Computational Methods for Global Change Research

Winter 2009

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Overview of Today

- **Introductory admin**
- Motivation – why this is interesting
- Modelling – potential and limitations

Scope of Course

- Introduction to three of the major areas in global change research which use modeling
- Introduction to the key computation modeling methods in these areas
- Hands on practice with modelling environments and models

Assessment

- 2 assignments (20% each)
  - Discover and review a computational model
- Exam (60%)
  - Lecture material and required readings

Draft Schedule (subject to revision)

- 21/1 – Agent-based models for ecosystems
- 28/1 – CGE models for economics
- 4/2 – System Dynamics models for ecosystems
- 11/2 – Agent-based models for economics
- 25/2 – System Dynamics models for energy economics
- 4/3 – Climate modelling I
- 11/3 – Climate modelling II
- 18/3 – Integrate models and Review

Overview of Today

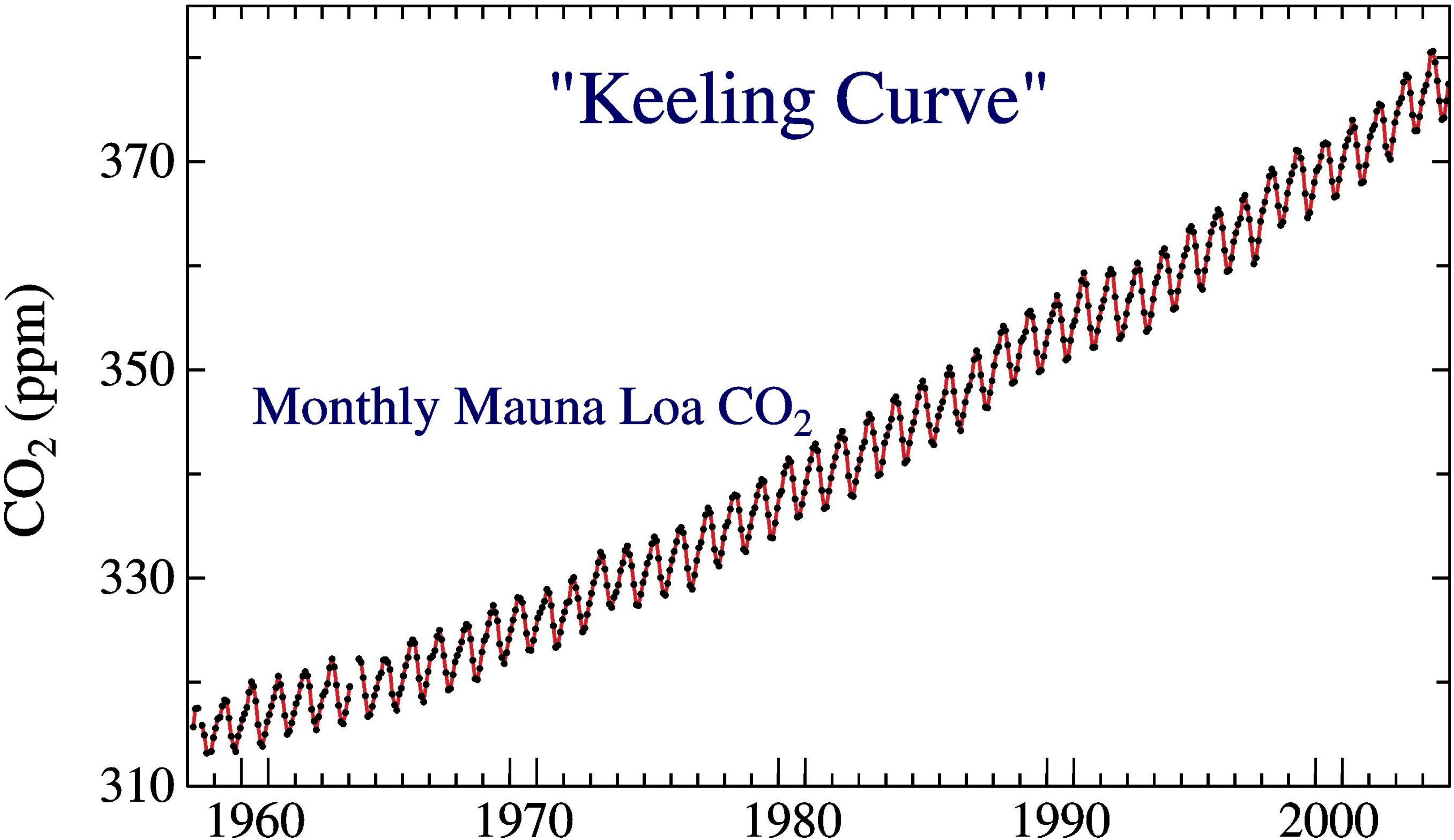
- **Introductory admin**
- Motivation
  - why you should be concerned and work to help
  - range of problems to work on is limitless
- Modelling – potential and limitations

Why global change is of interest

- Climate
- Ecosystems
- Economics
- Politics, national security, cultural developments...

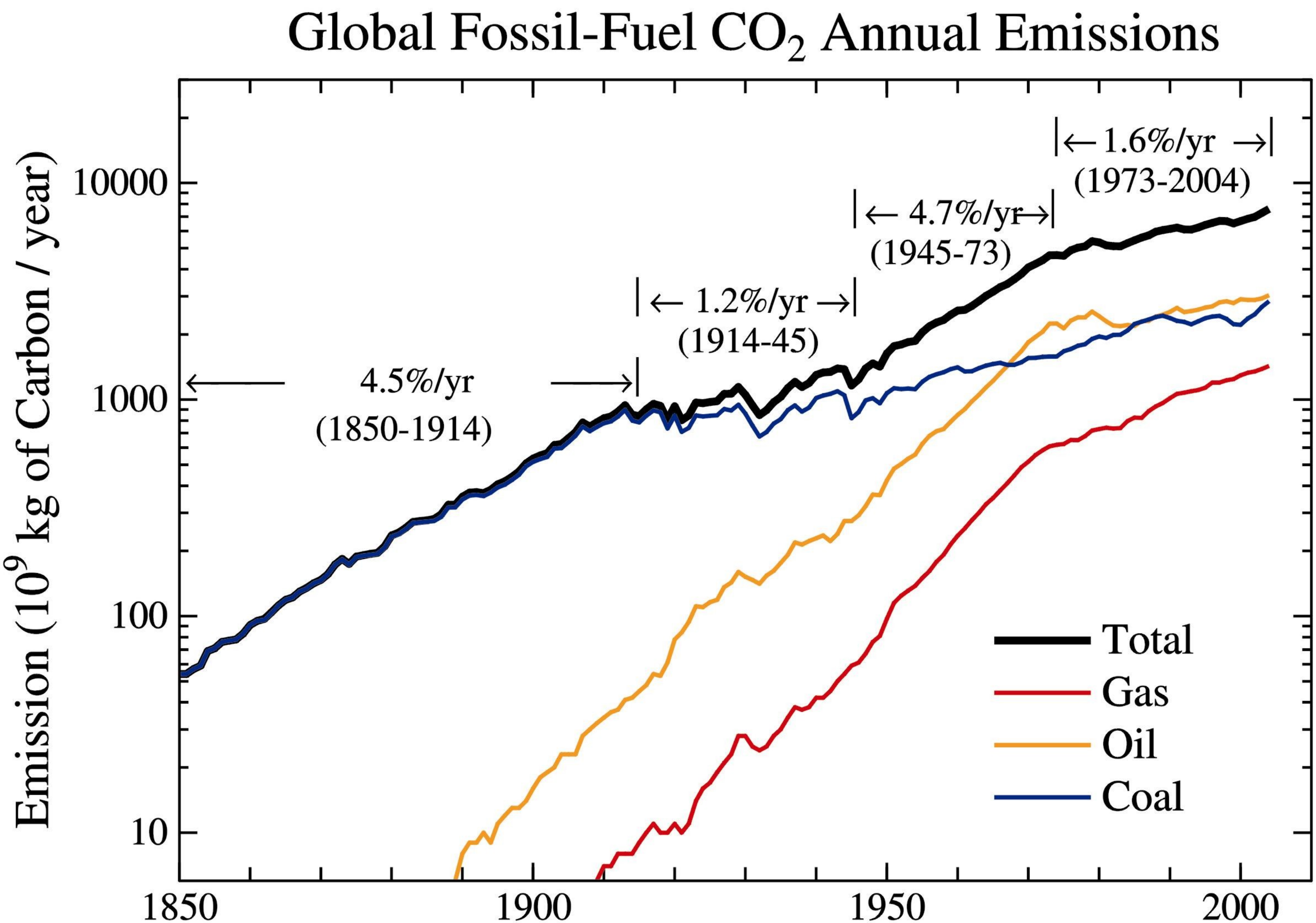
Climate

- Taken from Jim Hansen's December 2005 talk “Is There Still Time to Avoid Dangerous Anthropgenic Interference with Global Climate?”
- See readings



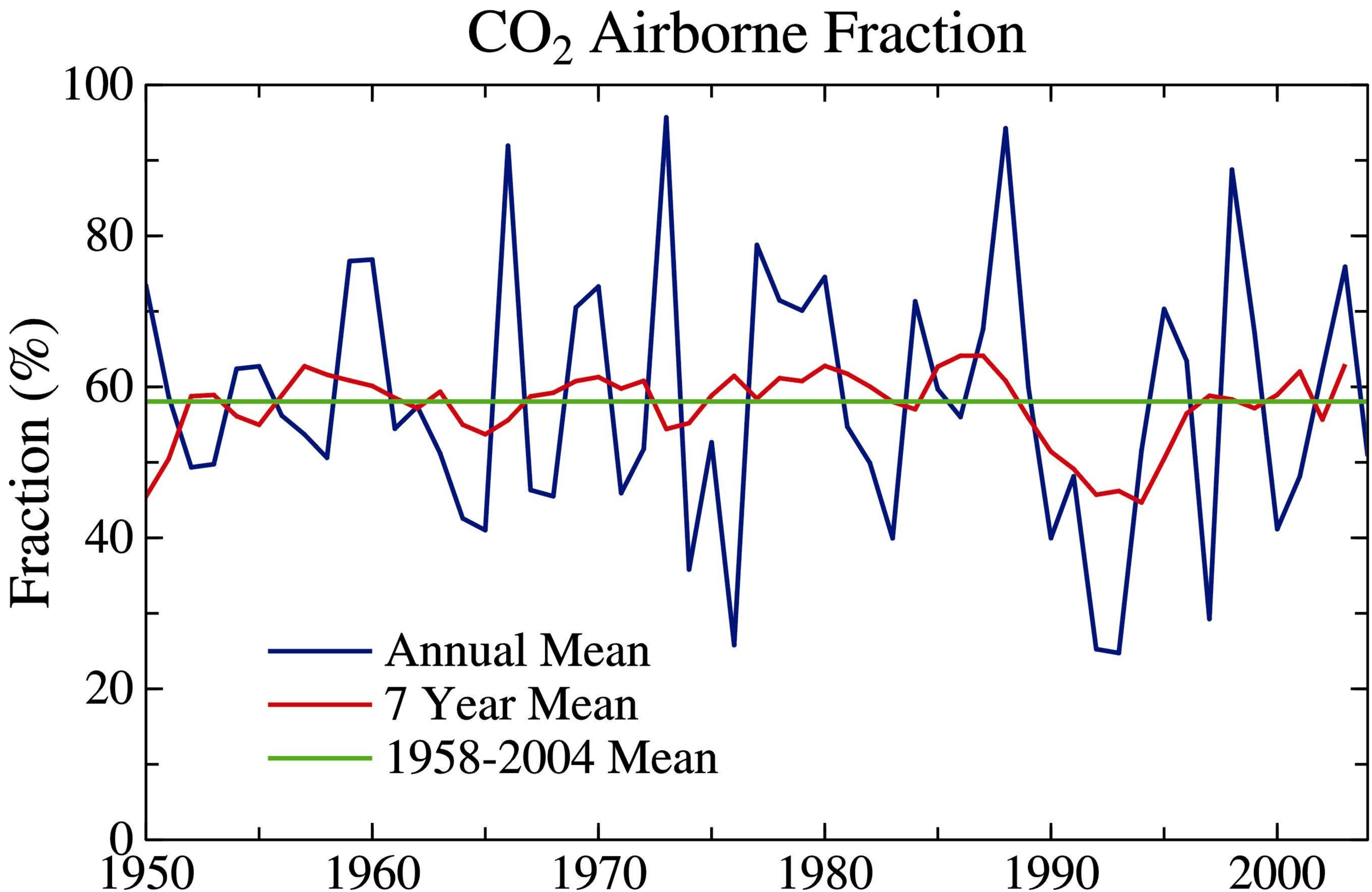
Atmospheric CO_2 measured at Mauna Loa, Hawaii.

Source: NOAA Climate Monitoring and Diagnostic Laboratory



Fossil fuel CO_2 emissions based on data of Marland and Boden (DOE, Oak Ridge) and British Petroleum.

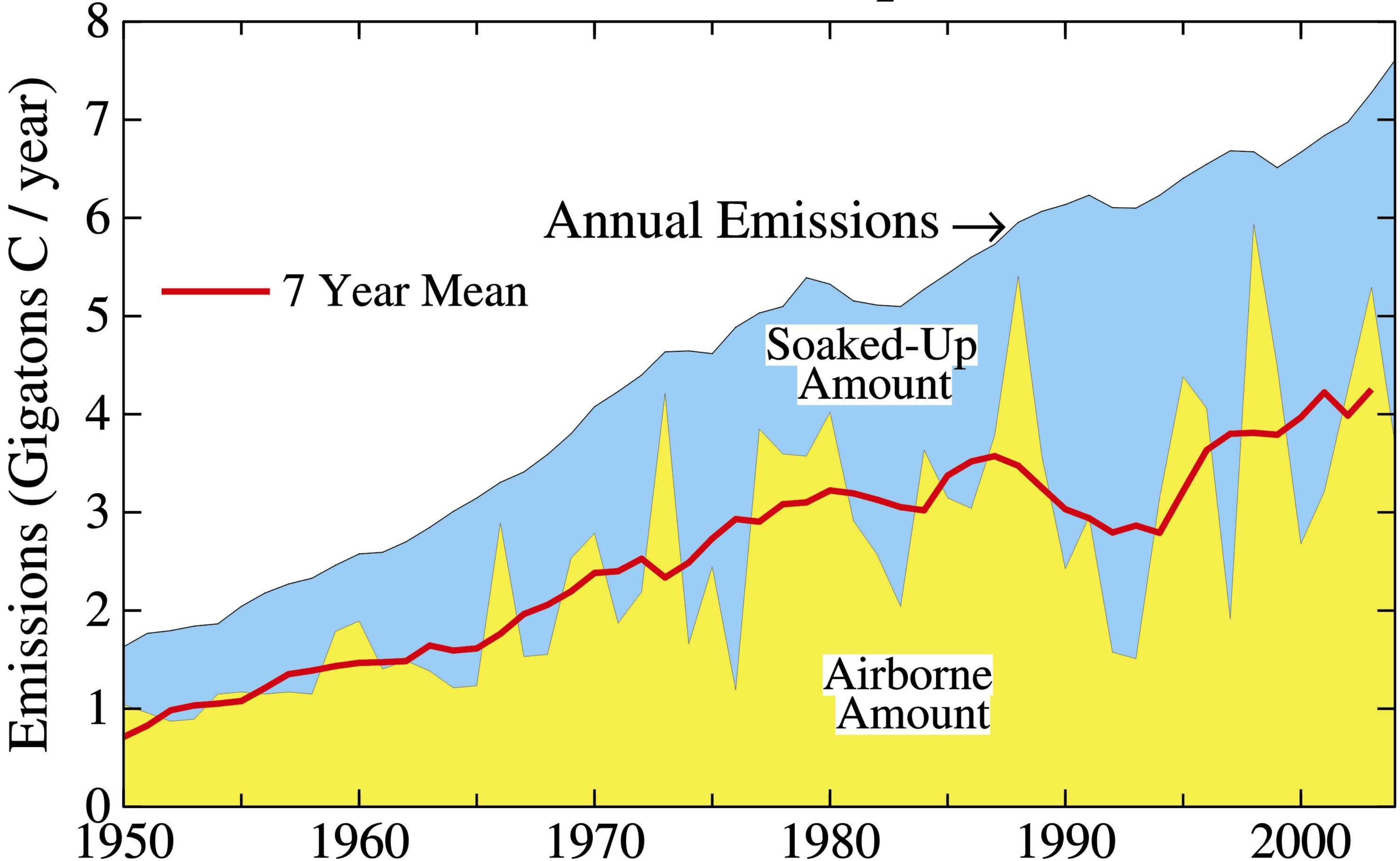
Source: Hansen and Sato, *PNAS,* **98**, 14778, 2001.



CO_2 airborne fraction, i.e., ratio of annual atmospheric CO_2 increase to annual fossil fuel CO_2 emissions.

