Reminders

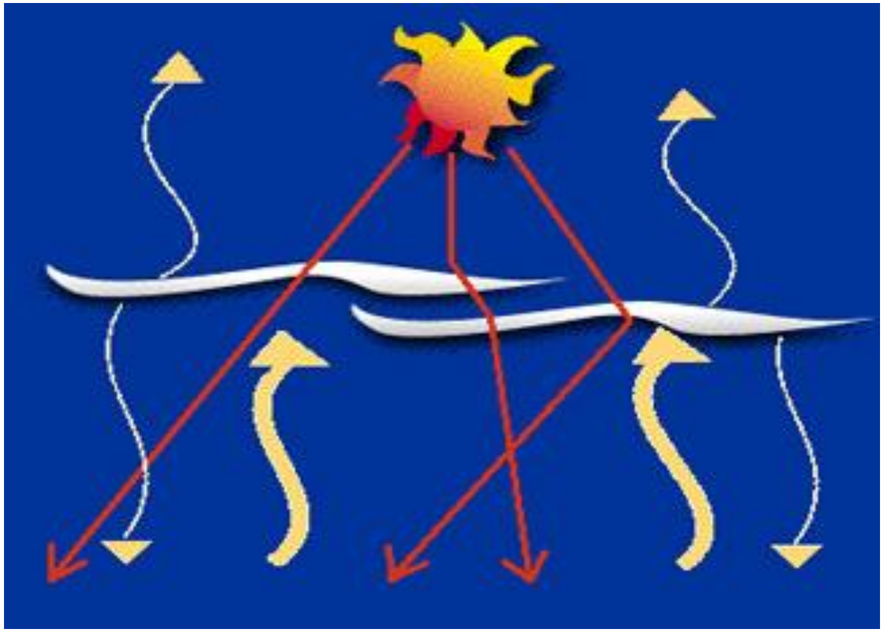
- **Final Exam next week**
- **Via Canvas, Wednesday June 12, 2:30pm – 5pm**
- **Contact me and/or Claire ASAP if you have a valid conflict (graduation, academic event, etc)**

Cloud Forcings and Feedbacks

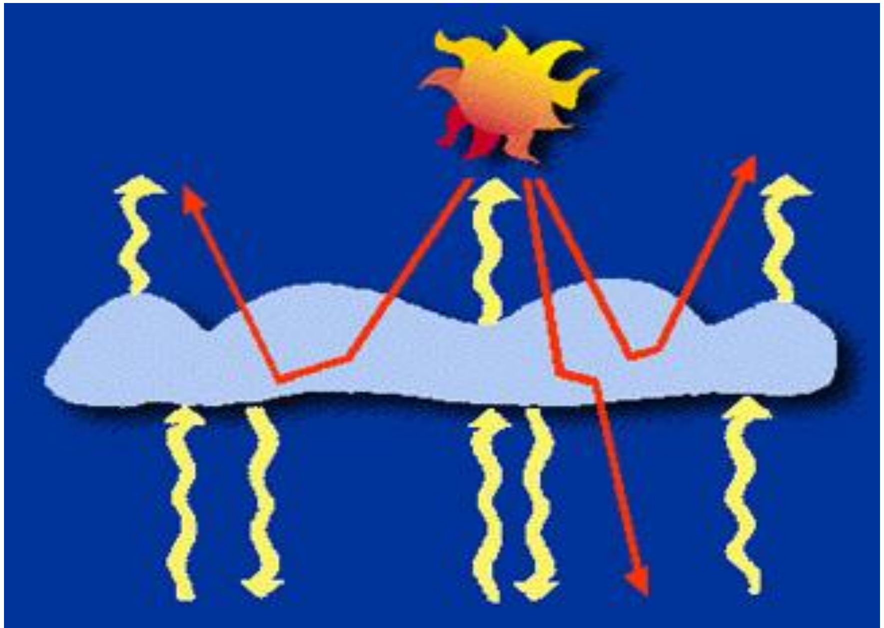
High altitude thin ice clouds
→ Cirrus

Low altitude thick clouds
→ Stratus

Clouds and Climate—a complex problem

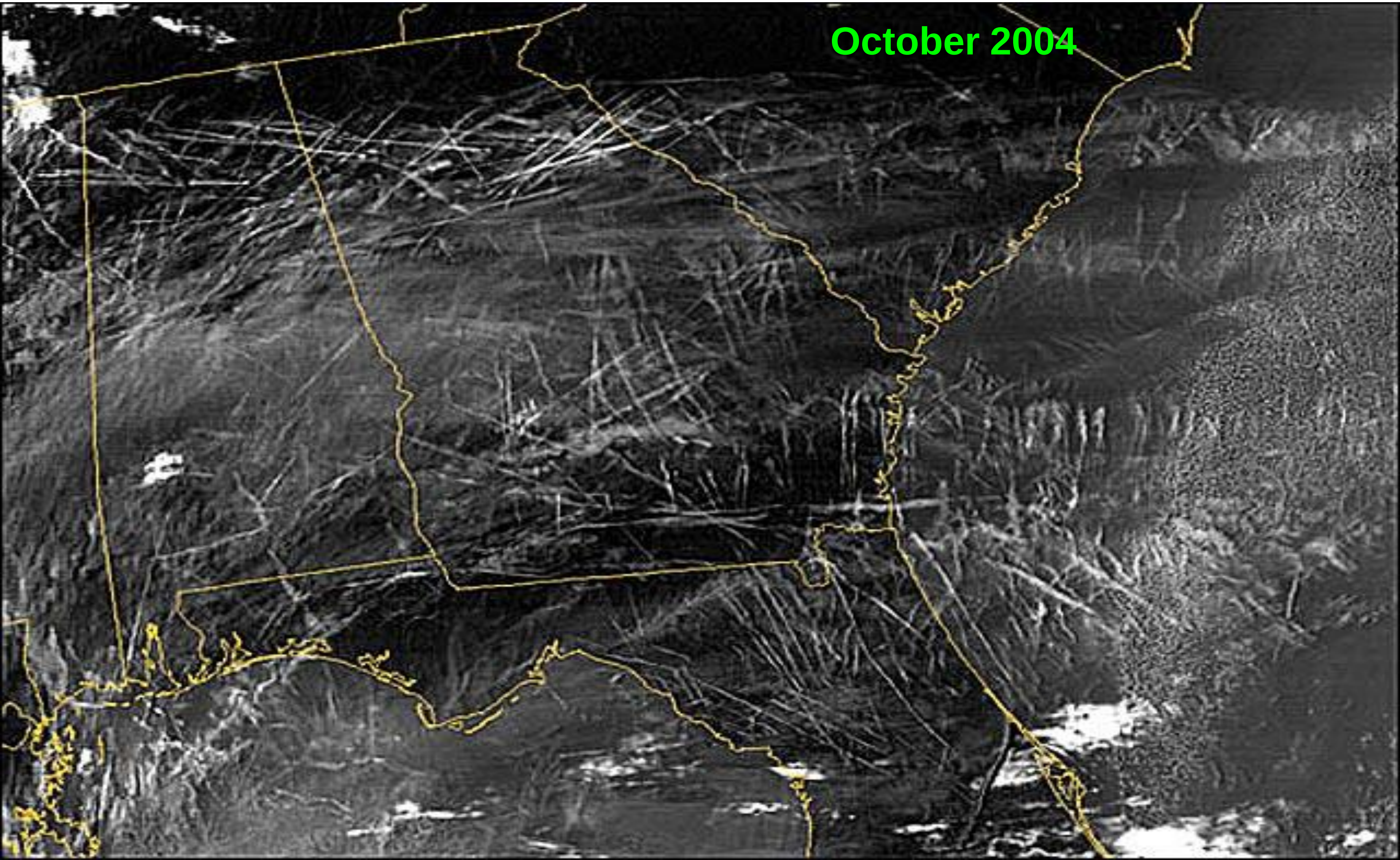


Cirrus: Not so reflective, but absorb IR and emit at cold T



Low Clouds: Reflective, do absorb IR but emit like warm surface.

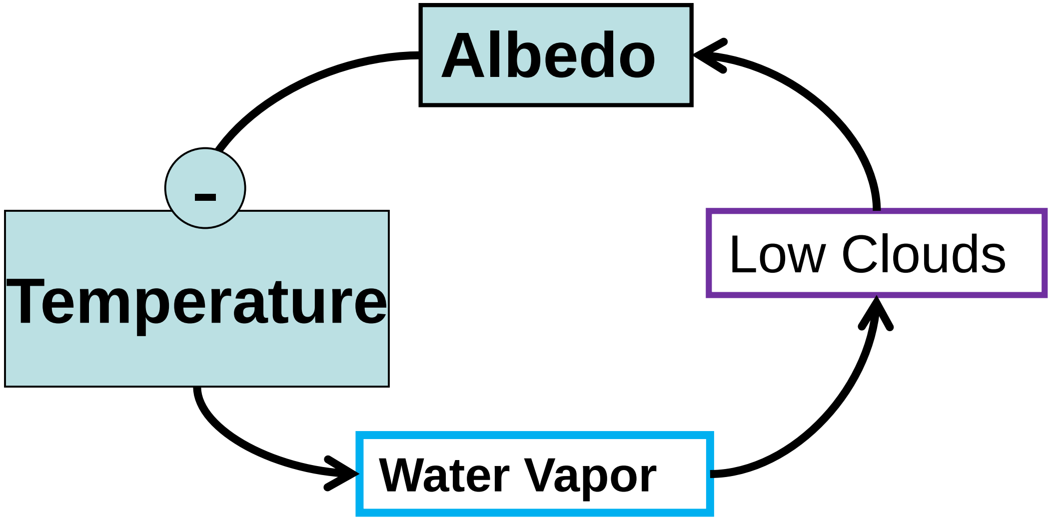
Aviation Contrails—Positive Forcing



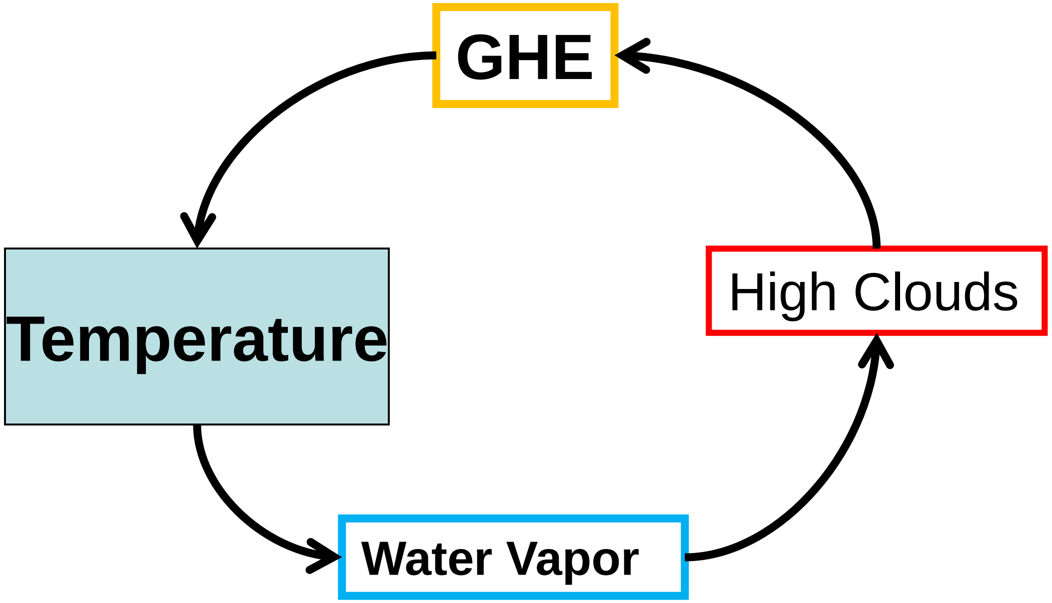
Clouds and Cloud Feedbacks (two examples)

Uncertain!

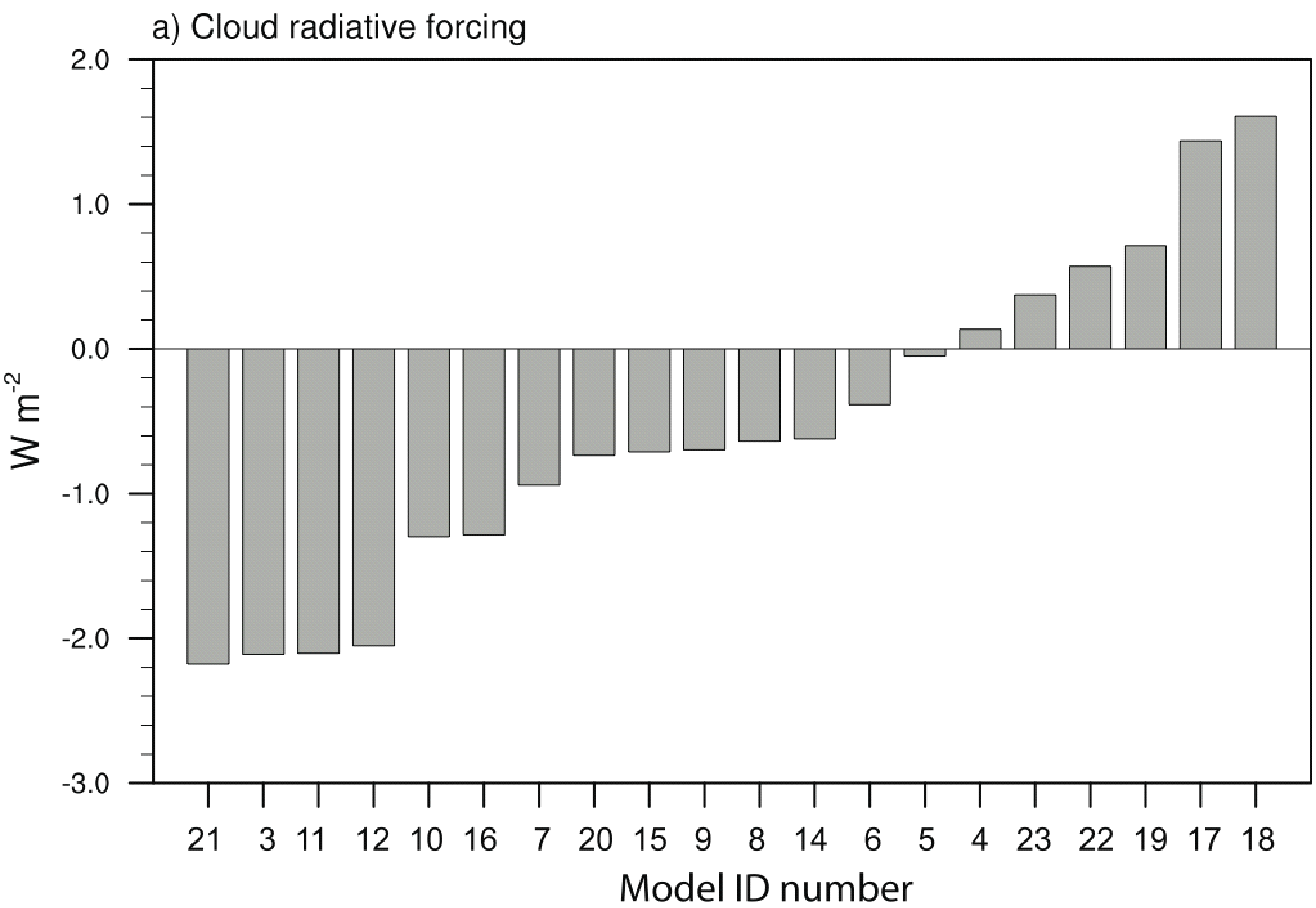
Overall Negative



Overall Positive



Cloud Forcing Predictions by Different Models



IPCC 2007

Impact #3: Cryosphere Melting

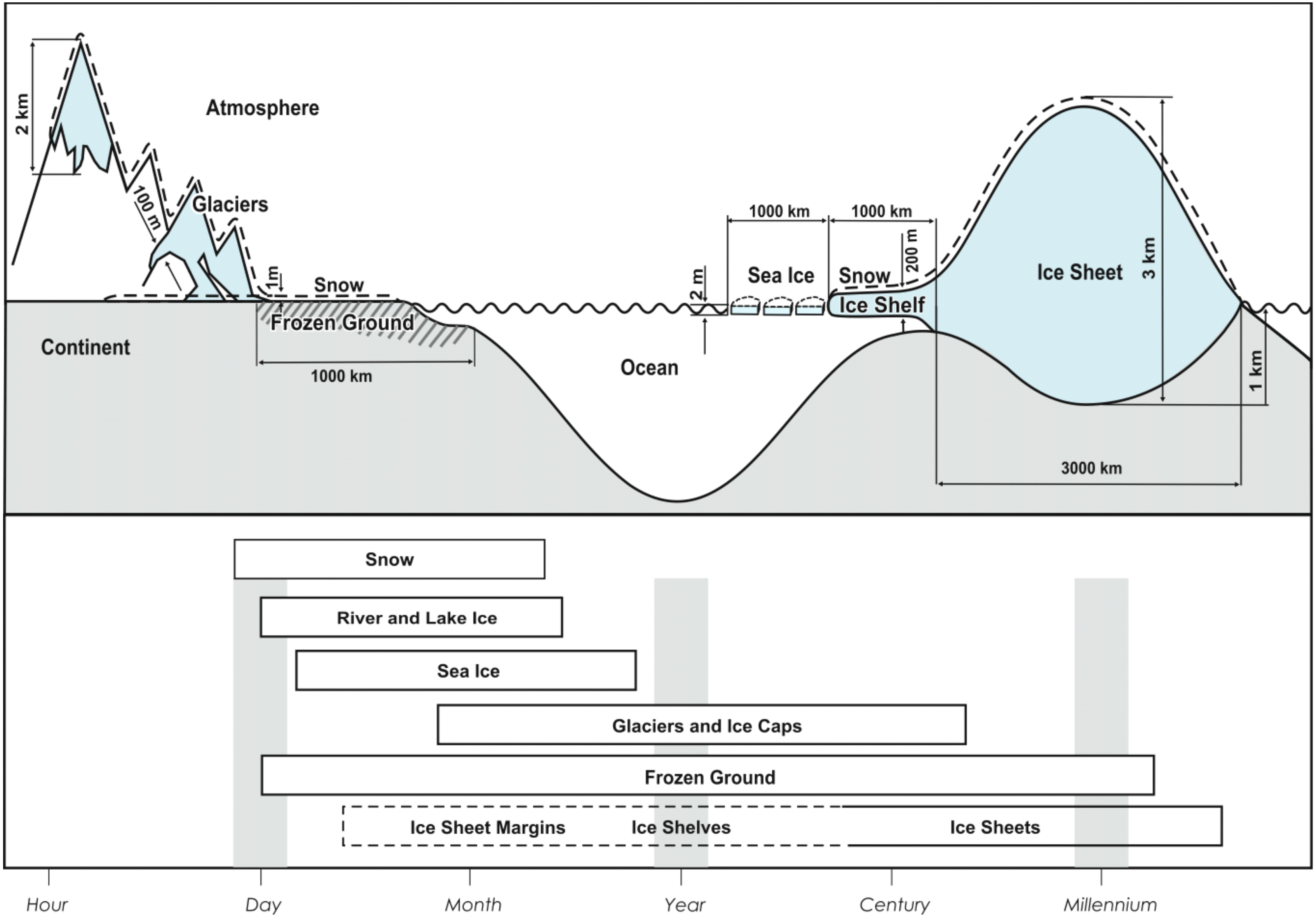
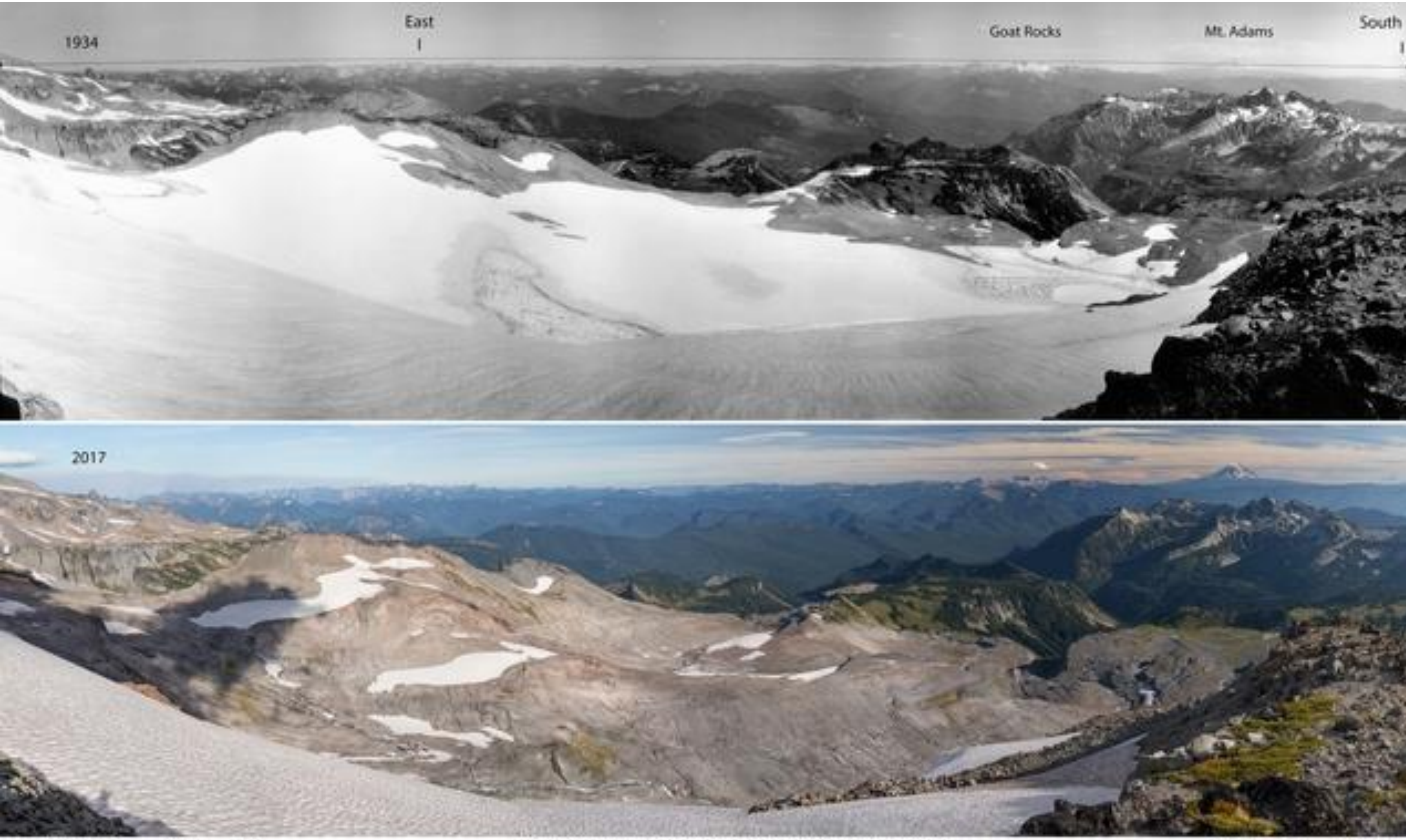


