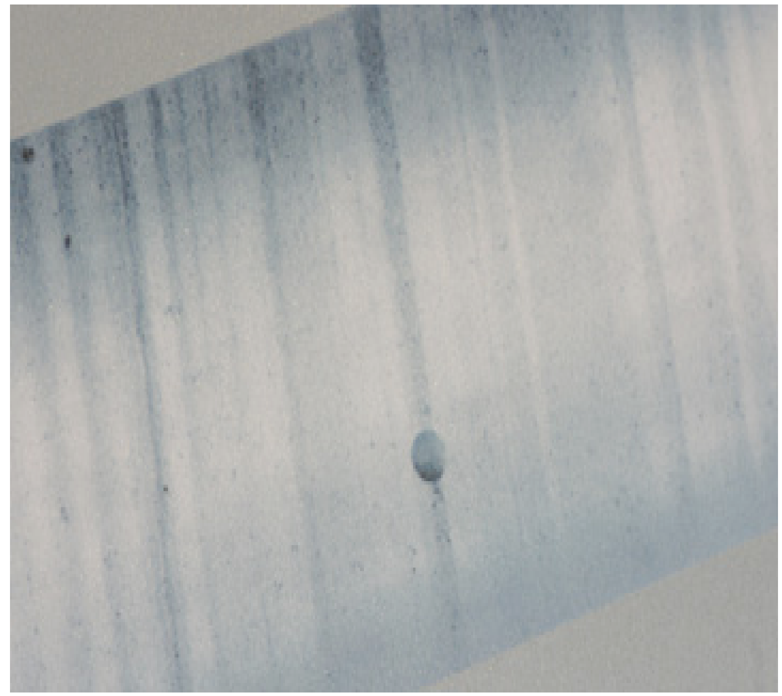


Ice cores drilled in the Antarctic ice sheet: Snowfall piles up year-by-year Isotopic composition of the snow records the temperature and bubbles of air trapped in the ice preserve a record of atmospheric composition.

Brook (*Nature* **453**, 291-292, 2008)

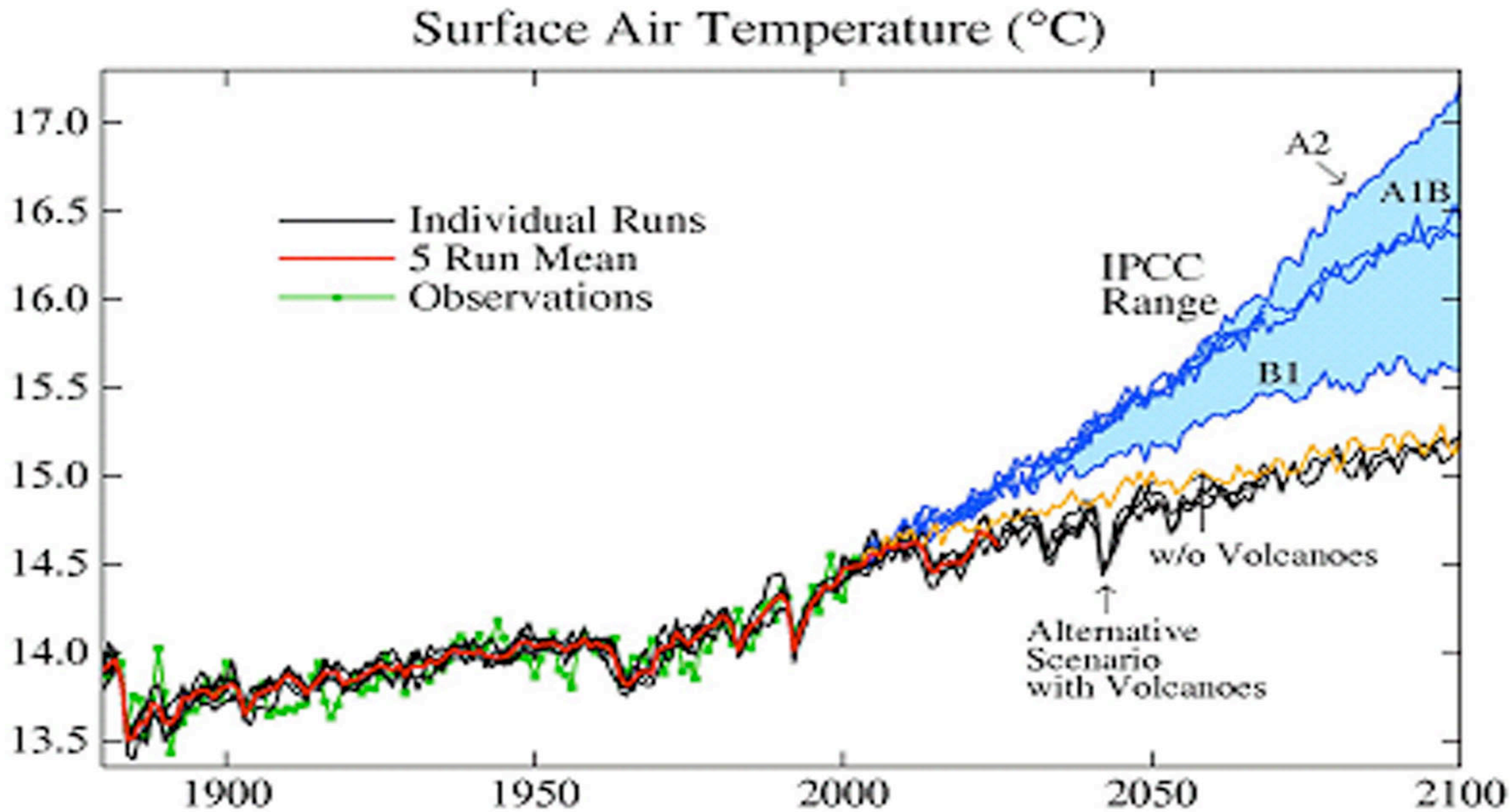
Observations before instrumentation

Sediments, tree rings, ice cores, corals



Source: National Academy of Sciences

21st Century Global Warming



(Hansen et al. 2007, ACP)

OUTLINE

Climate change - ~1 M yrs to present-day

Drivers of climate change

Understanding climate change

Global and Regional Signals - Industrial age

Future Climate

Natural and Anthropogenic drivers

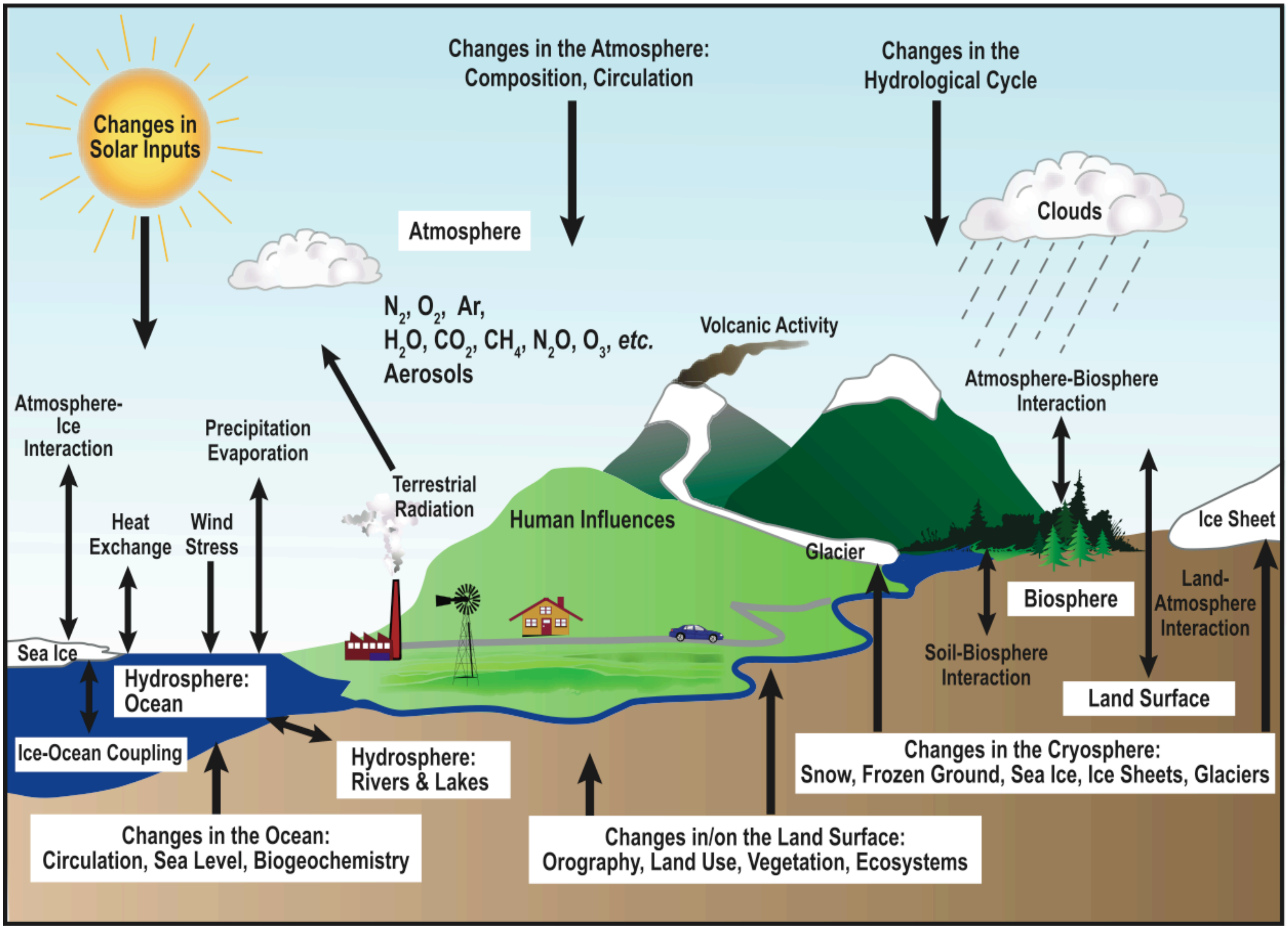
Greenhouse gases
- Carbon cycle
- Nitrogen cycle
- Ozone and methane chemistry

Aerosols
- Sulfates, carbonaceous, sea-salt, dust, nitrates

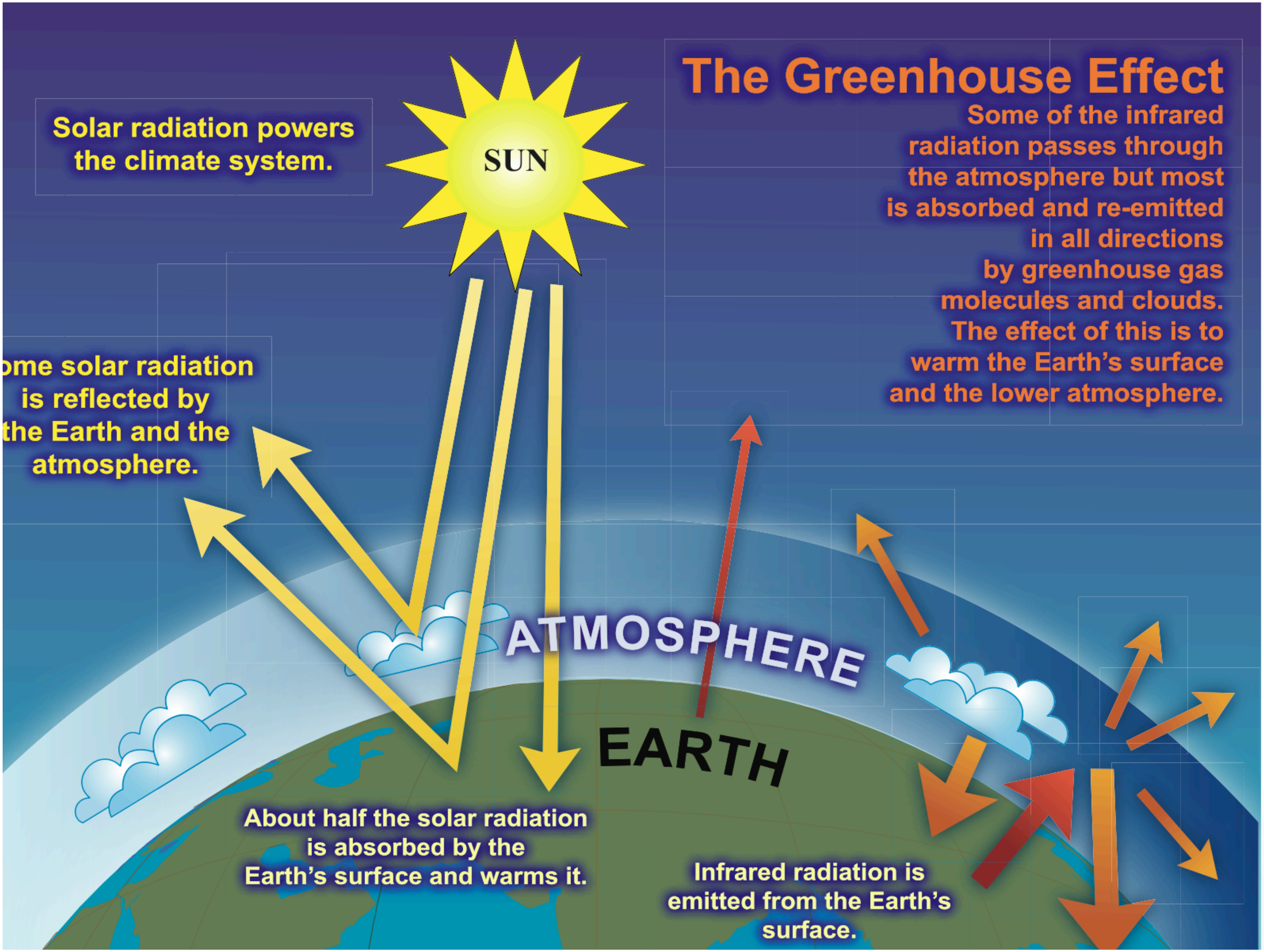
Water cycle

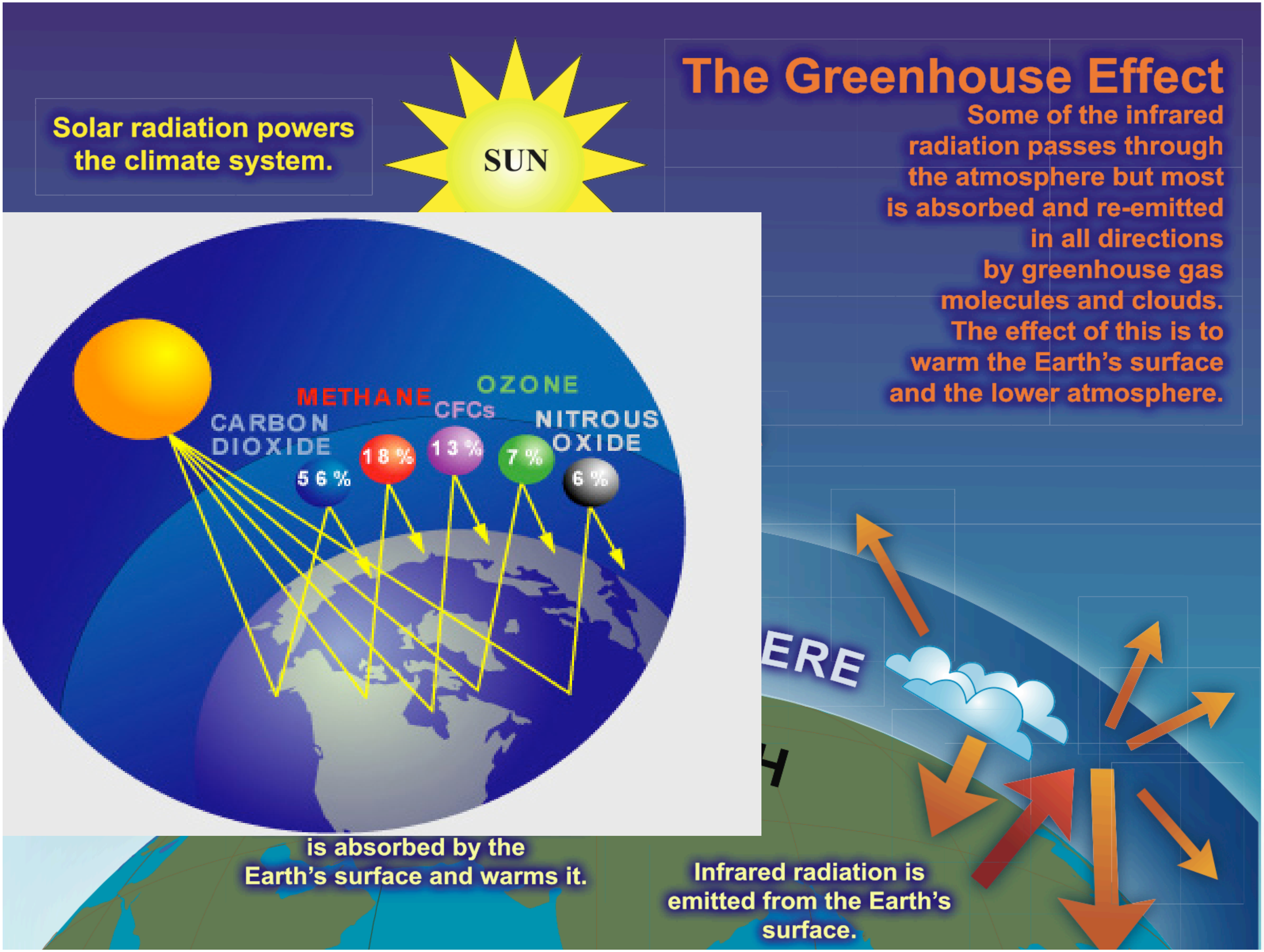
Land-use

Climate system



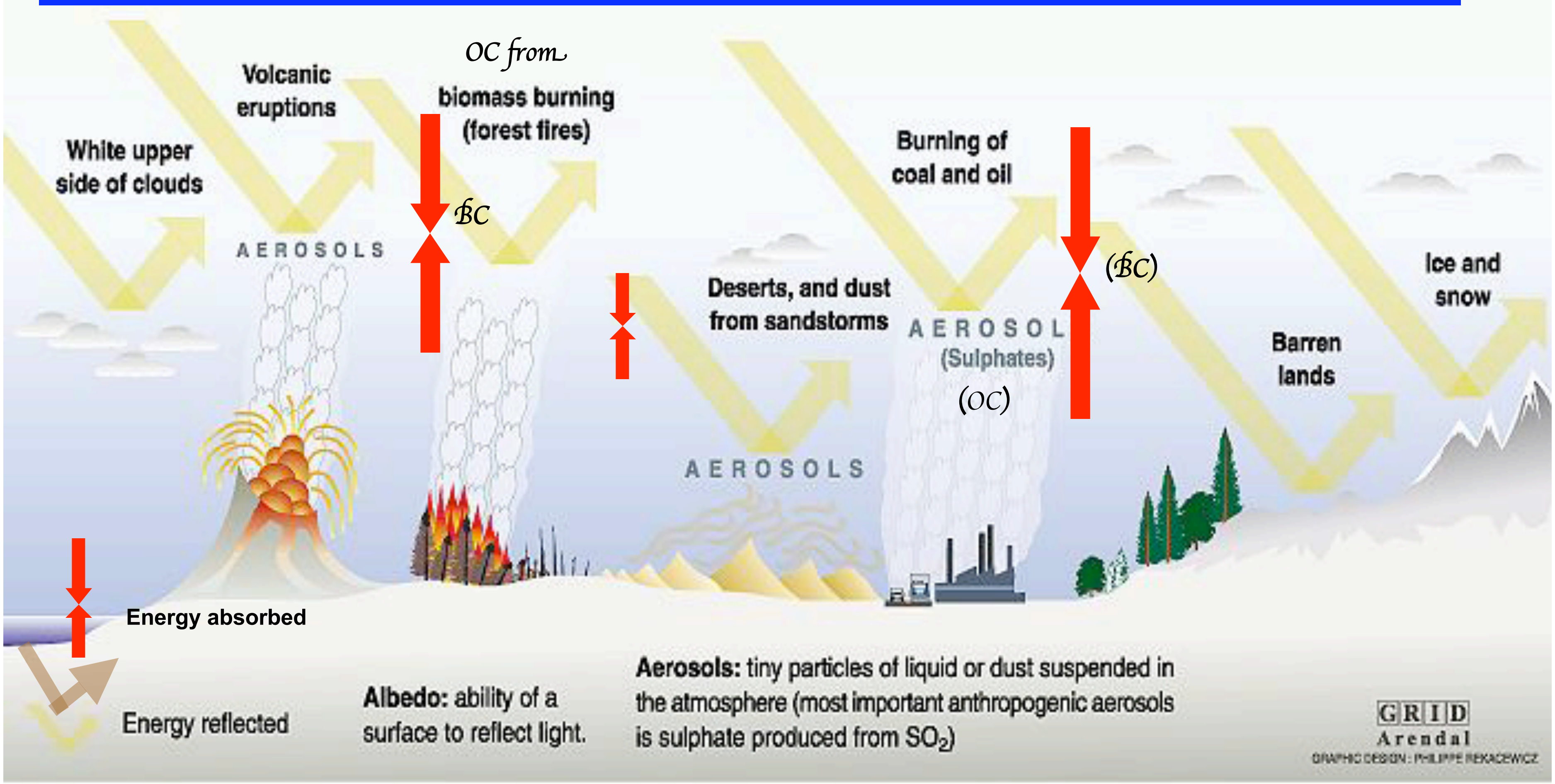
Source: IPCC 2007


The Greenhouse Effect
Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth's surface and the lower atmosphere.
Solar radiation powers the climate system.
SUN
ome solar radiation is reflected by the Earth and the atmosphere.
ATMOSPHERE
EARTH
About half the solar radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.