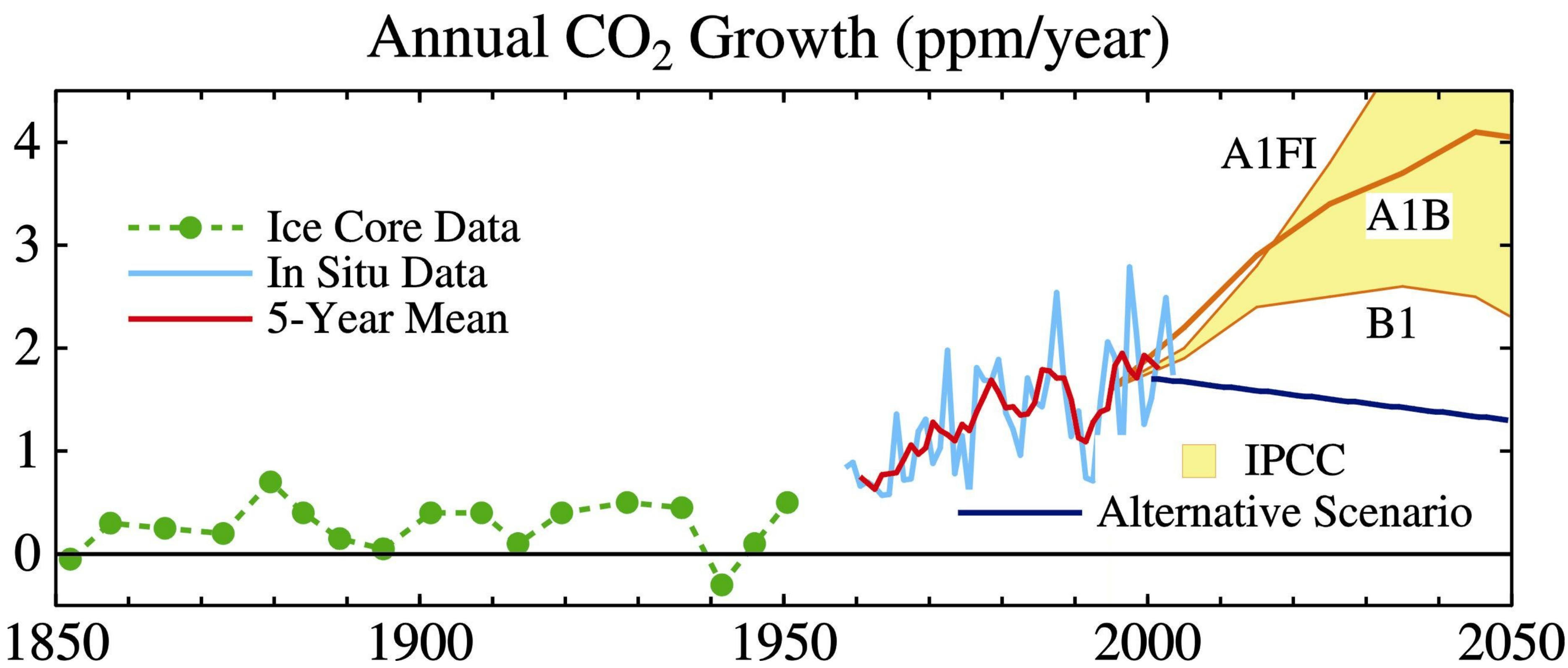
Source: Hansen and Sato, *PNAS,* **101**, 16109, 2004.

Global Fossil Fuel CO_2 Emissions



Global fossil fuel CO_2 emissions with division into portions that remain airborne or are soaked up by the ocean and land.

Source: Hansen and Sato, *PNAS,* **101**, 16109, 2004.



Growth rate of atmospheric CO_2 (ppm/year).

Source: Hansen and Sato, *PNAS,* **101**, 16109, 2004.

Carbon Dioxide

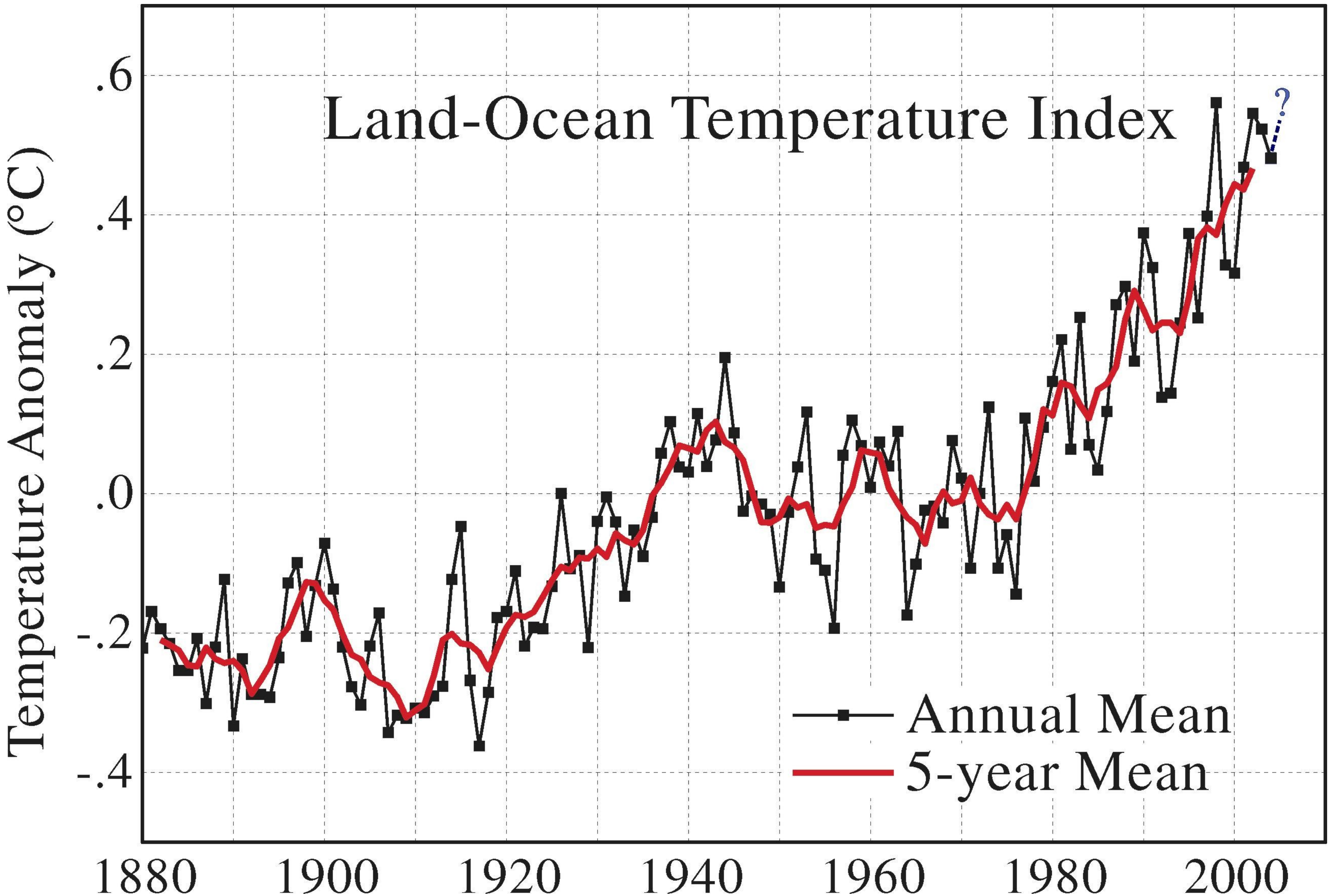
<u>Good News:</u>

1. ~42% of annual fossil fuel emissions continues to be "soaked up" by ocean, soil, vegetation

2. Uptake % could increase if emissions decreased, or via improved forestation/agricultural practices

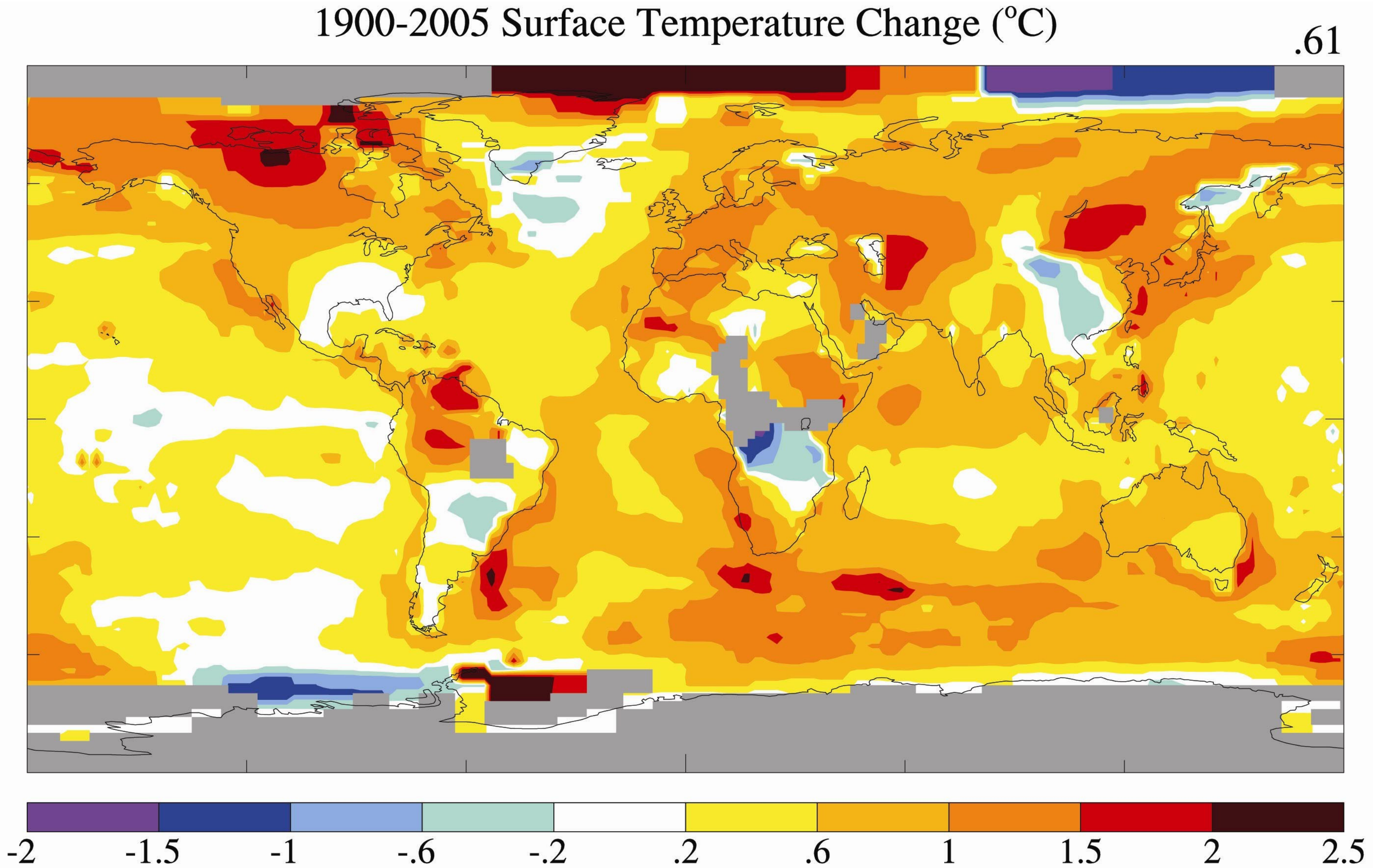
<u>Bad News:</u>

1. Stabilization of atmospheric CO_2 may require eventual reduction of emissions by 60-80%



Global mean surface temperature change based on surface air measurements over land and SSTs over ocean

Source: Update of Hansen et al., *JGR,* **106**, 23947, 2001; Reynolds and Smith, *J. Climate,* **7**, 1994; Rayner et al., *JGR,* **108**, 2003.

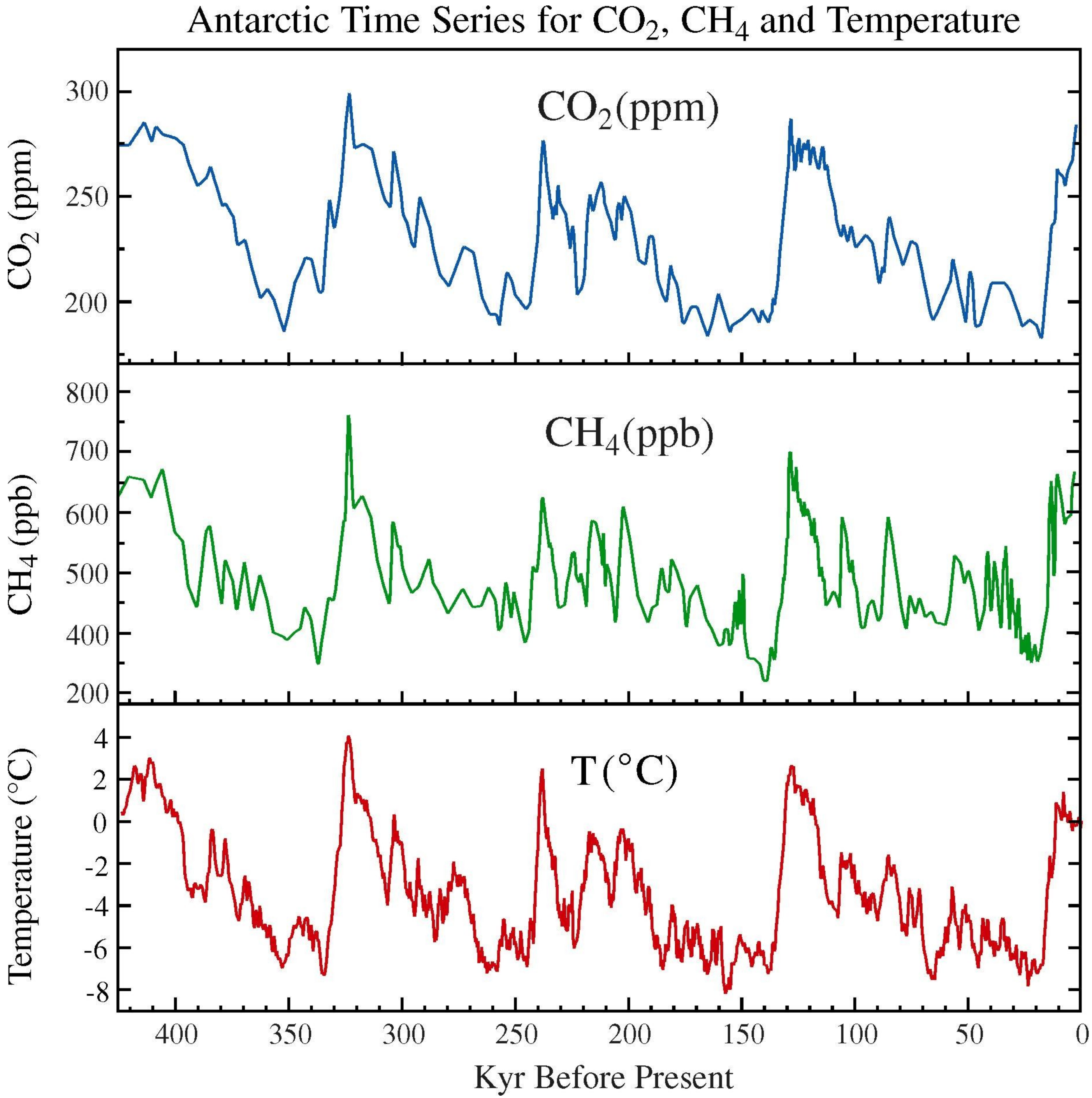


Change of surface temperature index based on local linear trends using surface air temperature over land and SST over ocean.

Sources: Hansen et al., *JGR*, **106**, 23947, 2001; Reynolds and Smith, *J. Climate*, **7**, 1994; Rayner et al., *JGR*, **108**, 2003.