Figure 4.1

Ice Stability and Climate

Mt. Rainier Glaciers



08/08/1934 George B. Clisby, USFS
National Archives and Records Admin.

Historic Photo Comparison from Sugarloaf Rock on Mt. Rainier
Note: Winter 1933-1934 was a low-snowfall year- 316 inches compared to 703 inches in 2016-2017

09/12/2017 John F Marshall
for The Nature Conservancy

Paradise Valley and Stevens

Mt. Rainier Glaciers

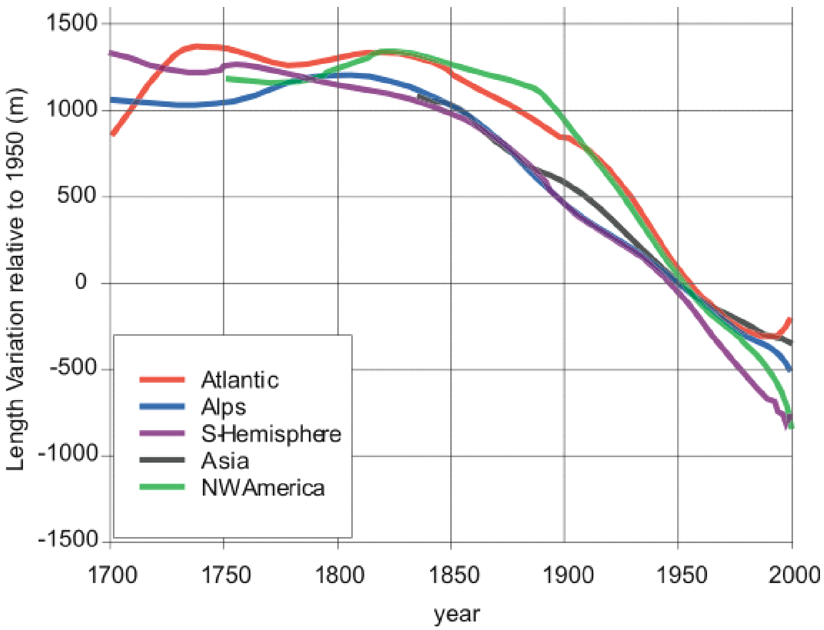
Nisqually

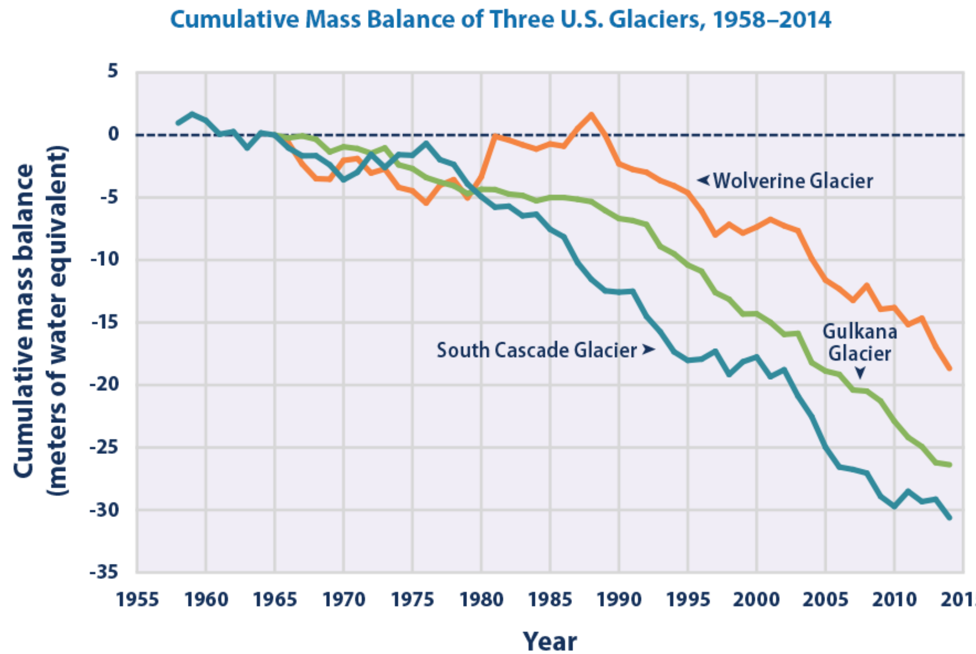
Tropical Glaciers

Qori Kalis

Andes (Peru)

Glacier Lengths





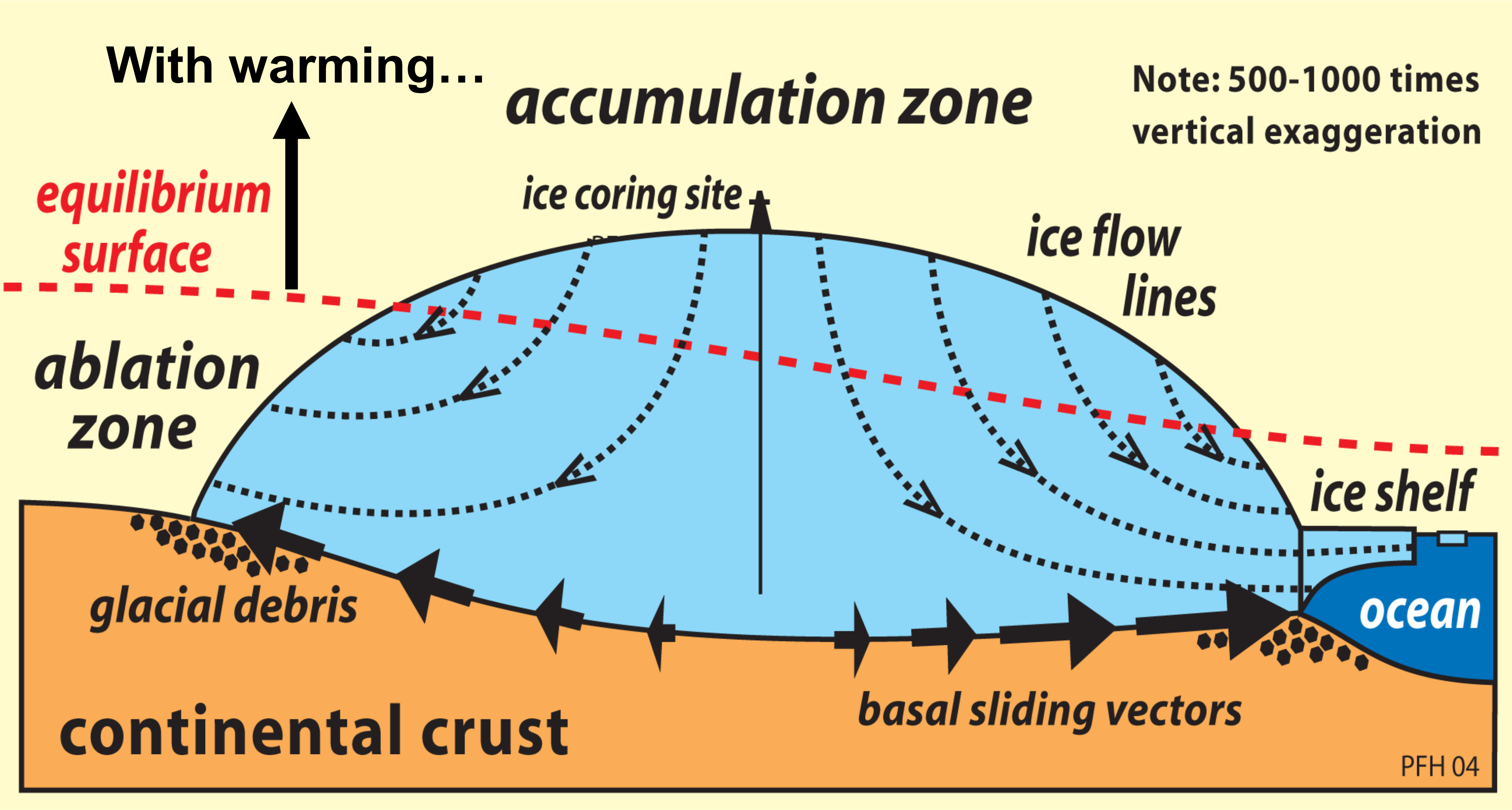
Data sources:

- O'Neel, S., E. Hood, A. Arendt, and L. Sass. 2014. Assessing streamflow sensitivity to variations in glacier mass balance. Climatic Change 123(2):329–341.
- USGS (U.S. Geological Survey). 2015. Water resources of Alaska—glacier and snow program, benchmark glaciers. http://ak.water.usgs.gov/glaciology.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

Ice Stability and Climate

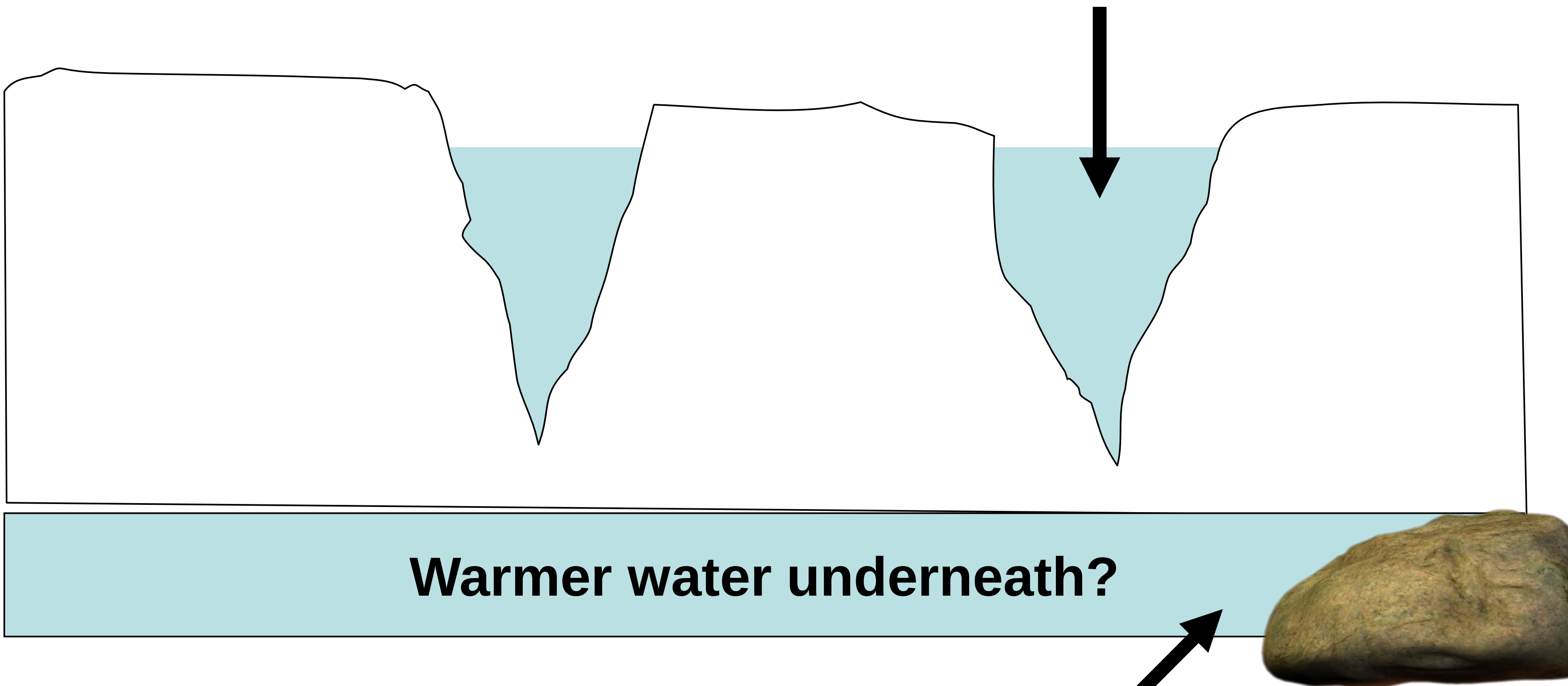
Ice Sheet Dynamics



Ice Sheet/Shelf Instabilities?

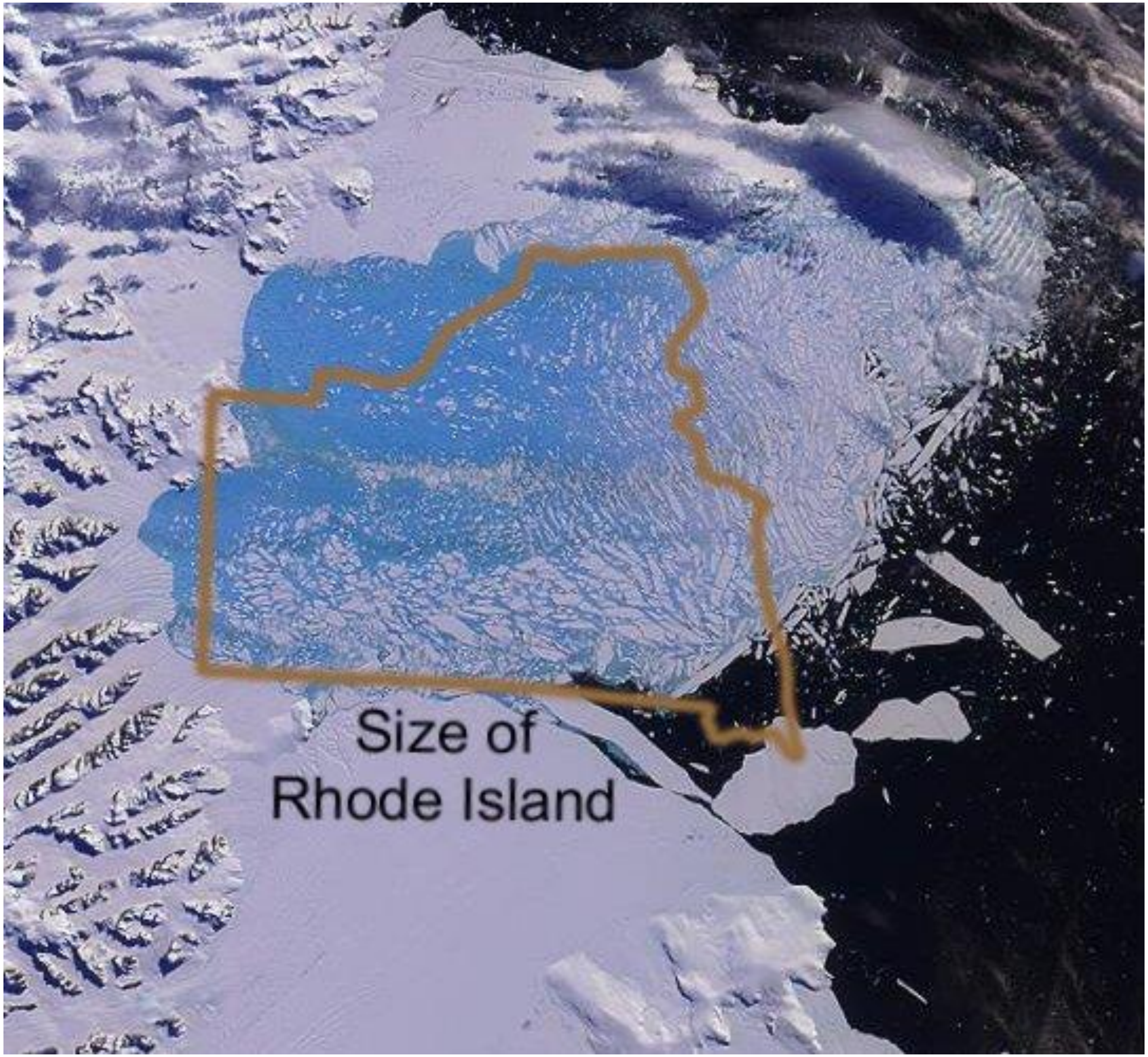
Potential for positive feedbacks and "tipping points"