Solar radiation powers the climate system.
SUN
The Greenhouse Effect
Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth's surface and the lower atmosphere.
CARBON DIOXIDE
56 %
METHANE
18 %
CFCs
13 %
OZONE
7 %
NITROUS OXIDE
6 %
is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.

Emissions and Radiative Exchange

Aerosols - Sulfates, organic and black carbon (OC and BC), dust, sea-salt, nitrates



Sources: Radiative forcing of climate change, the 1994 report of the scientific assessment working group of IPCC, summary for policymakers, WMO, UNEP; L.D. Danny Harvey, Climate and global environmental change, Prentice Hall, pearson Education, Harlow, United Kingdom, 2000.

Source: IPCC 2001

OUTLINE

Climate change - ~1 M yrs to present-day

Drivers of climate change

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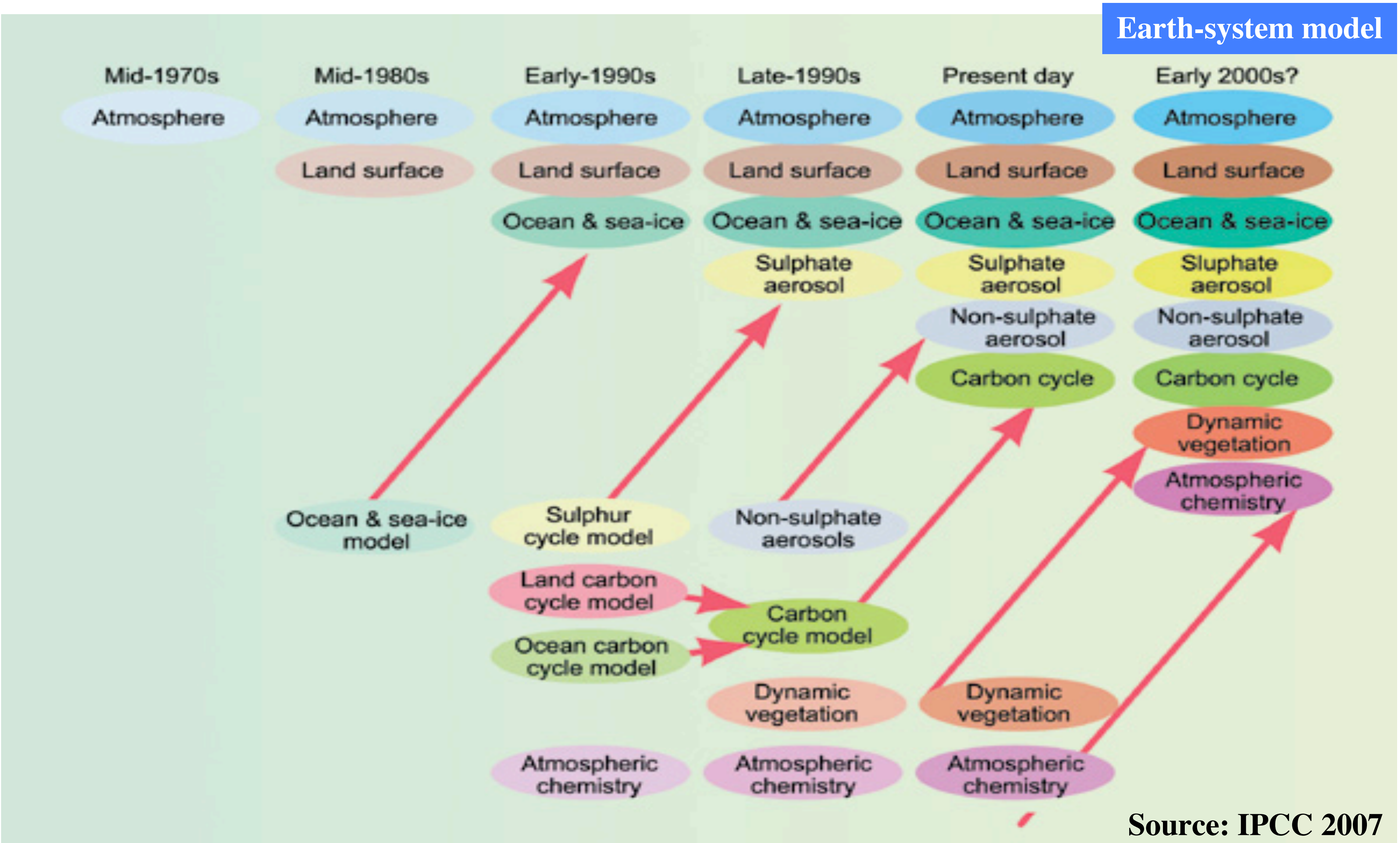
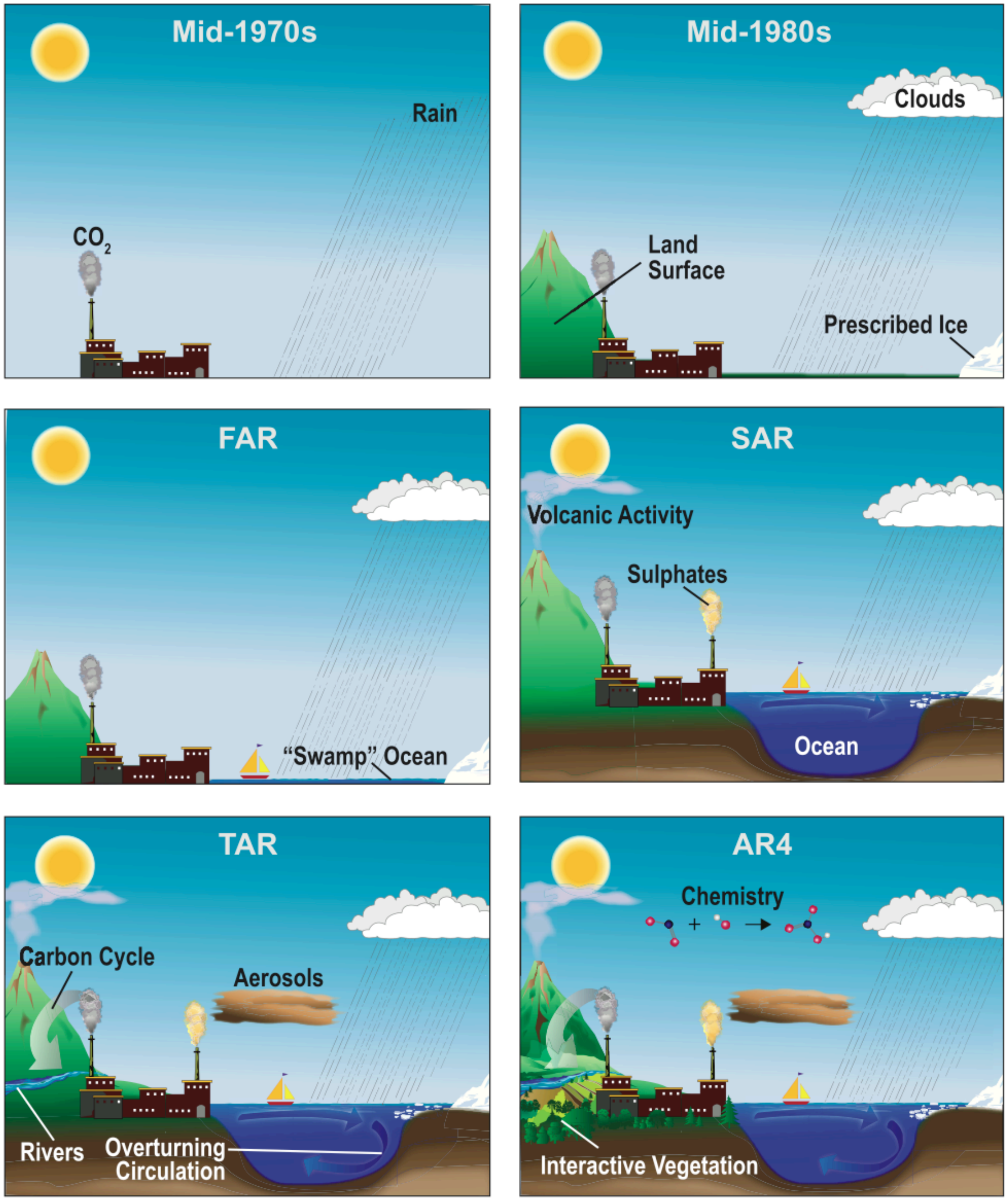
Future Climate

History of model development

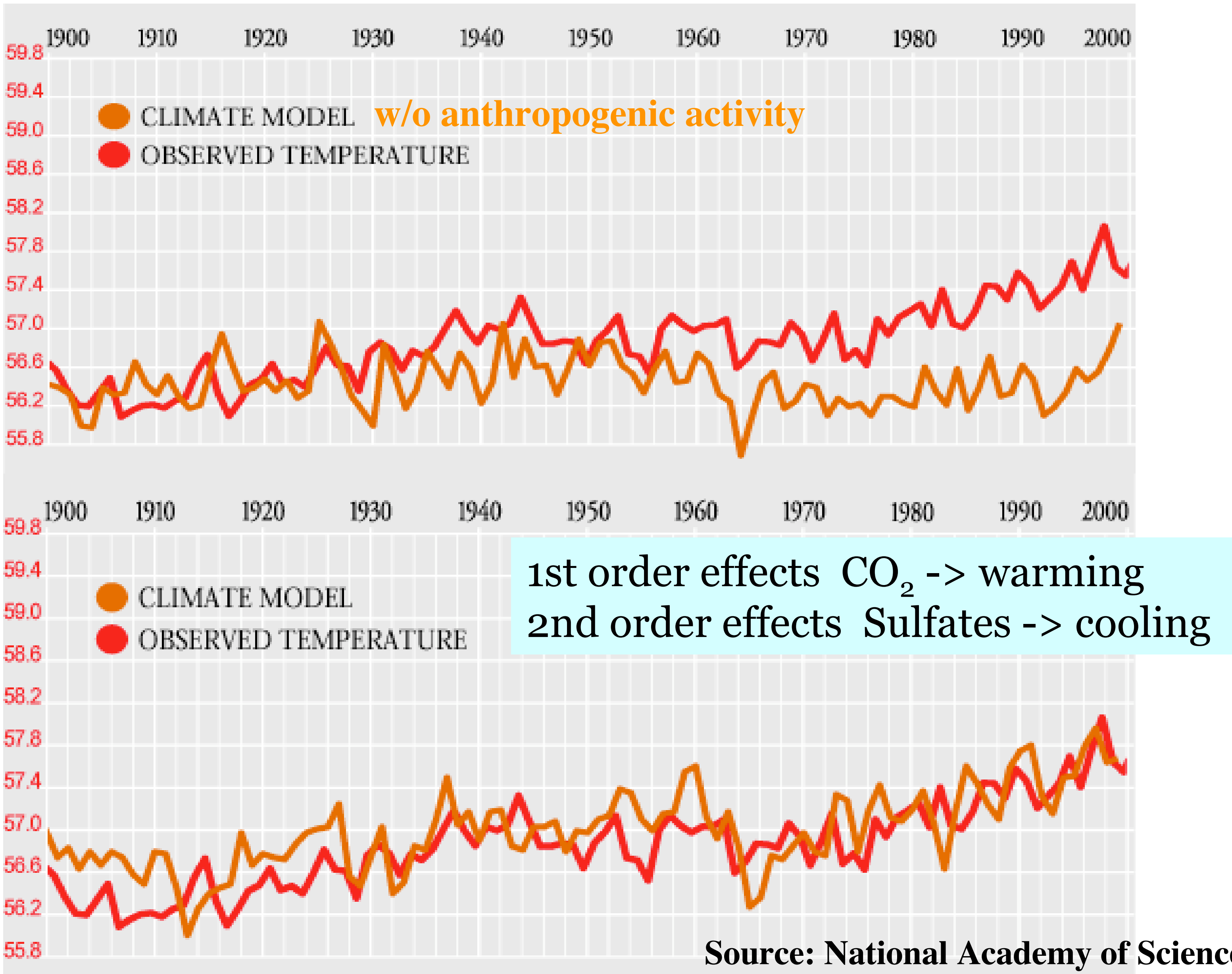


Model landscape approaching reality



Source: IPCC 2007

Temperature over the last 100 years



Source: National Academy of Sciences

Climate model - Goddard Institute for Space Studies

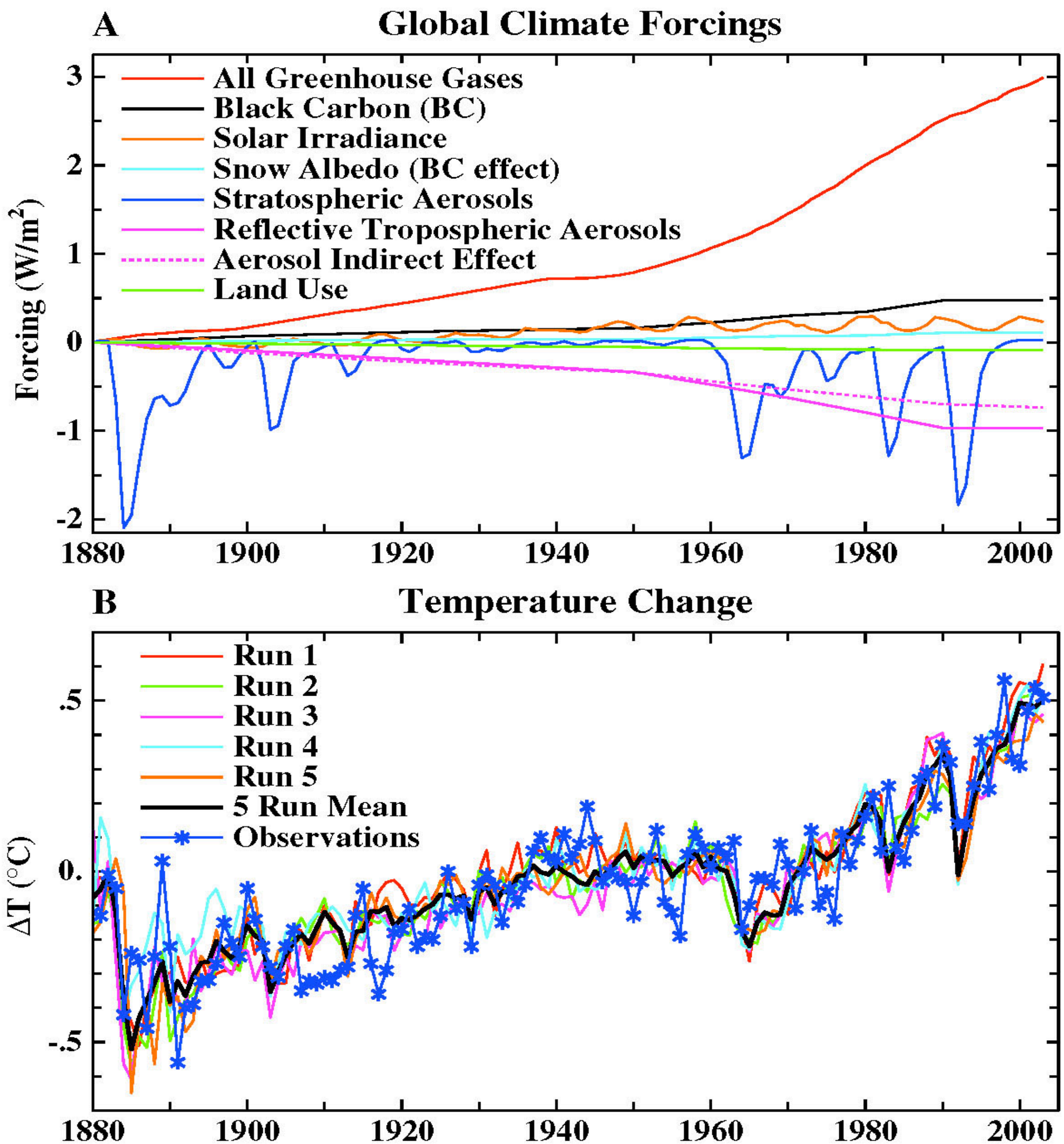
- **20-60** vertical layers, **4°x5°** horizontal resolution (Hansen et al. 1983, 2005).
- Interactive ozone, methane, aerosol chemistry (Koch et al. 2006, Shindell et al. 2007)
- Interactive aerosol-cloud-climate effects (Menon et al. 2002)
- Coupled to slab ocean or dynamic ocean/sea-ice model
- Carbon cycle and interactive vegetation being implemented

"All models are wrong, some models are useful"
(George Box, 1979)