Climate Sensitivity

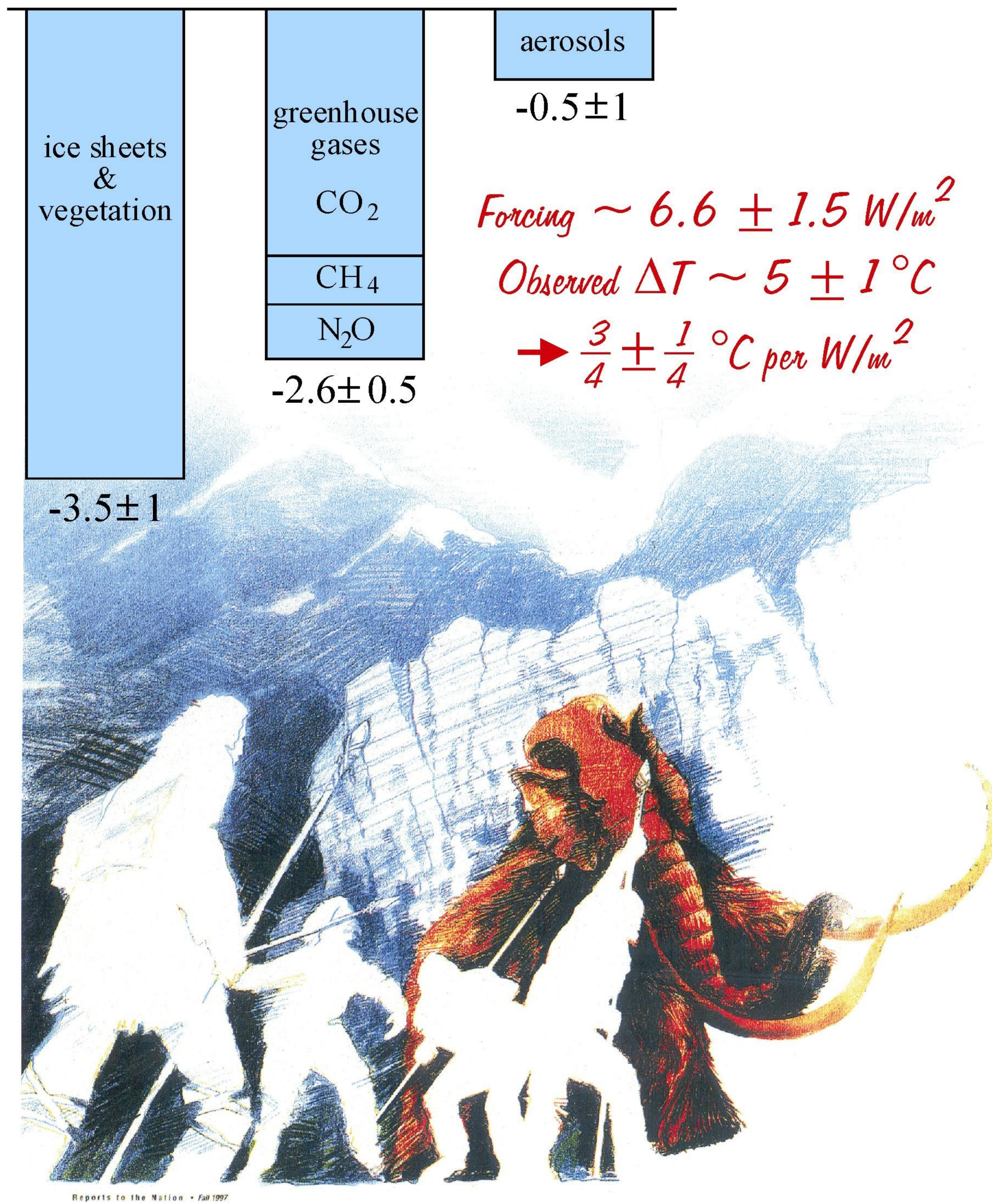
- Charney definition: equilibrium temperature change for doubling of CO_2
- Critical number – how fast will the climate heat up
- How do we estimate it?...



CO_2, CH_4 and temperature records from Antarctic ice core data

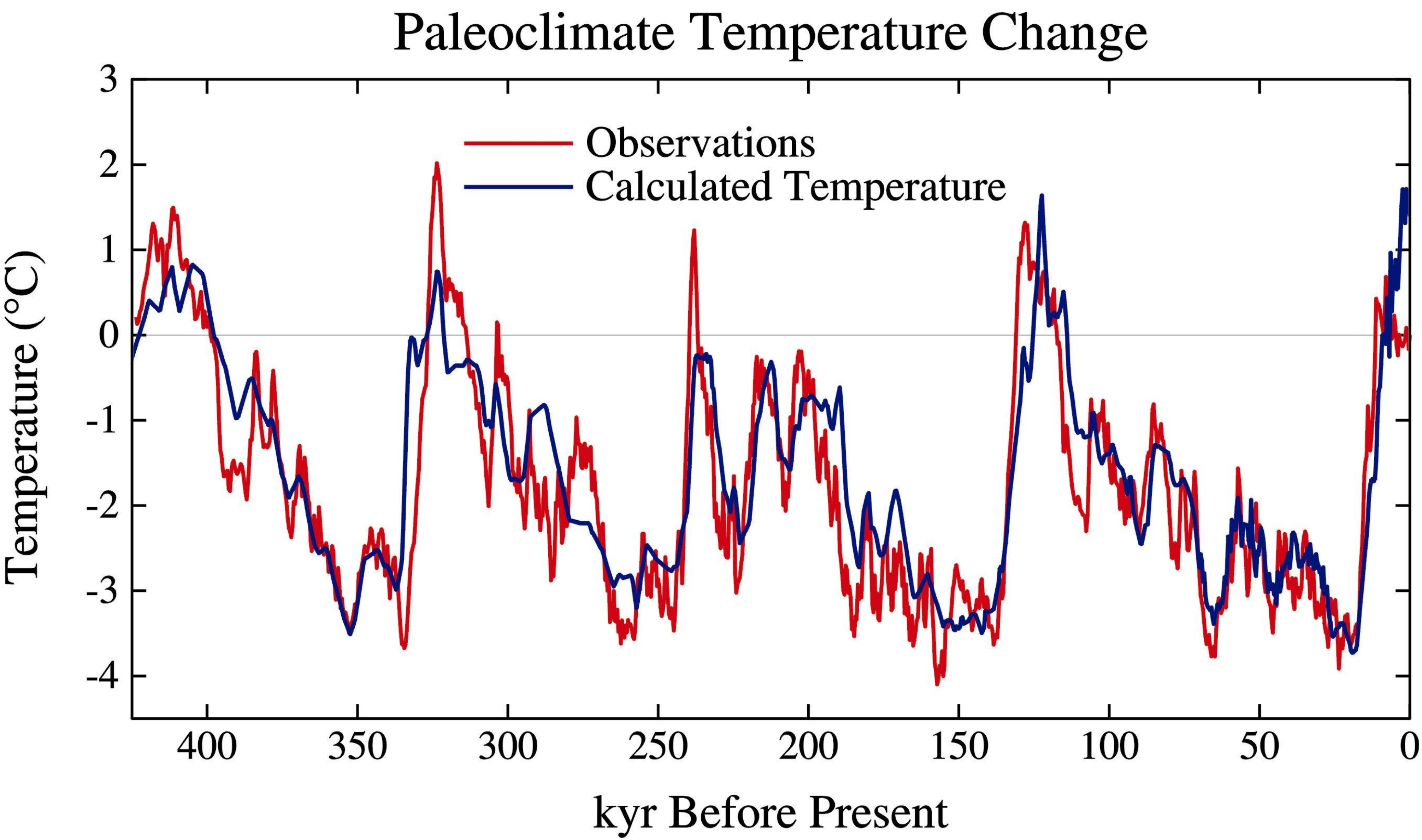
Source: Petit et al., Nature, 399, 429, 1999

Ice Age Climate Forcings (W/m^2)



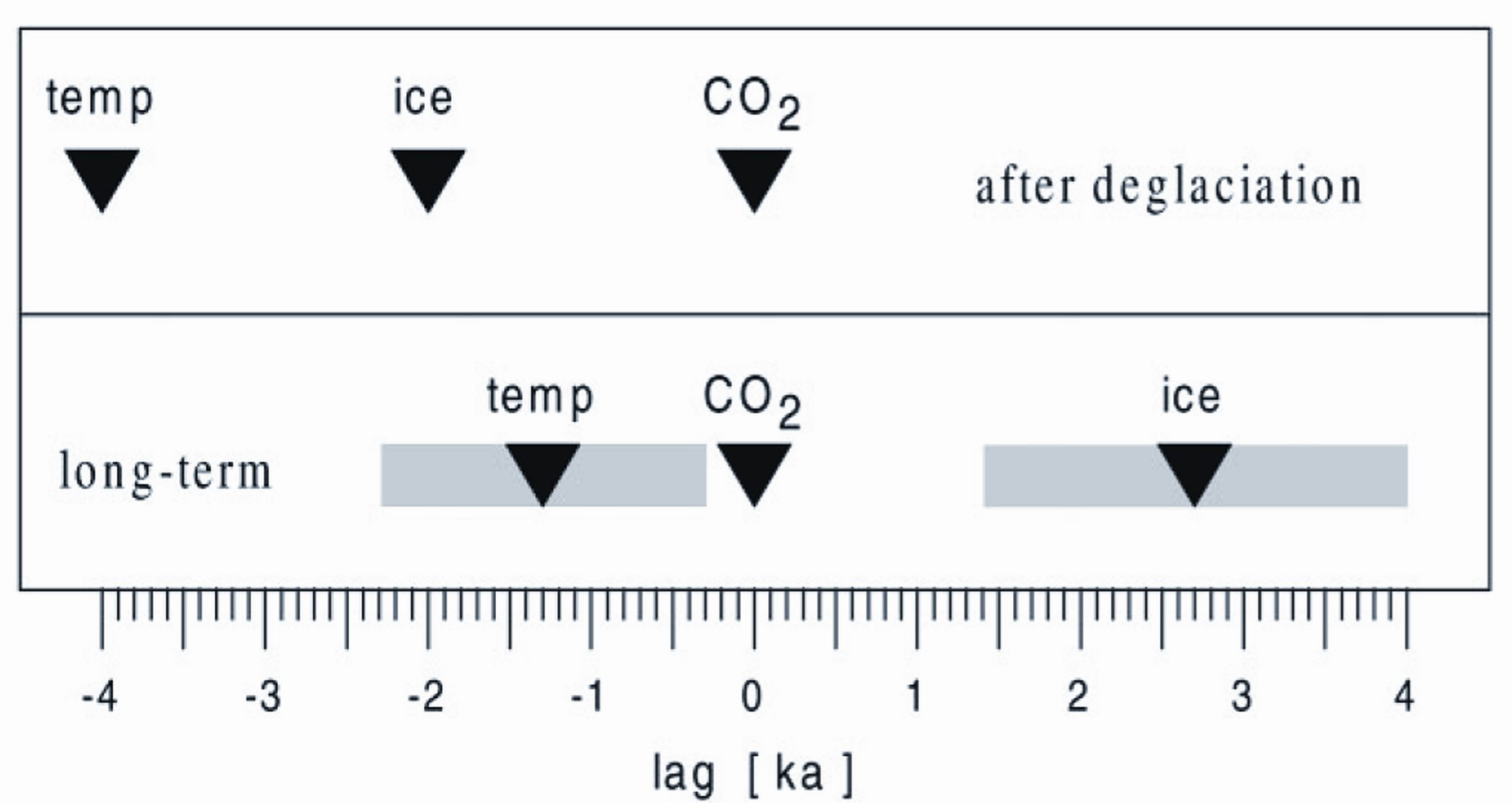
Ice Age Forcings Imply Global Climate Sensitivity ~ ¾°C per W/m^2.

Source: Hansen et al., *Natl. Geogr. Res. & Explor.*, **9**, 141, 1993.



Observations = Vostok ΔT/2.
Calculated temperature = Forcing x 0.75°C /W/m^2

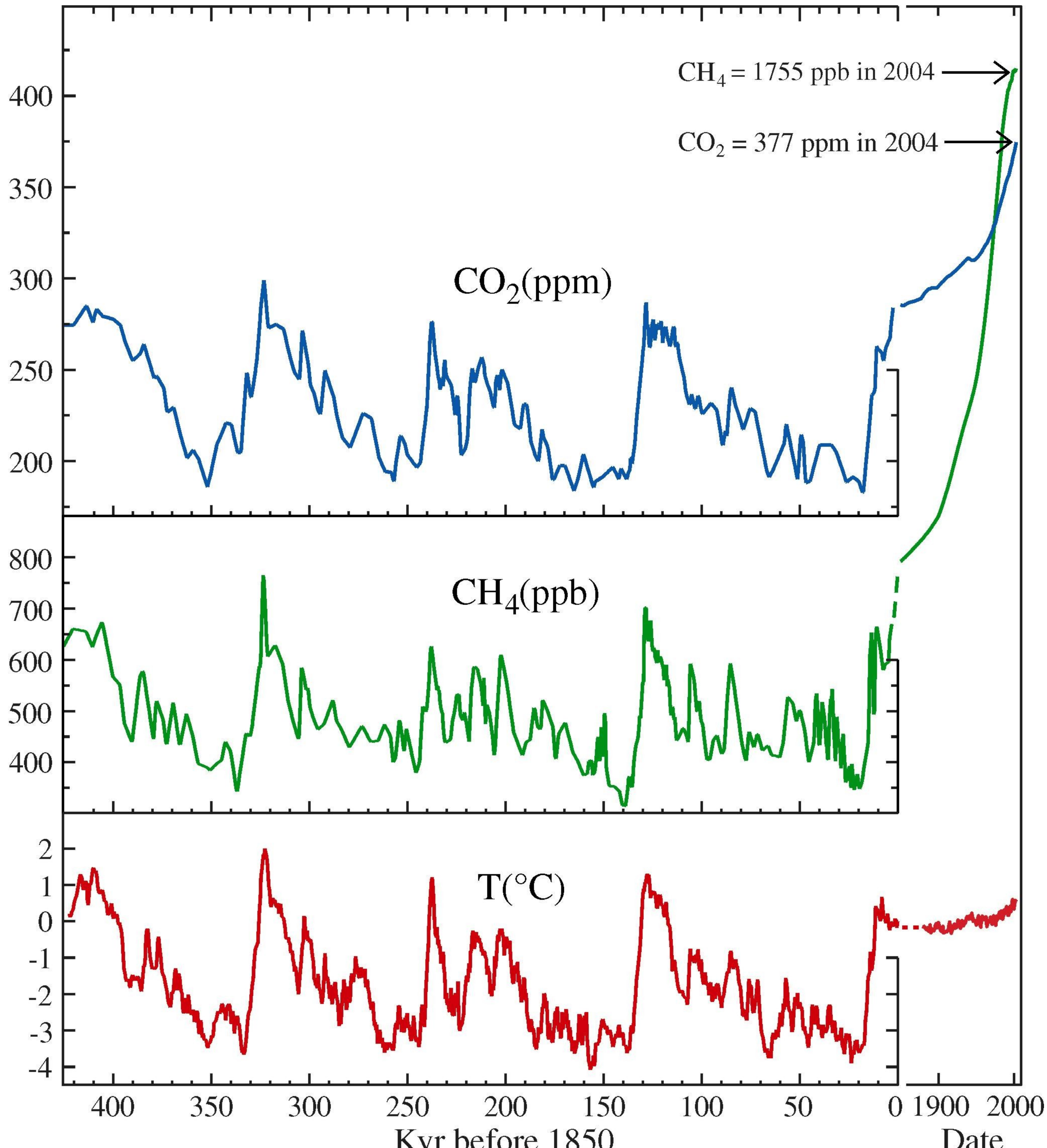
Lag of Global Ice & CO_2 Relative to S.H. Temperature



Leads and lags of Vostok temperature and global ice volume relative to CO_2. Shaded bar is 1σ uncertainty. Temperature and ice are more contemporaneous at some terminations.

Source: M. Mudelsee, Quat. Sci. Rev., **20**, 583, 2001.

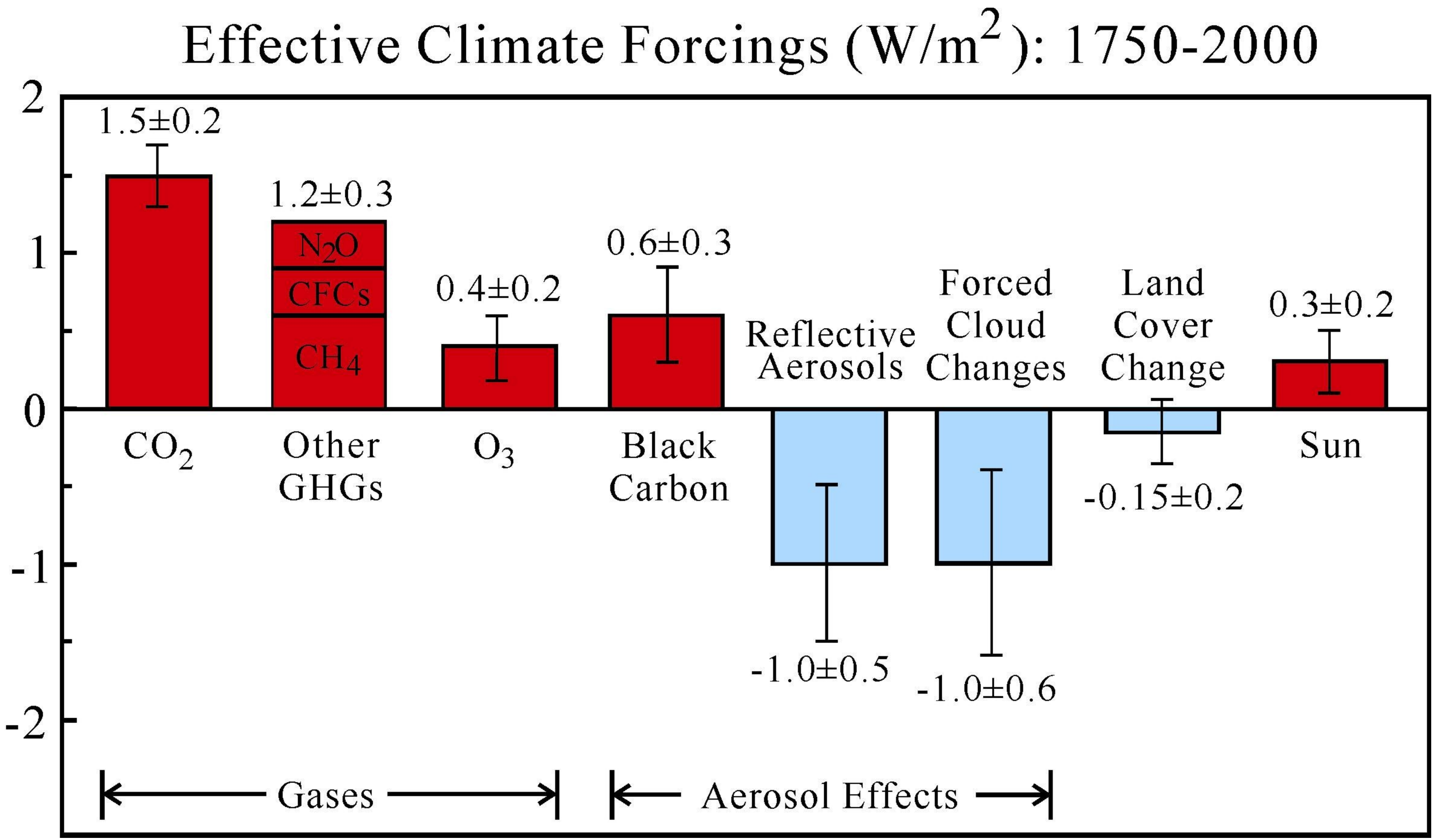
CO_2,CH_4 and estimated global temperature (Antarctic ΔT/2 in ice core era) 0 = 1880-1899 mean.