Surface melt water
→ Lower albedo



Liquid water between ice and rock is slippery

Larsen Ice Shelf Collapse



Impact #3: Cryosphere Melting

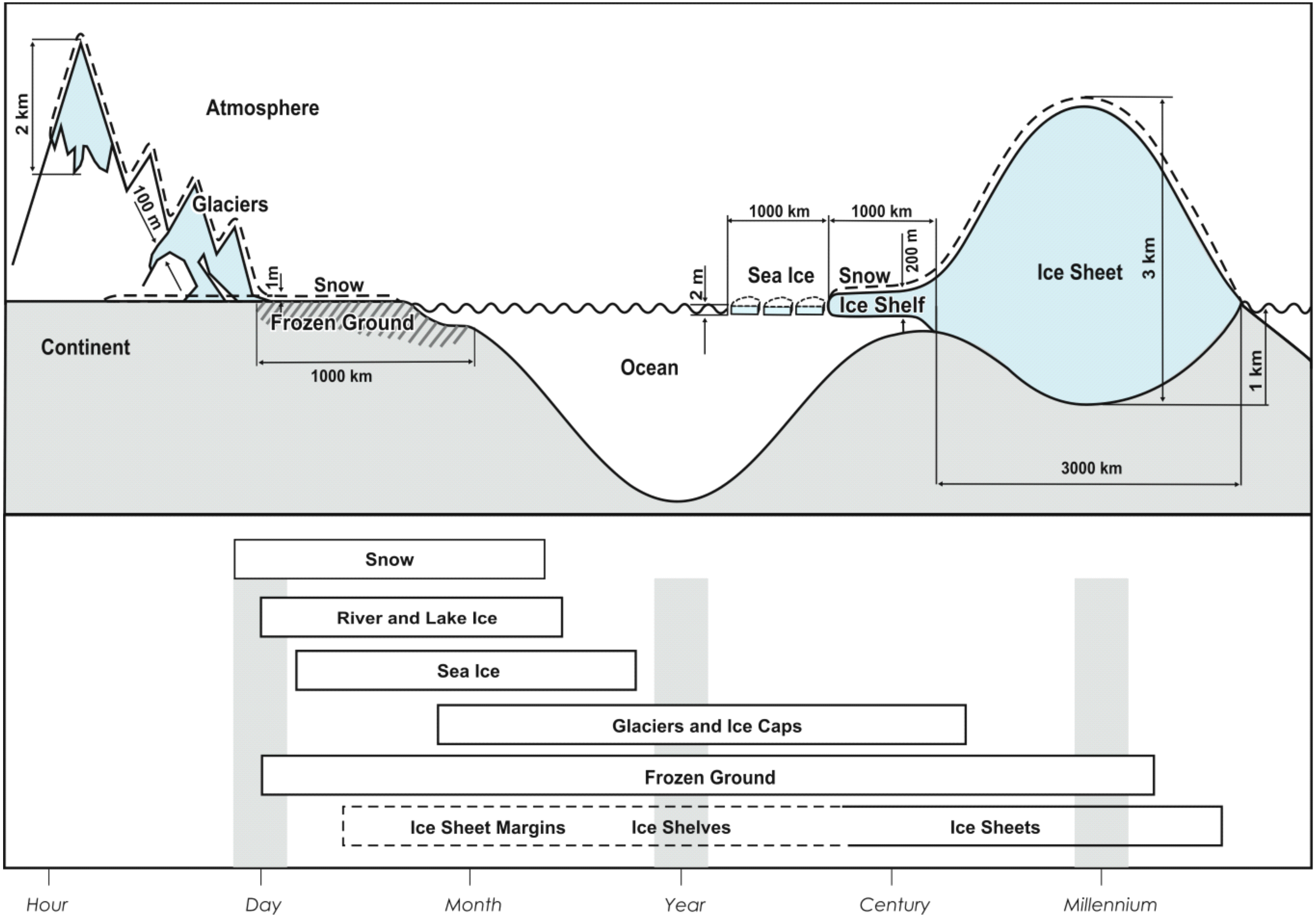
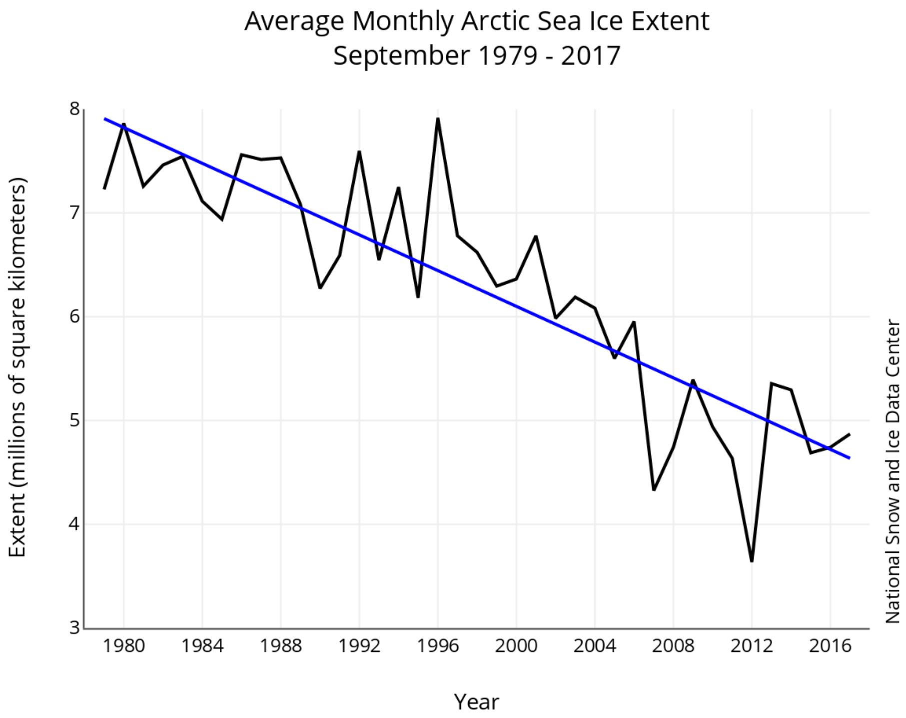
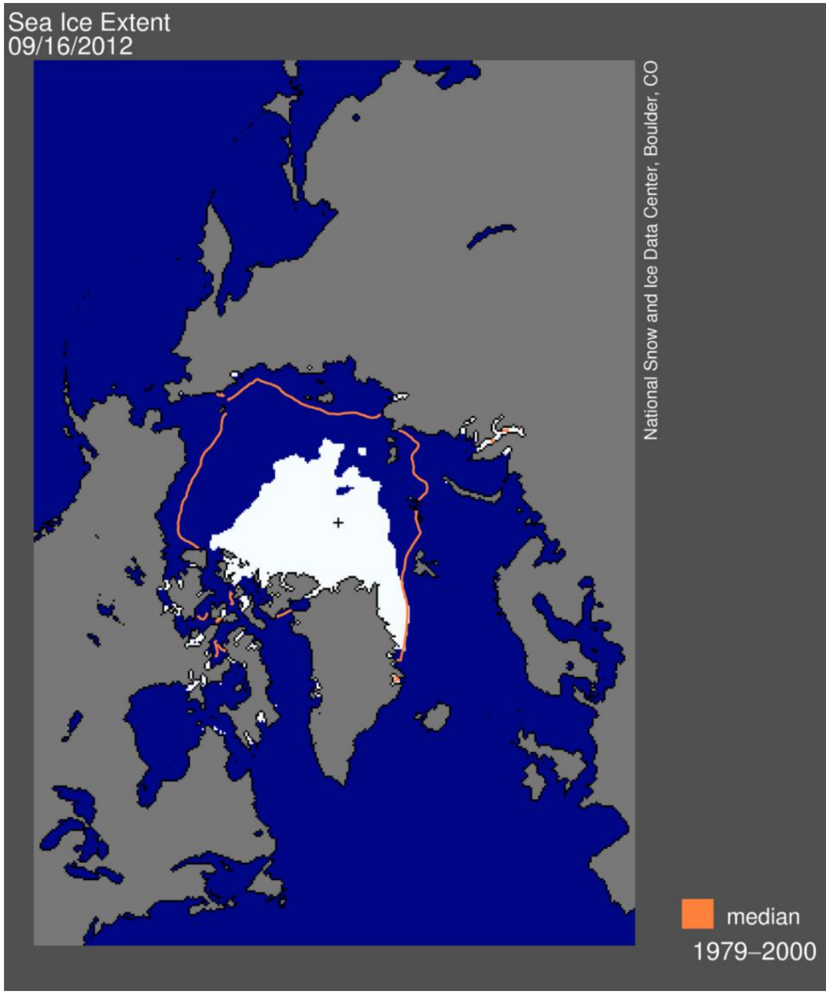


Figure 4.1

Sea Ice Melting

- **Record minimum sea ice extents**
- **Sea ice younger**
- **Young ice is thinner**





Sea-Ice Dependent Ecosystems

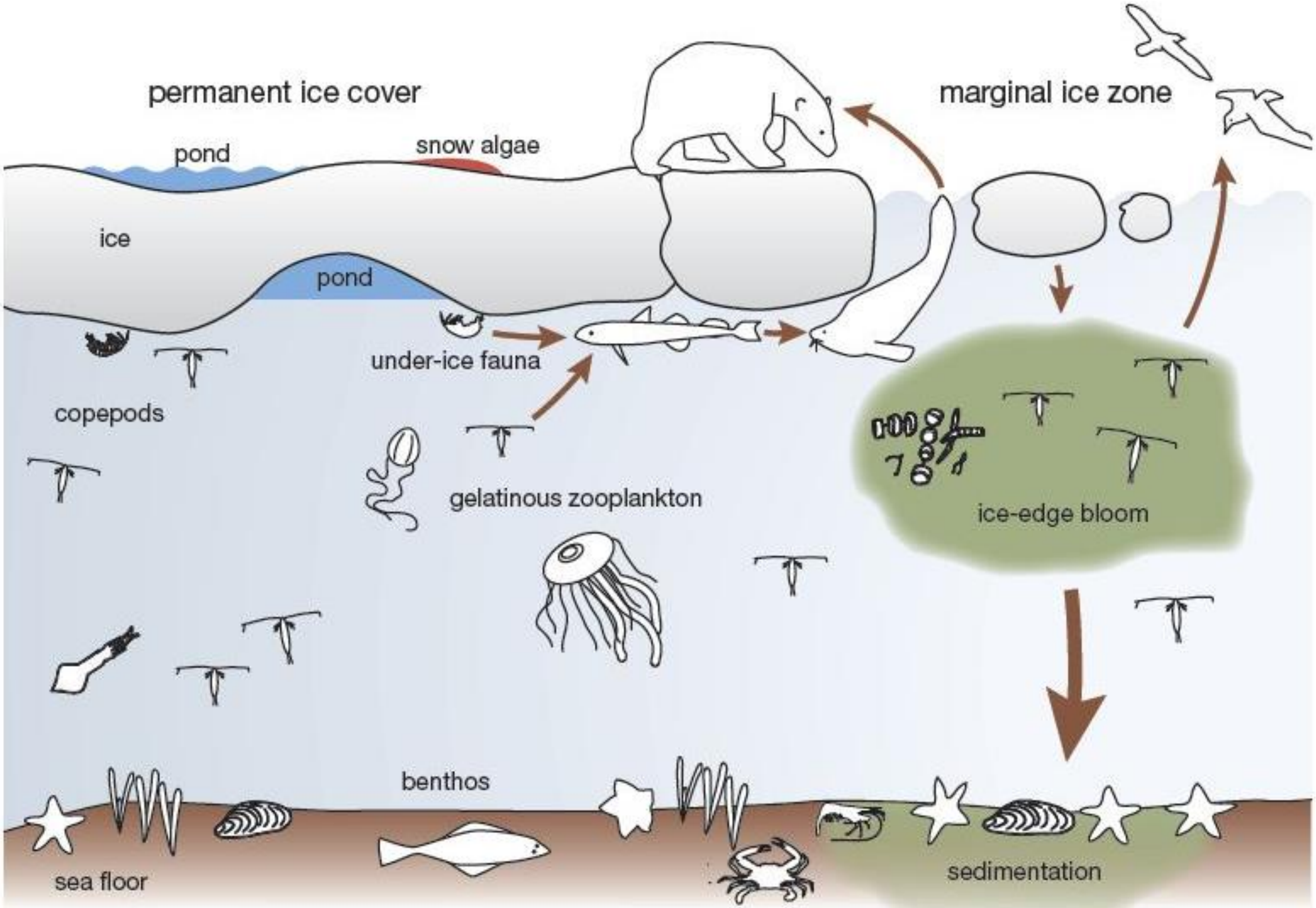
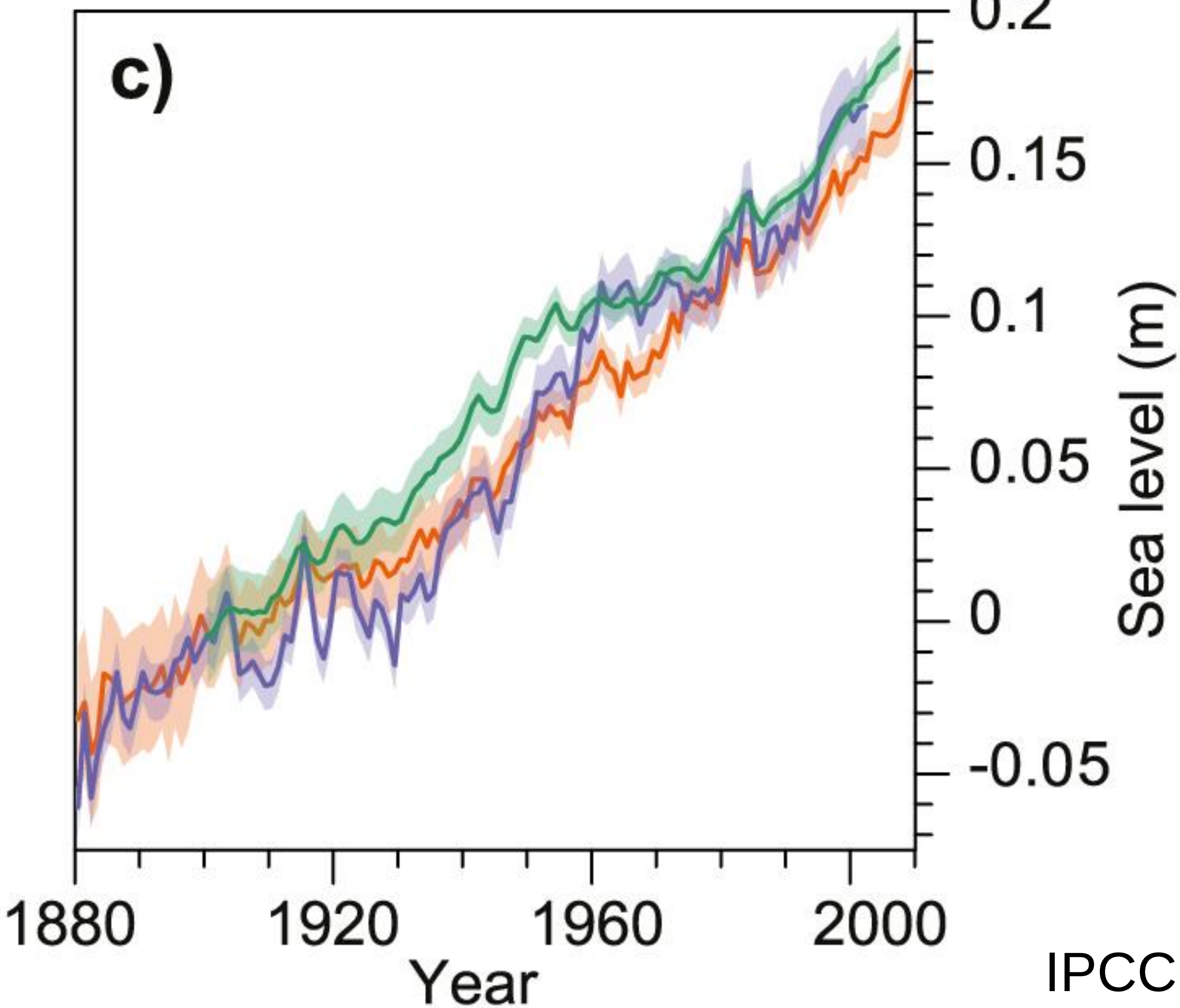


Figure 10.1: Schematic representation of the Arctic marine ecosystem and its interactions [1].

