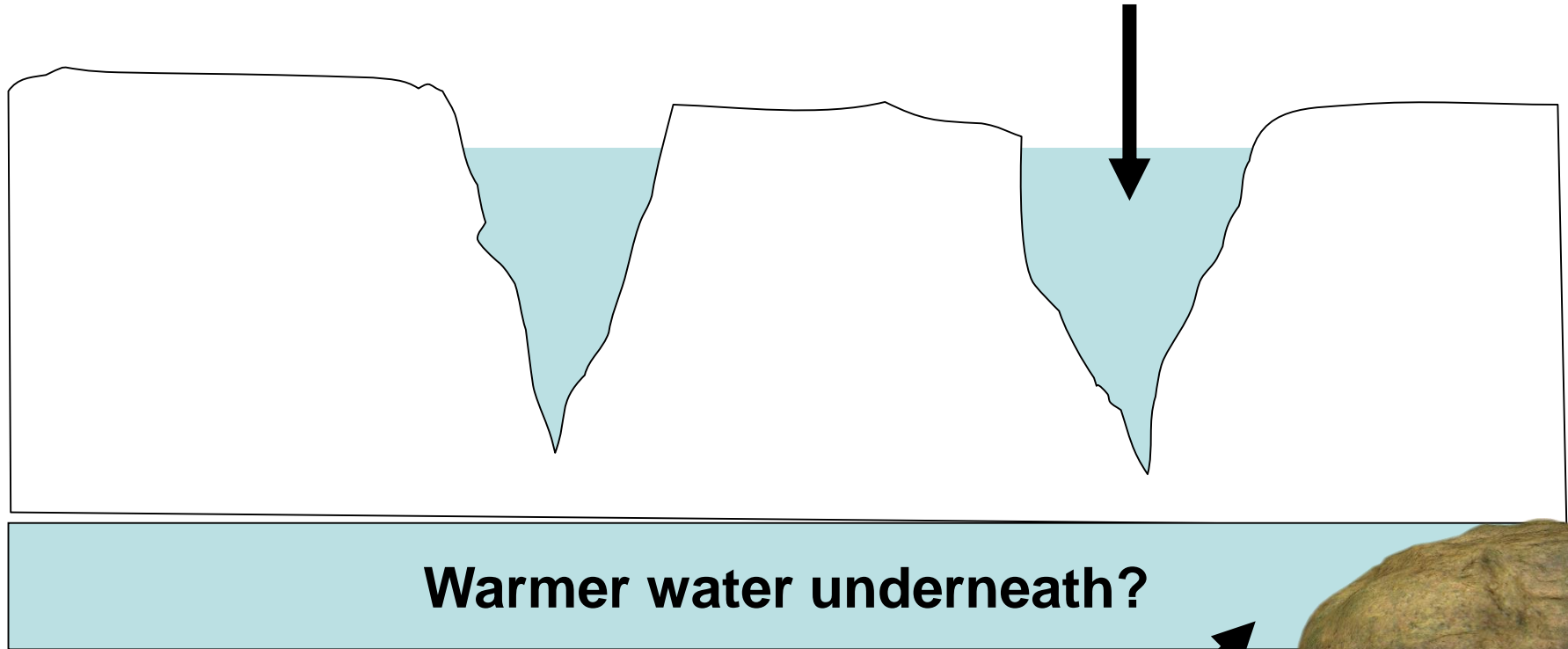


Ice Sheet/Shelf Instabilities?

Potential for positive feedbacks and
“tipping points”