Source: Hansen, *Clim. Change*, **68**, 269, 2005.

Implications of Paleo Forcings and Response

1. "Feedbacks" (or indirect forcings) cause almost all paleo temperature change.
2. Climate on these time scales is very sensitive to even small forcings.
3. Instigators of climate change must include: orbital variations, other small forcings, noise.
4. Another "ice age" cannot occur unless humans become extinct. Even then, it would require thousands of years. Humans now control



Climate forcing agents in the industrial era. "Effective" forcing accounts for "efficacy" of the forcing mechanism

Source: Hansen et al., JGR, **110**, D18104, 2005.

Consistency Check

1.85 W/m^2 = 1880-2003 forcing

1.00 W/m^2 = used for observed 2/3° C warming

0.85 W/m^2 = remains, not yet responded to

Implications

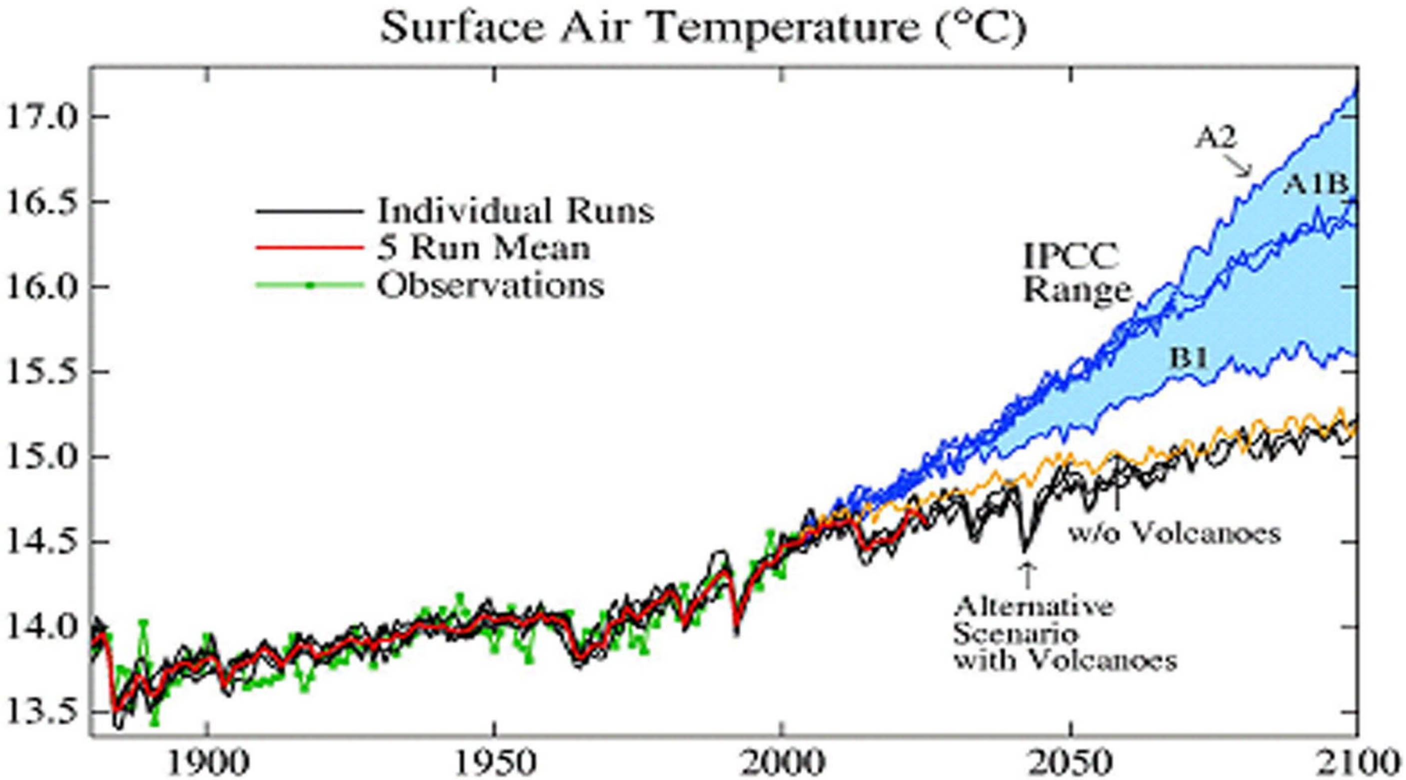
1. 0.6° C more warming in the pipeline

2. Confirms climate system lag

→ Need anticipatory actions to avoid any specified level of “dangerous” change

Source: Hansen et al., *Science*, **308**, 1431, 2005.

21st Century Global Warming



Climate Simulations for IPCC 2007 Report

► Climate Model Sensitivity ~ 2.7ºC for 2xCO_2
(consistent with paleoclimate data & other models)

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

► Simulated Global Warming < 1ºC in Alternative Scenario

Conclusion: Warming < 1ºC if additional forcing ~ 1.5 W/m^2

Source: Hansen et al., *to be submitted to J. Geophys. Res.*

Metrics for "Dangerous" Change

Physical Climate System Approach

Global Sea Level

1. Long-Term Change: Paleoclimate Data
2. Ice Sheet Response Time

Regional Climate Change

1. General Statement
2. Specific Cases

Ice Sheet Response Time: <u>Millennia or Centuries</u>?

1. Paleoclimate Data
   Dated "Terminations"
   ~10 m "Sub-orbital" Sea Level Change

2. Satellite & Field Data
   Linear Growth, Nonlinear Disintegration

3. Ice Sheet Models
   Fail paleoclimate & satellite tests

Paleoclimate Sea Level Data

1. **Rate of Sea Level Rise**
   - Data reveal numerous cases of rise of several m/century (e.g., MWP 1A)

2. **“Sub-orbital” Sea Level Changes**
   - Data show rapid changes ~ 10 m within interglacial & glacial periods

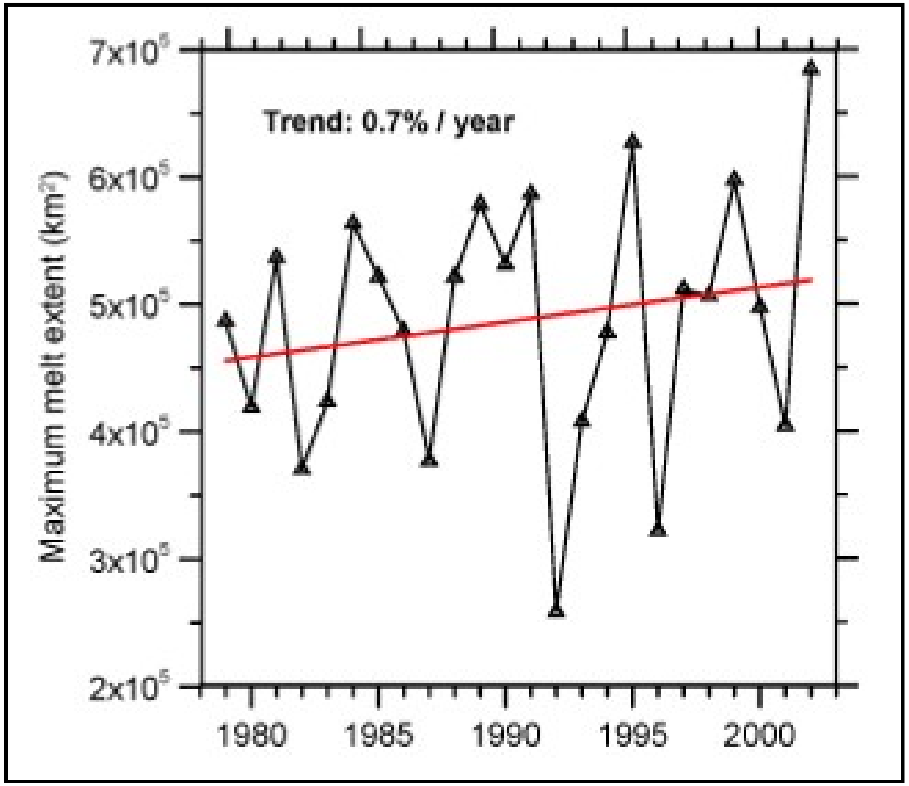
<u>Ice Sheet Models Do Not Produce These</u>

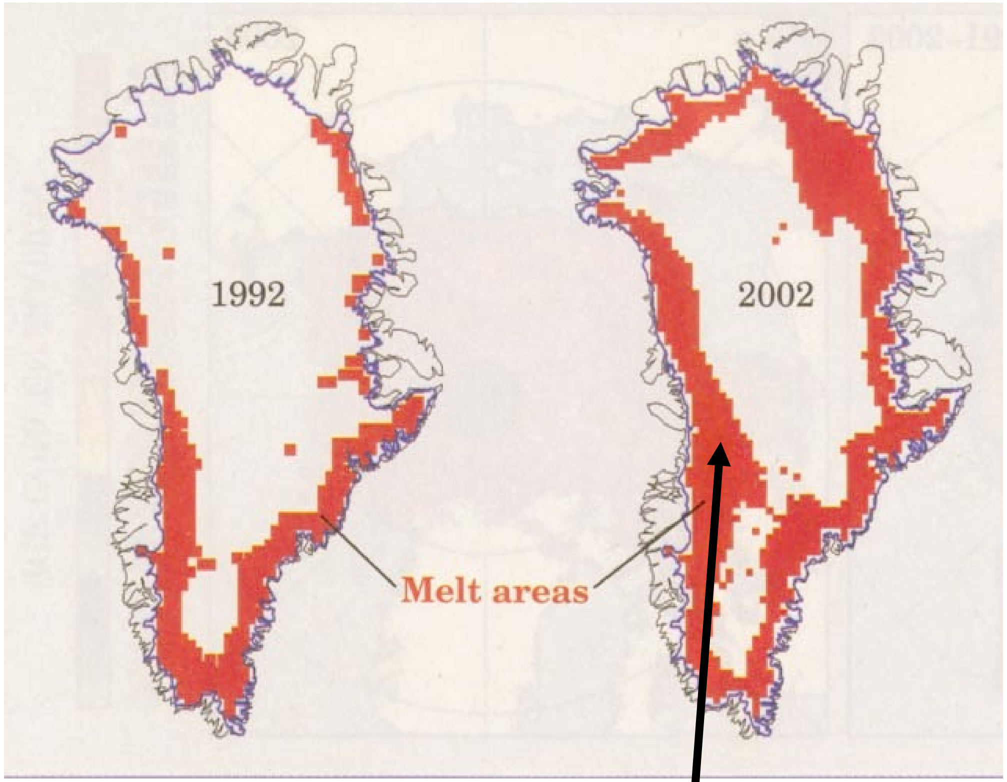
Surface Melt on Greenland

Melt descending
into a moulin,
a vertical shaft
carrying water
to ice sheet base.

Source: Roger Braithwaite,
University of Manchester (UK)

Increasing Melt Area on Greenland





- 2002 all-time record melt area
- Melting up to elevation of 2000 m
- 16% increase from 1979 to 2002

70 meters thinning in 5 years

Satellite-era record melt of 2002 was exceeded in 2005.

Source: Waleed Abdalati, Goddard Space Flight Center

Jakobshavn Ice Stream in Greenland

Discharge from major Greenland ice streams is accelerating markedly.

Source: Prof. Konrad Steffen, Univ. of Colorado

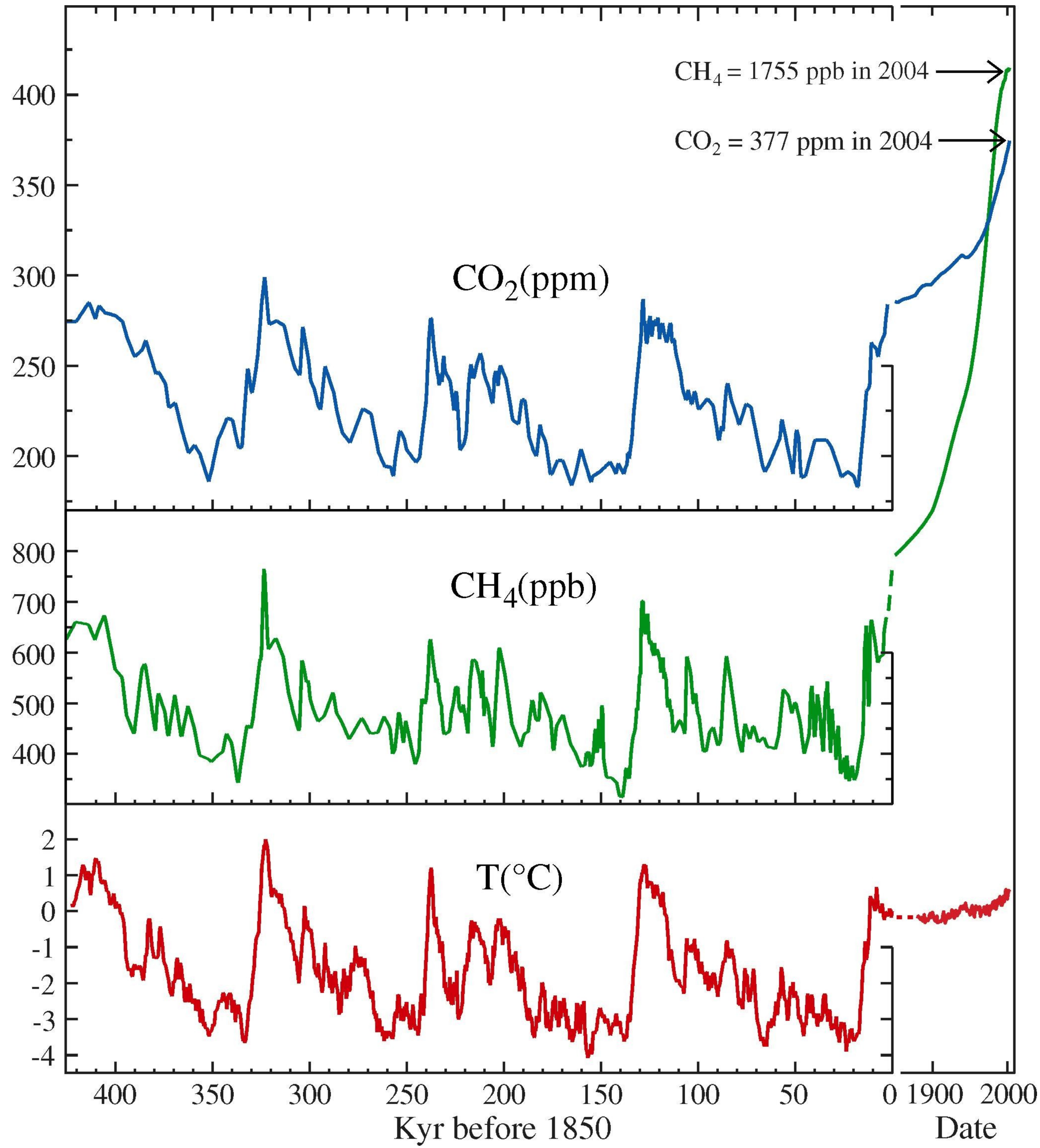
Summary: Ice Sheets

1. Human Forcing Dwarfs Paleo Forcing

2. Sea Level Rise Starts Slowly as Interior Ice Sheet Growth Temporarily Offsets Ice Loss at the Margins

3. Equilibrium Sea Level Response for ~3C Warming (25±10 m = 80 feet) Implies Potential for a System Out of Our Control

CO_2,CH_4 and estimated global temperature (Antarctic $\Delta T/2$ in ice core era) 0 = 1880-1899 mean.