Impact #4: Sea Level

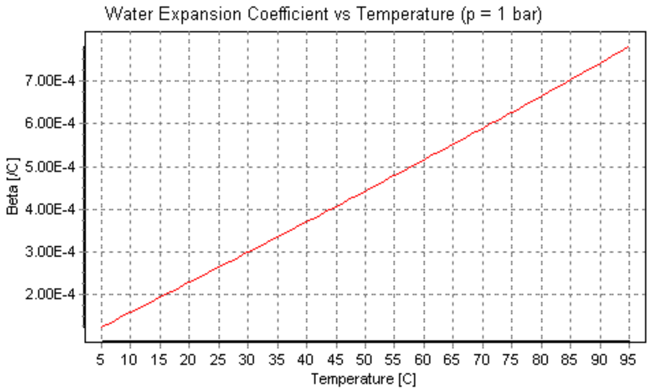
~ 20 cm = 8” ~ 0.5 ft

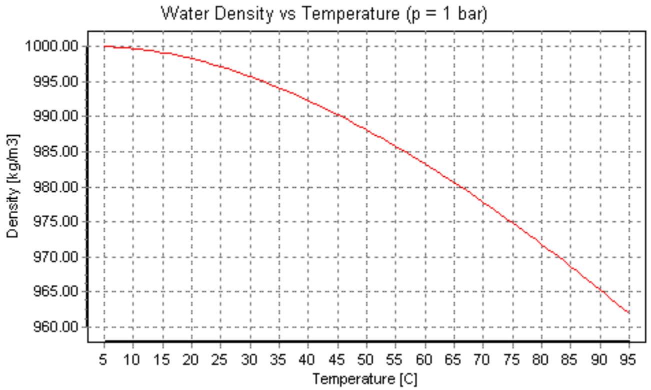


IPCC 2014

Two Contributions to Sea Level Rise

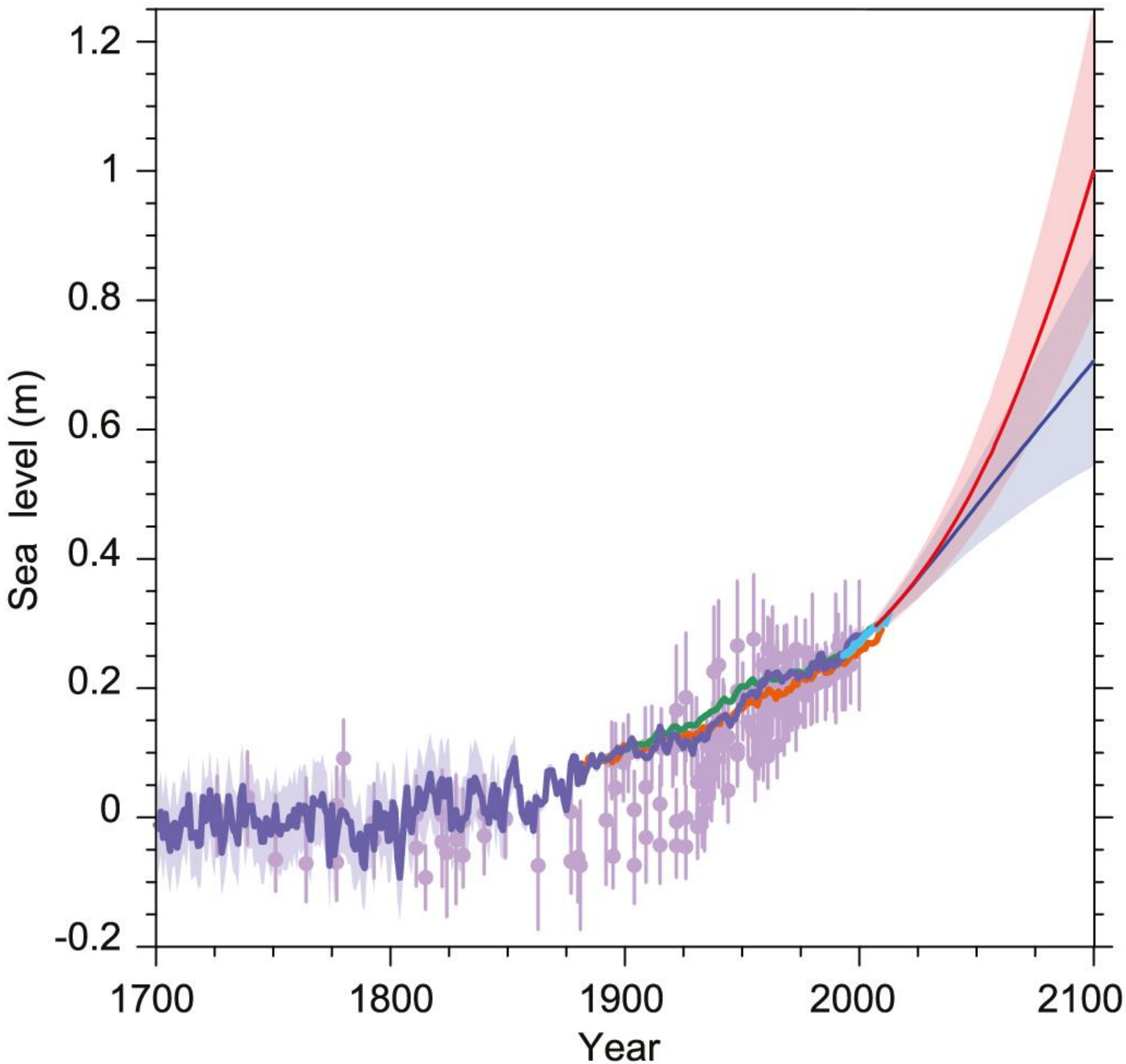
- **Liq. Water expands as it warms**





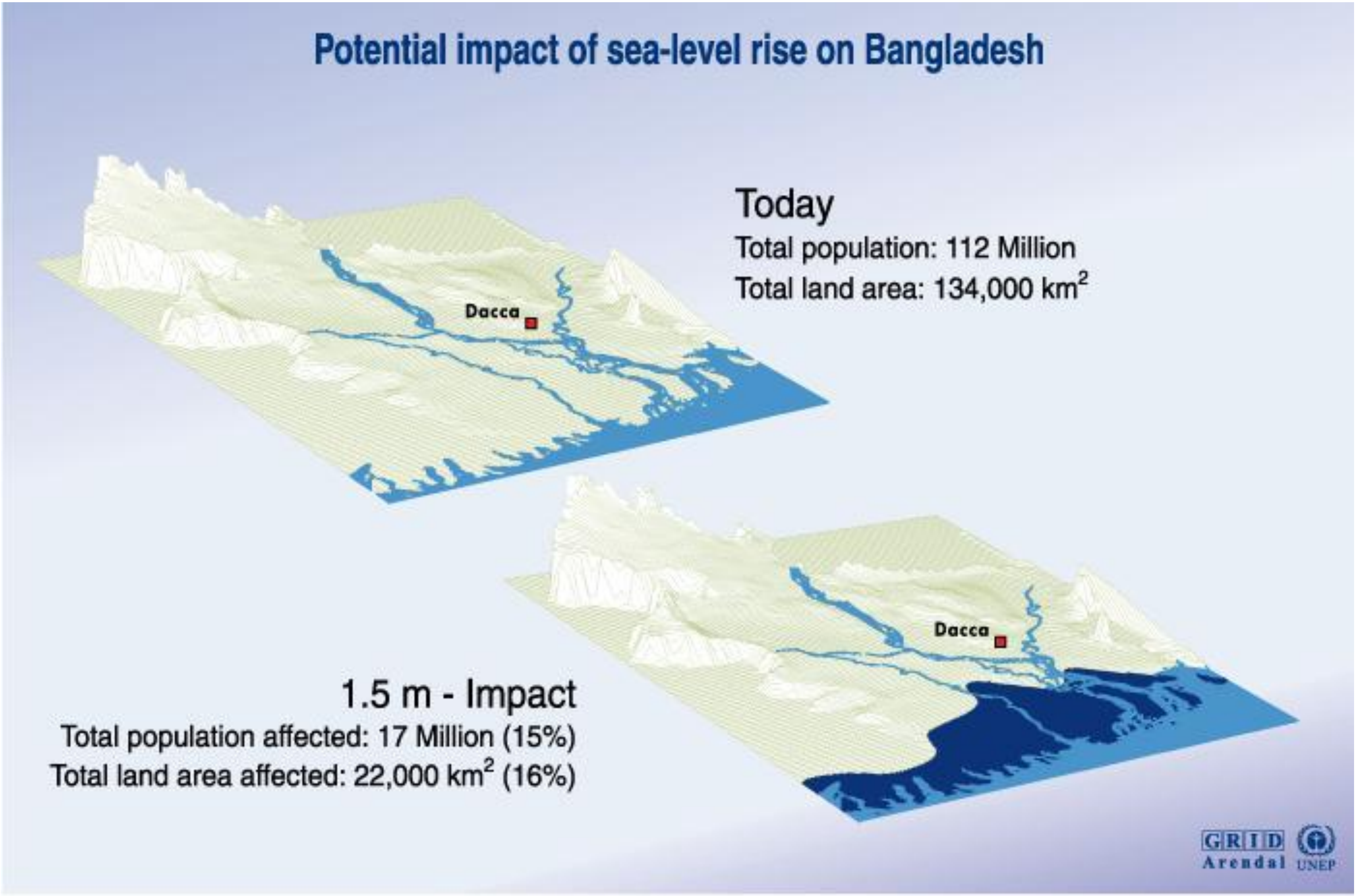
- **Land-based glacier / ice sheet melting**

Sea Level Projections



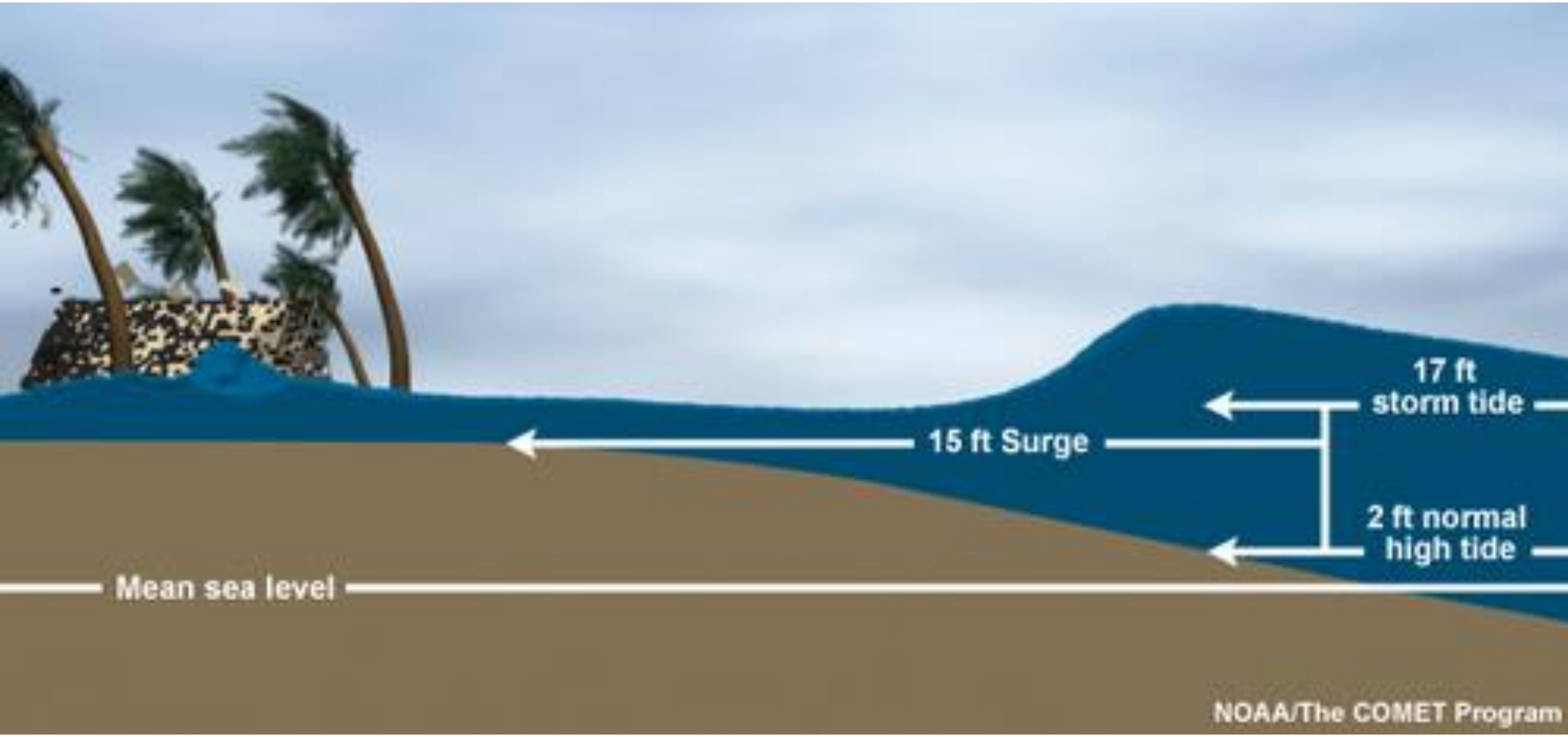
IPCC 2014

Bangladesh Under ~1.3 m Sea Level Rise



Source : UNEP/GRID Geneva; University of Dacca; JRO Munich; The World Bank; World Resources Institute, Washington D.C.

Sea level isn't static: storm surges



Hurricane Sandy Surge Damage

Storm Surge Vulnerability

- From 1990-2008, population density increased 32% in Gulf coastal counties, 17% in Atlantic coastal counties, and 16% in Hawaii (U.S. Census 2010)
- Much of densely populated US Atlantic and Gulf Coast coastlines lie < 3 m above mean sea level
- Over half US economic productivity is within coastal zones

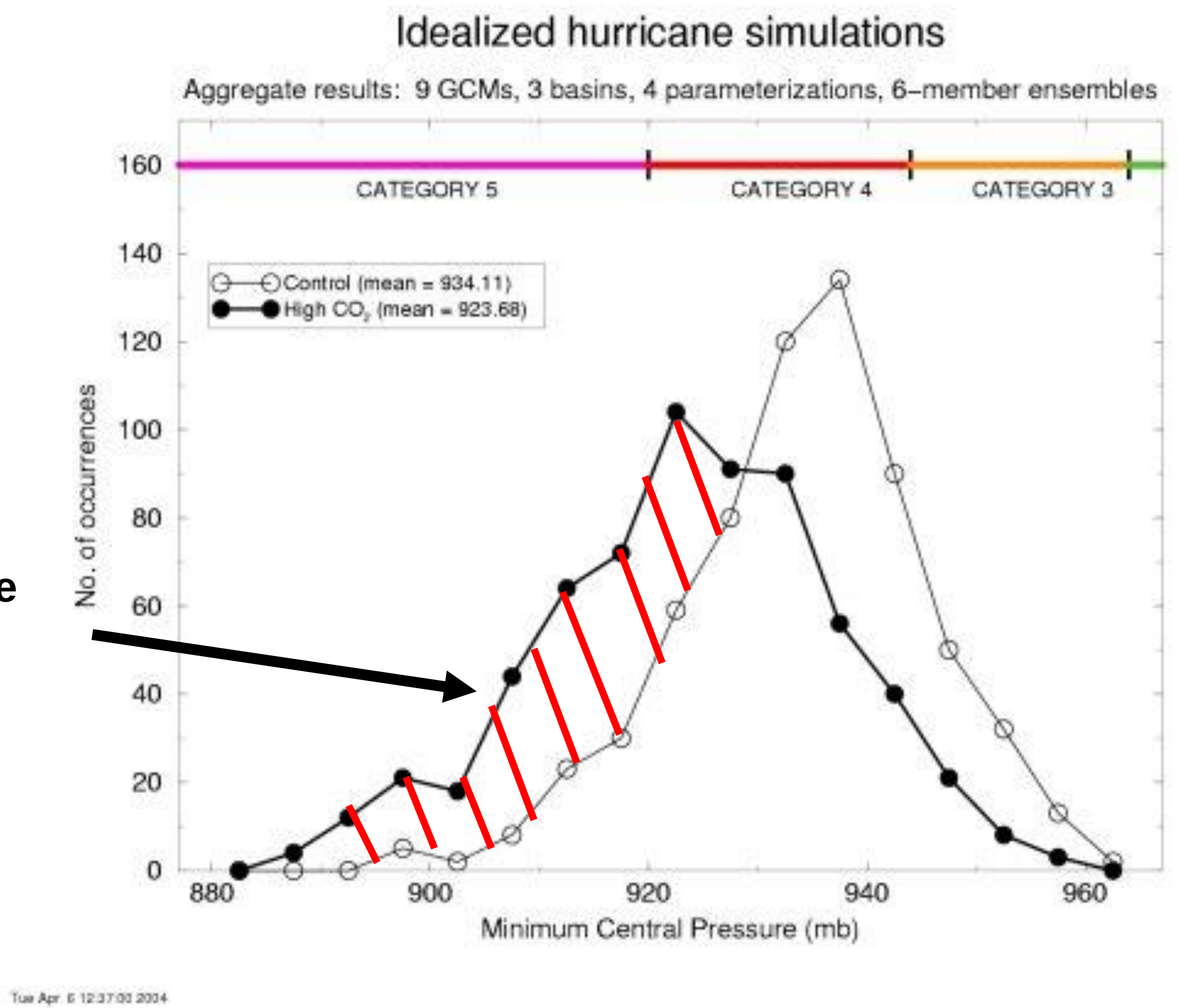
Storm Surge Vulnerability

- **72% of ports, 27% of major roads, and 9% of rail lines within the Gulf Coast region at or below 1.5 m elevation**

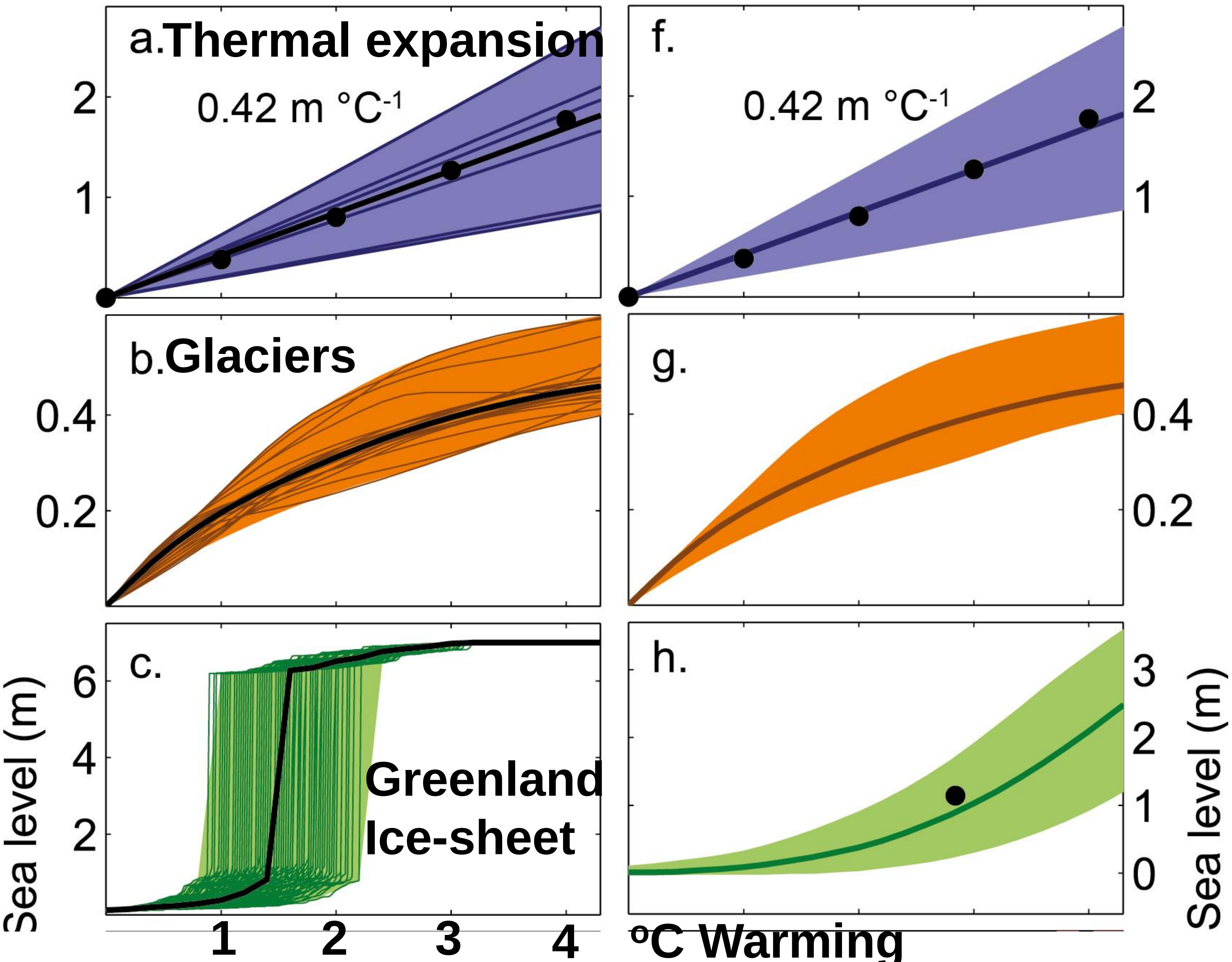
- **In the Gulf Coast (US) a storm surge of 8 m could inundate 67% of interstates, 57% of arterials, almost half of rail miles, 29 airports, and virtually all ports**

Hurricane Intensity Change – Storm Surges…

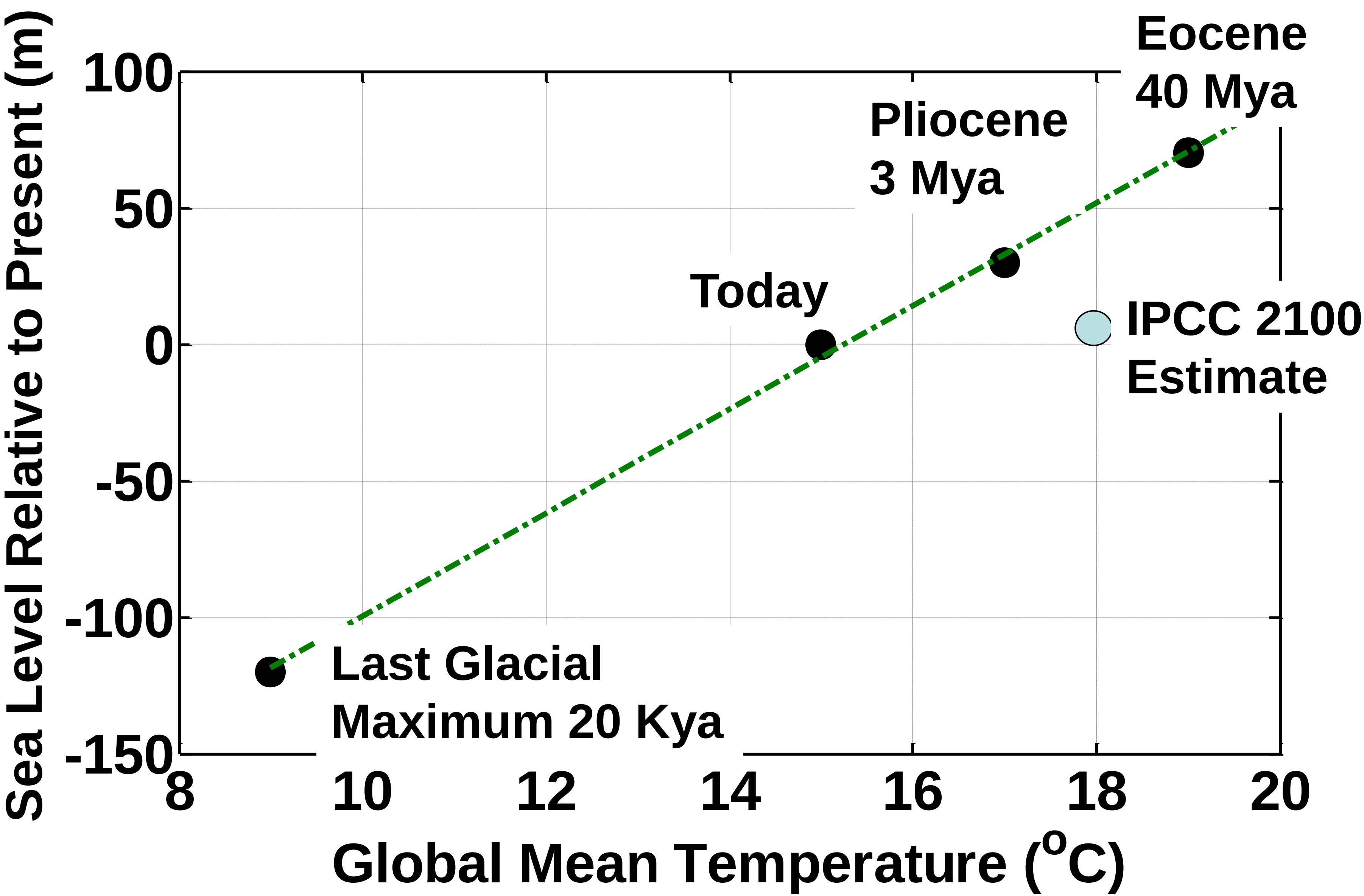
Models predict more intense hurricanes occur more often in higher CO_2 world