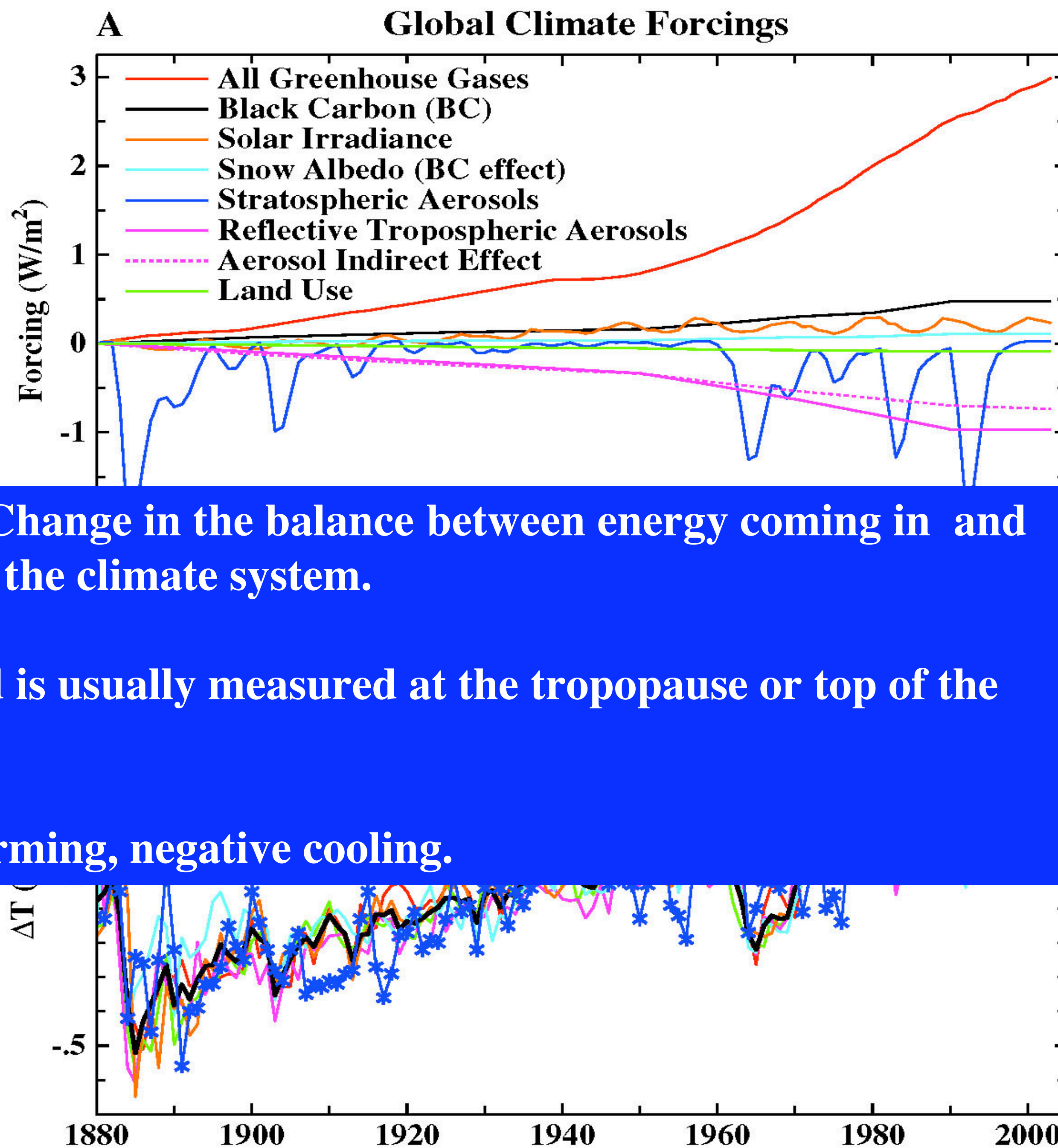
(A) Forcings used to drive climate simulations.

(B) Simulated and observed surface temperature change.

Source: Earth's energy imbalance: Confirmation and implications. *Science* **308**, 1431, 2005.



(A) Forcings used to drive climate simulations.



Radiative forcing: Change in the balance between energy coming in and energy going out in the climate system.

Units are W/m² and is usually measured at the tropopause or top of the atmosphere.

Positive implies warming, negative cooling.

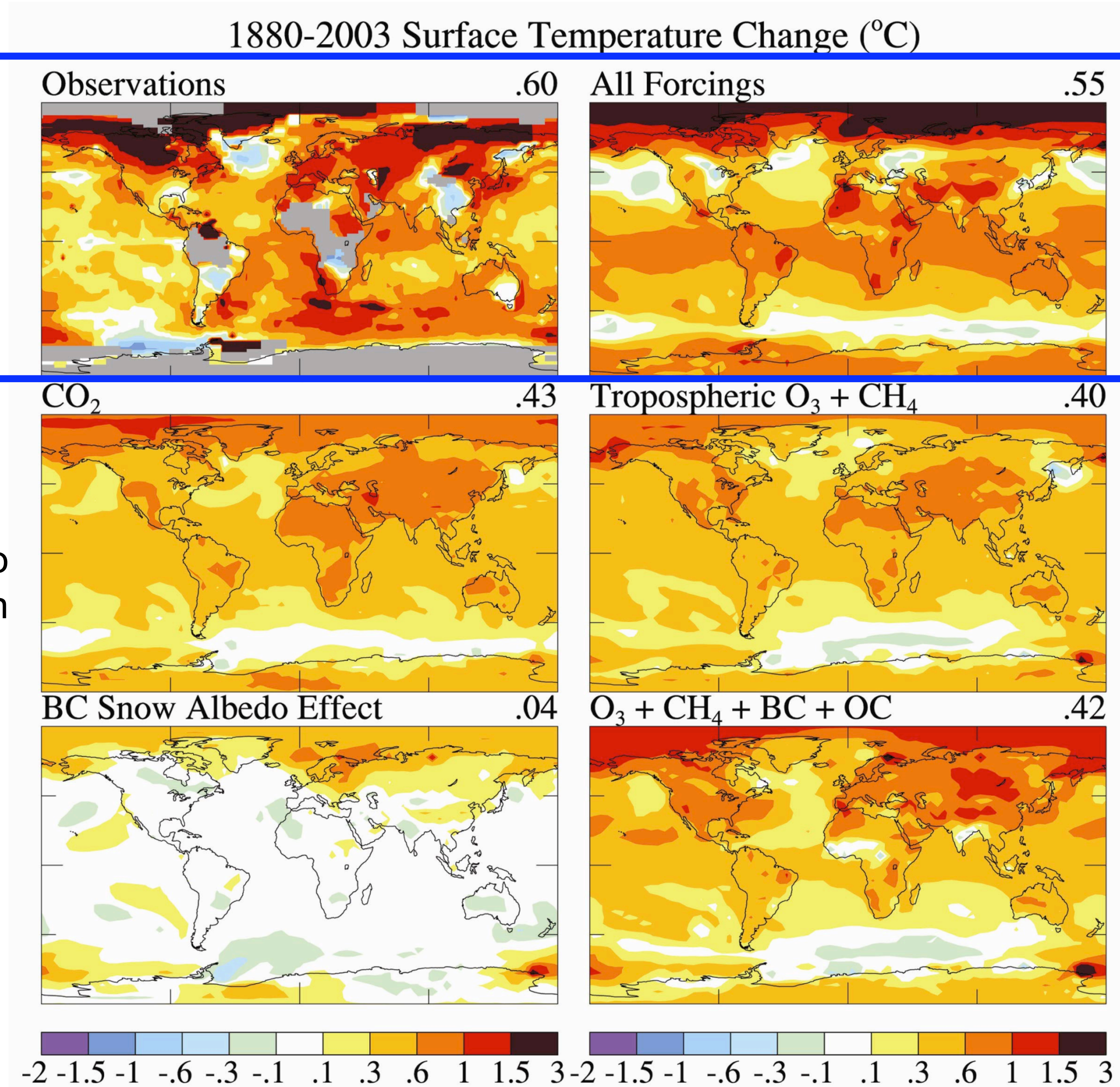
change.

Source: Earth's energy imbalance: Confirmation and implications. *Science* **308**, 1431, 2005.

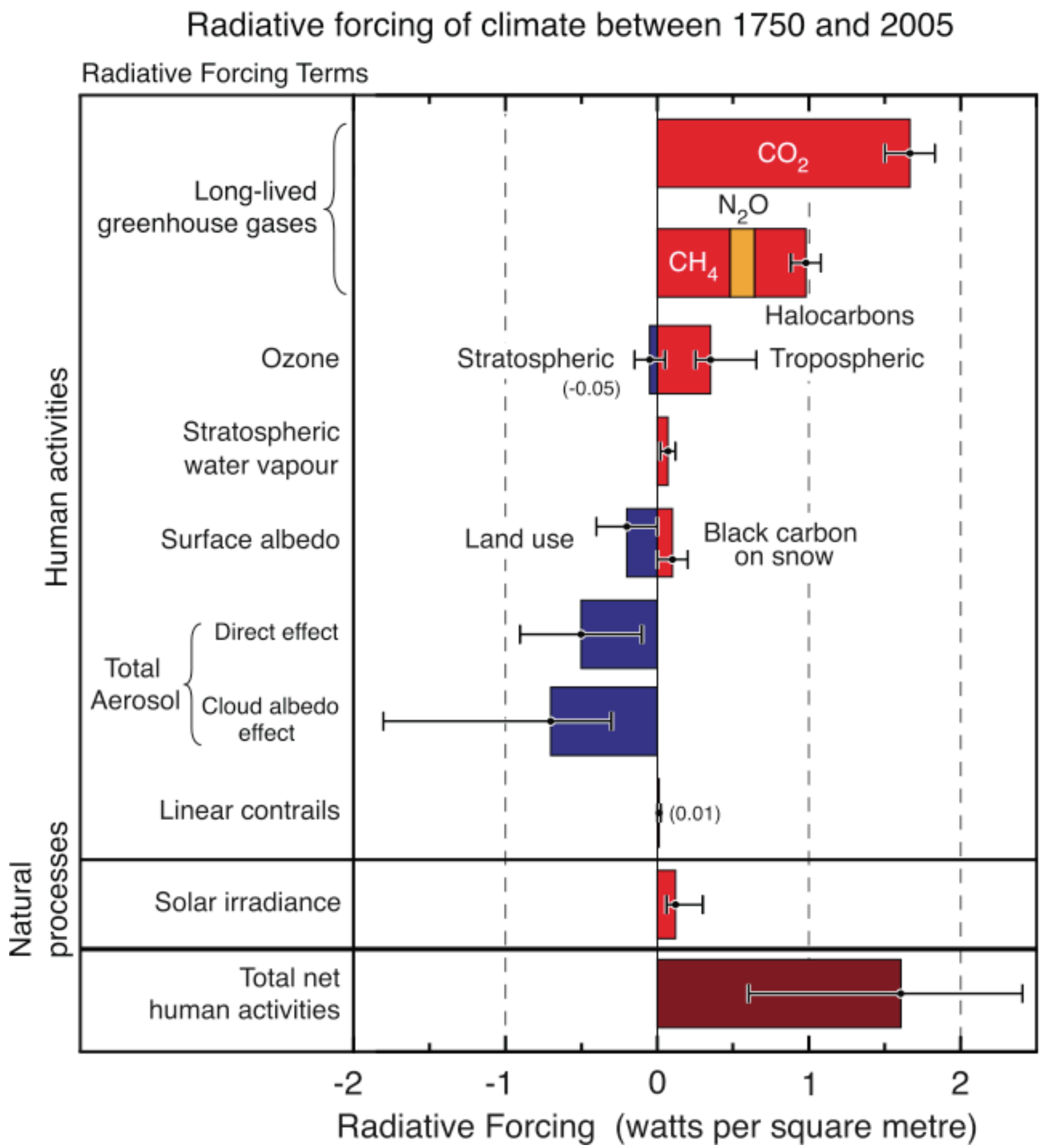
Temperature change observed & simulated

for different forcing mechanisms.

Aerosol forcing (negative) is thought to be slightly excessive in in the ‘all forcing’ simulation.



Source: Hansen et al., *J. Geophys. Res.*, 2005.



Source: IPCC 2007

OUTLINE

Climate change - ~1 M yrs to present-day

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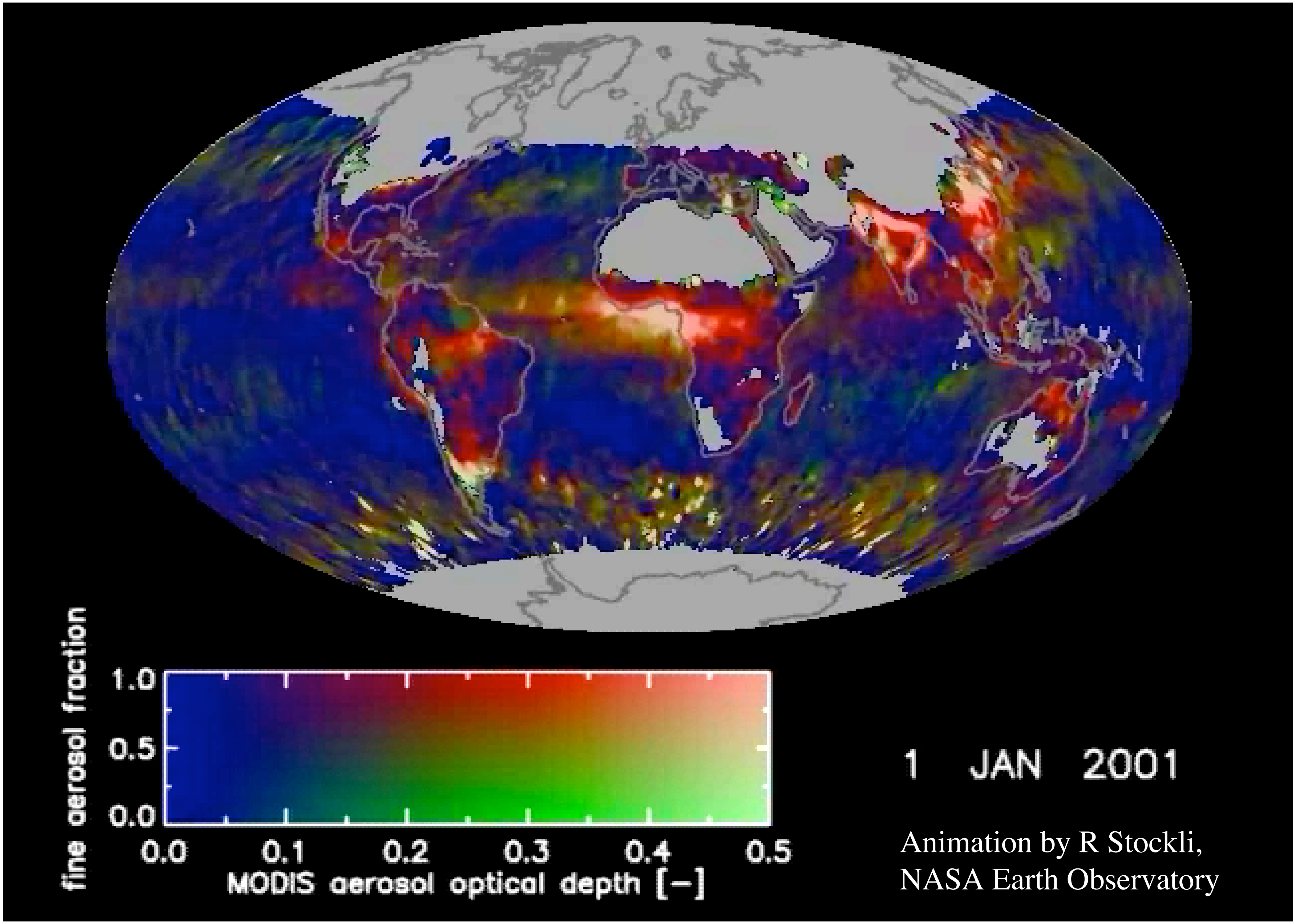
Global and Regional Signals - Industrial age

(3 examples: **GHG+Aerosols**, **Aerosols**, **GHG effects**)

Future Climate

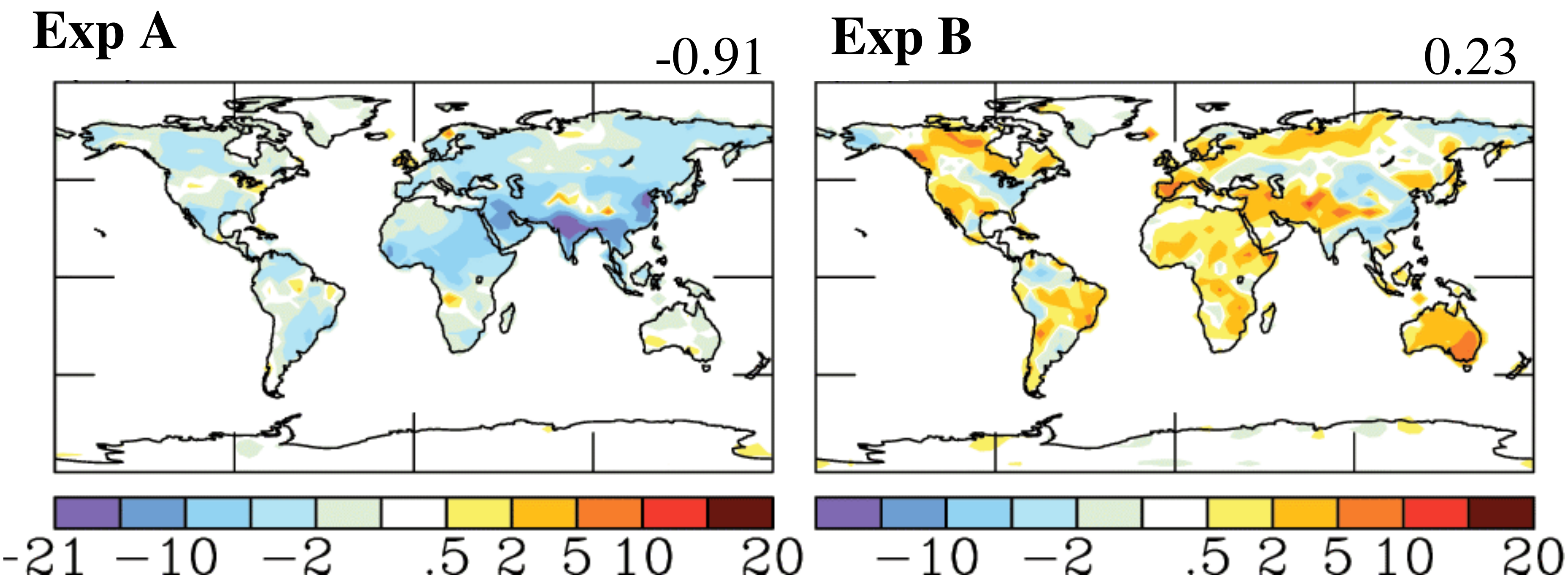
Aerosols: Satellite optical extinction data



Anthropogenic Aerosol Effects: 1960-2002

Observed: "Global dimming: 1960-1990; Reversal after 1990"