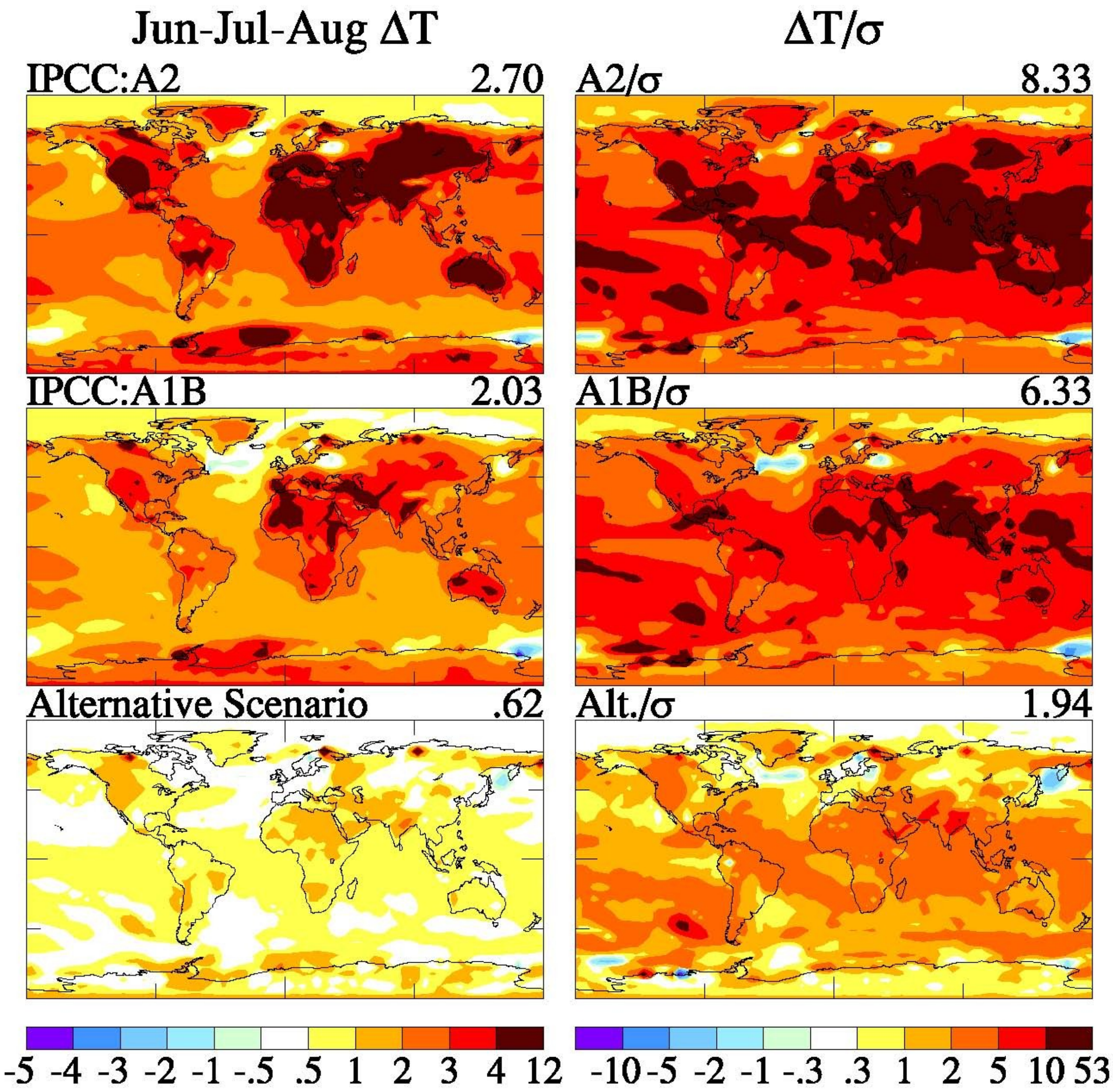


Source: Hansen, *Clim. Change*, **68**, 269, 2005.

Regional Climate Change:

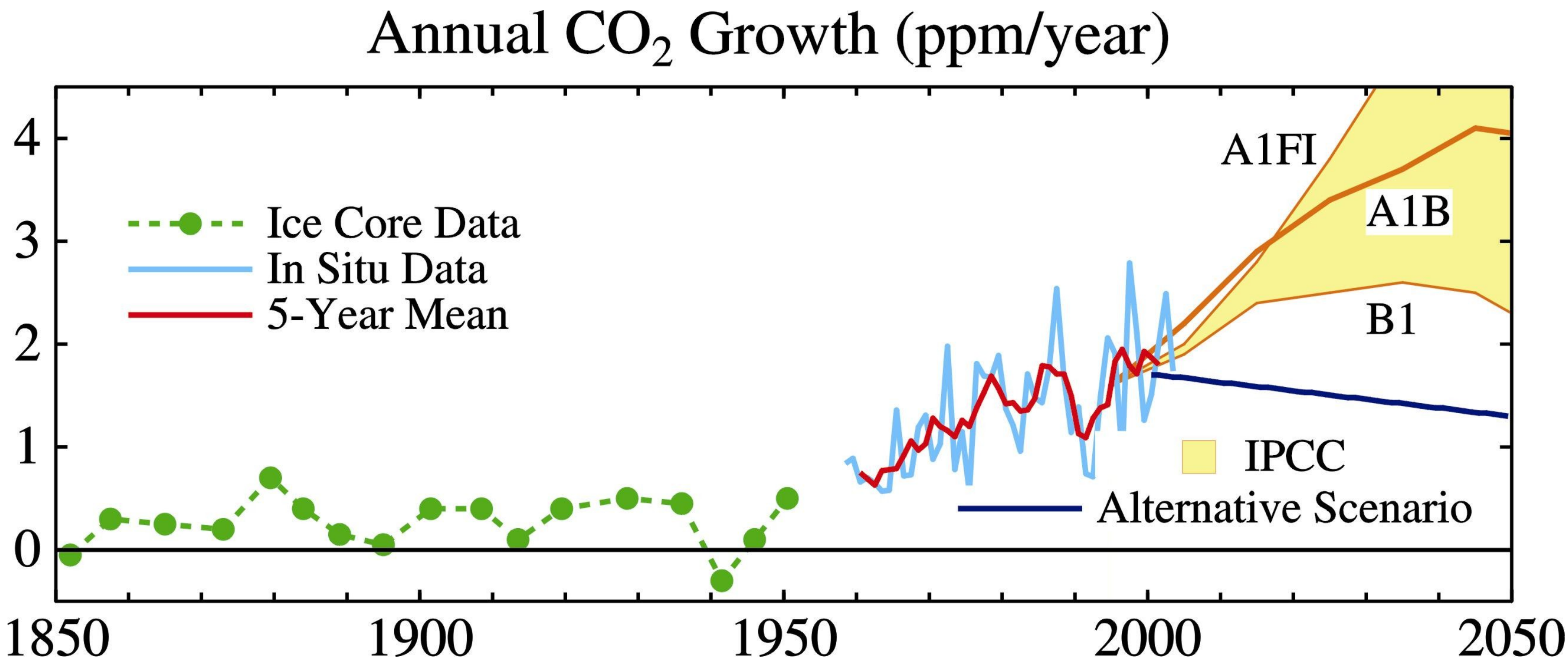
Simulated 2000-2100 Temperature Change

σ is interannual standard deviation of observed seasonal mean temperature for period 1900-2000.



Source: Hansen et al., *J. Geophys. Res.*, to be submitted.

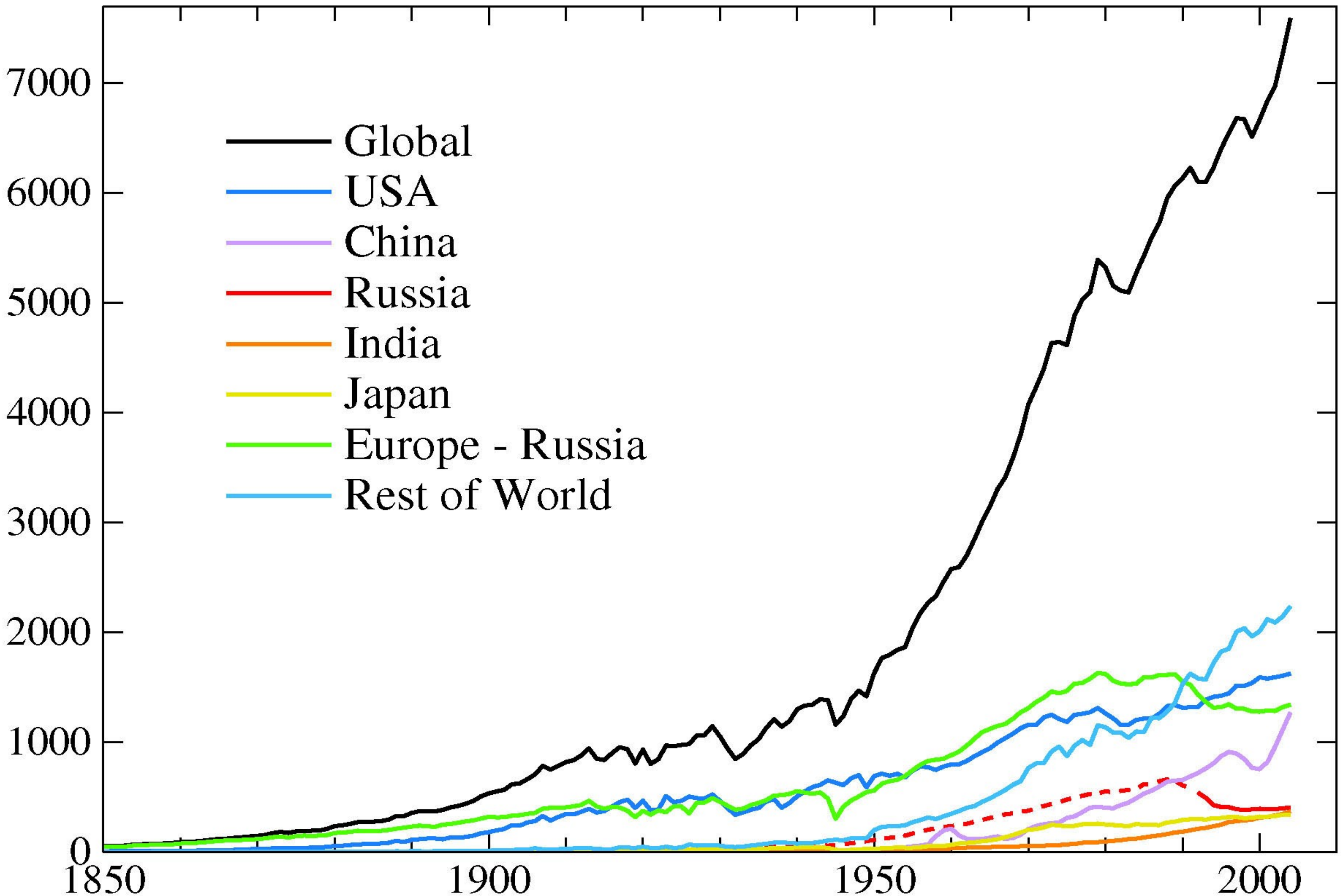
IPCC Scenarios



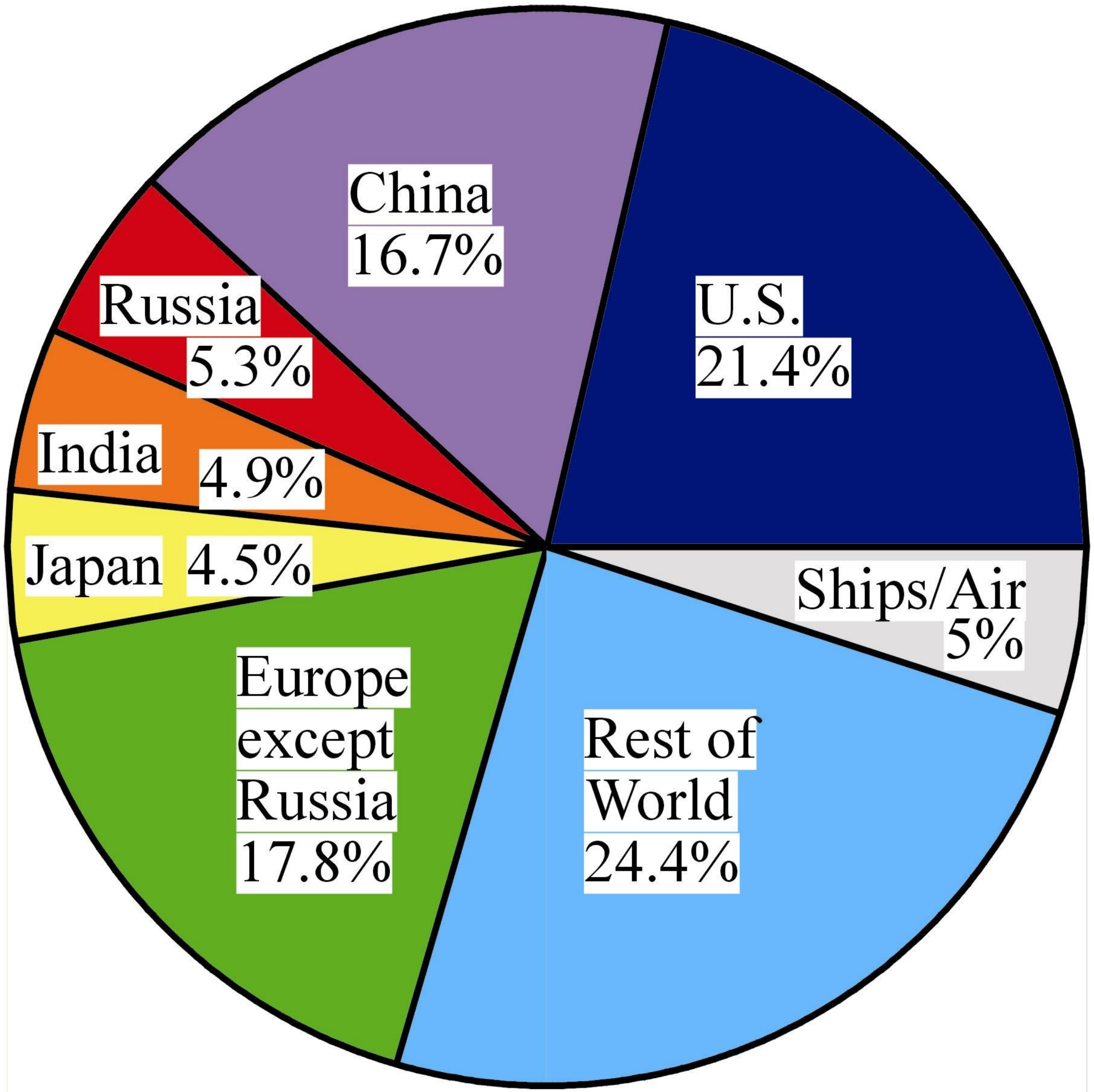
Growth rate of atmospheric CO_2 (ppm/year).

*Source: Hansen and Sato, PNAS, **101**, 16109, 2004.*

Country/Region Fossil Fuel CO_2 Annual Emissions



2004 Portions of CO_2 Emissions



Fossil Fuel CO_2 emissions by source country in 2004.

Source: Hansen et al, J. Geophys. Res., to be submitted

Summary: Is There Still Time?

Yes, But:

- Alternative Scenario is Feasible, But It Is Not Being Pursued
- Action needed now; a decade of BAU eliminates Alternative Scenario
- We Are All in This Together
- Role of the Public & Scientists

Why global change is of interest

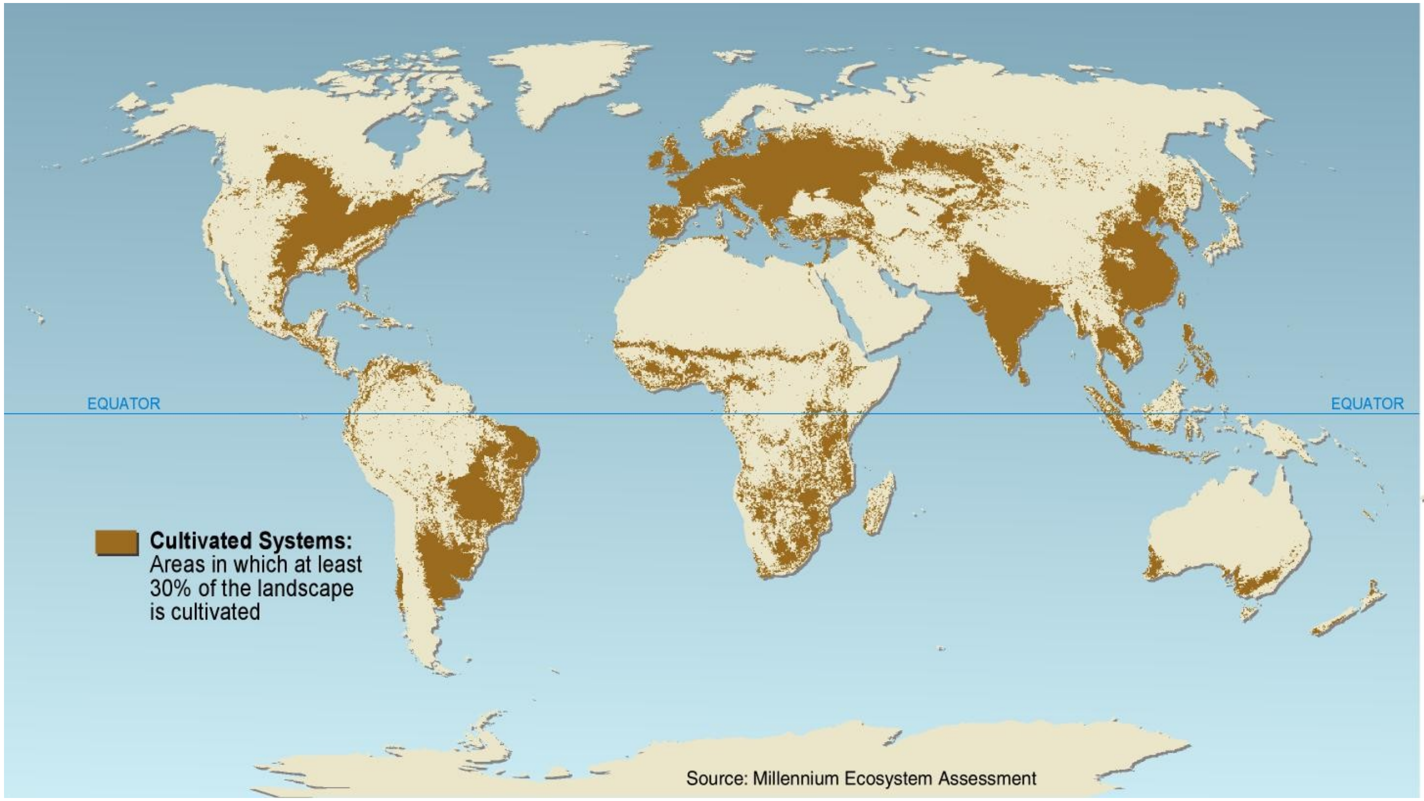
- Climate
- Ecosystems
- Economics
- Politics, national security, cultural developments...