Multi-Millenial compared to 2000 yr Sea Level Rise



Sea Level on Geologic Timescales



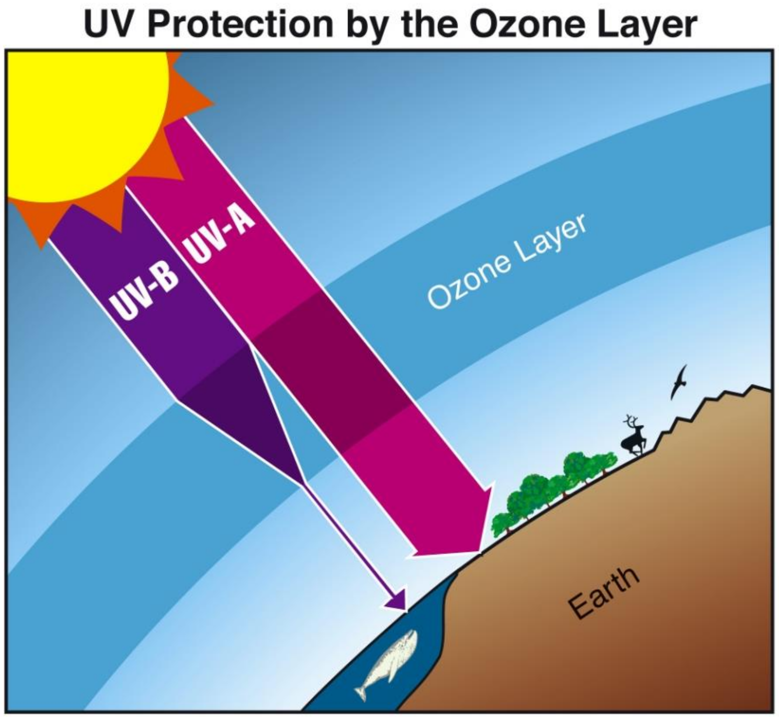
Adapted from Archer, Global Warming

Eastern U.S. 1 m of sea level rise

Eastern U.S. 30 m of sea level rise

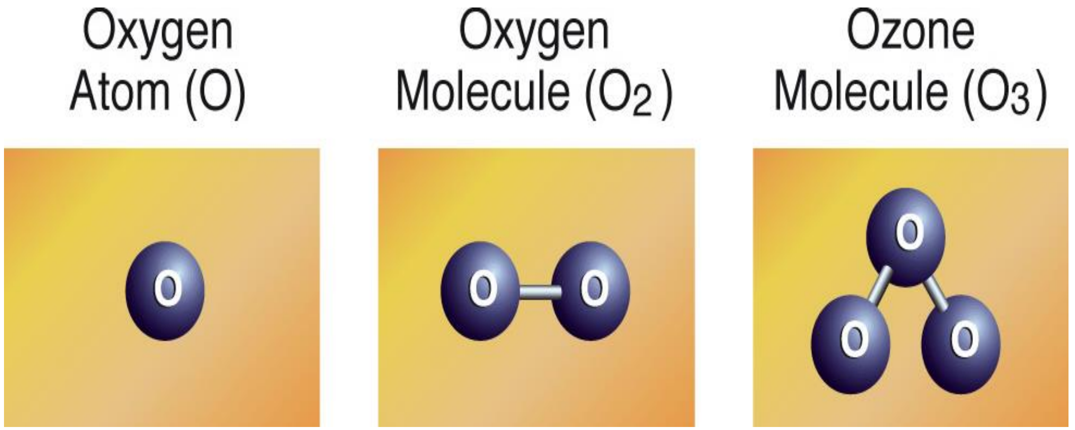
What can be done?

Stratospheric Ozone (O_3) Importance



→prevents exposure of terrestrial and surface water life to harmful UV radiation (causes DNA damage, skin cancer and loss of eyesite)

→ absorption of UV radiation important for atmospheric energy balance circulation, precipitation



Chlorofluorocarbons (CFCs)

Non-toxic, non-flammable, easily compressible gases

Used as refrigerants and as propellants in spray cans

Thought to be ideal…due to safety and durability.

"Aerosol" Spray Cans: NOT SAME AS ATMOSPHERIC AEROSOL PARTICLES

Early Warning Signs – But never predicted ozone hole!

Stratospheric sink for chlorofluoromethanes : chlorine atomc-atalysed destruction of ozone

Mario J. Molina & F. S. Rowland

Department of Chemistry, University of California, Irvine, California 92664

Chlorofluoromethanes are being added to the environment in steadily increasing amounts. These compounds are chemically inert and may remain in the atmosphere for 40–150 years, and concentrations can be expected to reach 10 to 30 times present levels. Photodissociation of the chlorofluoromethanes in the stratosphere produces significant amounts of chlorine atoms, and leads to the destruction of atmospheric ozone.

photolytic dissociation to $CFCl_2$ + Cl and to CF_2Cl +
respectively,at altitudes of 20–40 km. Each of the reactions crea
two odd-electron species—one Cl atom and one free radic
The dissociated chlorofluoromethanes can be traced to th
ultimate sinks. An extensive catalytic chain reaction leadi
to the net destruction of O_3 and O occurs in the stratosphere

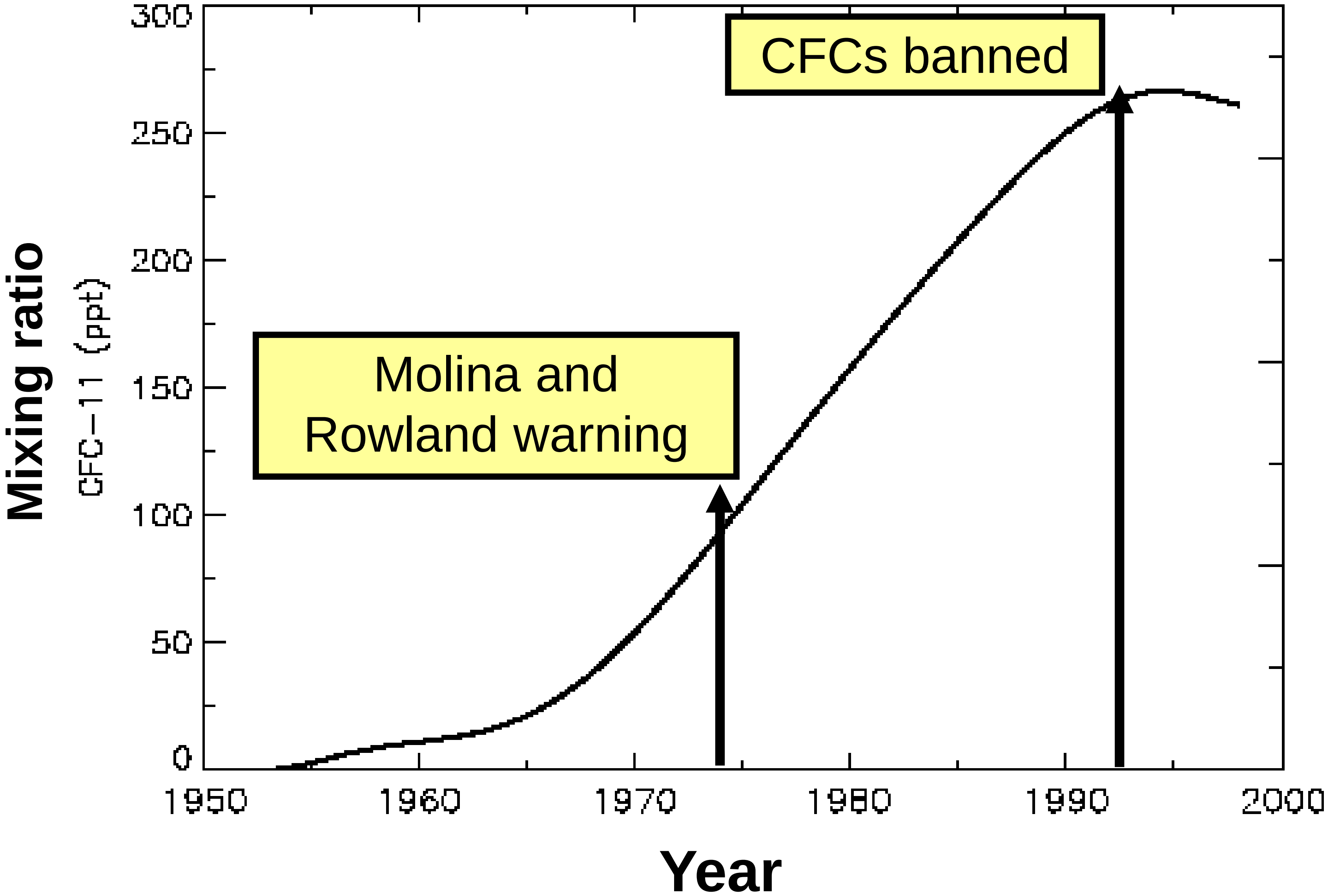
$$Cl + O_3 \rightarrow ClO + O_2$$
$$ClO + O \rightarrow Cl + O_2$$

This has important chemical consequences. Under m
conditions in the Earth's atmospheric ozone layer, (2) is
slower of the reactions because there is a much lower conc

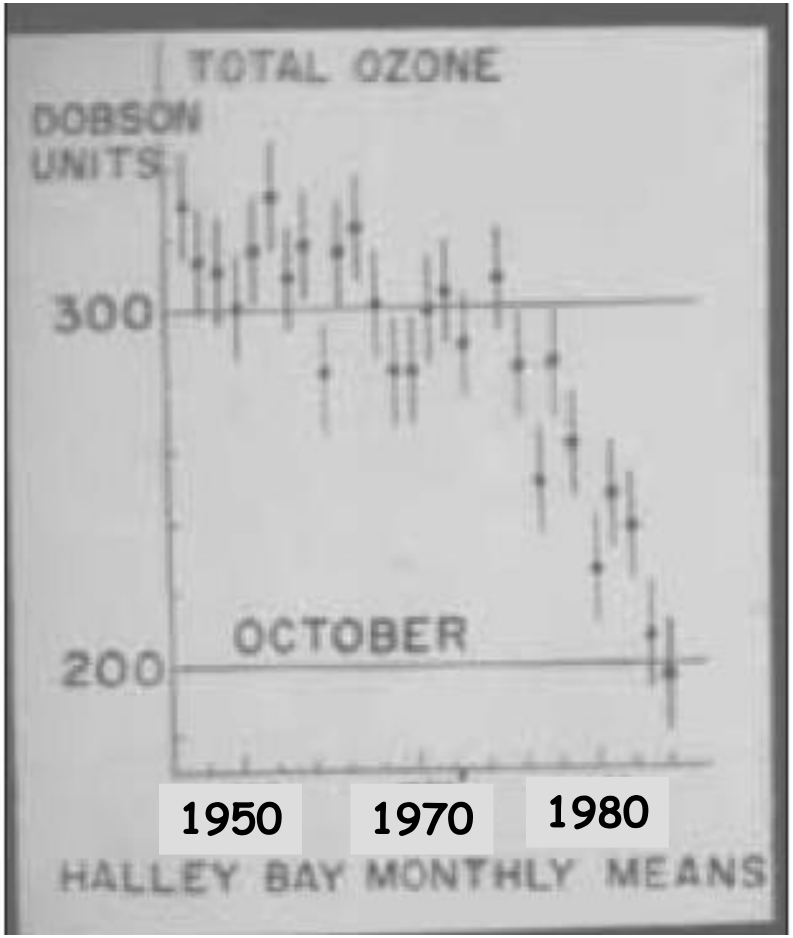
Nature, June 28, 1974

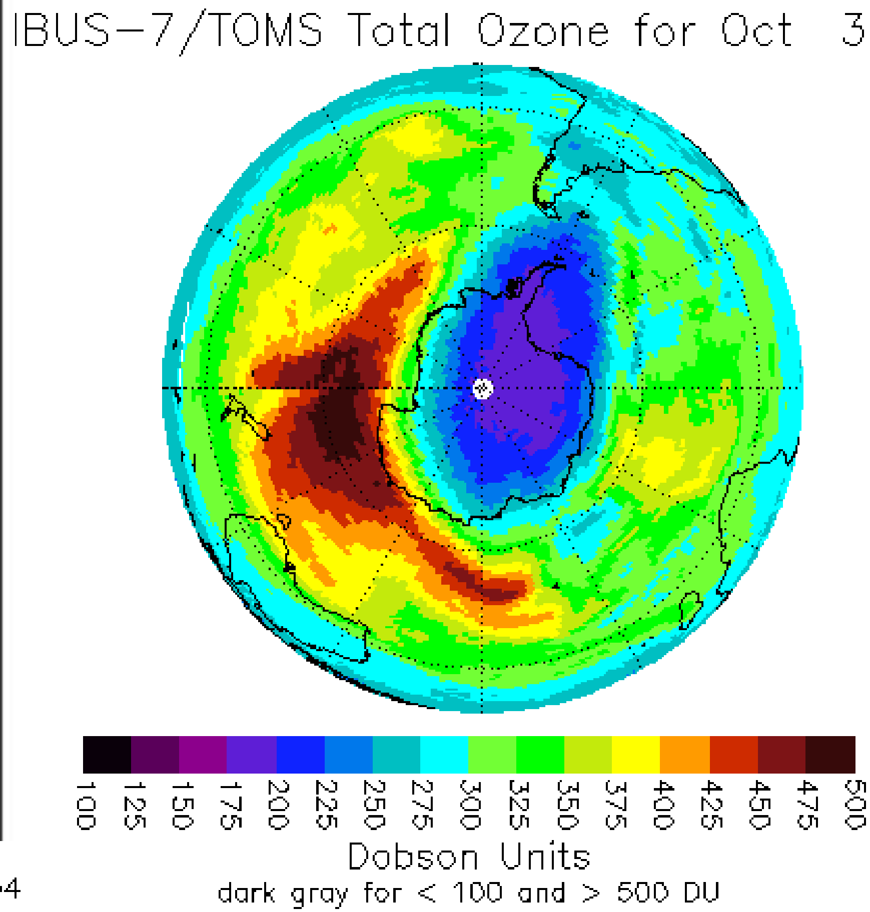
Molina, Rowland, and Crutzen win Nobel Prize in 1994

CFC-11 Atmospheric Abundance



Discovery of Antarctic Ozone Hole





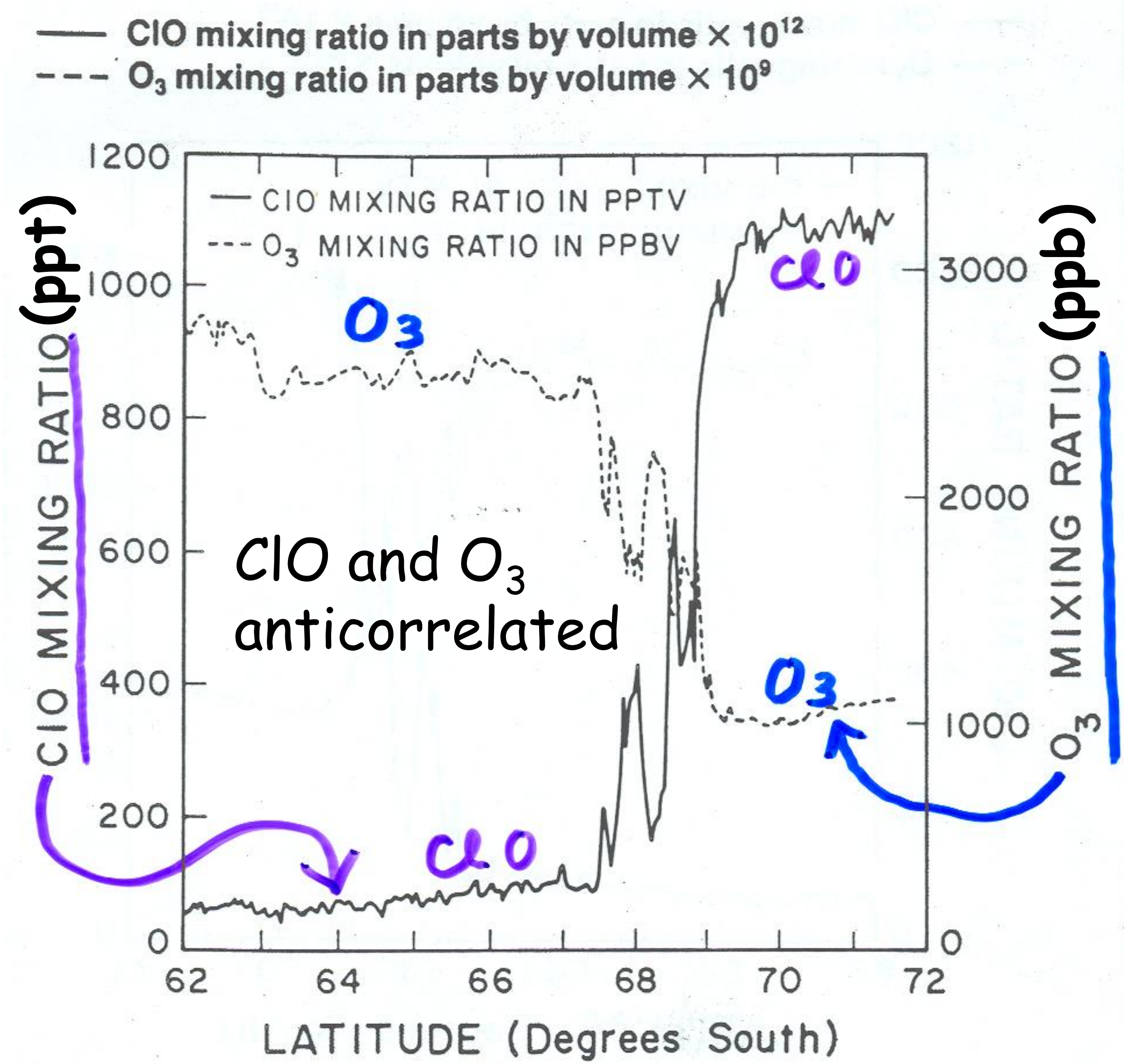
Reality was worse than the predictions!