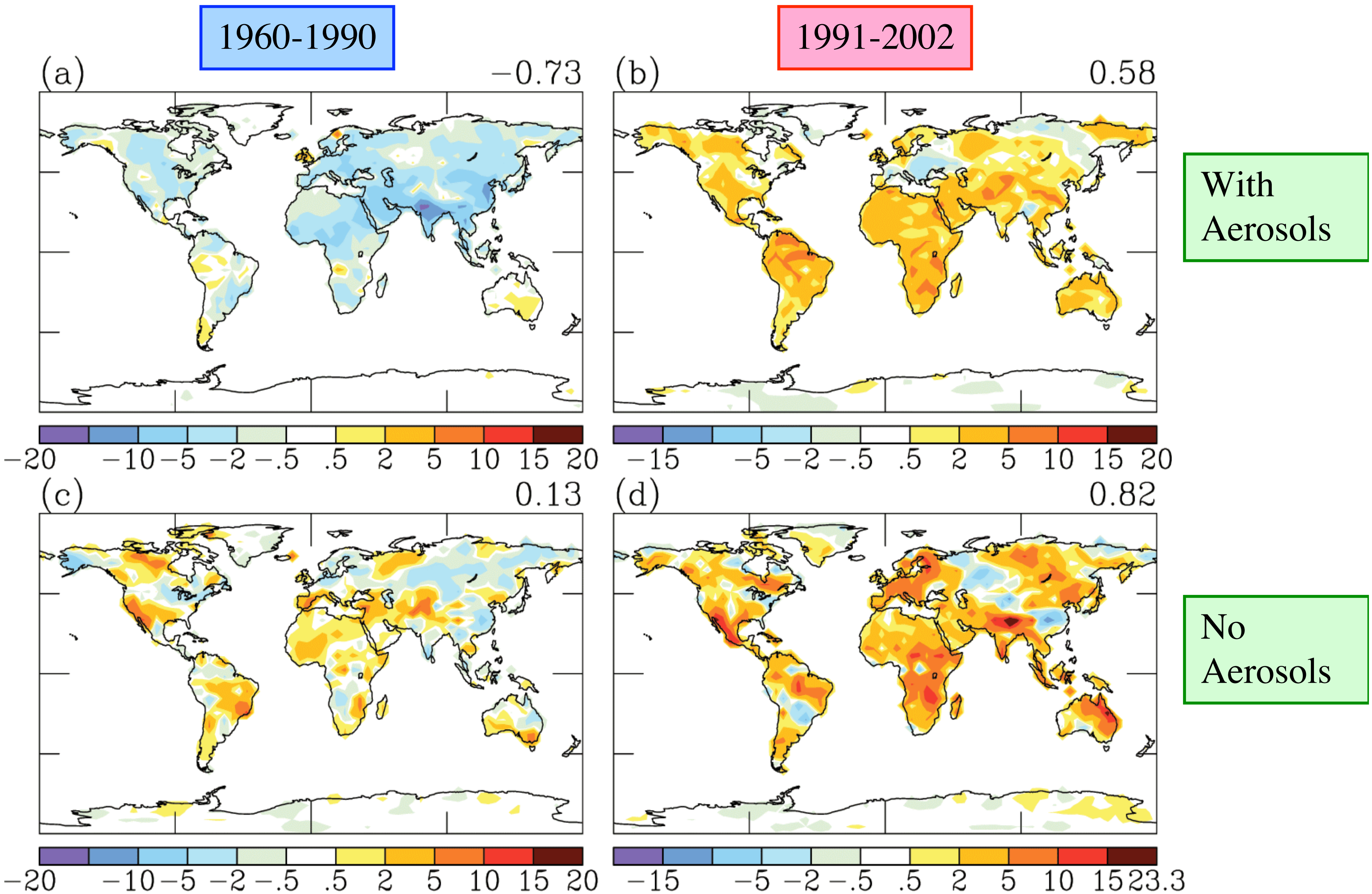
We calculate linear trend in absorbed solar radiation for 1960 to 2002:
Exp A: All forcings (ozone, land-use, snow/ice albedo change, solar, GHG, water vapor, aerosols)
Exp B: Similar to Exp A but <u>no anthropogenic aerosols</u>



Units (W m^{-2}); Global means: r.h.s of graph

(Nazarenko and Menon 2005, GRL)

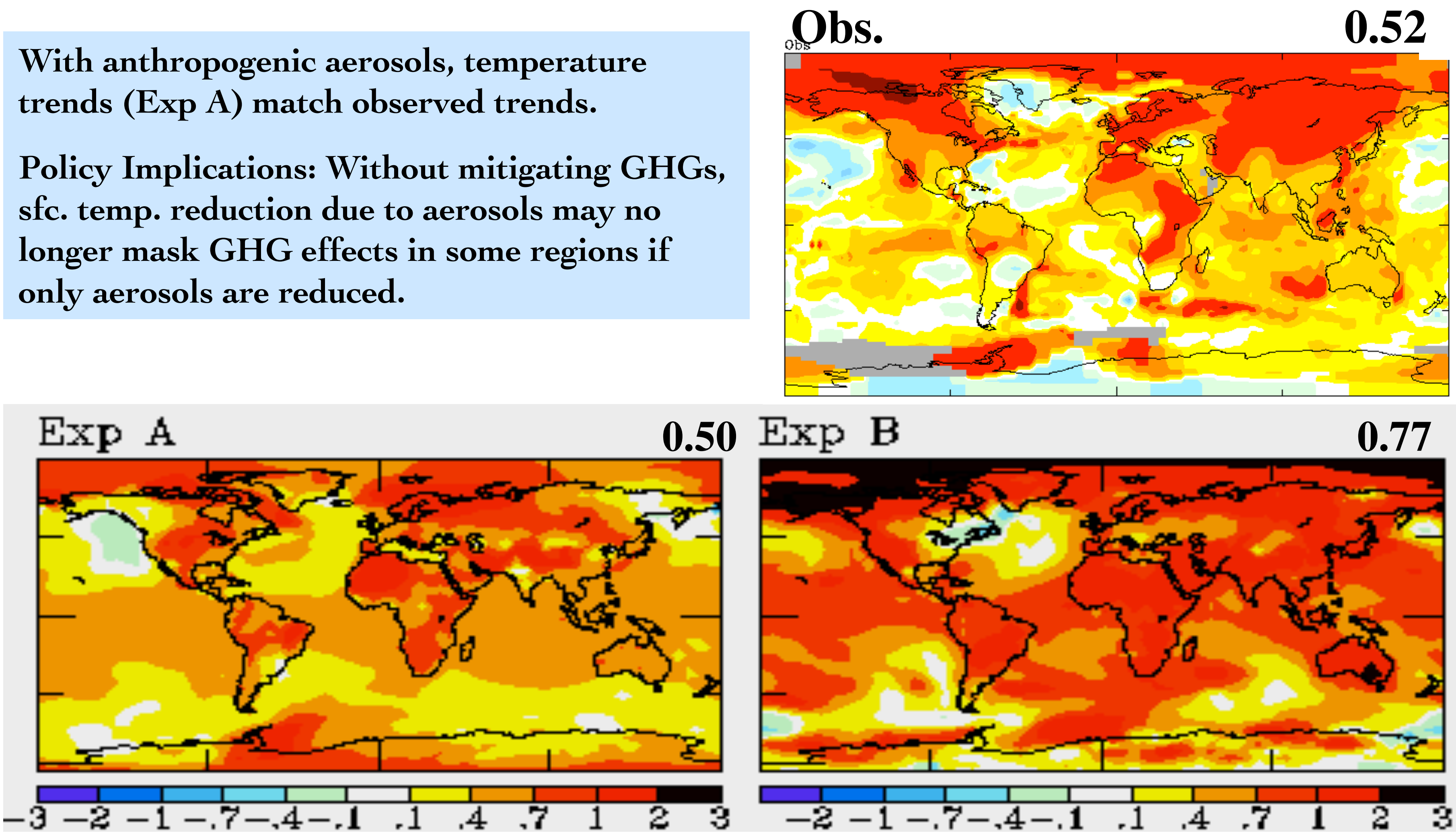
Trends in Global Surface Absorbed Solar Radiation



Surface Temperature Trends: 1960-2002

With anthropogenic aerosols, temperature trends (Exp A) match observed trends.

Policy Implications: Without mitigating GHGs, sfc. temp. reduction due to aerosols may no longer mask GHG effects in some regions if only aerosols are reduced.

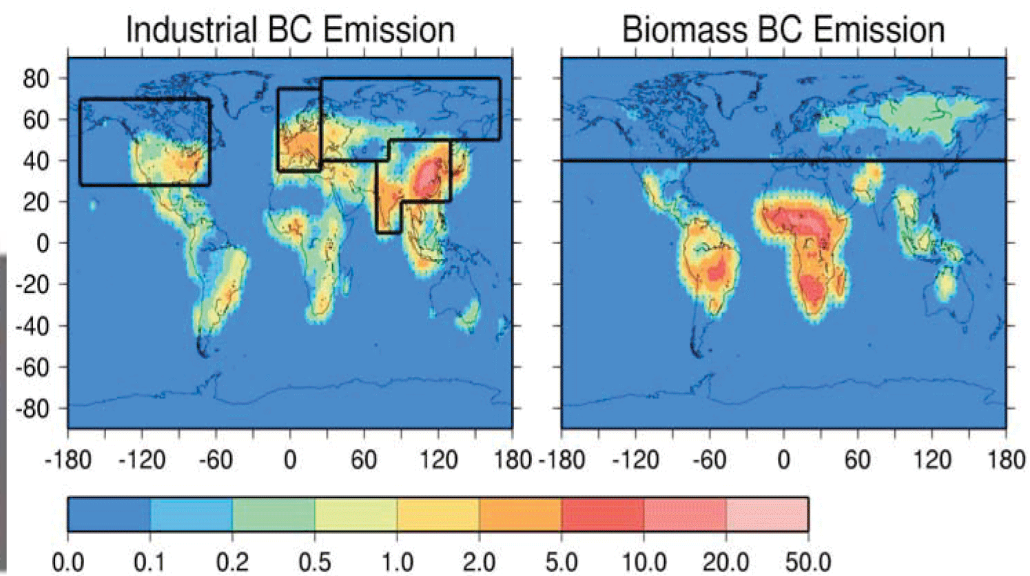


Units in K; Global means: r.h.s. of graph

Black Carbon Sources and Distribution

Black carbon is a product of
incomplete combustion.

Black carbon Distribution



(ng C m^{-2} s^{-1})

Koch et al. 2005

Images: http://www.asthmacure.com, NASA GSFC

Industrial Pollution: Shenyang, China, and India/Nepal

Snow cover change between urban and rural areas

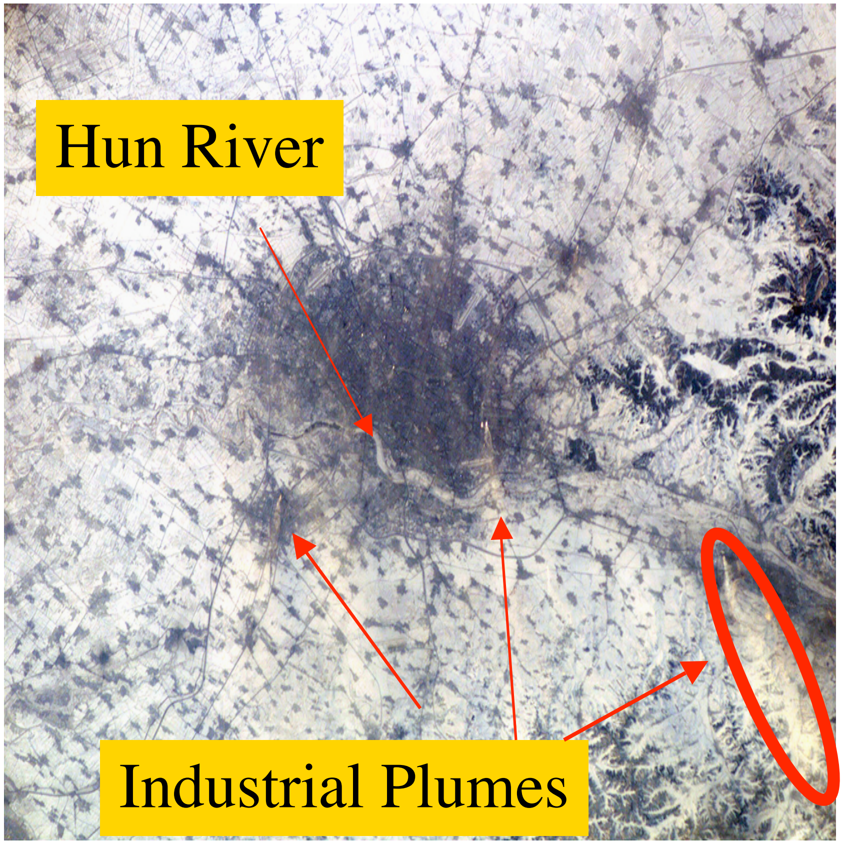
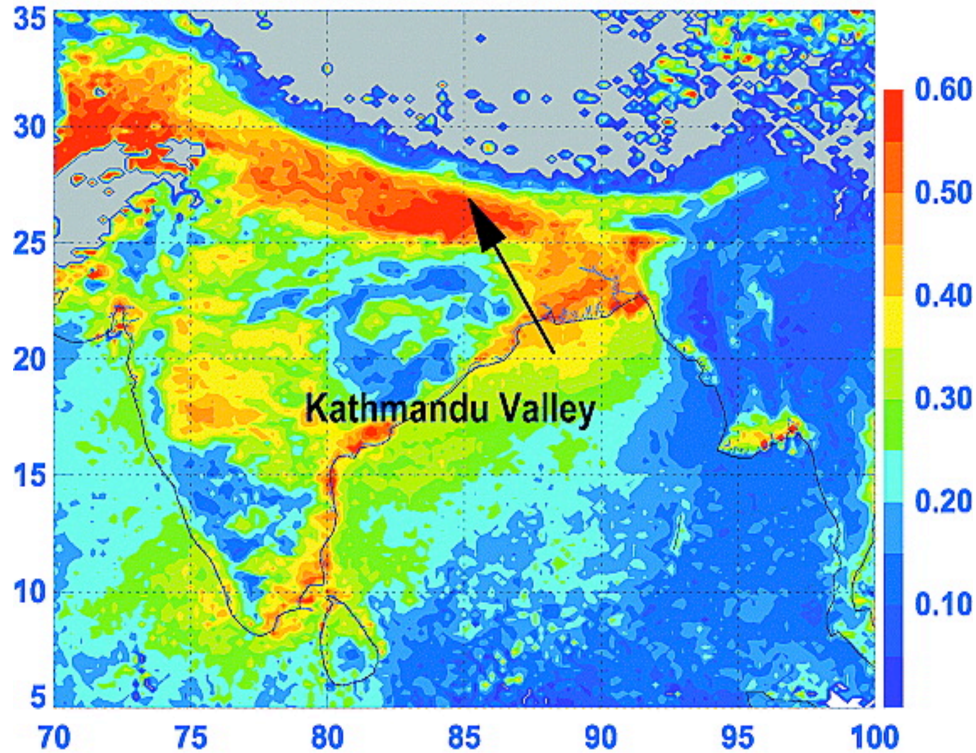


Image courtesy:Image Analysis Laboratory, NASA Johnson Space Center

Astronaut photograph ISS010-E-13807, acquired January 18, 2005

Aerosol optical depth from satellite (MODIS), Dec 2002



- Aerosol visible optical depths ~ 0.6
- Aerosol single scattering albedo ~ 0.78
- Inferred shortwave atmospheric forcing ~ 25 W m^{-2}

(Ramana et al. 2004, GRL)

China: Black Carbon and Summer Monsoon Trends

Observations over the last few decades:

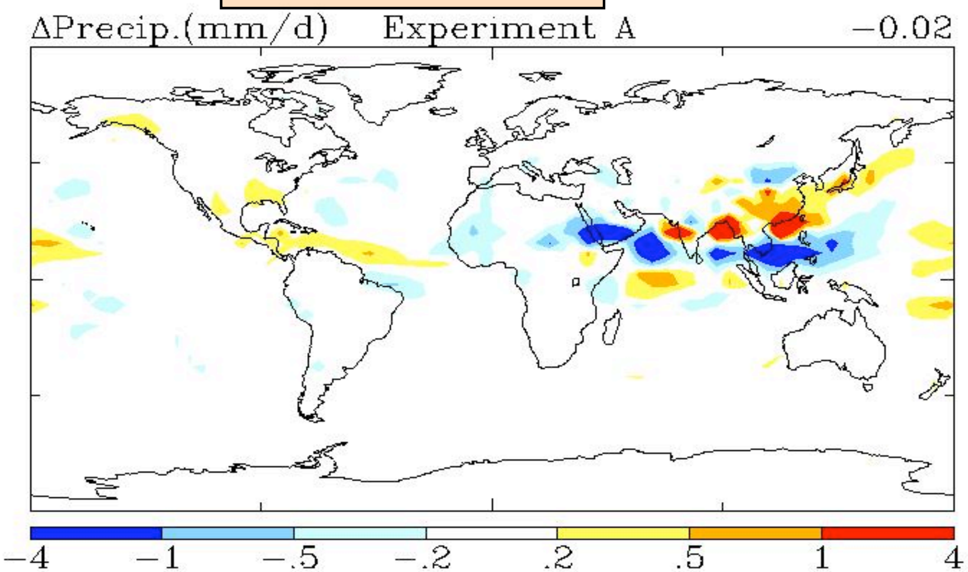
- increased floods/droughts in the south/north; increased dust storms in the spring;
- precipitation trends **largest observed since 950 AD.**

We link increased emissions over China (since the late 1970's) with observed climate.

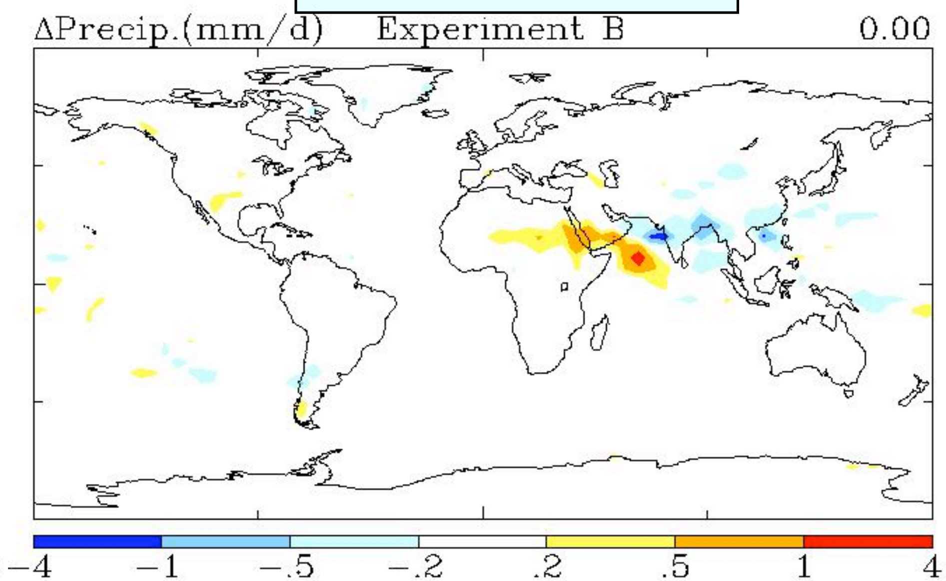
Assume a large proportion of aerosols are absorbing (**black carbon**).

Changes in **heating profile** affects convection, stability and spatial distribution of precipitation.