Ecosystems

- Millenium Ecosystems Assessment
  - http://www.maweb.org/en/index.aspx
- Newfoundland cod fishery

Unprecedented change in structure and function of ecosystems

More land was converted to cropland in the 30 years after 1950 than in the 150 years between 1700 and 1850.

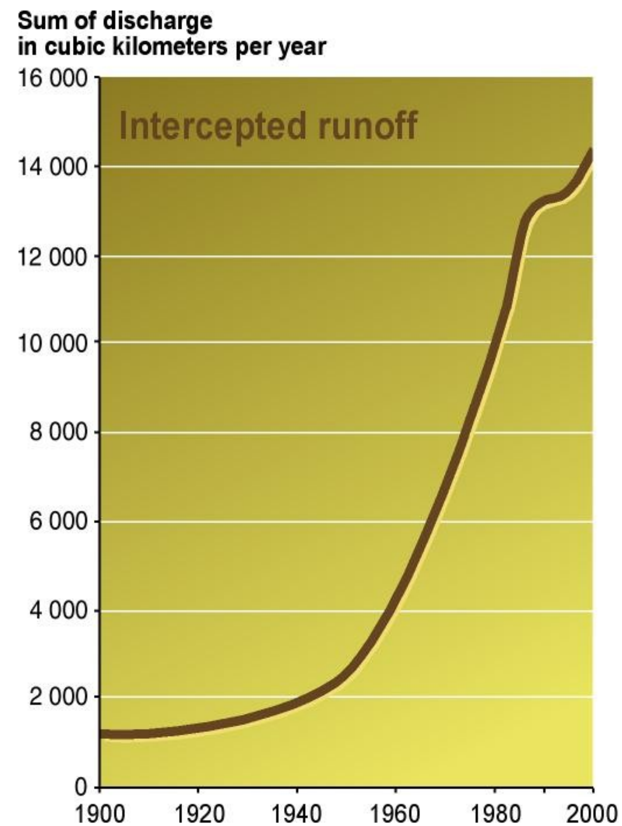


Cultivated Systems in 2000 cover 25% of Earth's terrestrial surface

(Defined as areas where at least 30% of the landscape is in croplands, shifting cultivation, confined livestock production, or freshwater aquaculture)

Unprecedented change: Ecosystems

- 20% of the world's coral reefs were lost and 20% degraded in the last several decades
- 35% of mangrove area has been lost in the last several decades
- Amount of water in reservoirs quadrupled since 1960
- Withdrawals from rivers and lakes doubled since 1960

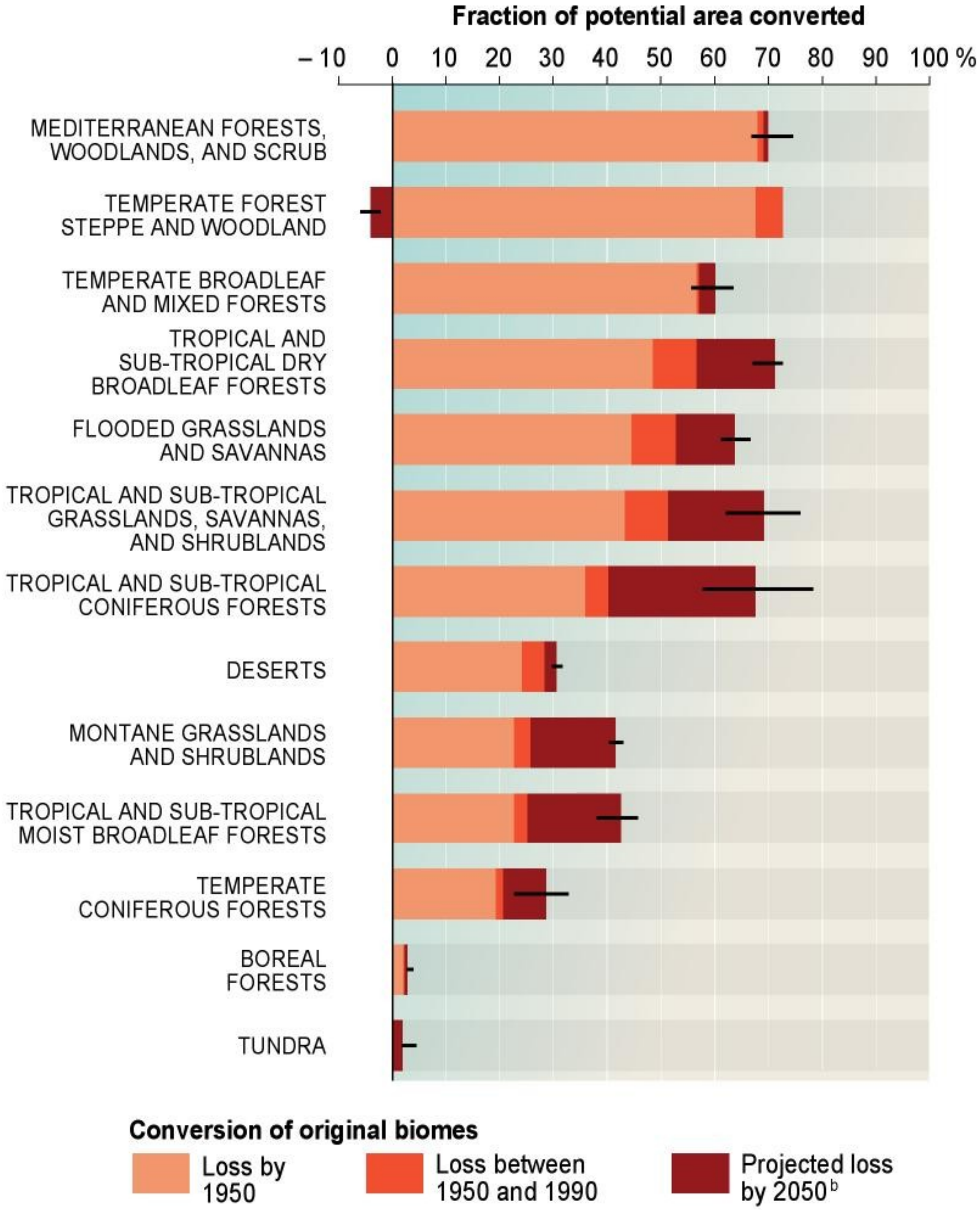


Intercepted Continental Runoff: 3-6 times as much water in reservoirs as in natural rivers

(Data from a subset of large reservoirs totaling ~65% of the global total storage)

Unprecedented change: Ecosystems

- 5-10% of the area of five biomes was converted between 1950 and 1990
- More than two thirds of the area of two biomes and more than half of the area of four others had been converted by 1990



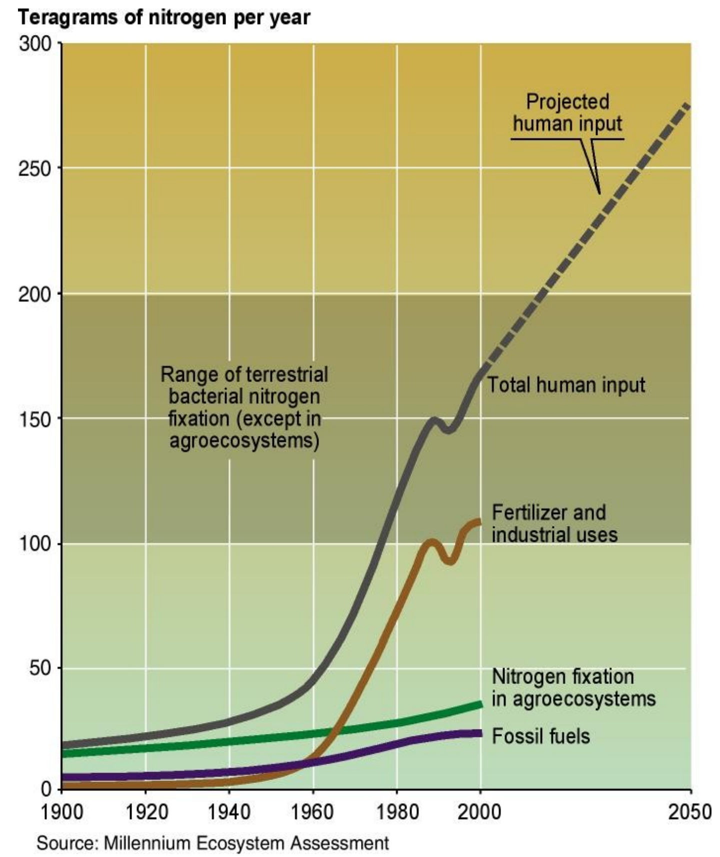
Unprecedented change: Biogeochemical Cycles

Since 1960:

- Flows of biologically available nitrogen in terrestrial ecosystems doubled
- Flows of phosphorus tripled

> 50% of all the synthetic nitrogen fertilizer ever used has been used since 1985

60% of the increase in the atmospheric concentration of CO_2 since 1750 has taken place since 1959

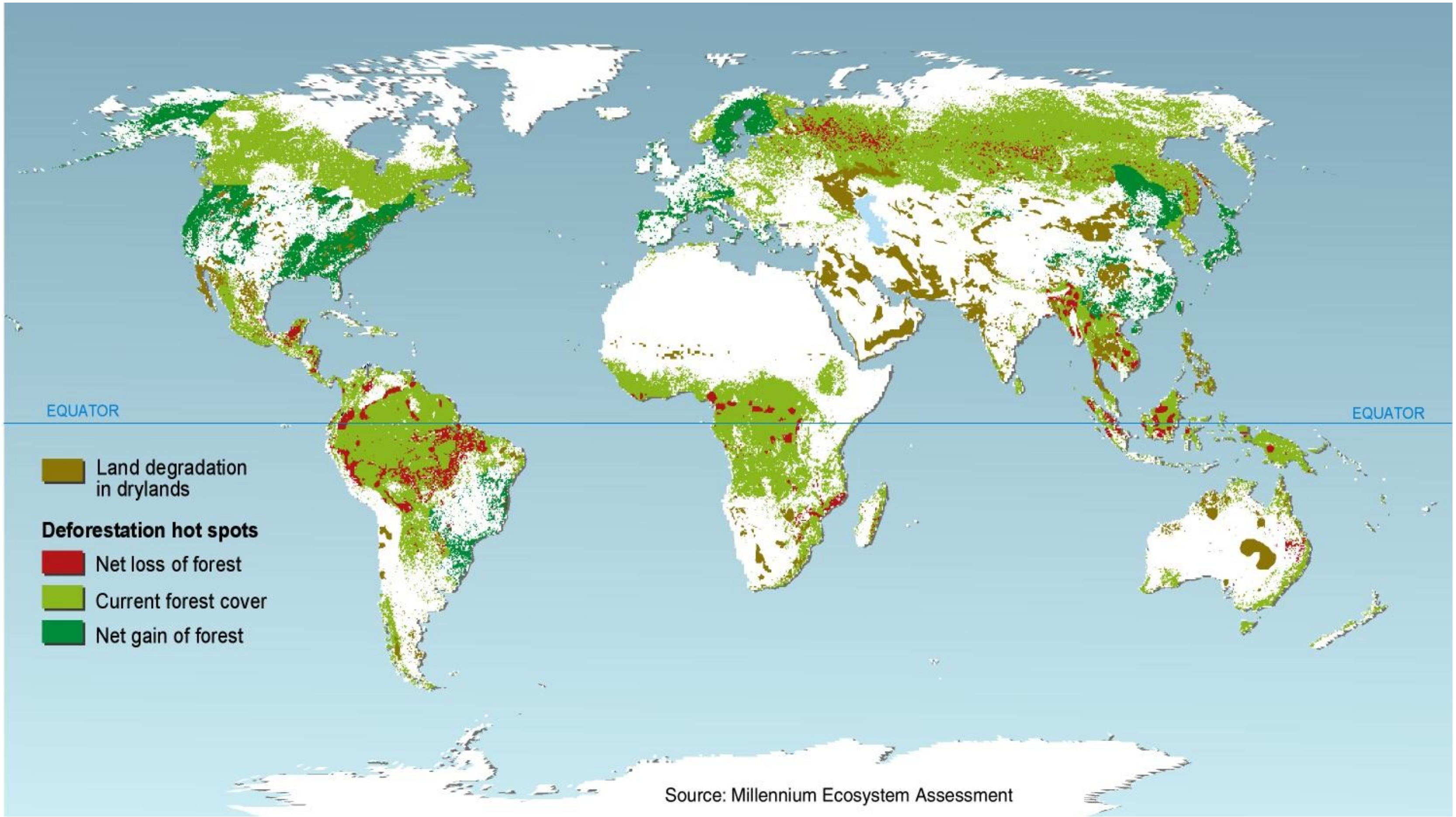


Human-produced Reactive Nitrogen

Humans produce as much biologically available N as all natural pathways and this may grow a further 65% by 2050

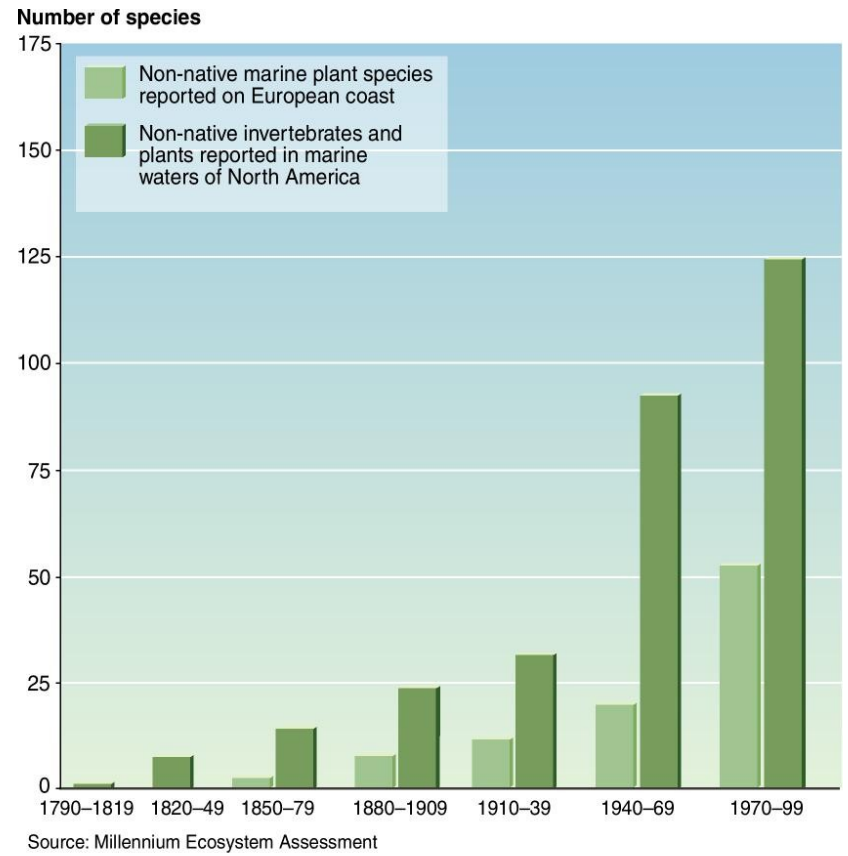
Some ecosystem recovery now underway but high rates of conversion continue