Antarctic Ozone Hole Theories

Also a real scientific debate

- chemistry versus meteorology
- human versus natural
- solar cycles (again!)

"Human Finger Prints": Chlorine

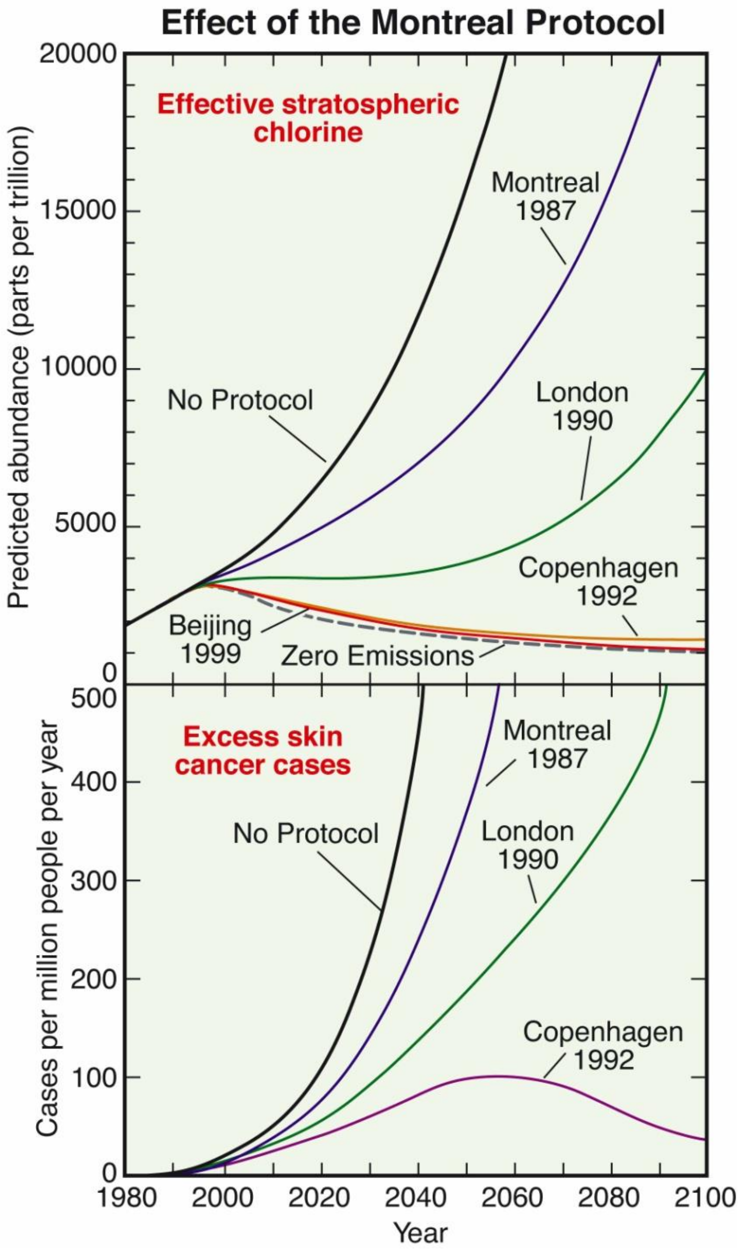


Montreal Protocol (Think "Paris Climate Accord")

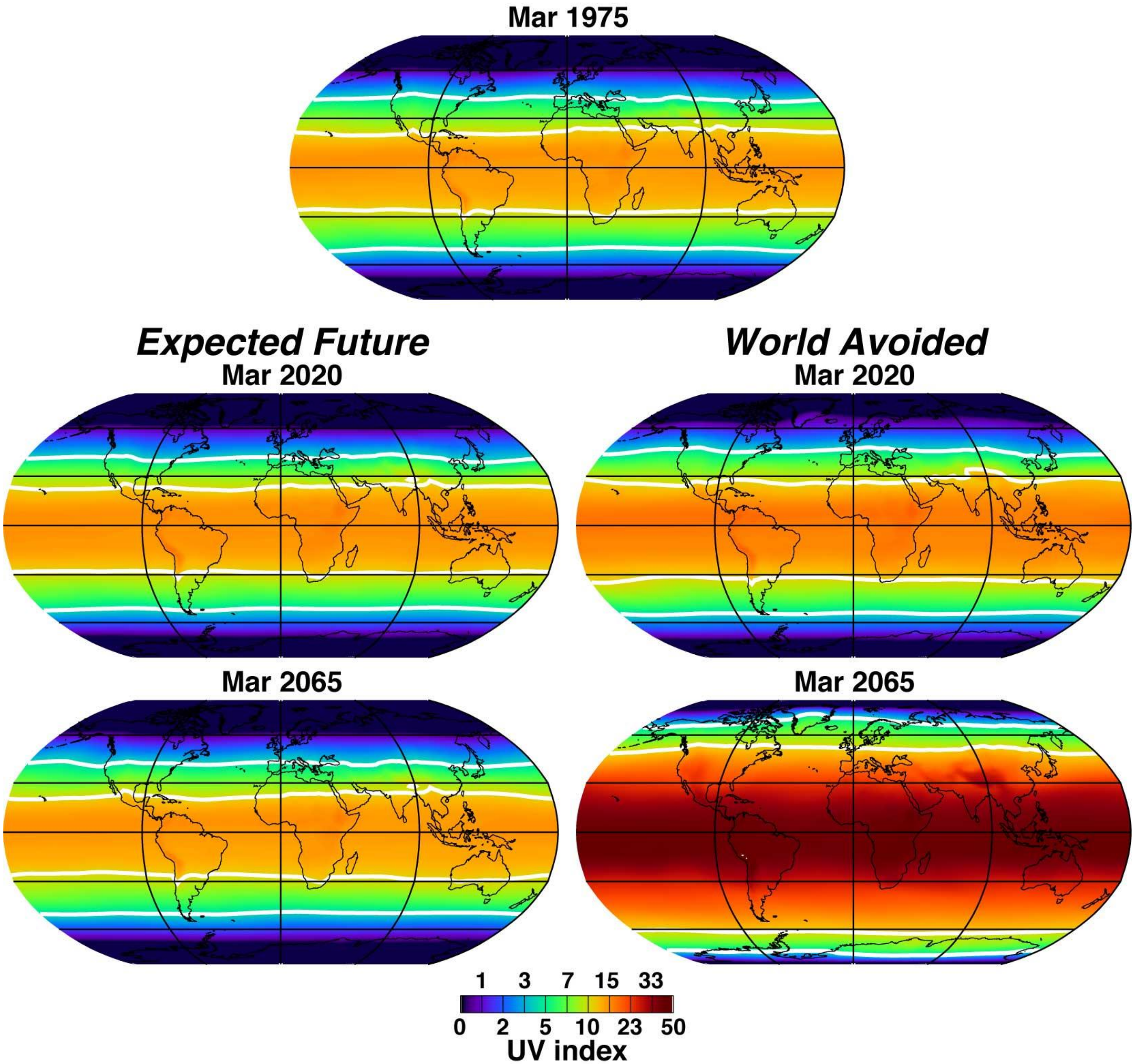
Montreal, 1987: First legally binding international agreement

By 1992: a near complete ban on production and use of CFCs.

Replacements for CFCs, known as HCFCs fairly easily implemented

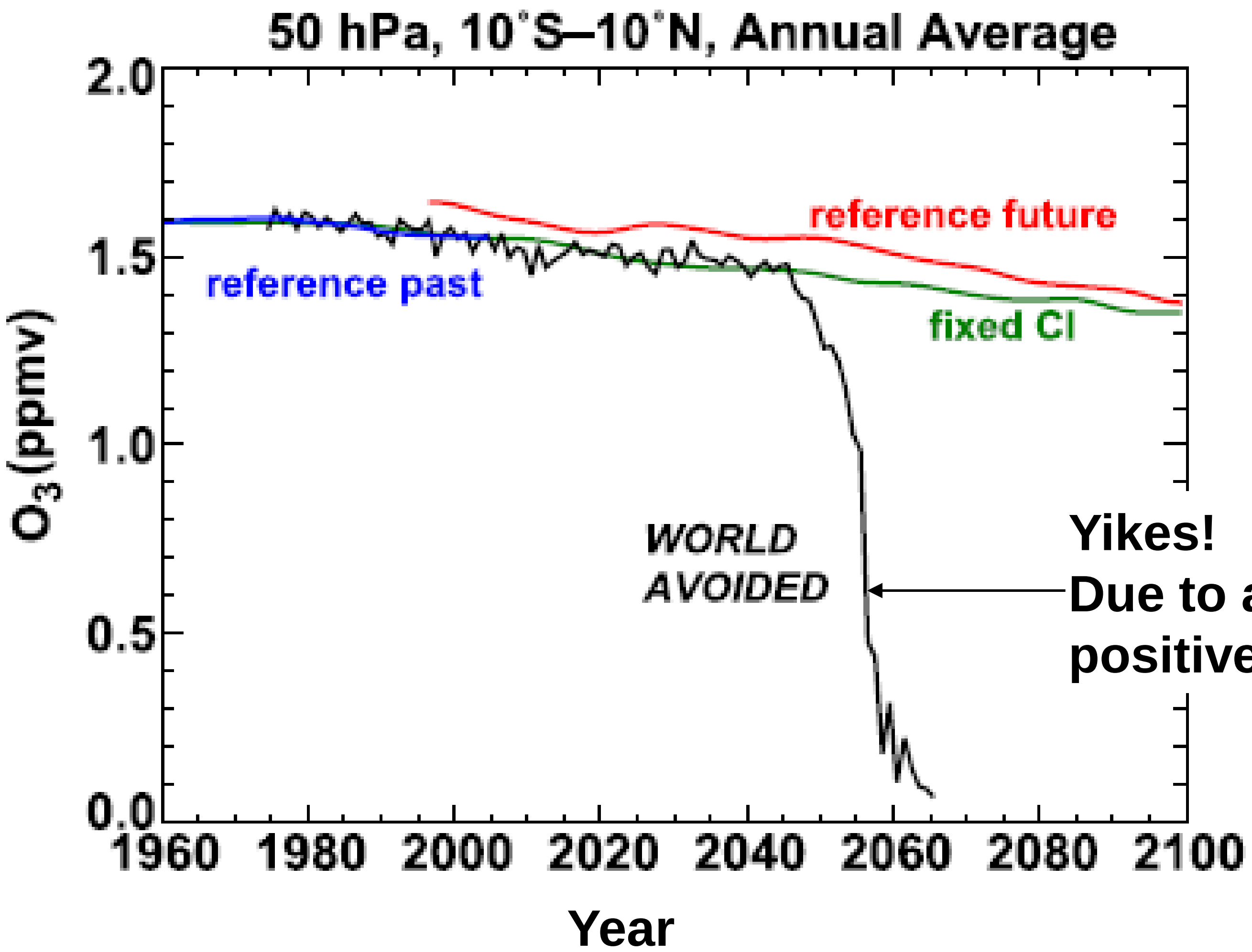


World Avoided: Health (Cancer and Cataracts)



What might have happened w/out Montreal Protocol?

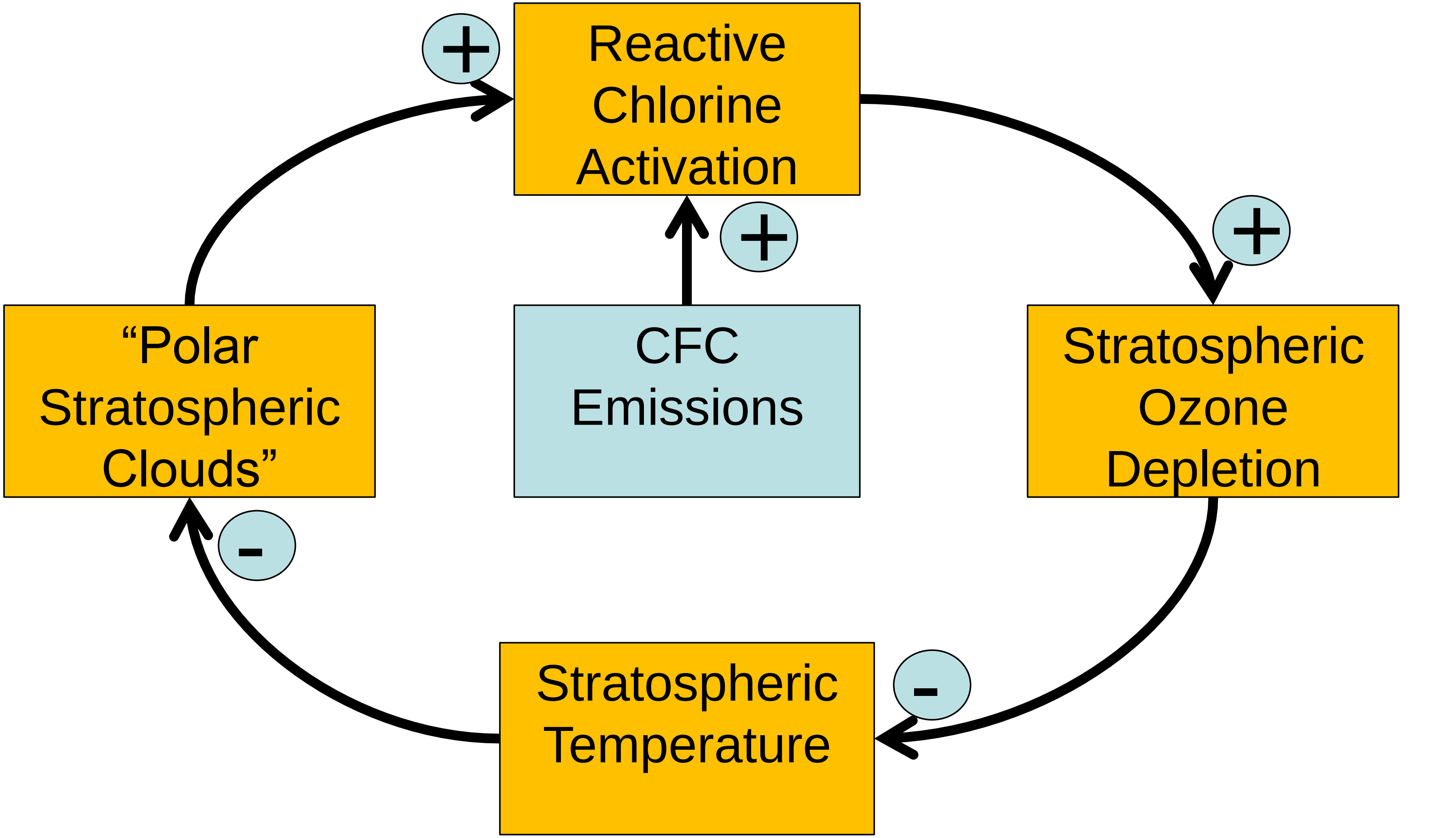
Tropical Ozone! → **40% of world's population!**



Yikes!
Due to a vicious positive feedback

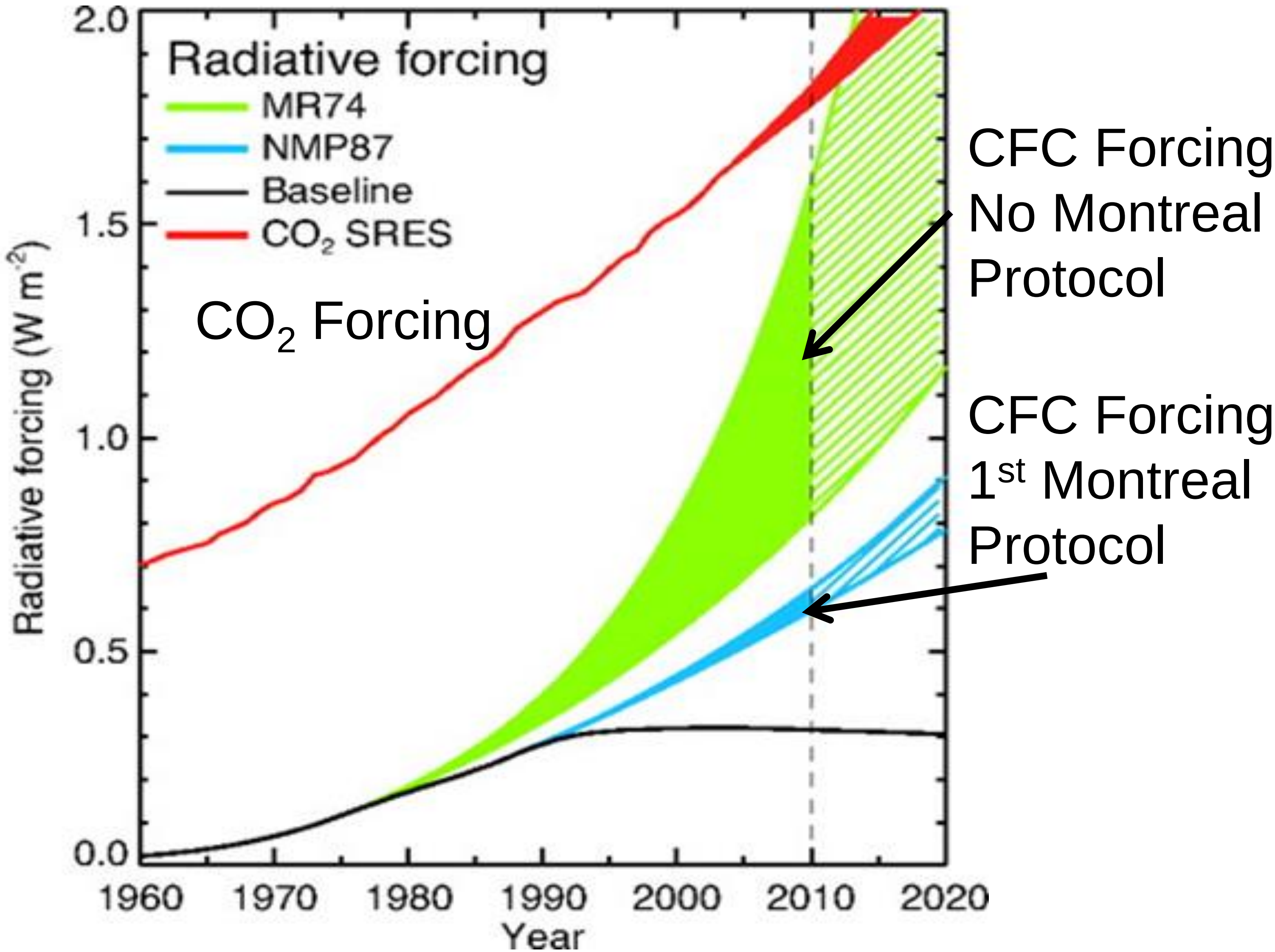
Neuman, et al *Atmos. Chem. Phys.* 2009

A Positive Feedback



An Ozone Depletion – Global Warming Connection

CFCs are potent Greenhouse Gases!



Ozone Depletion Problem vs Global Warming

- **Ozone depletion is not a cause of global warming, but it was a global scale environmental problem with consequences in the distant future**

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  - Are global warming predictions too conservative? Or are climate scientists “crying wolf?”