With black carbon



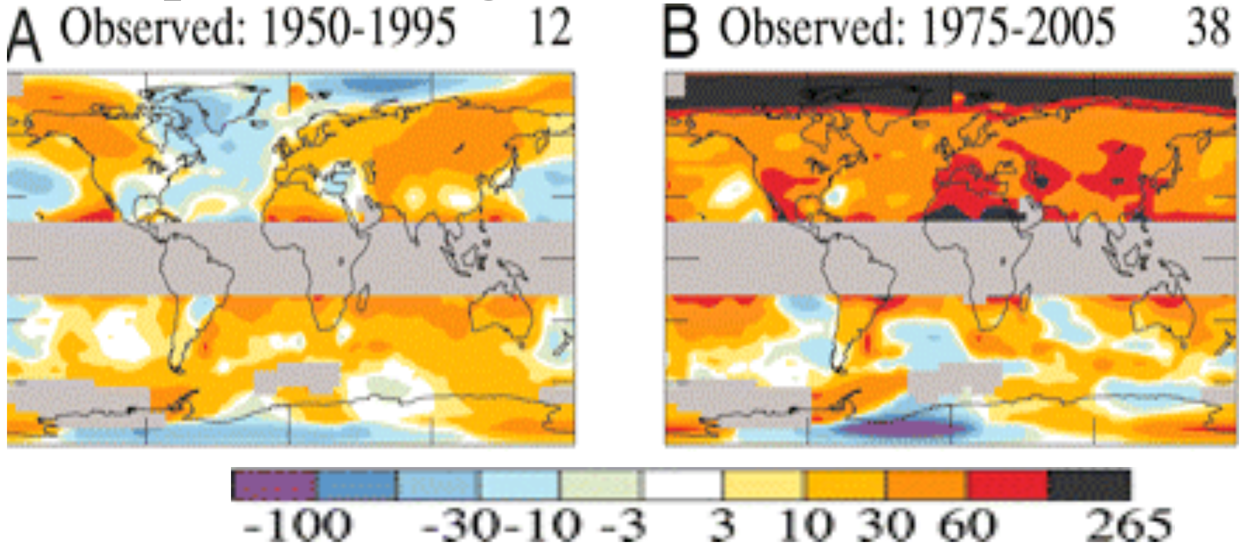
Without black carbon



(Menon, Hansen et al. 2002, Science)

Climate impacts on species

Observed poleward migration rate of isotherms (km/decade)



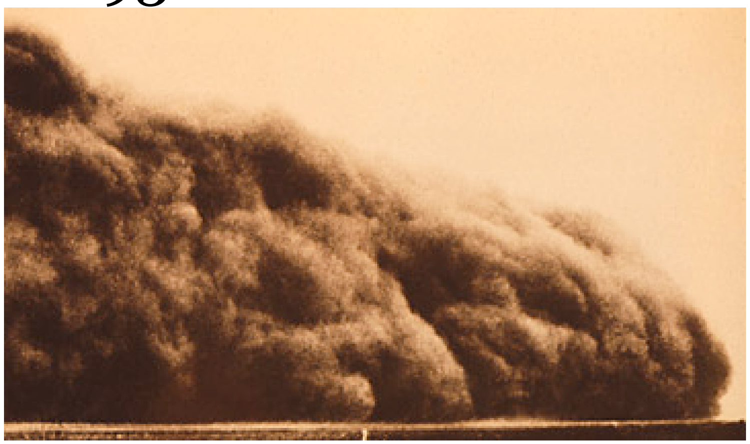
Based on a study of 1700 species: Poleward migration of 6 km/decade and vertical migration in alpine regions of 6 m per decade in the second half of the 20th century (Parmesan and Yohe, 2003, Nature)

Global warming of **3°C** over the 21st century could eliminate **~60%** of species.

In the past several mass extinctions of **50–90%** of species for global temperature changes of **~5°C**. (Hansen et al. 2006, PNAS)

Climate and extreme weather

1930's US Dust Bowl



Cooler than normal tropical Pacific Ocean surface temperatures and warmer tropical Atlantic Ocean temperatures created shifts in the large-scale weather patterns and low level winds that reduced the normal supply of moisture from the Gulf of Mexico and inhibited rainfall throughout the Great Plains. (Schubert et al., 2004, Science)

Satellite image of hurricane

Sea-surface temperatures have a strong influence on hurricanes.

For 1906–2005: 84% chance that **external forcing** explains at least 67% of **observed SST increases** in the two tropical cyclogenesis regions (Santer et al., 2006, PNAS)

OUTLINE

Climate change - ~1 M yrs to present-day

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Future Climate

Arctic sea-ice decline

1982

2007

Melting permafrost peatlands (Noyabrsk, Western Siberia)

l Snow and Ice Data Center, 2007

2010 - 2030

2070 - 2090

Climate Impact Assessment, 2004

Arctic sea-ice decline

1982

2007

National Snow and Ice Data Center, 2007

2010 - 2030

2040 - 2060

2070 - 2090

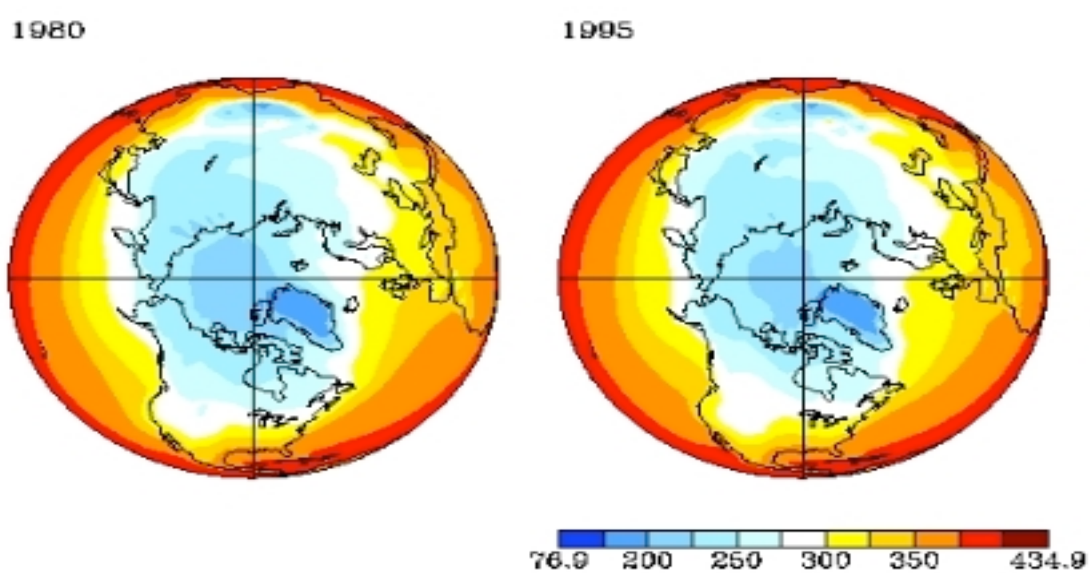
Arctic Climate Impact Assessment, 2004

Aerosol Impacts on the Arctic

For short-term mitigation, we have investigated future climate change for short-lived species (ozone and aerosols).

Our modeling work indicates that aerosol effects on cloud properties can affect Arctic surface heating more than ozone does (Menon et al. 2008, ERL).

For the future scenario (2030) considered, increased downwelling longwave (LW) radiation, due to cloud changes, implies increased surface warming.

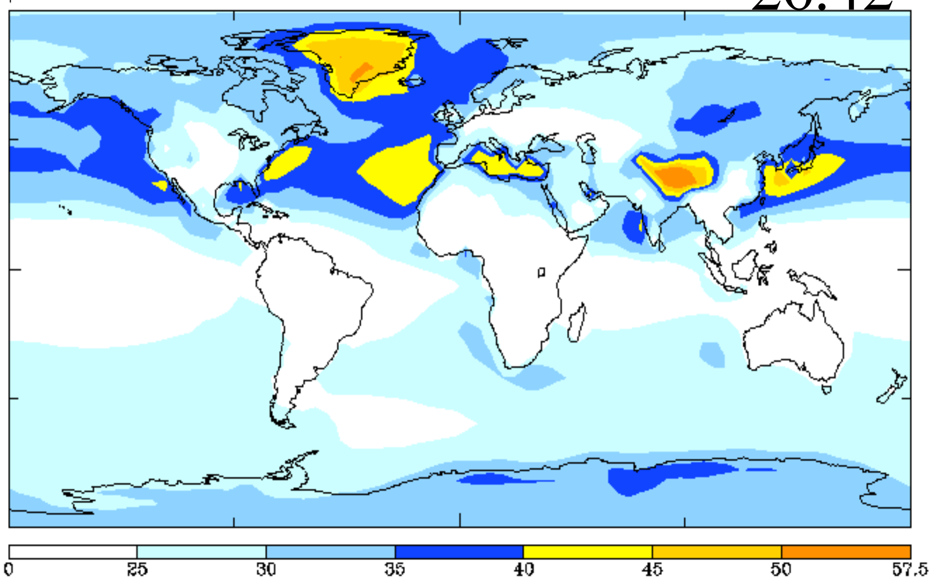


Downwelling LW radiation (W/m^2)

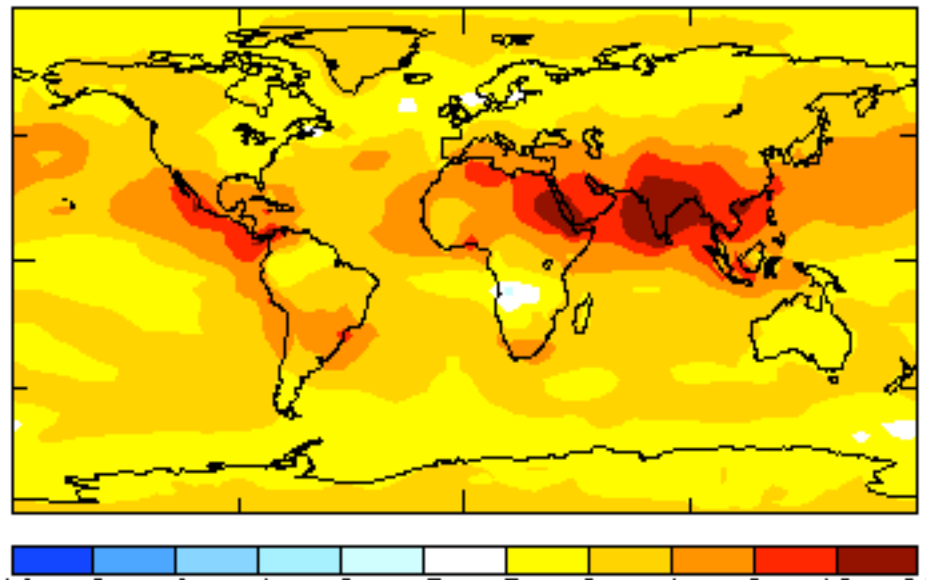
Future Air Quality

Global annual amount and change in surface amount

1995 Surface Ozone 26.42



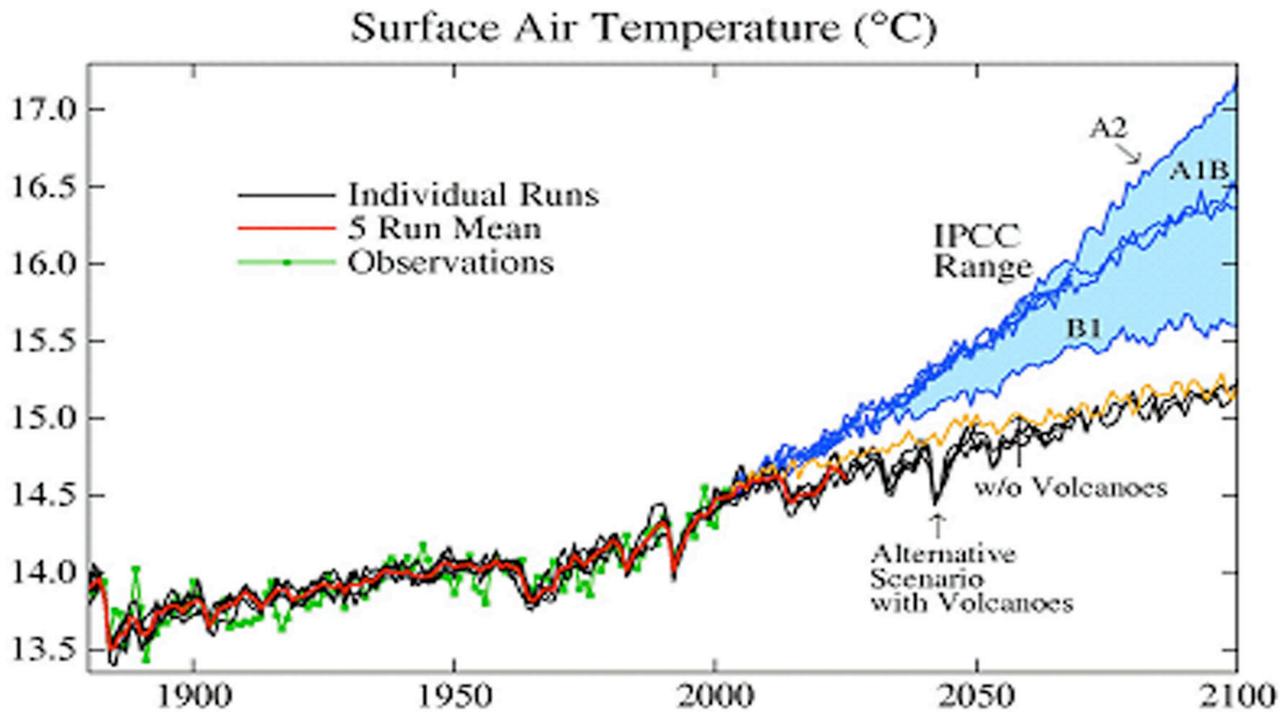
Change in Surface Ozone 3.43



Background ozone level of ~ 30 ppbv is exceeded in several tropical locations for the future scenario (2030) considered.

(Menon et al. 2008, ERL)

21st Century Global Warming



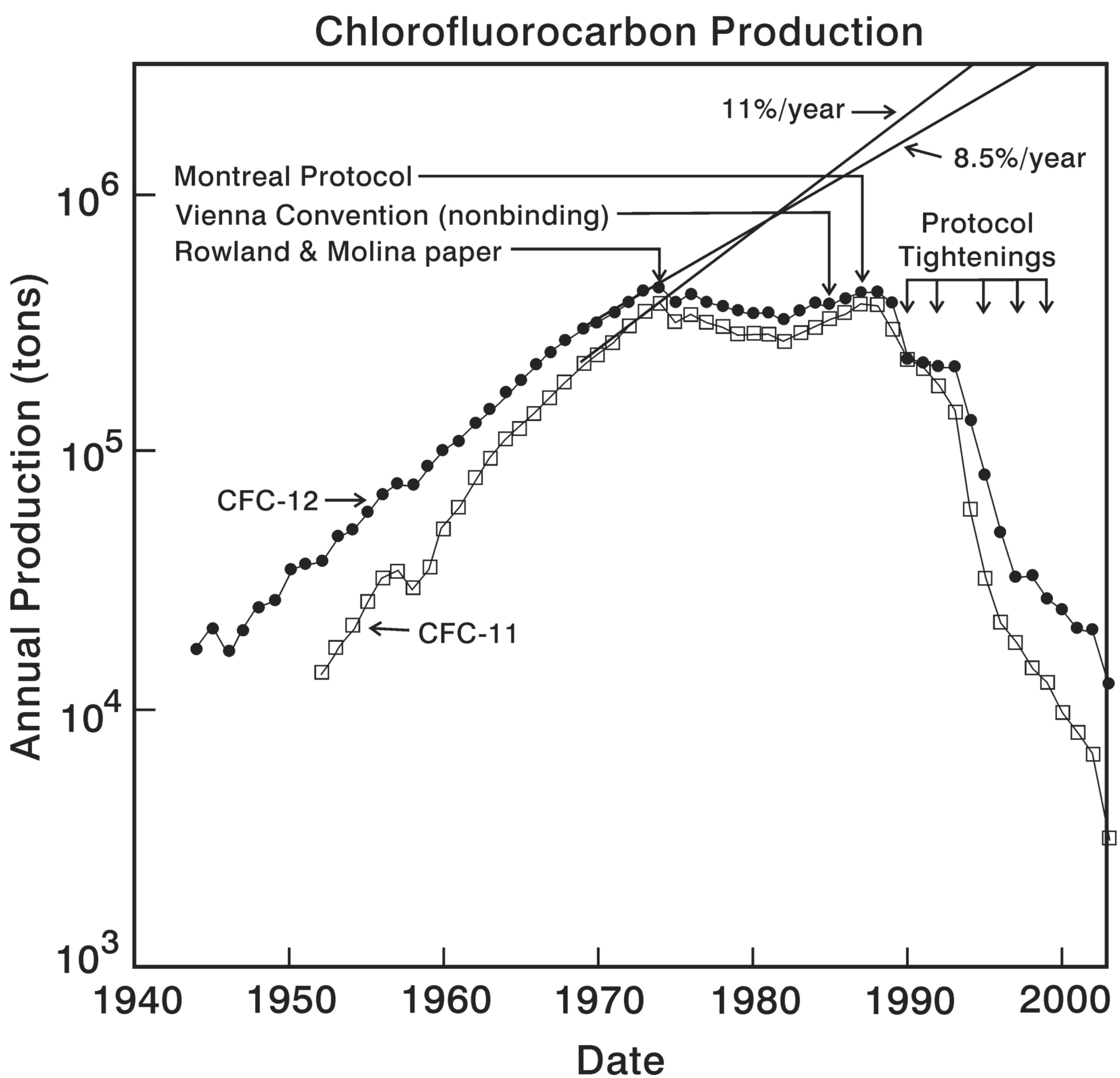
Climate Simulations for IPCC 2007 Report

▶ **Climate Model Sensitivity 2.7-2.9°C for 2xCO_2**
(consistent with paleoclimate data & other models)

▶ **Simulations Consistent with 1880-2003 Observations**
(key test = ocean heat storage)

Source: Hansen et al., 2005, *2007a,b*.

CFC success story



Source: J Hansen

Climate Change Summary

Climate change: 1880 to Present

- **Increased surface temperatures - from greenhouse gases.**
- **Global dimming: 1960-1990 and "dimming" reversal beyond 1990 observed only if anthropogenic aerosol effects are included.**

Man-made aerosols directly impact climate and may mask GHG effects.

Future climate change: 2000 to 2100

- **Depends on emission pathways followed that are guided by policy.**
- **Arctic region vulnerable to climate change from aerosols.**
- **Ozone and aerosol effects stronger over tropical regions such as India, where such effects were not dominant before.**

Large unknown in climate change: emission sources and interactions/feedbacks of the climate system.