- Ecosystems in some regions are returning to conditions similar to their pre-conversion states
- Rates of ecosystem conversion remain high or are increasing for specific ecosystems and regions



Significant and largely irreversible changes to species diversity

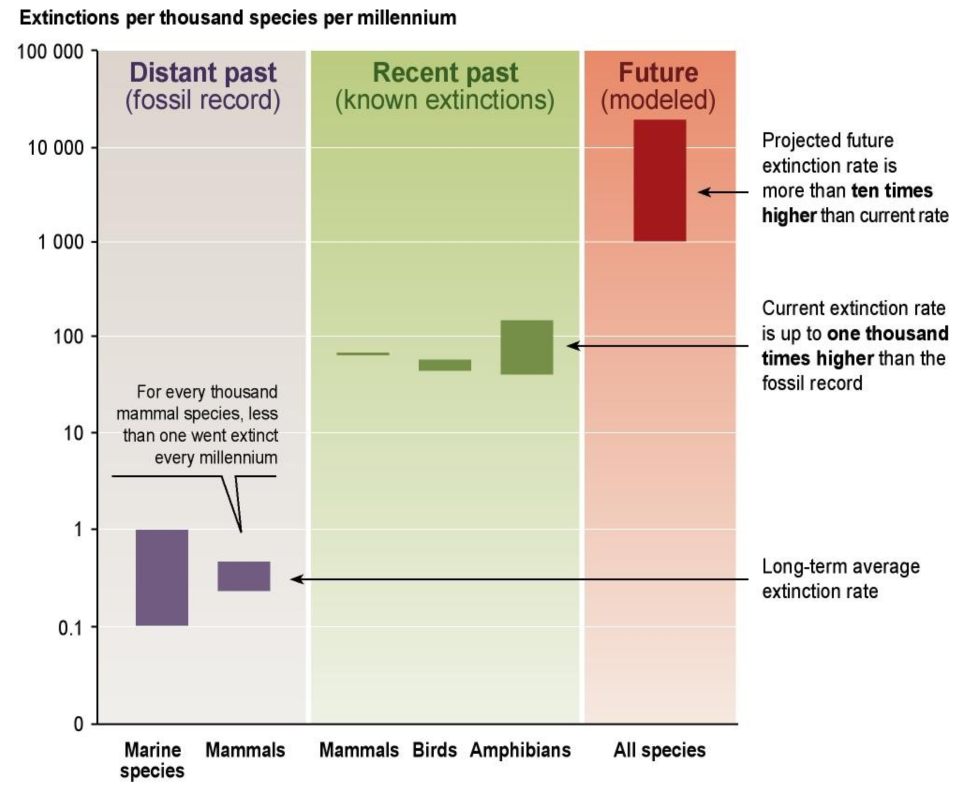
- The distribution of species on Earth is becoming more homogenous
- The population size or range (or both) of the majority of species across a range of taxonomic groups is declining



Growth in Number of Marine Species Introductions in North America and Europe

Significant and largely irreversible changes to species diversity

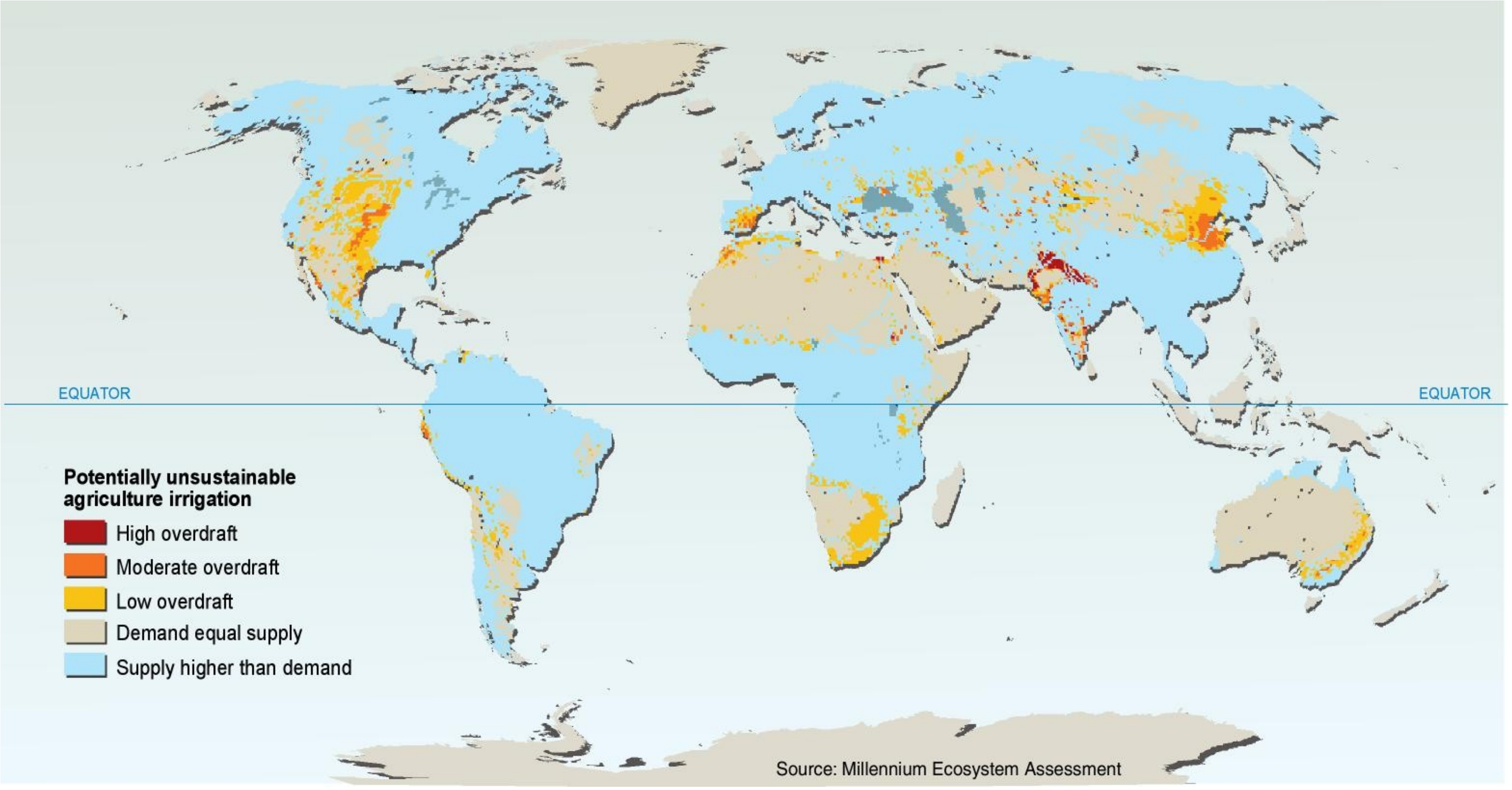
- Humans have increased the species extinction rate by as much as 1,000 times over background rates typical over the planet's history (*medium certainty)*
- 10–30% of mammal, bird, and amphibian species are currently threatened with extinction (*medium to high certainty)*



Source: Millennium Ecosystem Assessment

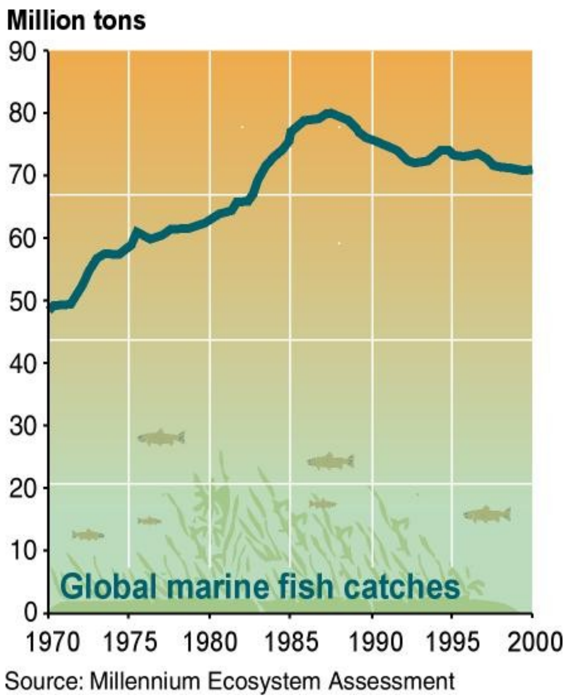
Water

- 5 to possibly 25% of global freshwater use exceeds long-term accessible supplies (*low to medium certainty)*
- 15 - 35% of irrigation withdrawals exceed supply rates and are therefore unsustainable (*low to medium certainty)*

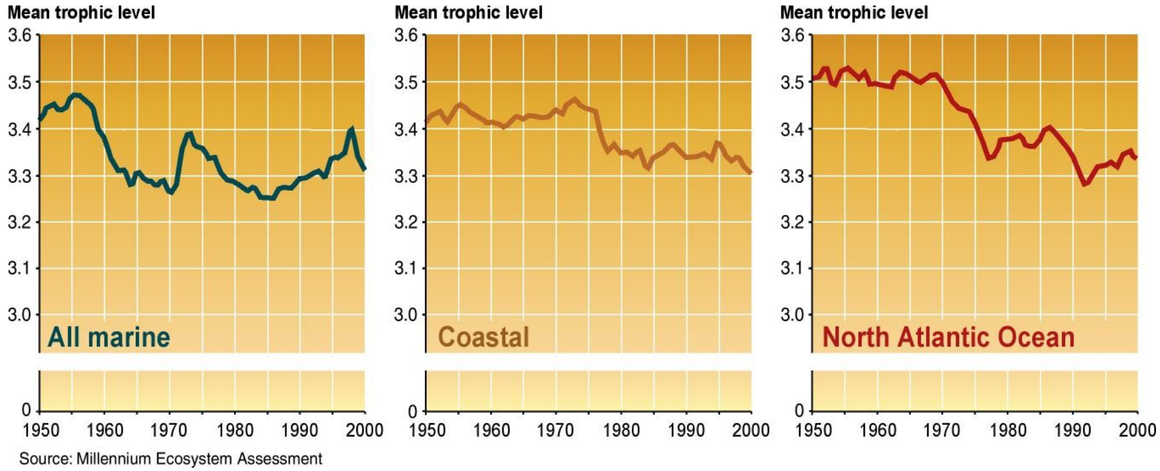


Capture Fisheries

25% of commercially exploited marine fish stocks are overharvested (*high certainty)*



Marine fish harvest declining since the late 1980s



Trophic level of fish captured is declining in marine and freshwater systems

Example – Newfoundland cod fisher

Why global change is of interest

- Climate
- Ecosystems
- Economics
- Politics, national security, cultural developments...

Economics

- Overview of the Stern report (2006)
- See readings

The Economics of Climate Change

Nicholas Stern

15 November 2006

Presentation to the Convention Dialogue, Nairobi

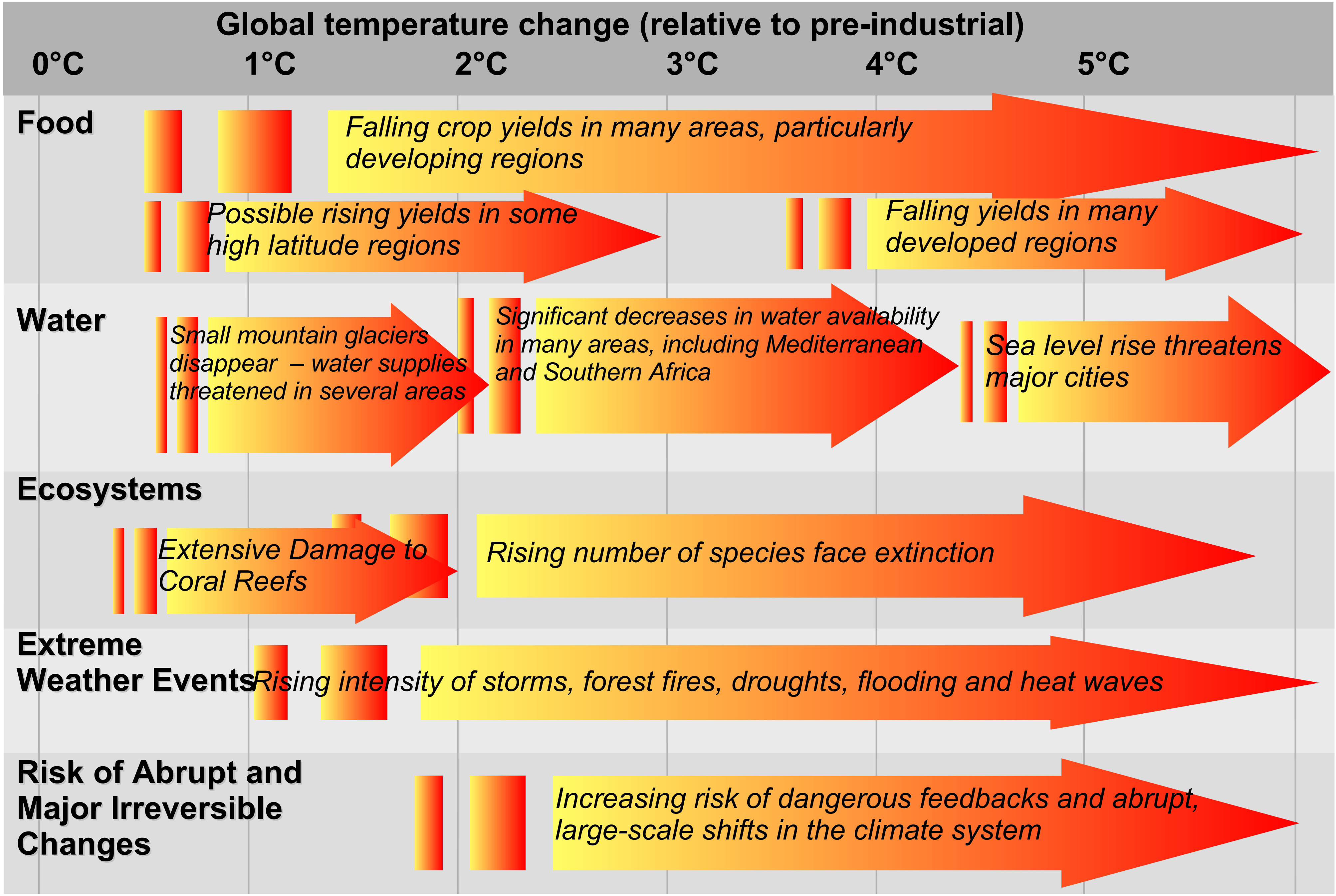
What is the **economics of climate change** and how does it depend on the **science**?

Analytic foundations

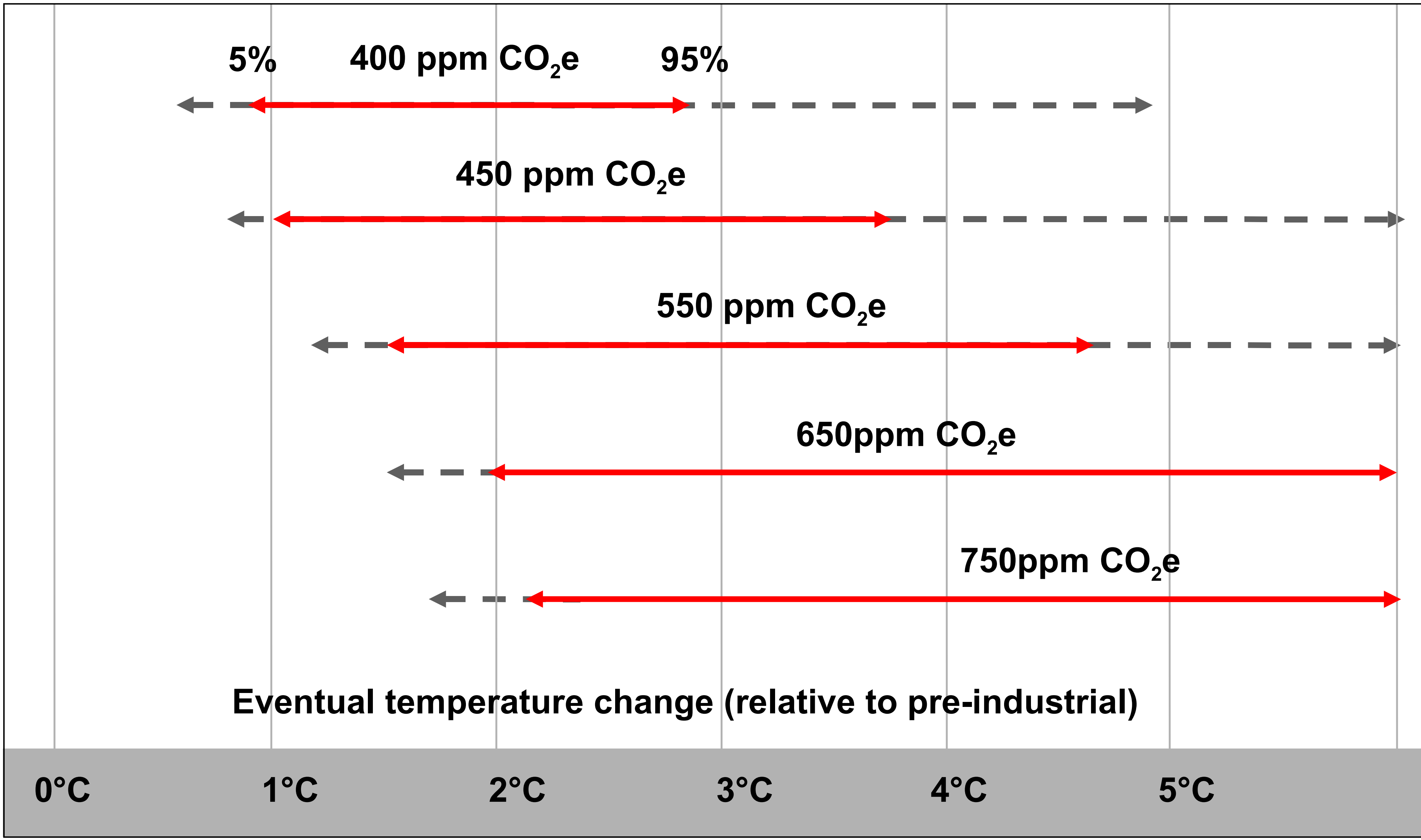
Climate change is an externality with a difference:

- Global
- Long-term
- Uncertain
- Potentially large and irreversible

Projected impacts of climate change



Stabilisation and commitment to warming



Aggregate estimates of impacts

- Essential to take account of risk and uncertainty
- Models do not provide precise forecasts
- Models embody a relationship between temperature and economic damage
- Assumptions on discounting and risk aversion affect the results

	Base climate	High Climate
Market impacts	5%	7%
Broad impacts	11%	14%

Adjusting for income inequality raises estimates by at least one quarter

Delaying mitigation is dangerous and costly

Stabilising below 450ppm CO2e would require emissions to peak by 2010 with 6-10% p.a. decline thereafter.