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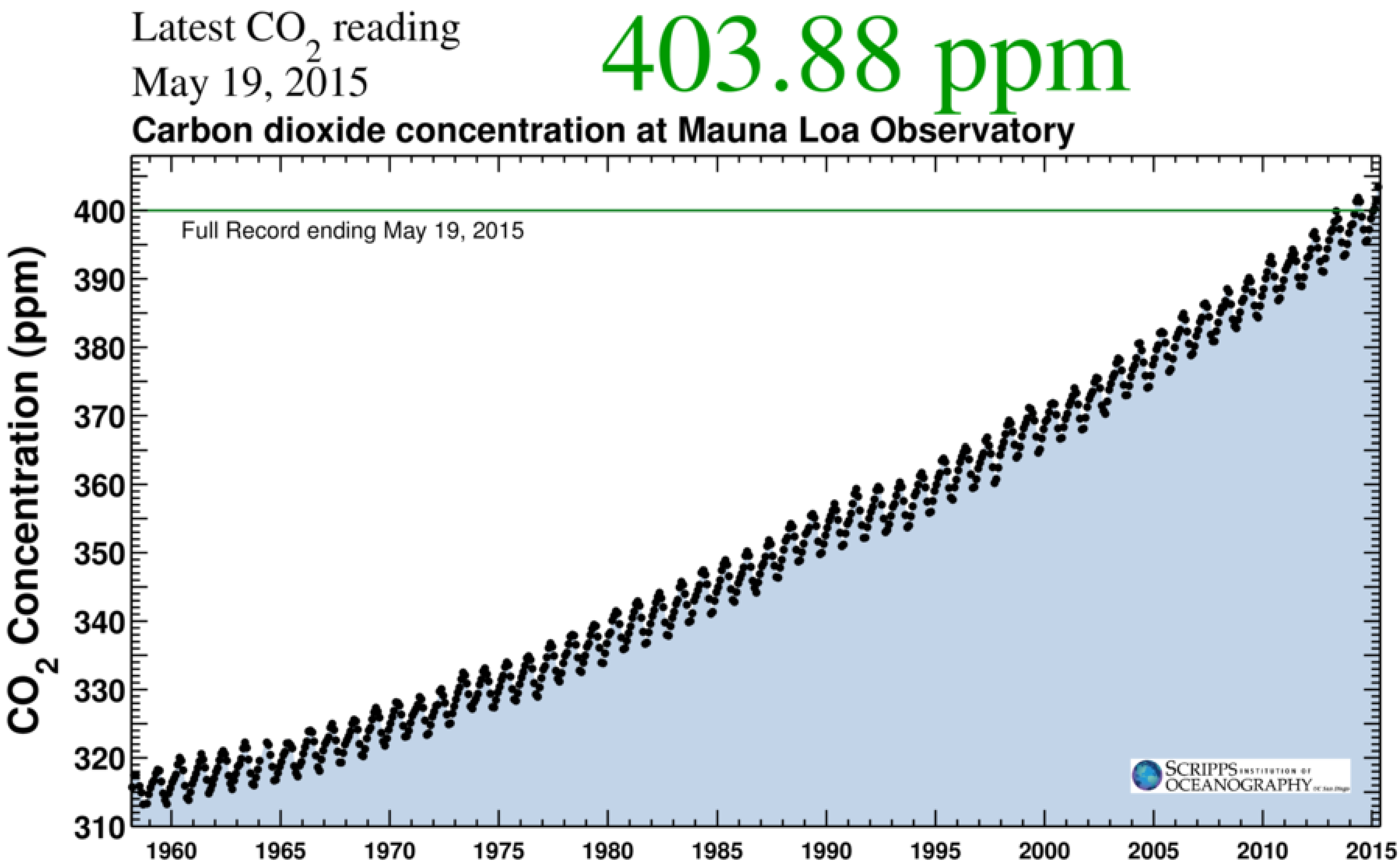
  - **Are global warming predictions too conservative? Or are climate scientists "crying wolf?"**

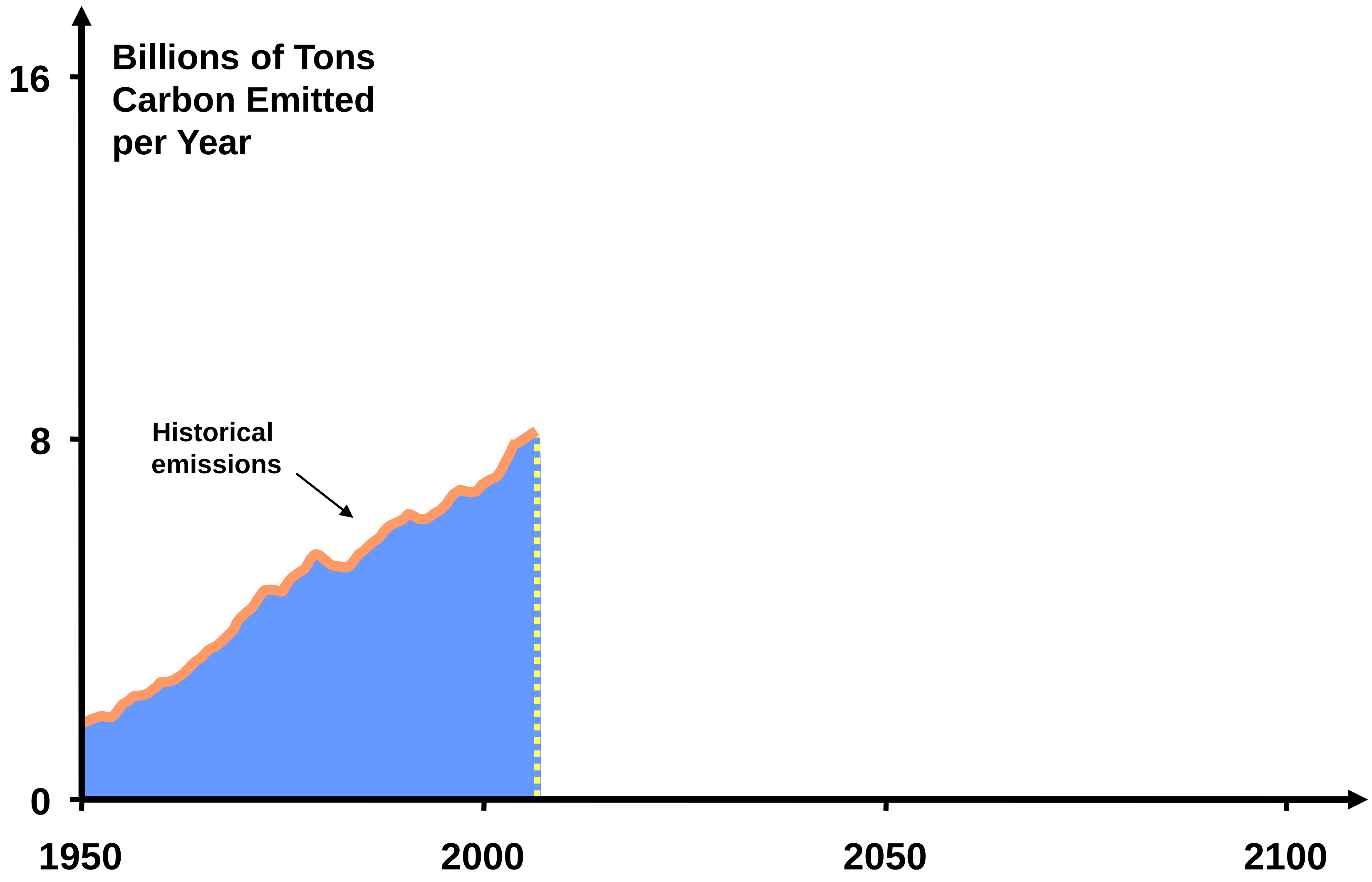
- **Solution of the ozone depletion problem required (and still requires) international cooperation and changes to consumer/industry practices**

- **Solving the ozone depletion problem was the largest and most successful global warming mitigation policy to date – by banning CFCs which are potent GHGs**

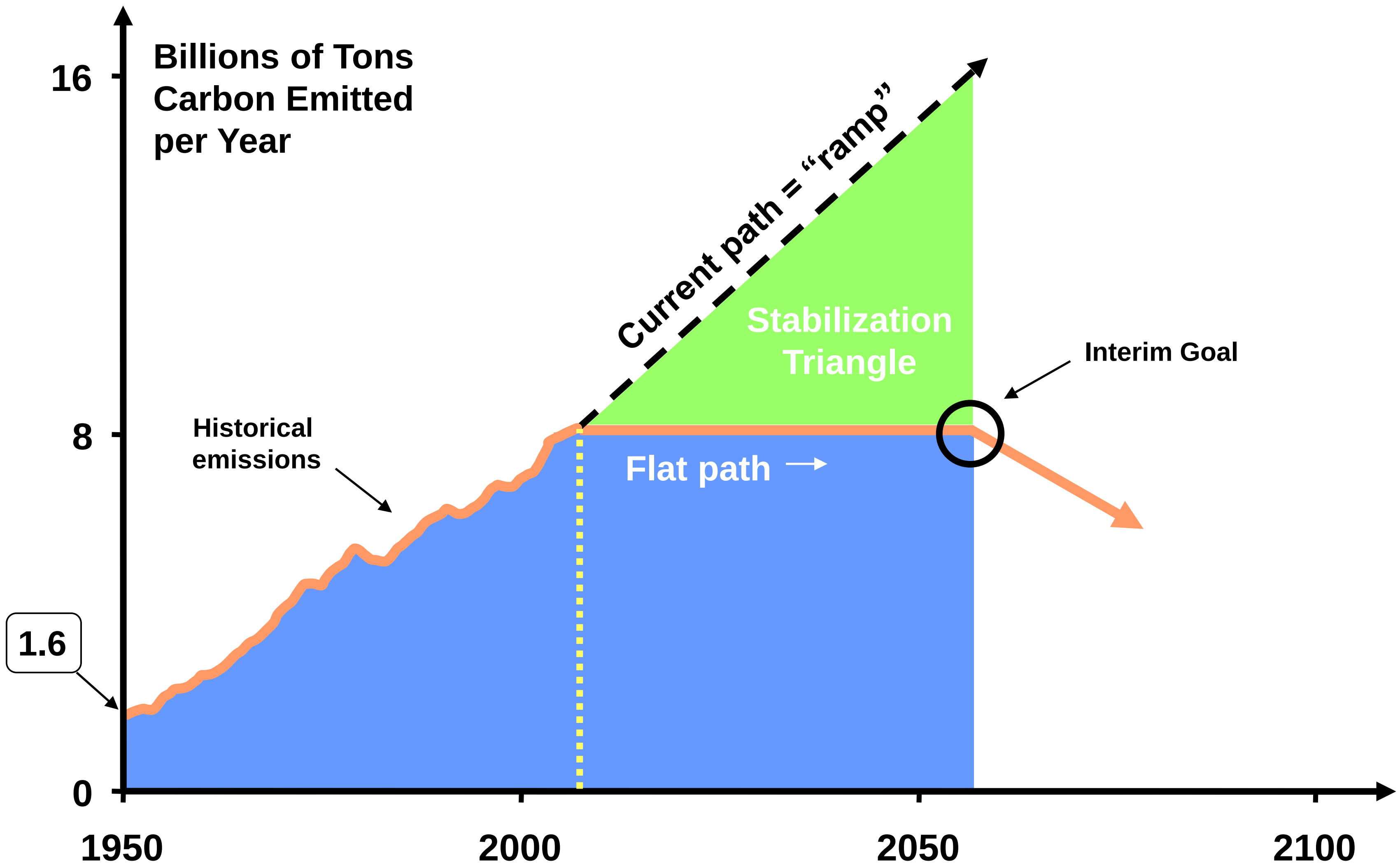
Anthropogenic GHG Forcing



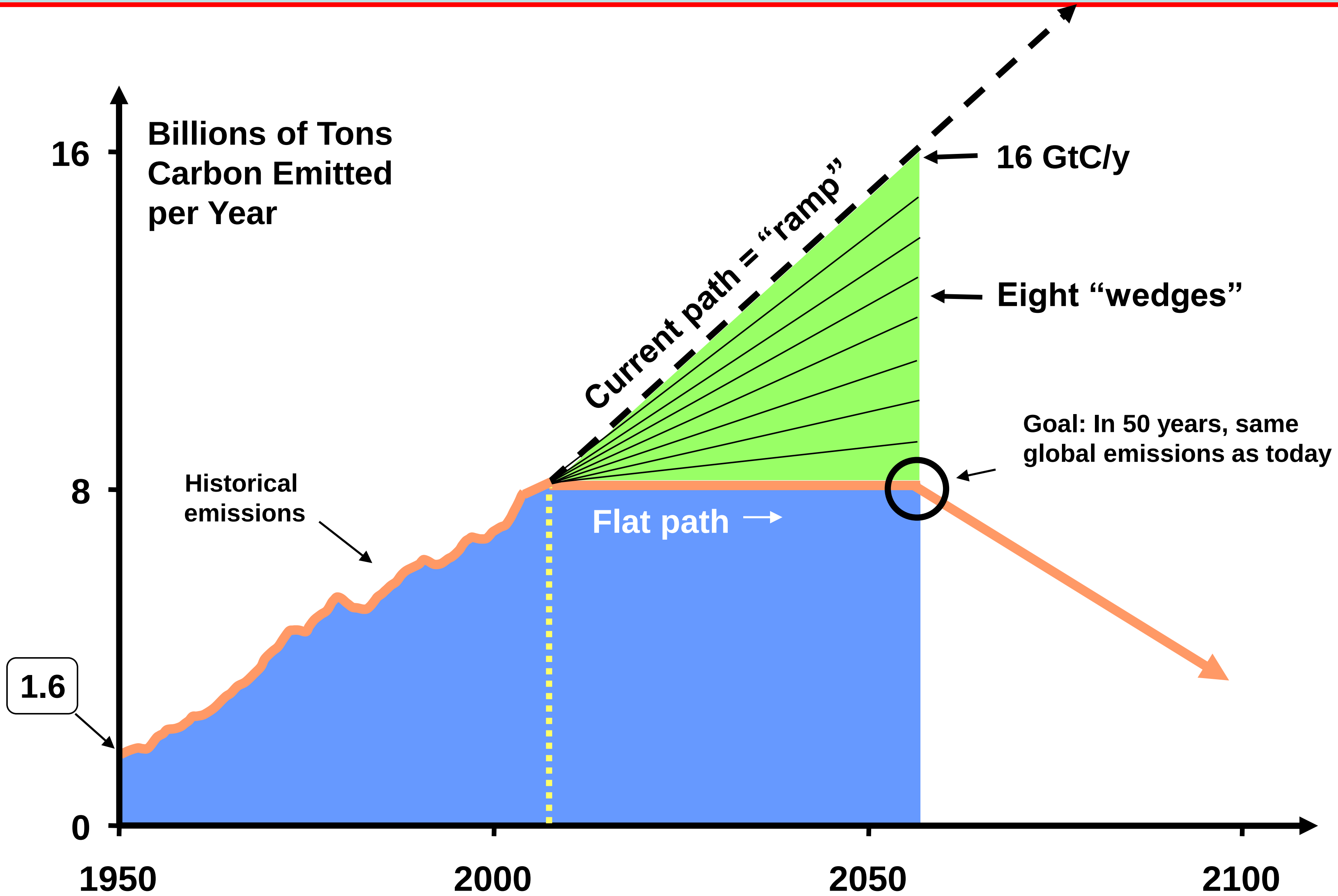
Historical Emissions



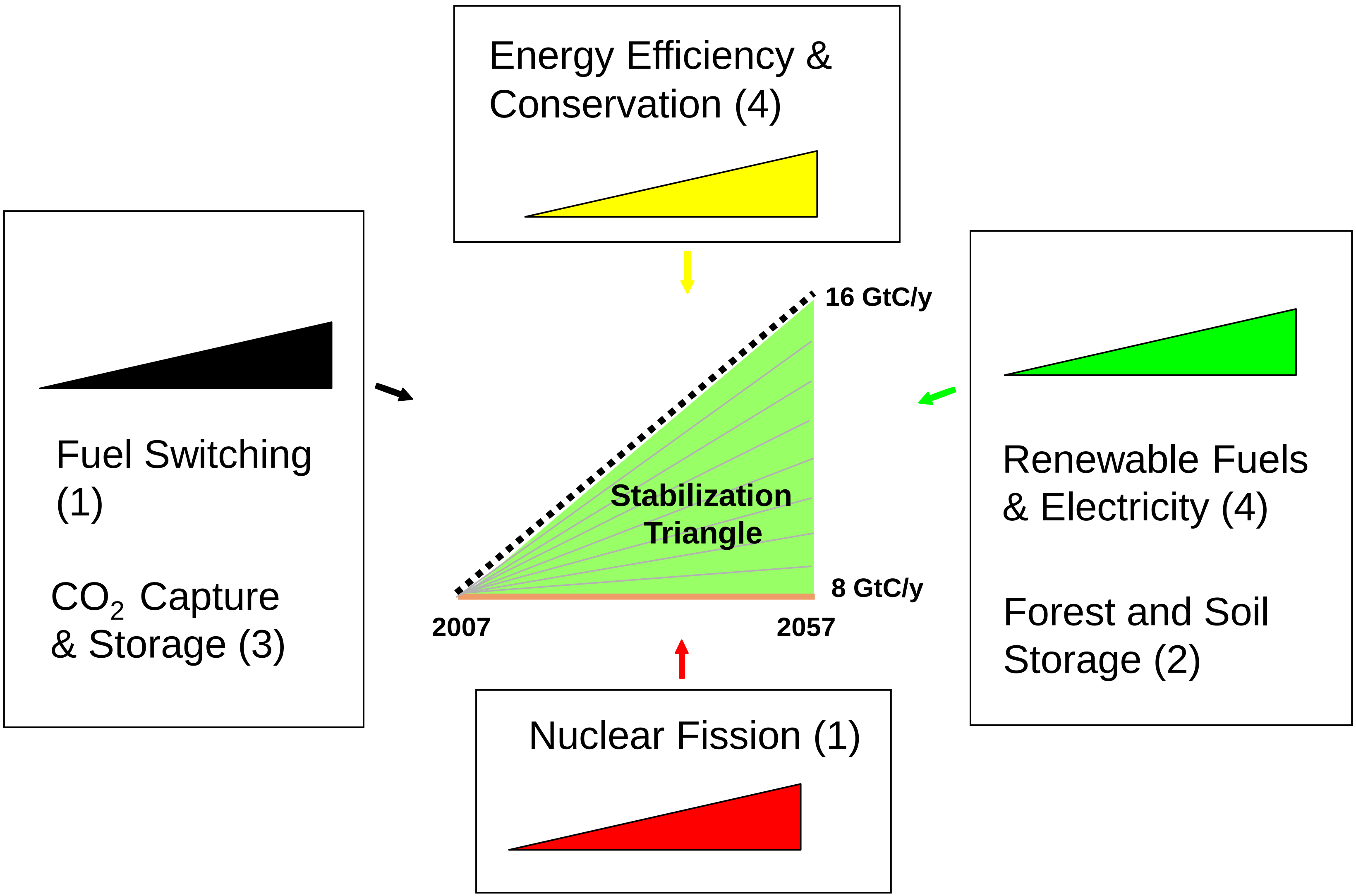
The Stabilization Triangle



Stabilization Wedges



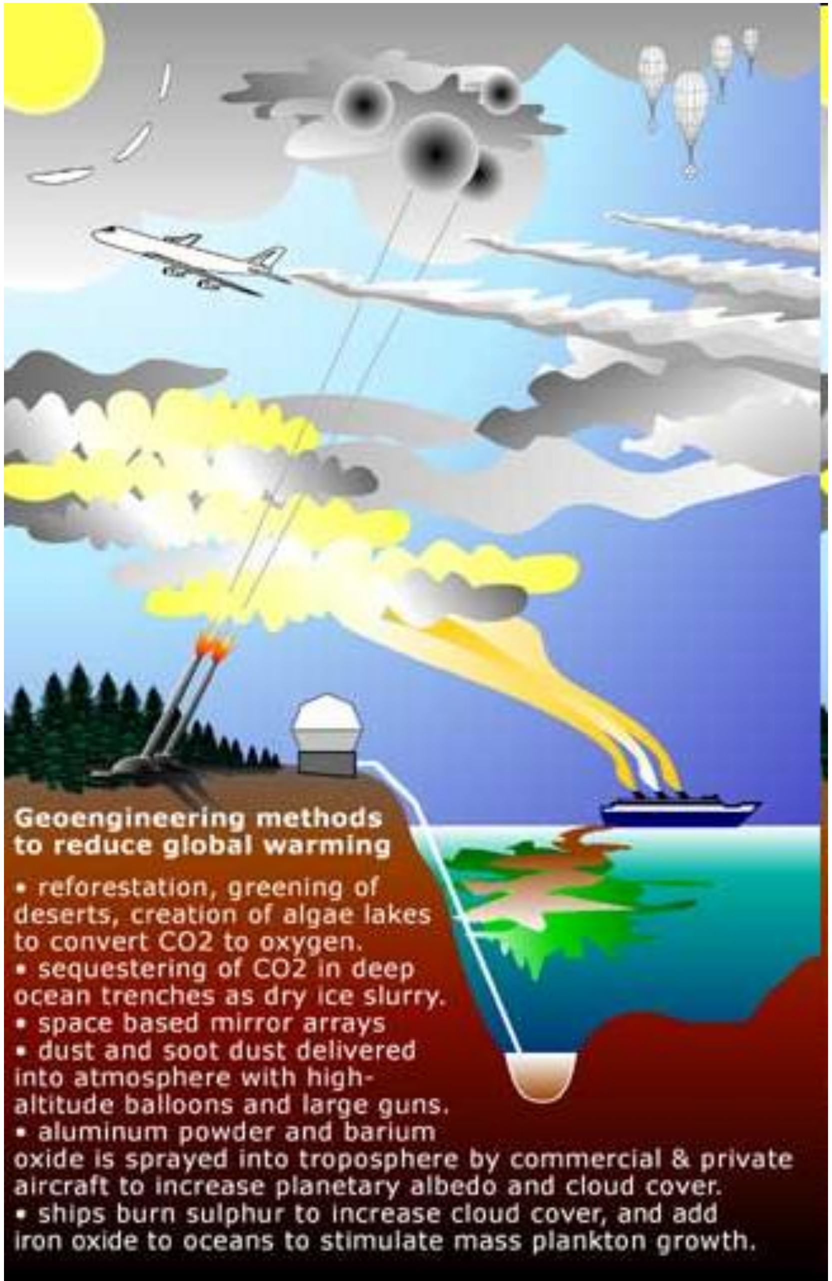
15 Wedge Strategies in 4 Categories



See [Carbon Mitigation Initiative]

Alternative to the Wedges Approach: Geo-engineering?