Acknowledgement

Funding Support:
NASA : Radiation Sciences Program
Modeling, Analysis and Prediction Program
LBNL: LDRD
DOE: Atmospheric Radiation Program,
Integrated Climate Assessment Program

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NASA Goddard Institute for Space Studies
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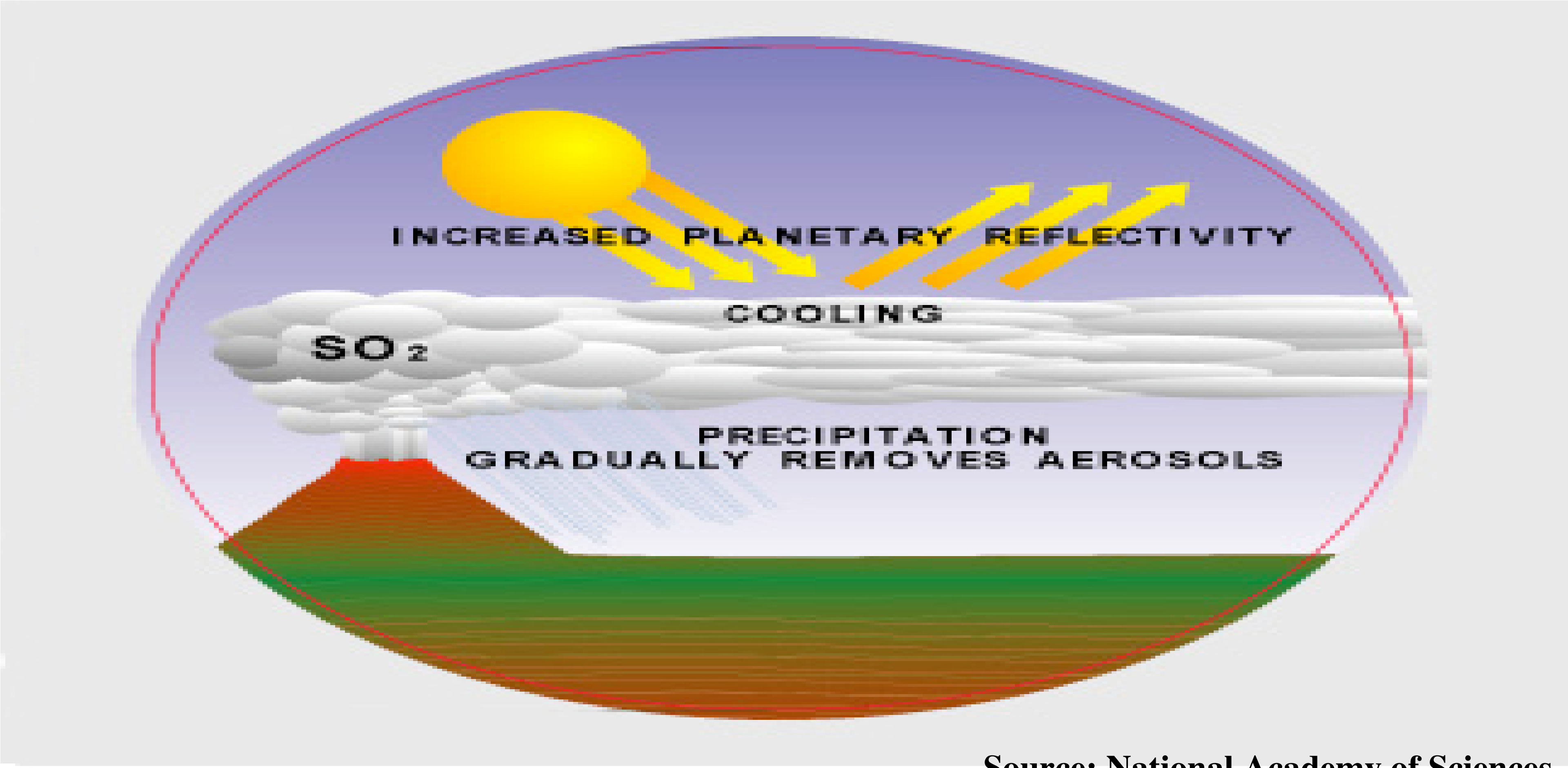
LBNL: Environmental Energy Technologies Division
Tica Novakov, Igor Sednev
Summer students: Nick Burns, Nick Chmura, Parmendar Singh, Banglun Zheng, Geeta Persad

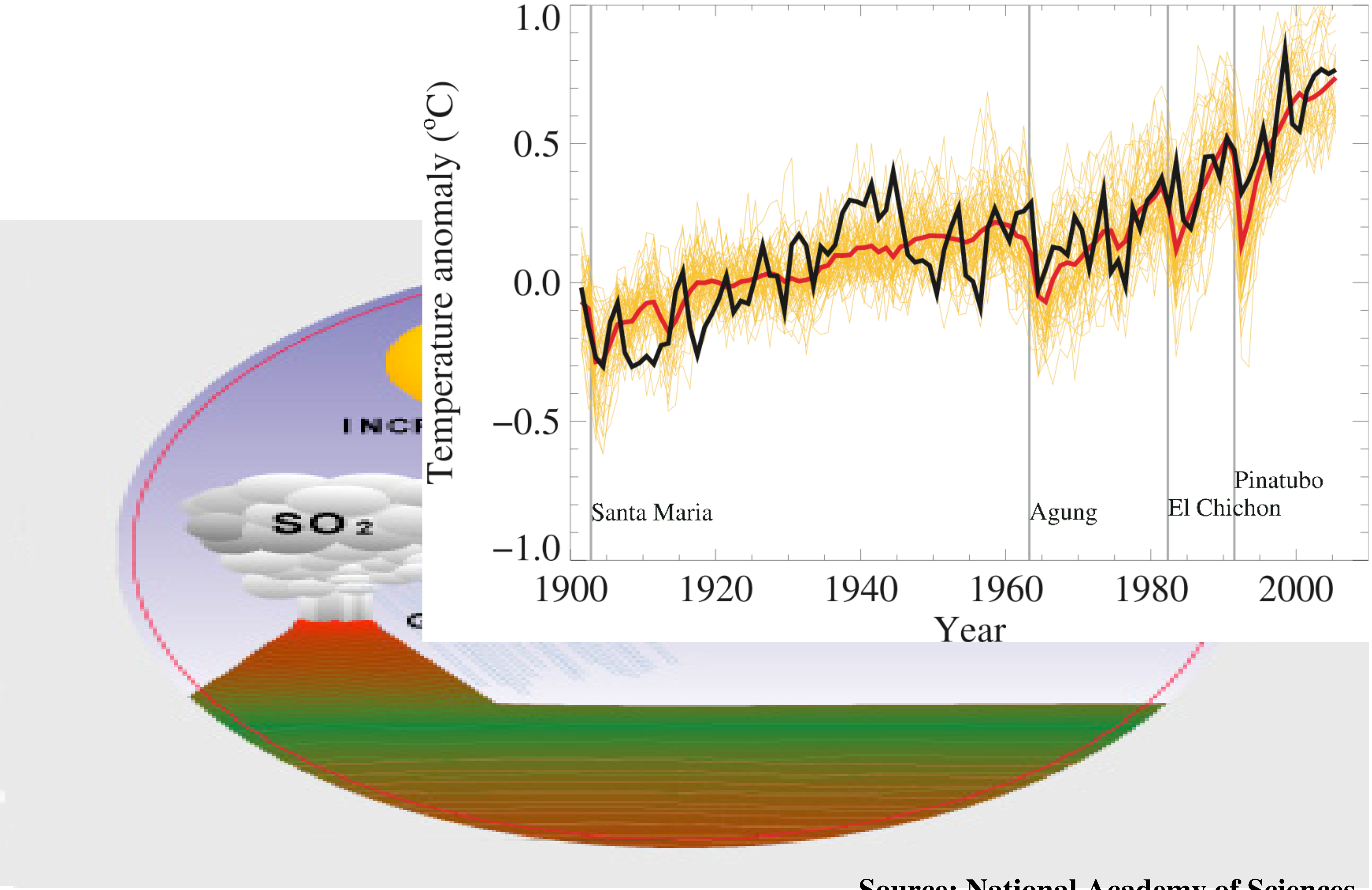

SOLVING GLOBAL WARMING
DOING SOMETHING
WATCH AN INCONVENIENT TRUTH
LEARN MORE
YOUR VOTE COUNTS
GLOBAL WARMING IS HAPPENING!
TALK
ENCOURAGE FRIENDS, WORK SCHOOL
BE A CATALYST
FORCE YOURSELF
BE STRONG
HAVE AN ENERGY AUDIT
SAVE POWER, SAVE MONEY
PLANT TREES
BUY CO2 CREDITS
EAT LESS MEAT
Methane
USE LESS
USE A CLOTH BAG
USE RECYCLED PAPER (SAVES FORESTS)
CANCEL JUNK MAIL
HAVE NO MORE THAN 2 CHILDREN
BUY LOCAL FOOD
BUY FRESH FOOD NOT FROZEN
CO2
DON'T FLY
BAD TRAVEL
TRAVEL
BEST TRAVEL
CAR
FUEL EFFICIENT
ELECT
CAR POOL
TYRES — KEEP FULL EVERY WEEK
WALK
BIKE
USE PUBLIC TRANSPORT
BUS
TRAIN
SWITCH TO GREEN POWER
LIGHT BULBS
CHANGE TO ENERGY EFFICIENT LIGHT BULBS
HOME
CHOOSE ENERGY EFFICIENT ONES
APPLIANCES
ELECTRICITY
OFF
TURN OFF APPLIANCES AT THE POWER POINT
USE CLOTHES LINE NOT DRYER
INSTALL PHOTO-VOLTAIC PANELS
HAVE A SOLAR WATER HEATER
HOME CHP
HAVE INSULATION
NOVESE ©