If emissions peak in 2020, we can stabilise below 550ppm CO2e if we achieve annual declines of 1 – 2.5% afterwards.

A 10 year delay almost doubles the annual rate of decline required.

Given the costs of impacts, taking urgent action is good economics

Expected cost of cutting emissions consistent with a 550ppm CO_2e stabilisation trajectory averages 1% of GDP per year.

- Resource cost: 1% of GDP in 2050, in range –1% to +3.5%.
- Macroeconomic models: 1% of GDP in 2050, in range +/- 3%.

Costs will not be evenly distributed:

- Competitiveness impacts can be reduced by acting together.

There will be opportunities and co-benefits:

- New markets will be created: worth over $500bn a year by 2050
- Climate policy consistent with energy access, energy security, air quality.

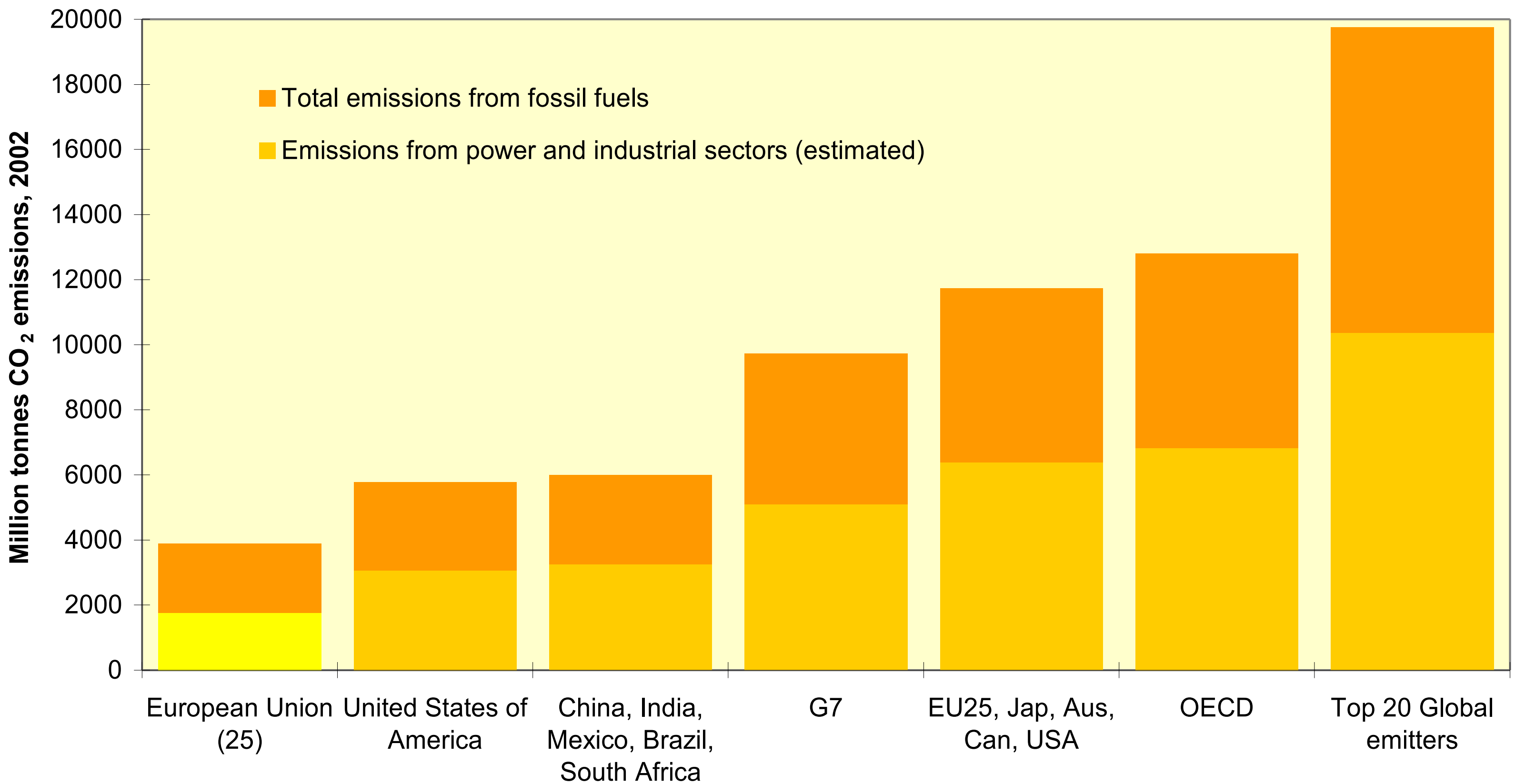
Strong mitigation is fully consistent with the aspirations for growth and development in poor and rich countries.

Economic principles for international action

Effective action requires:

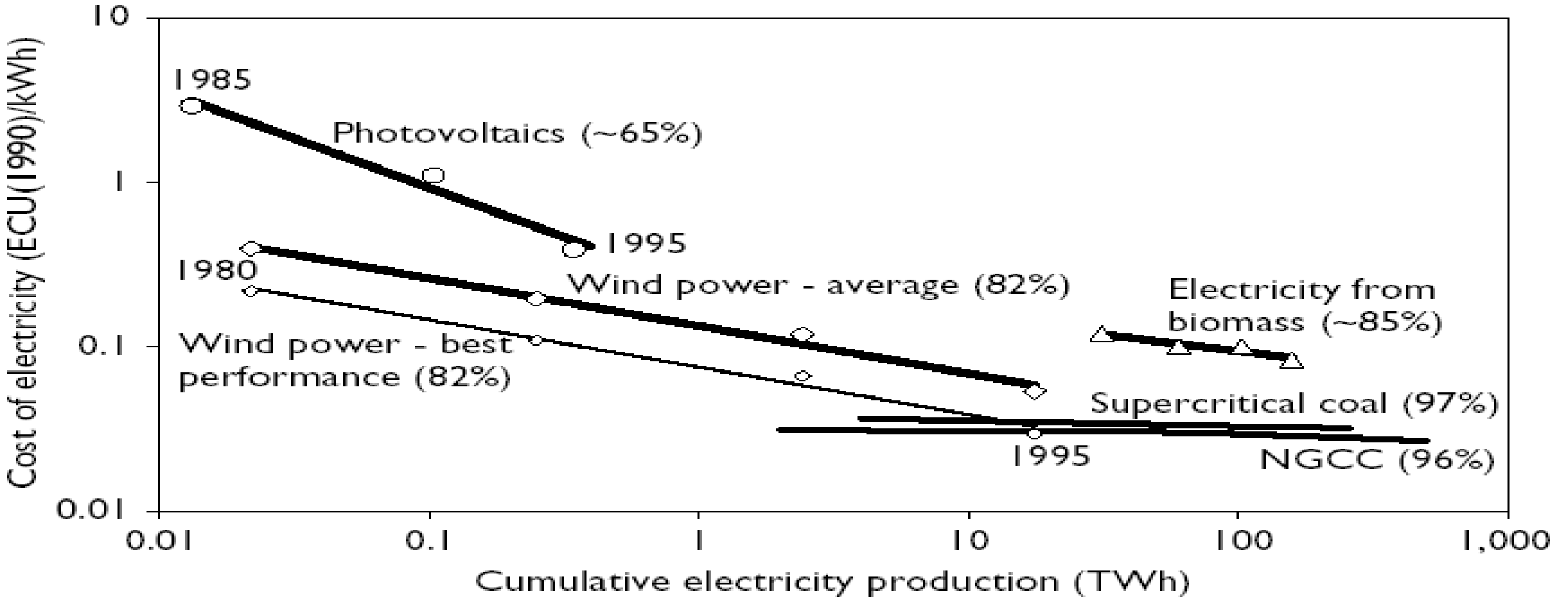
- Long-term quantity goals to limit risk; short-term flexibility to limit costs
- A broadly comparable global price for carbon
- Cooperation to bring forward technology
- Regulation, standards and persuasion
- Equitable distribution of effort
- Transparency and mutual understanding of actions and policies

Global carbon markets can be expanded



- Increasing the size of global carbon markets – by expanding or linking schemes globally – and ambitious global emissions reductions goals can drive large flows across countries and promote action in developing countries

Technology needs more than a carbon price

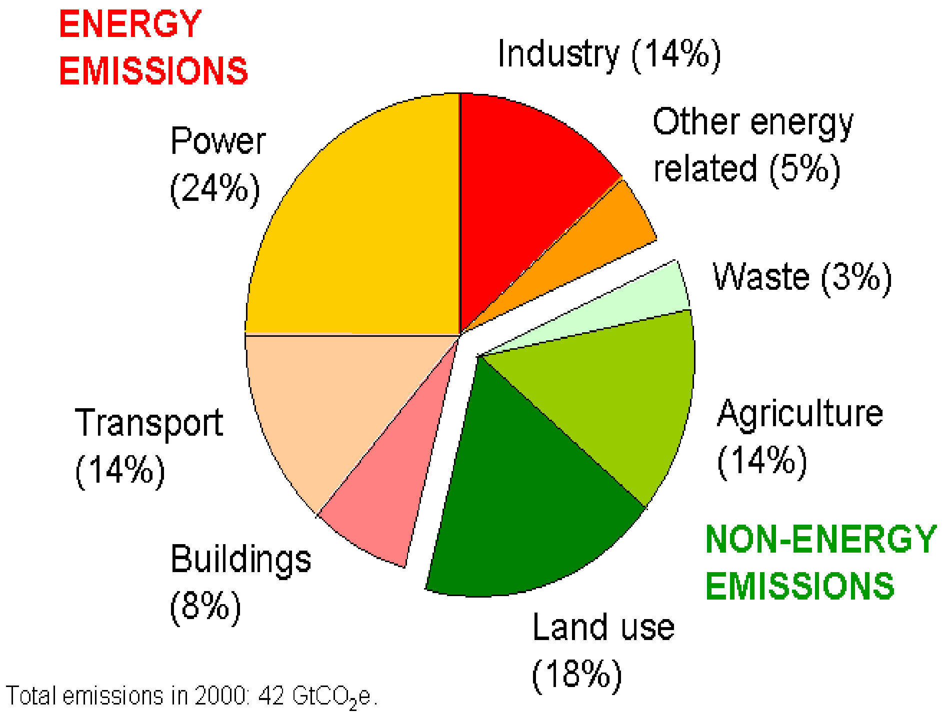


Carbon price alone not enough to bring forward the technologies we need

International co-operation on technology can take many forms:

- Global public R&D funding should double, to around $20 bn
- Co-ordination and increase of deployment incentives
- Product standards eg for appliances, vehicles

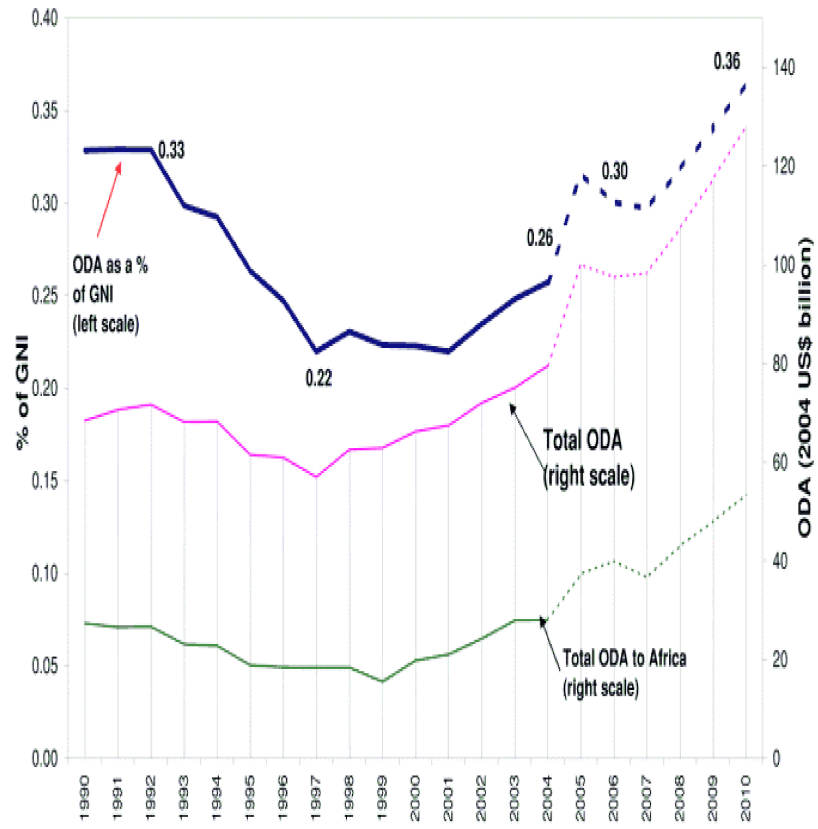
Avoiding deforestation



- Curbing deforestation is highly cost-effective
- Forest management should be shaped and led by nation where the forest stands
- Large-scale pilot schemes could help explore alternative approaches to provide effective international support

Adaptation

- Development increases resilience
- International action also has a key role in supporting global public goods for adaptation
  - Disaster response
  - Crop varieties and technology
  - Forecasting climate and weather
- Adaptation will put strong pressure on developing country budgets and ODA: essential to meet 2010 and 2015 commitments



Conclusions

Unless emissions are curbed, climate change will bring high costs for human development, economies and the environment

– Concentrations of 550ppm CO_2e and above are associated with high risks of serious economic impacts
– Concentrations of 450ppm CO_2e and below will be very difficult to achieve given where we are now and given current and foreseeable technology

Limiting concentrations within this range is possible. The costs are modest relative to the costs of inaction, and consistent with growth.

Decisive and strong international action is urgent: delay means greater risks and higher costs.

STERN review ON THE ECONOMICS OF CLIMATE CHANGE

www.sternreview.org.uk

Stern’s estimates of damages of temperature change

- Earlier models used scenario of 2-3 degree Celsius warming, predicted losses equal to 0-3% of annual gross world product (GWP).
- Recent evidence suggests greater climate change, possible 5-6 degrees. Existing IAMs show a loss (including only market losses) of over 5% of GWP at these levels.
- Including non-market losses (direct impacts on health and environment) increases estimate to 15% of GWP.
- Costs fall disproportionately on poor. Weighting these costs more heavily increases estimate to 20% of GWP.

Cost estimates of stabilization

- Stabilization at or below 550ppm requires emissions to peak within the next 10-20 years and then fall at an annual rate of 1-3%.
- Global emissions by 2050 would have to be 25% below current levels
- Since world economy may be 3-4 times current size by 2050, emissions per $ output in 2050 would have to be ¼ of current levels.
- They estimate that this would cost about 1% of GWP.
- They conclude that a stabilization target of 550 ppm is reasonable; a more ambitious target might be too costly.

Overview of Today

- **Introductory admin**
- Motivation – why this is interesting
- Modelling – potential and limitations

Role of Computational Models

- Force us to be explicit about theories
- Show where data is lacking/inadequate
- Prediction (testable?)
- Allow “what if” experiements *in-silico*
- Bring diverse disciplines/data-sources together
- Allow greater complexity than analytical methods
- Model system behaviour, not just data

Limitations of Computational Models

- Is there enough data to constrain the model?
- Model doesn't capture key complexities
  - e.g., ice-sheet dynamics, fast feedbacks
- Does the model provoke insights
  - level of detail is key – less is more, or not!
- Can provide a false sense of certainty
  - ensemble runs in climate modeling
  - really should be modeling probability distributions