Various Geo-engineering Schemes



What laws and treaties exist or are needed?

Who will control the desired climate?

What happens if there is an interruption in the scheme (CO_2 still increasing)?

Global average T is not the only problem associated with increasing CO_2, what about those?

Geo-engineering: Particles in Stratosphere

GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L02809, doi:10.1029/2007GL032179, 2008

Click Here for Full Article

Exploring the geoengineering of climate using stratospheric sulfate aerosols: The role of particle size

Philip J. Rasch,[1] Paul J. Crutzen,[2,3] and Danielle B. Coleman[1]

Received 1 October 2007; revised 26 November 2007; accepted 19 December 2007; published 26 January 2008.

[1] Aerosols produced in the lower stratosphere can brighten the planet and counteract some of the effects of global warming. We explore scenarios in which the amount of precursors and the size of the aerosol are varied to assess their interactions with the climate system. Stratosphere-troposphere exchange processes change in response to greenhouse gas forcing and respond to geoengineering by aerosols. Nonlinear feedbacks influence the amount of aerosol required to counteract the warming. More aerosol

impacts. The first response of society to this evidence ought to be to reduce greenhouse gas emissions, but a second step might be to explore strategies to mitigate some of the planetary warming. Two recent papers [*Crutzen*, 2006; *Wigley*, 2006] explored a geoengineering idea going back to *Budyko* [1974], who speculated that a deliberate production of stratospheric aerosols might increase the planetary albedo, and cool the planet, ameliorating some (but not all) of the effects of increasing CO_2 concentrations.

Estimates: Need 1 – 5 Tg S/yr to negate doubled CO_2

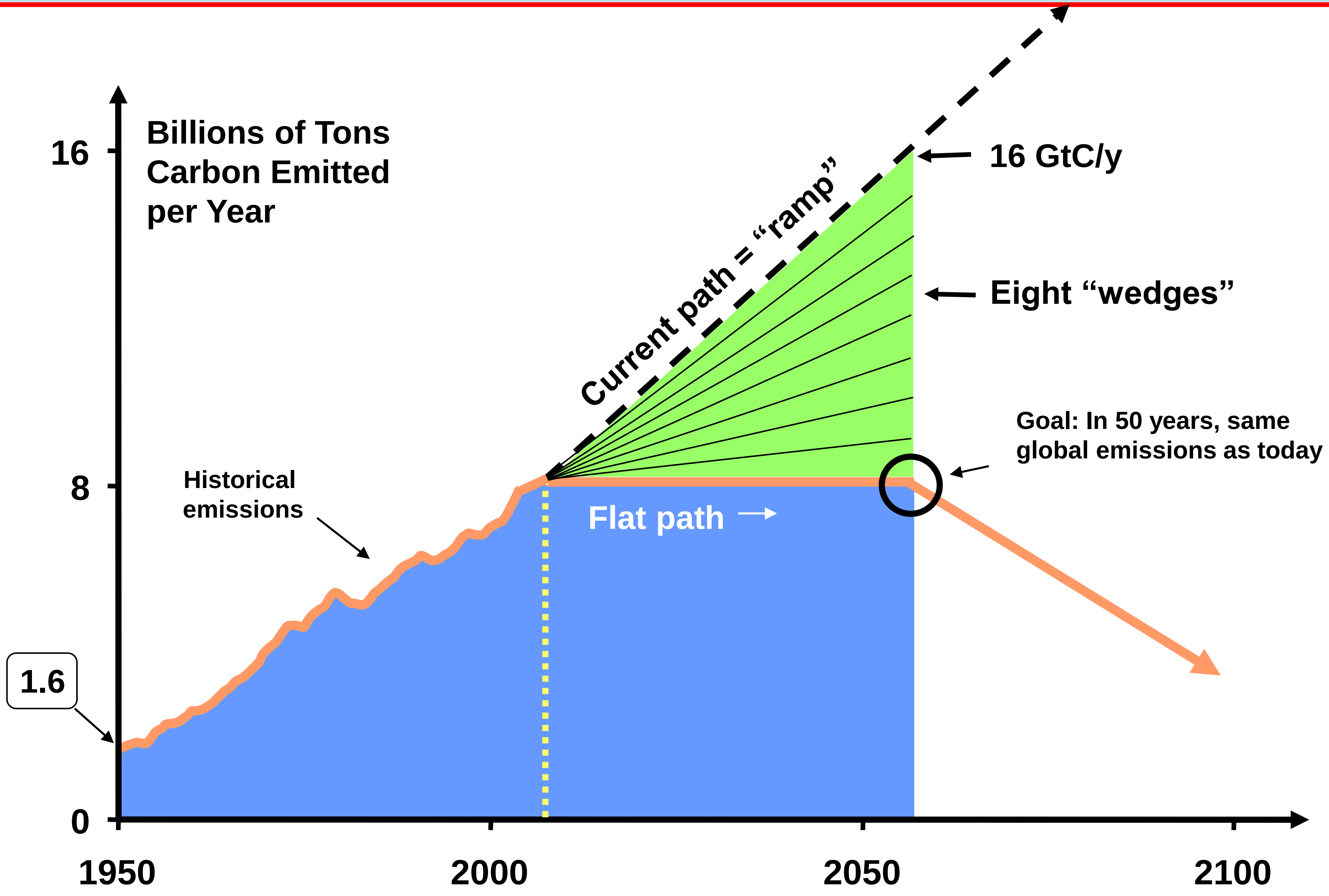
Geo-engineering: Particles in Stratosphere

~20 Tg S in stratosphere

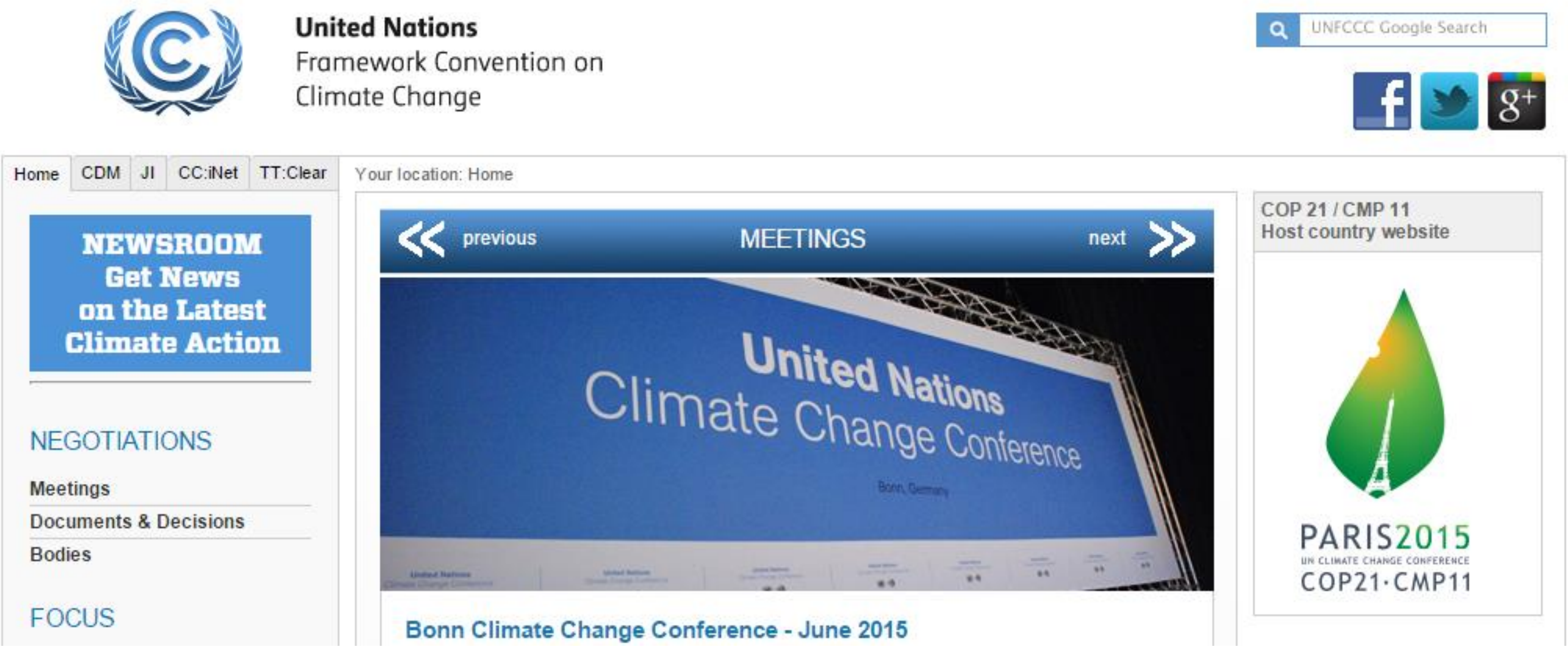
↓

Need Mt. Pinatubo every 2-4 years…

Stabilization Wedges



A Global Problem Requires a Global Solution



An Economic Approach

American Economic Review 2015, 105(4): 1339–1370
http://dx.doi.org/10.1257/aer.15000001

Climate Clubs: Overcoming Free-riding in International Climate Policy†

By William Nordhaus*

Notwithstanding great progress in scientific and economic understanding of climate change, it has proven difficult to forge international agreements because of free-riding, as seen in the defunct Kyoto Protocol. This study examines the club as a model for international climate policy. Based on economic theory and empirical modeling, it finds that without sanctions against non-participants there are no stable coalitions other than those with minimal abatement. By contrast, a regime with small trade penalties on non-participants, a Climate Club, can induce a large stable coalition with high levels of abatement. (*JEL* Q54, Q58, K32, K33)

International Agreements are Voluntary

While free-riding is pervasive, it is particularly difficult to overcome for global public goods. Global public goods differ from national market failures because no mechanisms—either market or governmental—can deal with them effectively. Arrangements to secure an international climate treaty are hampered by the Westphalian dilemma. The 1648 Treaty of Westphalia established the central principles of modern international law. First, nations are sovereign and have the fundamental right of political self-determination; second, states are legally equal; and third, states are free to manage their internal affairs without the intervention of other states. The current Westphalian system requires that countries consent to joining international agreements, and all agreements are therefore essentially voluntary (Treaty of Vienna 1969, article 34).

Climate Club Example

The theory of clubs is a little-known but important corner of the social sciences. (For an early analysis, see Buchanan 1965, while for a fine survey, see Sandler and Tschirhart 1980.) The major conditions for a successful club include the following: (i) that there is a public-good-type resource that can be shared (whether the benefits from a military alliance or the enjoyment of a golf course); (ii) that the cooperative arrangement, including the dues, is beneficial for each of the members; (iii) that non-members can be excluded or penalized at relatively low cost to members; and (iv) that the membership is stable in the sense that no one wants to leave. For the current international-trade system, the advantages are the access to other countries' markets with low trade barriers. For military alliances, the benefits are peace and survival. In all cases, countries must contribute dues—these being low trade barriers for trade or burden sharing in defense treaties. If we look at successful international clubs, we might see the seeds of an effective international system to deal with climate change.

"Club" of countries agree to emissions reductions

Countries not agreeing (and not meeting targets) are penalized via tariffs on imports

Climate Clubs

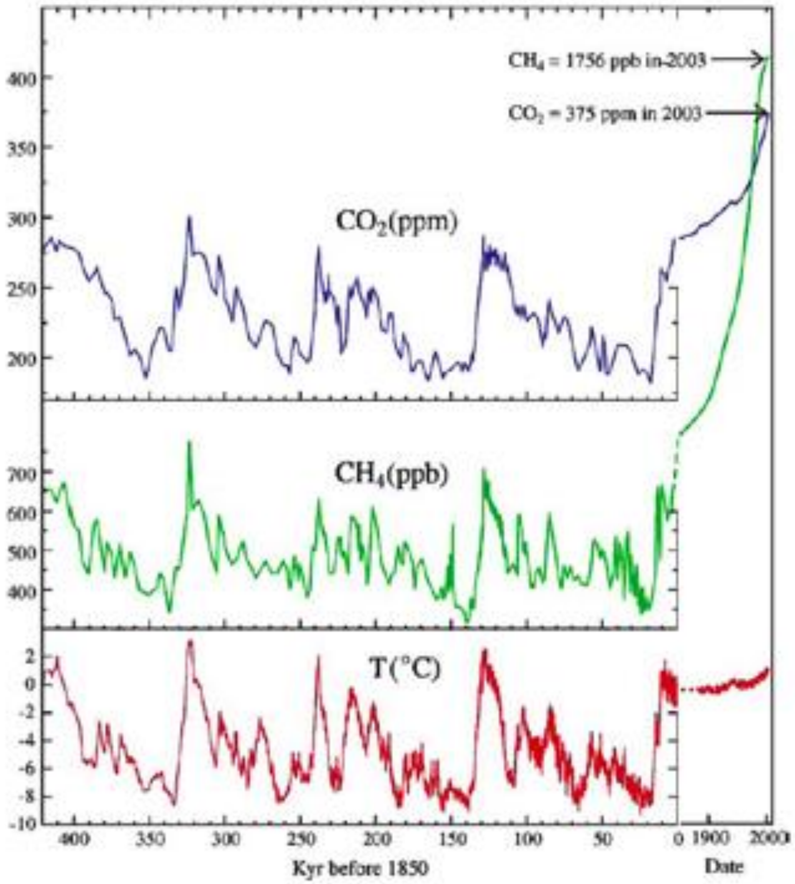
New York Times: Climate Deal Needs a Big Stick, Eduardo Porter

June 2, 2015

According to calculations by William Nordhaus, an expert on the economics of climate change at Yale, the United States, on net, would gain $8 billion a year by benefiting from everybody else's efforts to slow down the Earth's warming without having to exert any effort itself.

But if the other advanced nations had a stick — a tariff of 4 percent on the imports from countries not in the "climate club" — the cost-benefit calculation for the United States would flip. Not participating in the club would cost Americans $44 billion a year.

Course Goals

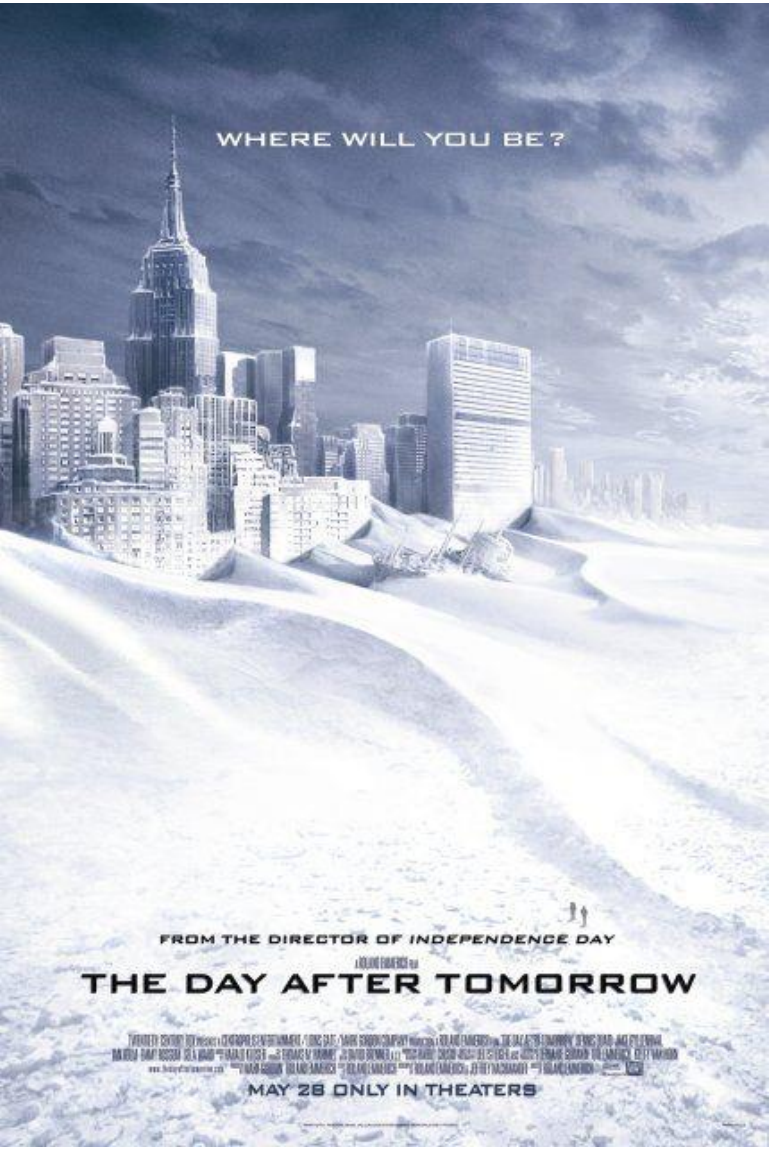


1. Introduce you to climate science and the scientific method

2. Give you tools to understand and <u>critically evaluate</u> modern environmental problems

https://uw.iasystem.org/survey/190740

It isn't rocket science



1. **Increasing greenhouse gases is a positive radiative forcing.**

2. **Temperature should increase (1880's physics): natural positive feedbacks amplify warming**

3. **Impacts of increased temperature: ice melts, sea water expands, soil moisture evaporates faster, more water vapor means heavier rains**

Some opinions (not necessarily endorsed by me)

http://thedailyshow.cc.com/videos/8q3nmm/burn-noticed

https://www.youtube.com/watch?v=3E0a_60PMR8

https://www.youtube.com/watch?v=YDL4Bs3NbB0