Geo-engineering Climate



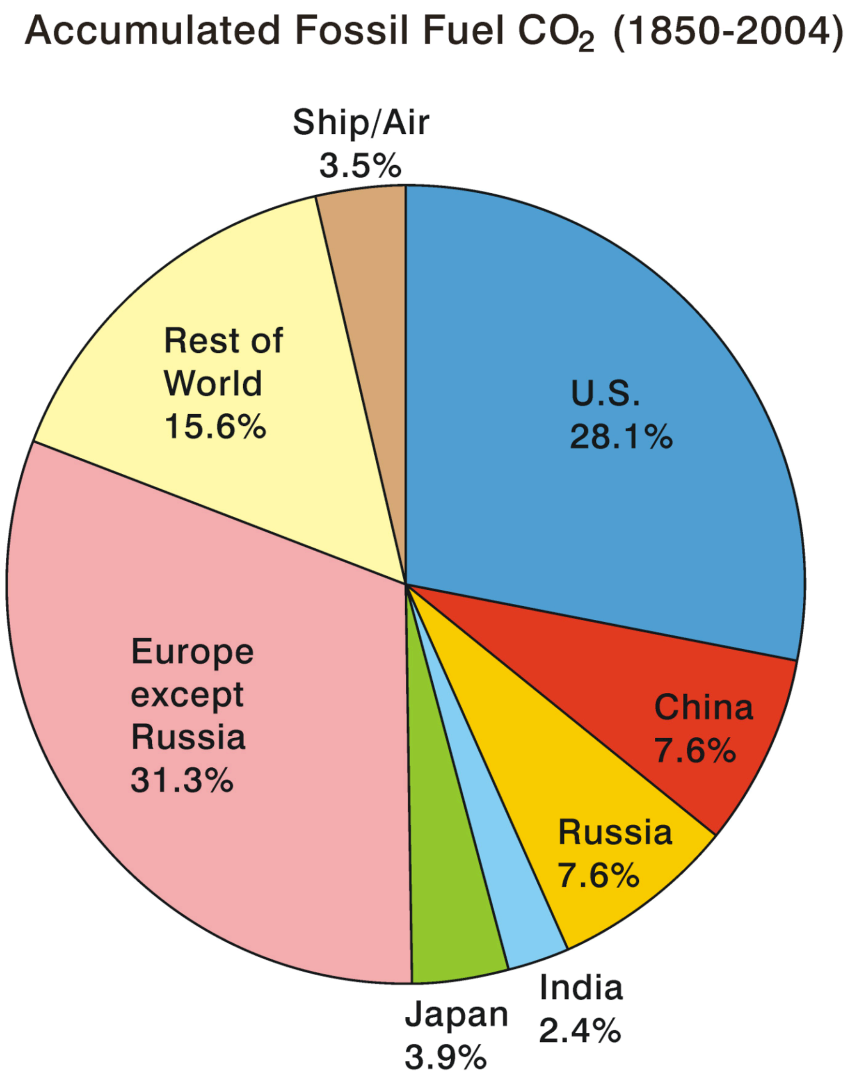
Source: National Academy of Sciences

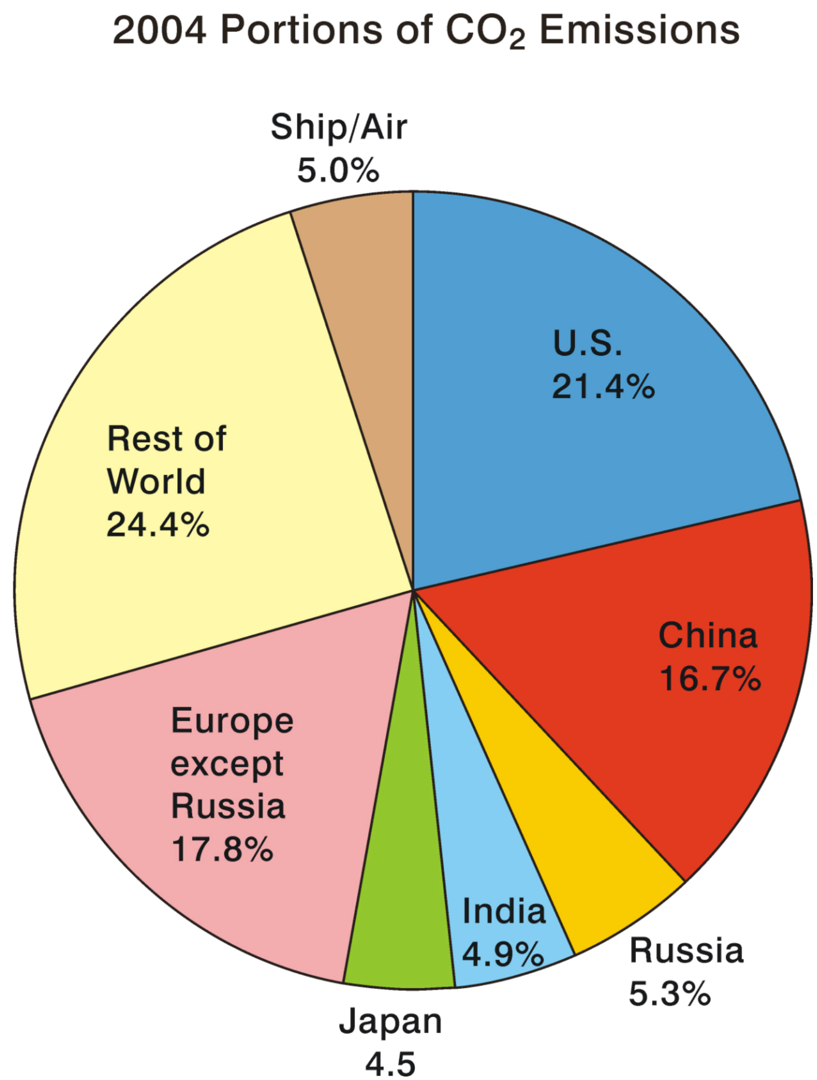
Geo-engineering Climate



Source: National Academy of Sciences

Fossil Fuel CO_2 Emissions

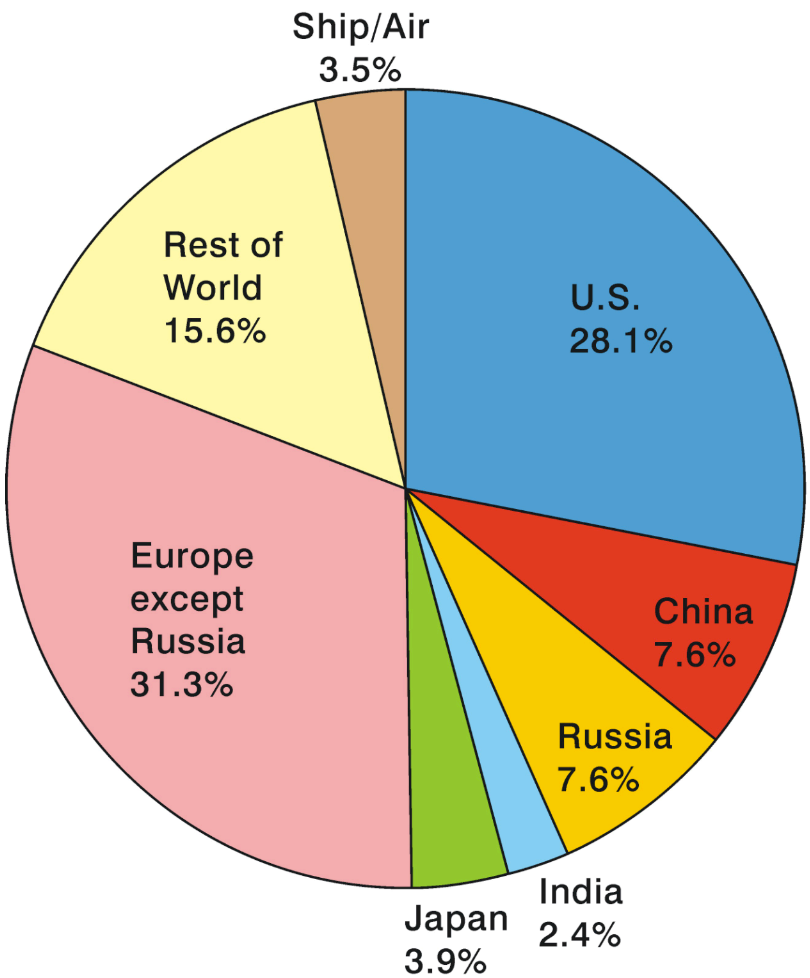


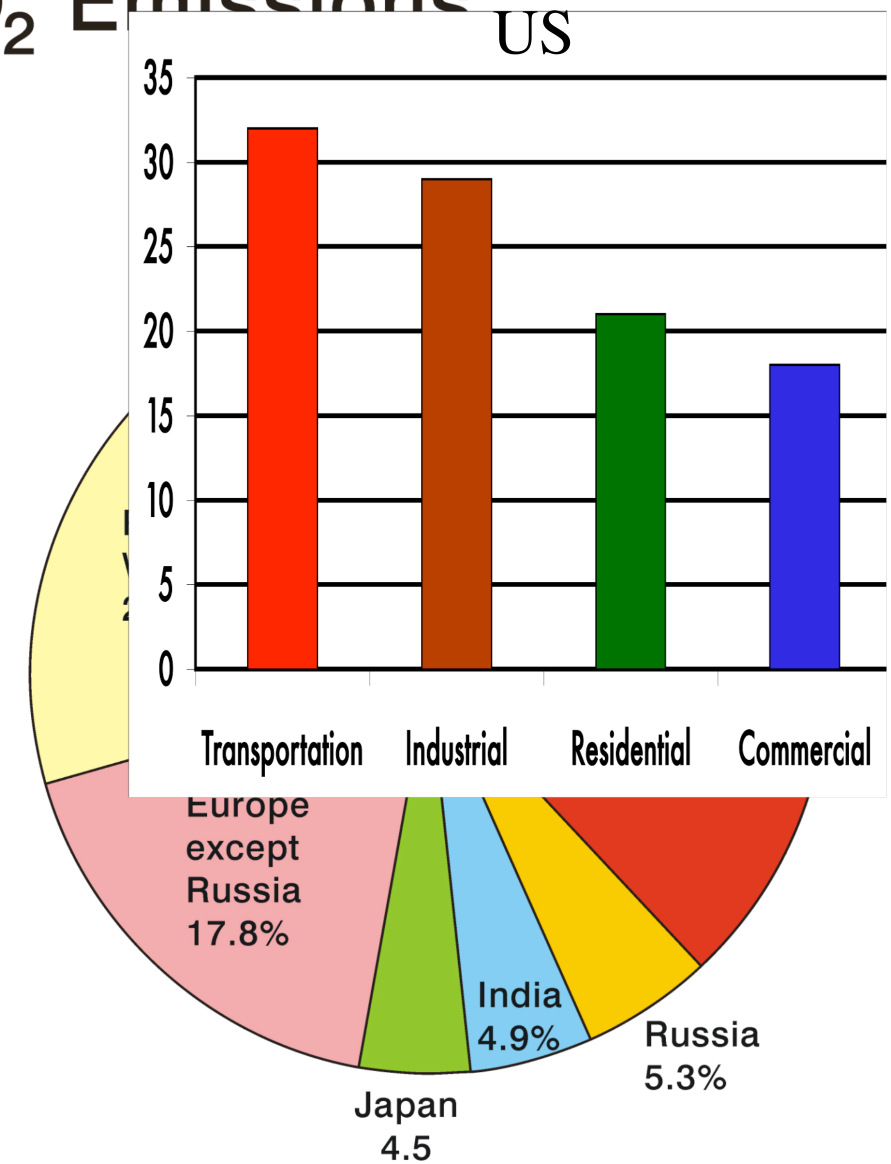


Source: J Hansen

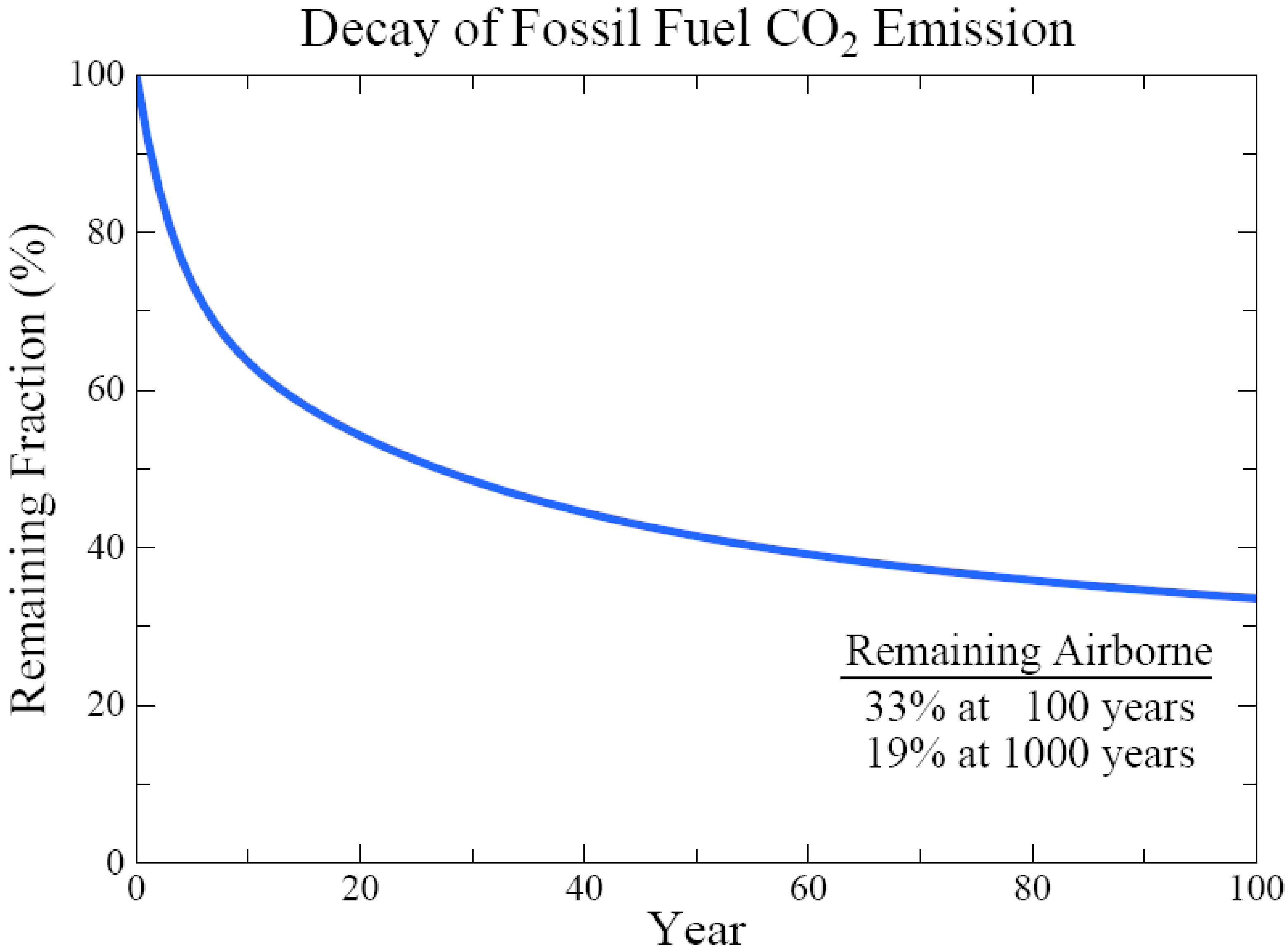
Fossil Fuel CO_2 Emissions

Accumulated Fossil Fuel CO_2 (1850-2004)





Source: J Hansen



The fraction of CO_2 remaining in the air, after emission by fossil fuel burning, declines rapidly at first, but 1/3 remains in the air after a century and 1/5 after a millennium (Hansen et al. 2007, *Atmos. Chem. Phys.* **7**, 2287-2312, 2007).

Methane more potent than CO_2

GWP: Ratio of heat trapped by one unit mass of the GHG to that of one unit mass of CO_2 over a specified time period.

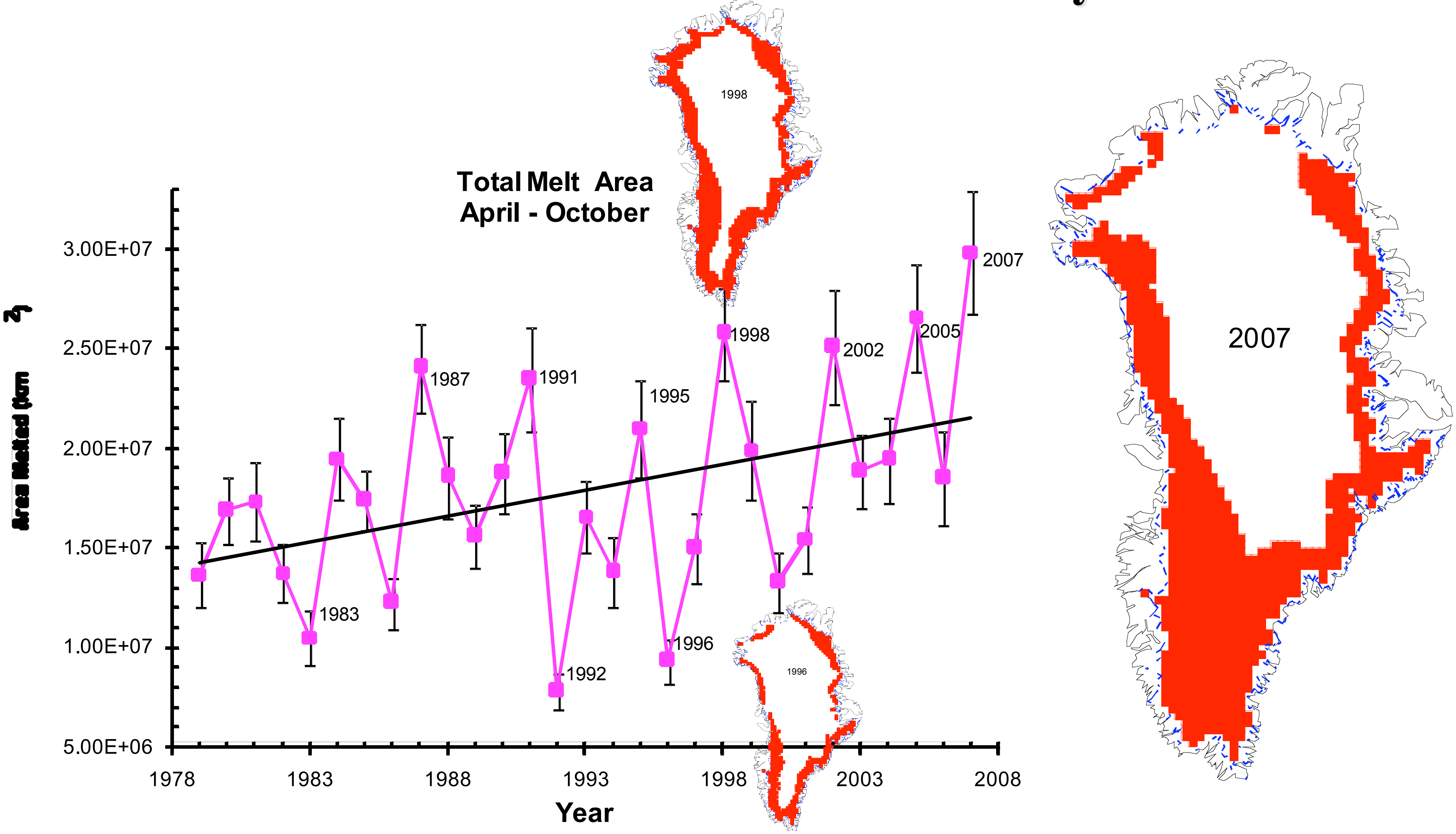
As the permafrost thaws as a result of global warming caused by increasing CO_2, large quantities of CH4 are released-- causes more warming and the release of even more CH4.

Effects of methane

- Helps control amount of OH (hydroxyl) in the troposphere
- Affects concentrations of water vapor and O_3 in the stratosphere
- Reaction with hydroxyl (OH) radical (~90%) in the troposphere
  OH is formed by photodissociation of tropospheric ozone and water vapor
- OH is the primary oxidant for most tropospheric pollutants (CH_4, CO, NO_x)
- Amount CH_4 removed constrained by OH levels and reaction rate
- Dissociation of CH_4 leads to CO_2: additional climatic forcing

Greenland Total Melt Area

2007 value exceeds last maximum by 10%



Source: J Hansen

Konrad Steffen and Russell Huff, CIRES, University of Colorado at Boulder

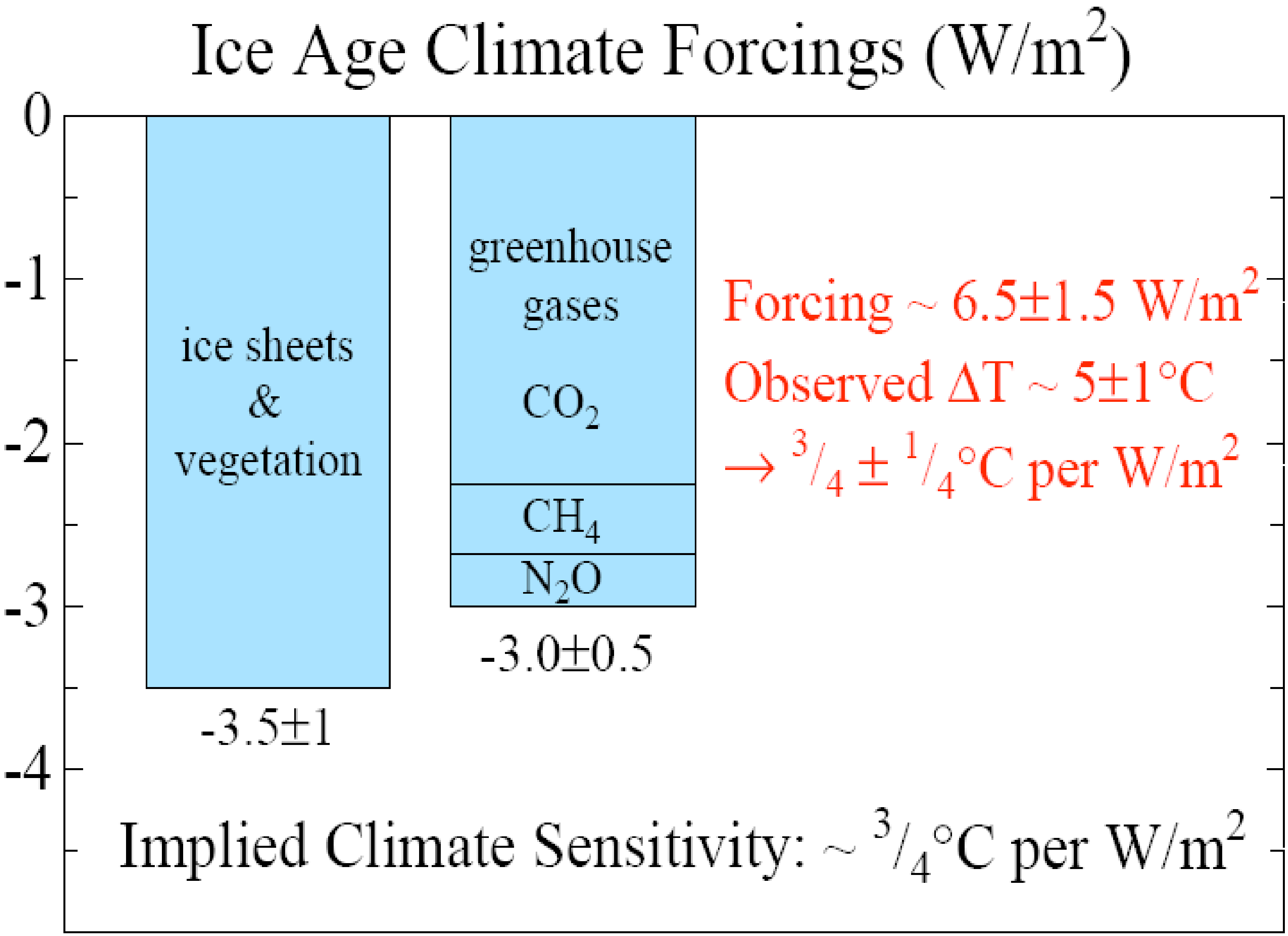


Fig. S2. Climate forcings during ice age 20 ky BP, relative to the present (pre-industrial) interglacial period.

Source: Hansen, J

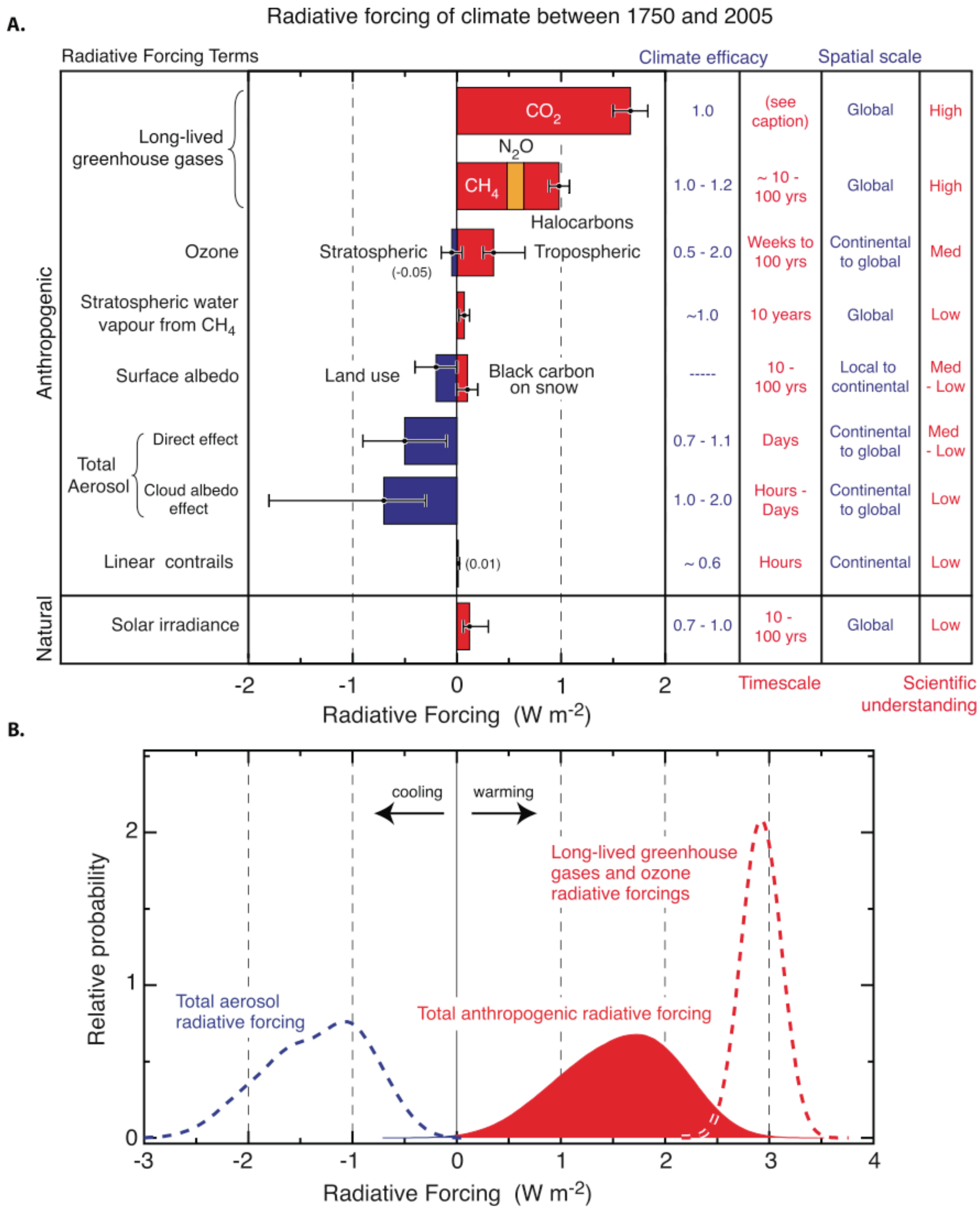
Assessment of Target CO_2

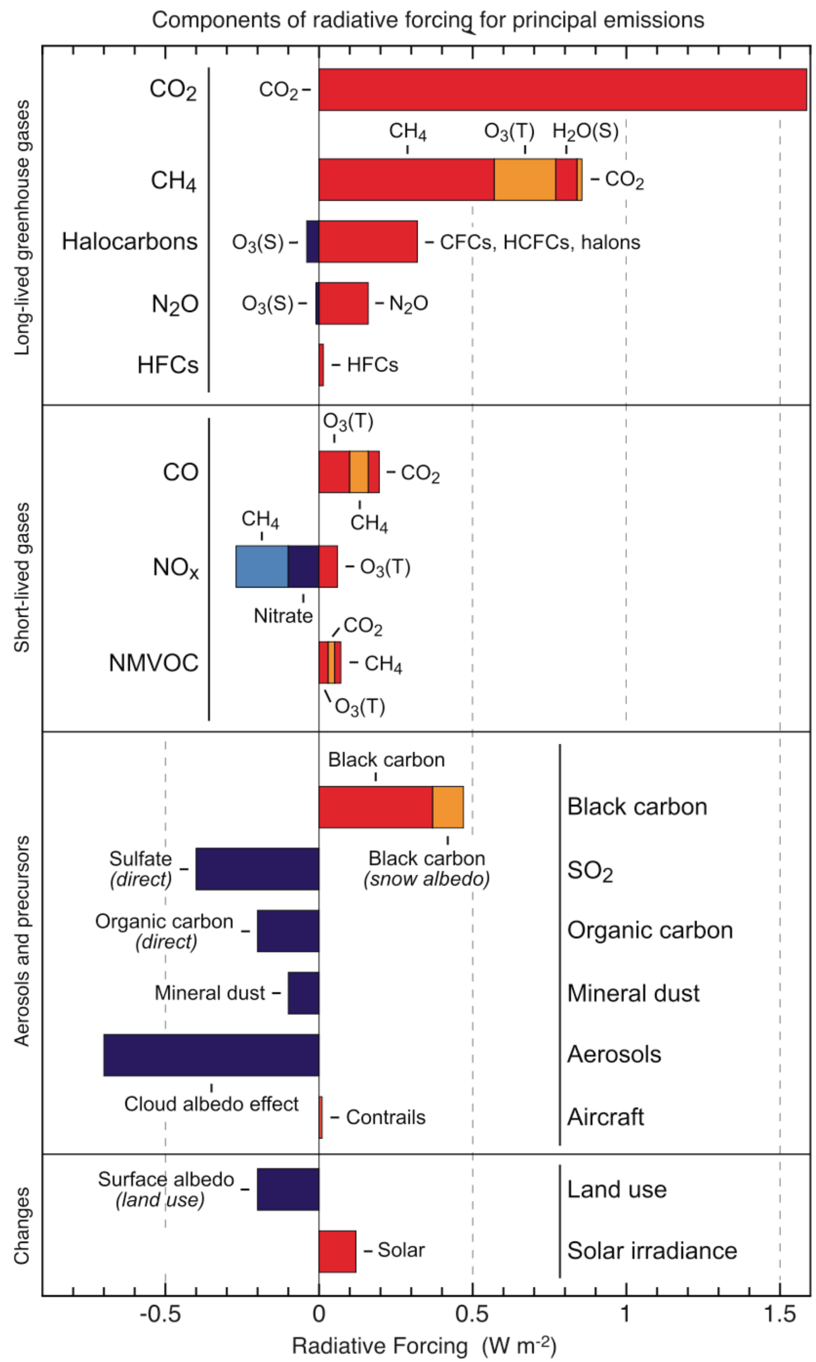
Phenomenon	Target CO_2 (ppm)
1. Arctic Sea Ice	300-325
2. Ice Sheets/Sea Level	300-350
3. Shifting Climatic Zones	300-350
4. Alpine Water Supplies	300-350
5. Avoid Ocean Acidification	300-350

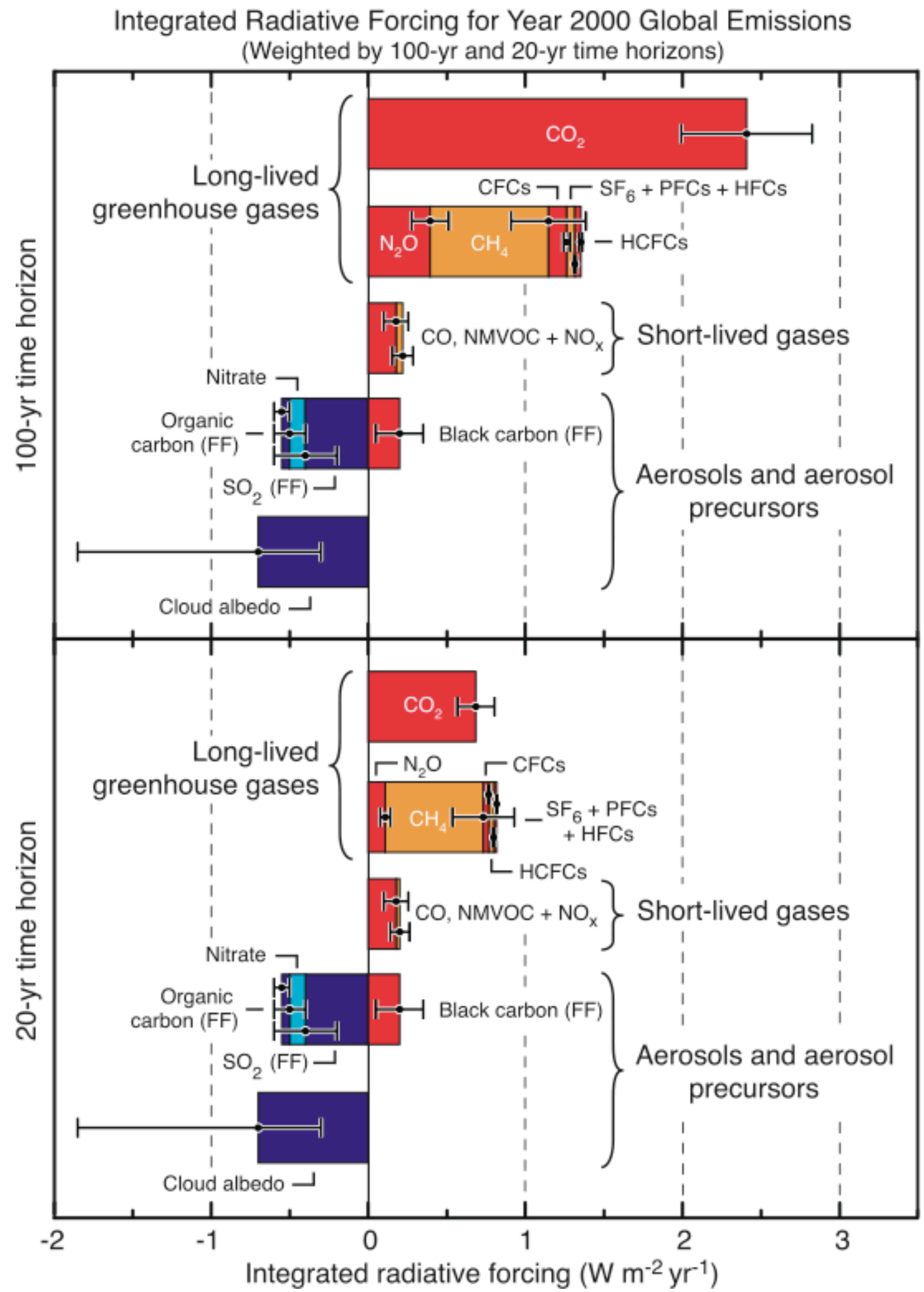
◊ **Initial Target CO_2 = 350* ppm**

***assumes CH_4, O_3, Black Soot decrease**

Source: J Hansen


A.
Radiative forcing of climate between 1750 and 2005
Radiative Forcing Terms
Climate efficacy
Spatial scale
Long-lived greenhouse gases
CO2
N2O
CH4
Halocarbons
Ozone
Stratospheric
(-0.05)
Tropospheric
Stratospheric water vapour from CH4
Surface albedo
Land use
Black carbon on snow
Total Aerosol
Direct effect
Cloud albedo effect
Linear contrails
(0.01)
Solar irradiance
Anthropogenic
Natural
1.0
(see caption)
Global
High
1.0 - 1.2
~ 10 - 100 yrs
Global
High
0.5 - 2.0
Weeks to 100 yrs
Continental to global
Med
~1.0
10 years
Global
Low
-----
10 - 100 yrs
Local to continental
Med - Low
0.7 - 1.1
Days
Continental to global
Med - Low
1.0 - 2.0
Hours - Days
Continental to global
Low
~ 0.6
Hours
Continental
Low
0.7 - 1.0
10 - 100 yrs
Global
Low
-2
-1
0
1
2
Radiative Forcing (W m-2)
Timescale
Scientific understanding
B.
cooling
warming
Long-lived greenhouse gases and ozone radiative forcings
Total aerosol radiative forcing
Total anthropogenic radiative forcing
Relative probability
0
1
2
-3
-2
-1
0
1
2
3
4
Radiative Forcing (W m-2)


Components of radiative forcing for principal emissions
Long-lived greenhouse gases
Short-lived gases
Aerosols and precursors
Changes
CO2
CH4
Halocarbons
N2O
HFCs
CO2
CH4
O3(T)
H2O(S)
CO2
O3(S)
CFCs, HCFCs, halons
O3(S)
N2O
HFCs
CO
NOx
NMVOC
O3(T)
CO2
CH4
CH4
O3(T)
Nitrate
CO2
CH4
O3(T)
Black carbon
Black carbon
(snow albedo)
Sulfate
(direct)
Organic carbon
(direct)
Mineral dust
Cloud albedo effect
Contrails
Black carbon
SO2
Organic carbon
Mineral dust
Aerosols
Aircraft
Surface albedo
(land use)
Solar
Land use
Solar irradiance
-0.5
0
0.5
1
1.5
Radiative Forcing (W m-2)



Integrated Radiative Forcing for Year 2000 Global Emissions
(Weighted by 100-yr and 20-yr time horizons)
100-yr time horizon
Long-lived greenhouse gases
CO2
CFCs
SF6 + PFCs + HFCs
N2O
CH4
HCFCs
CO, NMVOC + NOx
Short-lived gases
Nitrate
Organic carbon (FF)
Black carbon (FF)
SO2 (FF)
Aerosols and aerosol precursors
Cloud albedo
20-yr time horizon
Long-lived greenhouse gases
CO2
N2O
CFCs
CH4
SF6 + PFCs + HFCs
HCFCs
CO, NMVOC + NOx
Short-lived gases
Nitrate
Organic carbon (FF)
Black carbon (FF)
SO2 (FF)
Aerosols and aerosol precursors
Cloud albedo
-2
-1
0
1
2
3
Integrated radiative forcing (W m-2 yr-1)

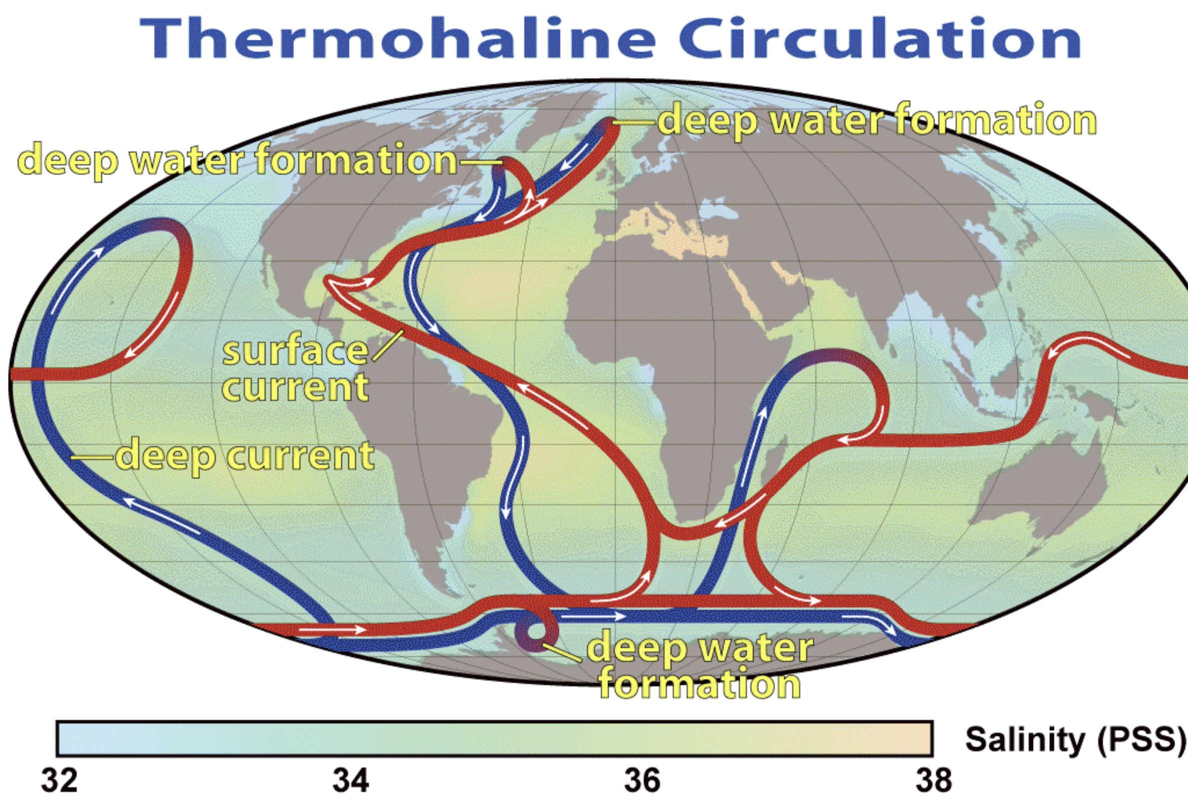
Pliocene: 5.332 million to 1.806 million years before present
Zanclean (5.3 - 3.6 Ma)
Piacenzian (3.6 - 2.6 Ma)
Gelasian (2.6 - 1.8 Ma)

Pleistocene: 1.8 million to 10,000 years BP covering recent period of repeated glaciations
Early Pleistocene (1.8 - 0.78 Ma)
Middle Pleistocene (780 - 130 ka)
Late Pleistocene (130 - 10 ka)
Older Dryas (14 - 13.6 ka)
Allerød (13.6 - 12.9 ka)

Younger Dryas (12.9 - 11.5 ka) Brief (~ 1300 ± 70 years) cold climate period approximately 12,800 to 11,500 years BP.
Holocene (10 ka - present)
Boreal and Atlantic

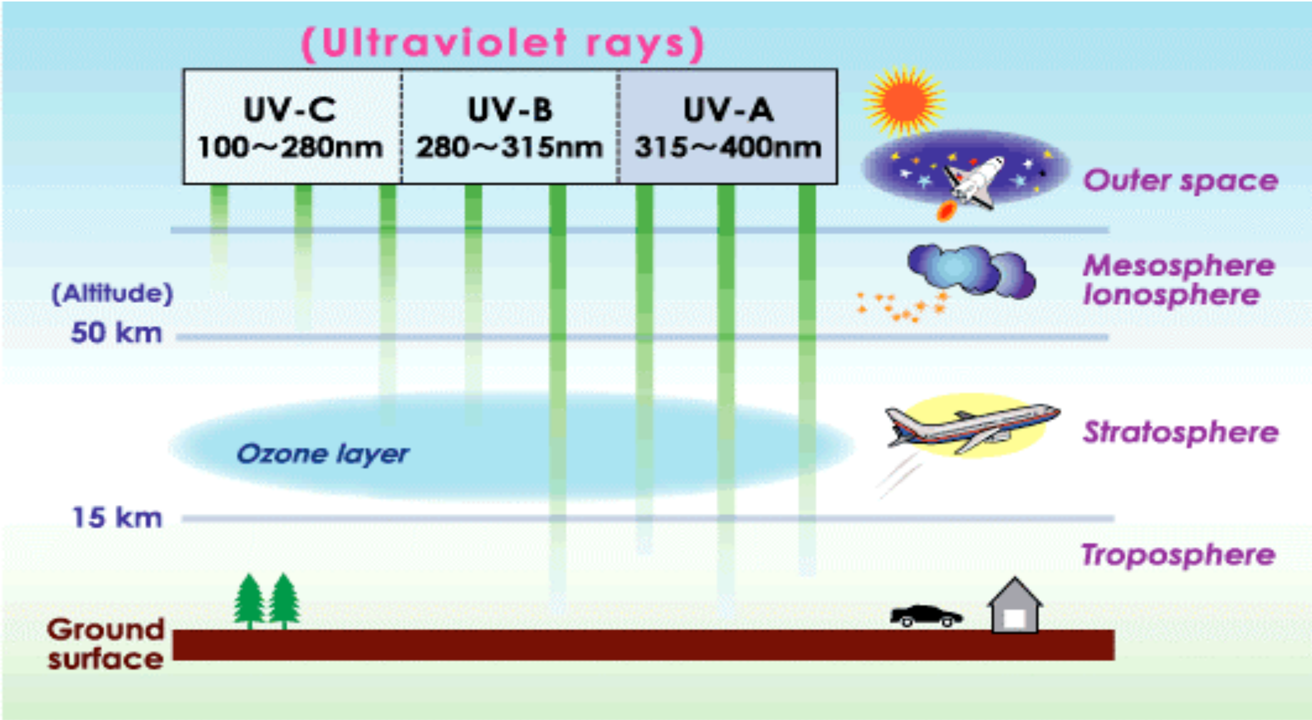
- The prevailing theory holds that the Younger Dryas was caused by a significant reduction or shutdown of the North Atlantic thermohaline circulation in response to a sudden influx of fresh water from Lake Agassiz

  and deglaciation in North America



Large-scale ocean circulation that is thought to be driven by global density gradients created by surface heat and freshwater fluxes.

Global warming could, via a shutdown or slowdown of the thermohaline circulation, trigger localized cooling in the North Atlantic and lead to cooling, or lesser warming, in that region. This would affect in particular areas like Iceland, Ireland, the Nordic countries, and Britain that are warmed by the North Atlantic drift.



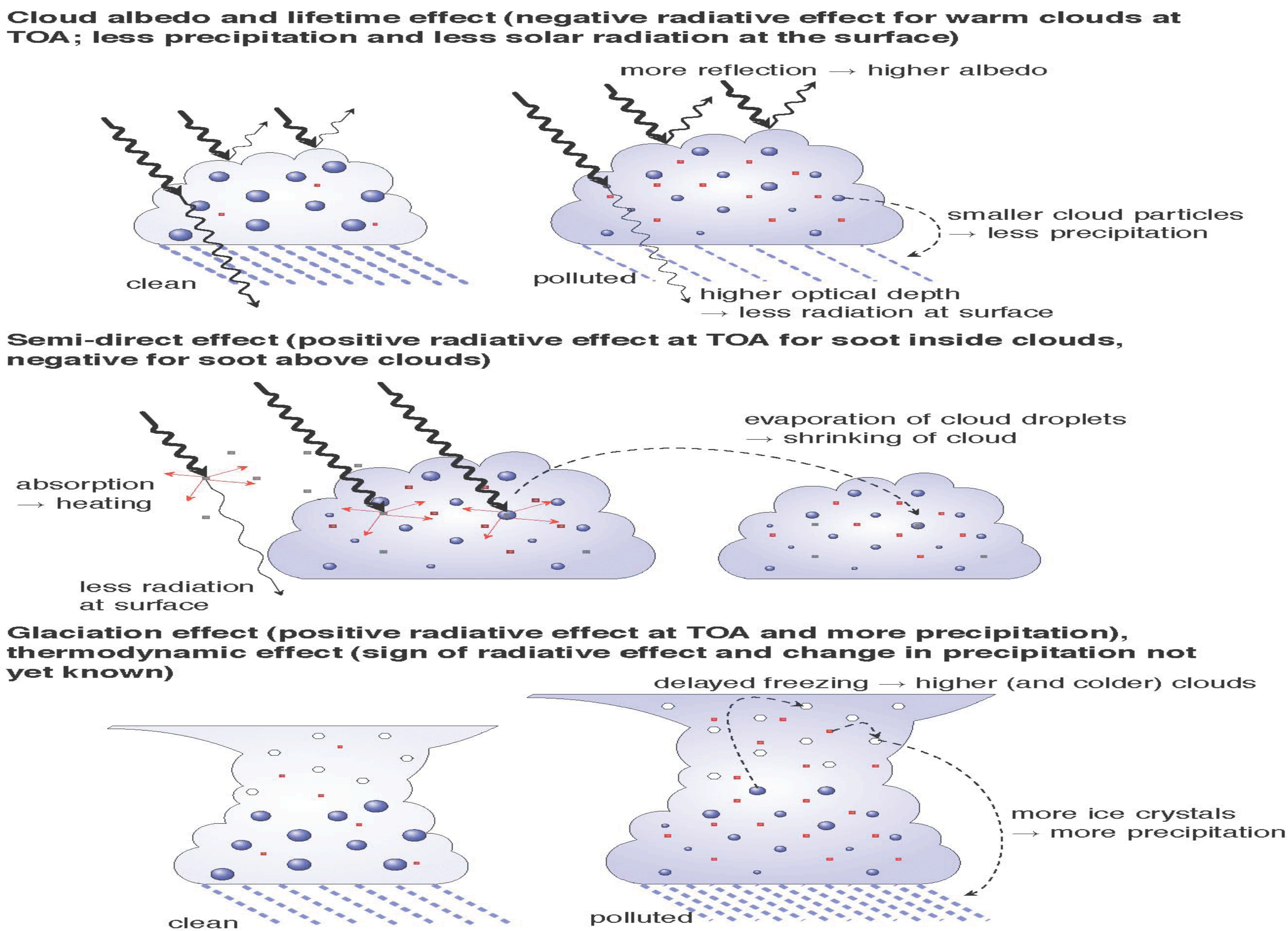
Each spring in the stratosphere over Antarctica, atmospheric ozone is rapidly destroyed by chemical processes. As winter arrives, a vortex of winds develops around the pole and isolates the polar stratosphere. When temperatures drop below -78C, thin clouds form of ice, nitric acid, and sulphuric acid mixtures.

Chemical reactions on the surfaces of ice crystals in the clouds release active forms of CFCs. Ozone depletion begins, and the ozone hole appears.

Over the course of 2-3 months, ~ 50% of the total column ozone disappears. At some levels, the losses approach 90%. This has come to be called the Antarctic ozone hole.

In spring, temperatures begin to rise, the ice evaporates, and the ozone layer starts to recover.

Role of Particles : Effects on Clouds



Source: IPCC 2007

Schematic of Aerosol Effects