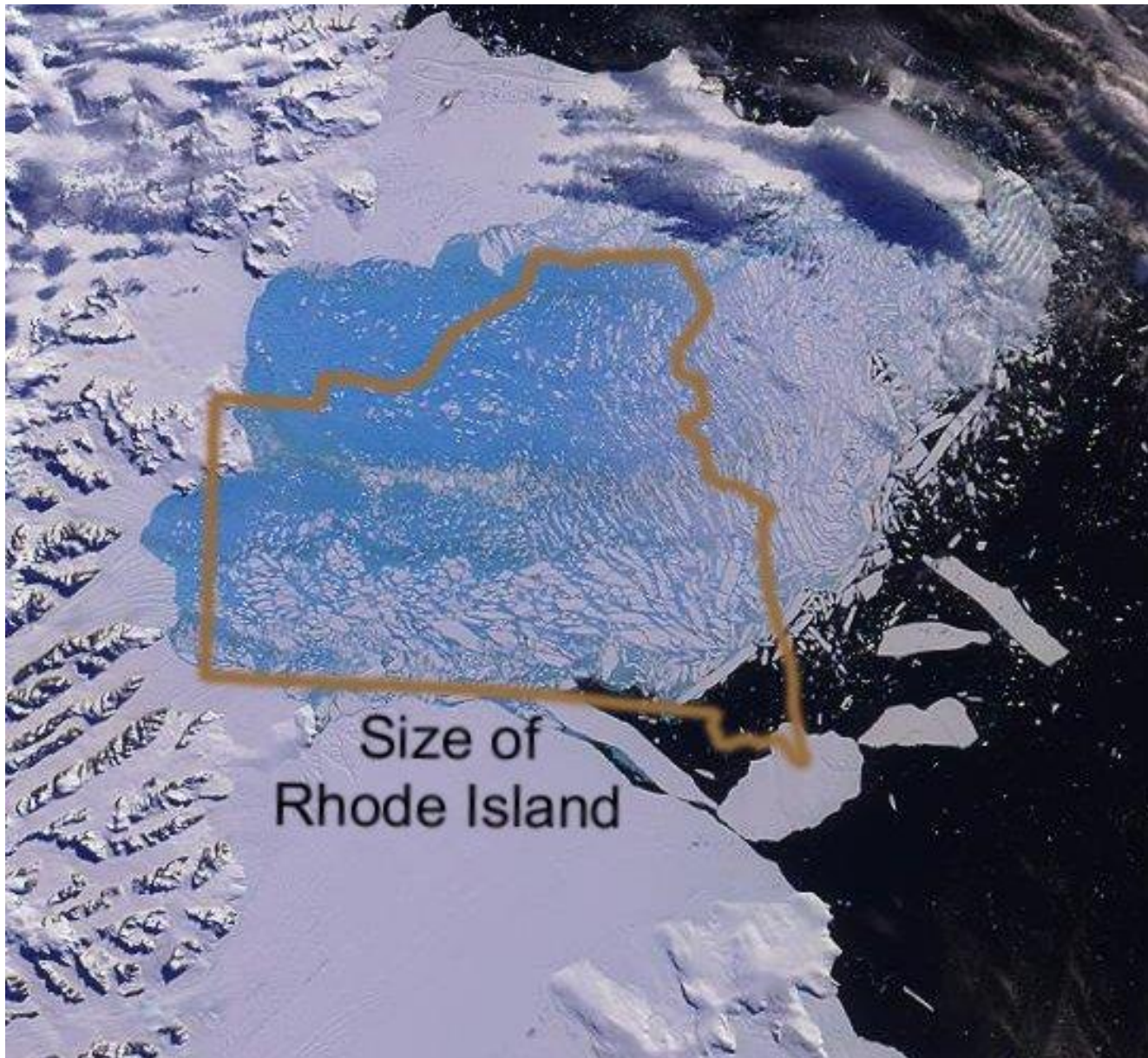
Surface melt water
→ Lower albedo



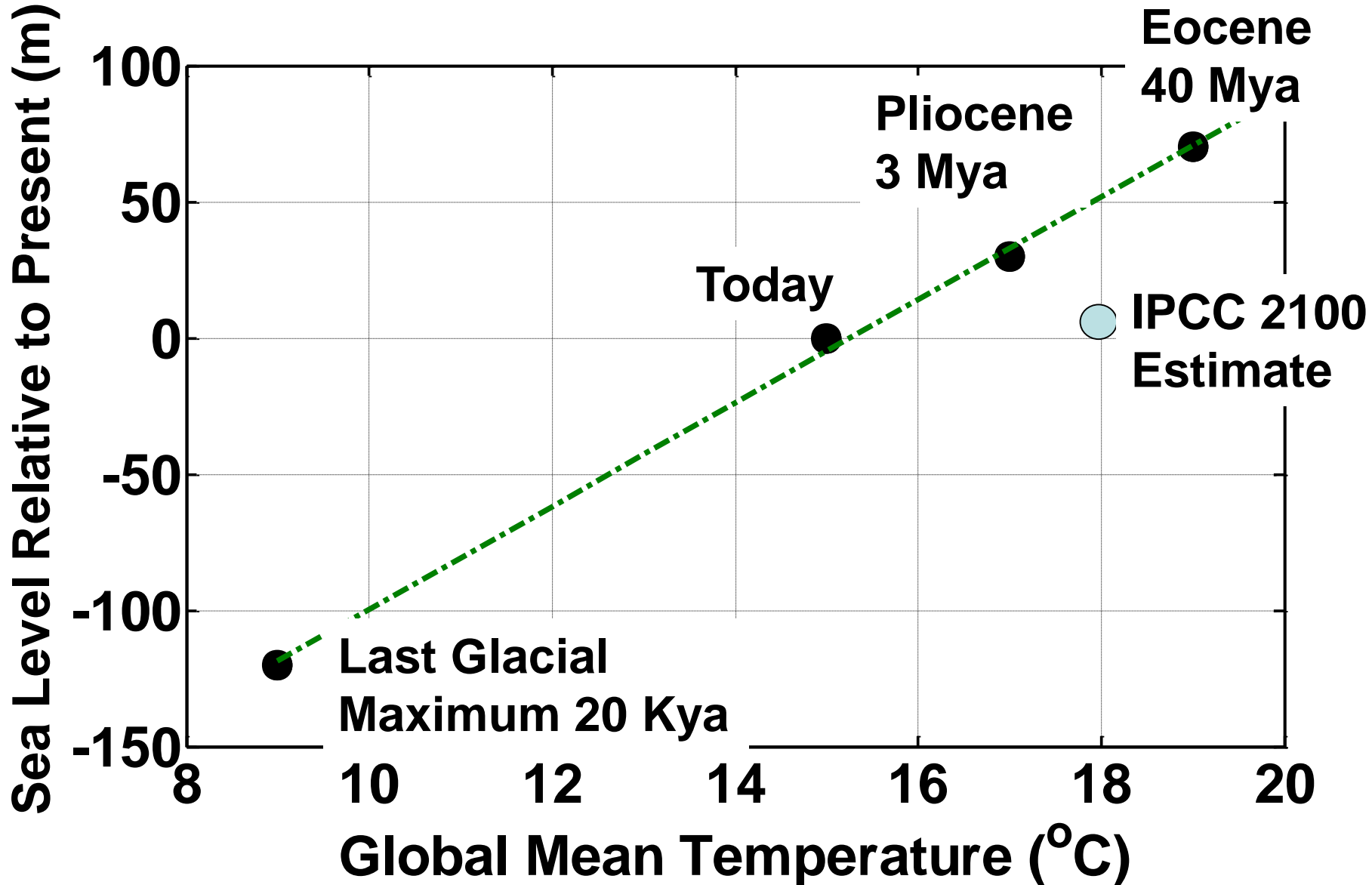
Warmer water underneath?

Liquid water between
ice and rock is slippery

Larsen Ice Shelf Collapse



Sea Level on Geologic Timescales



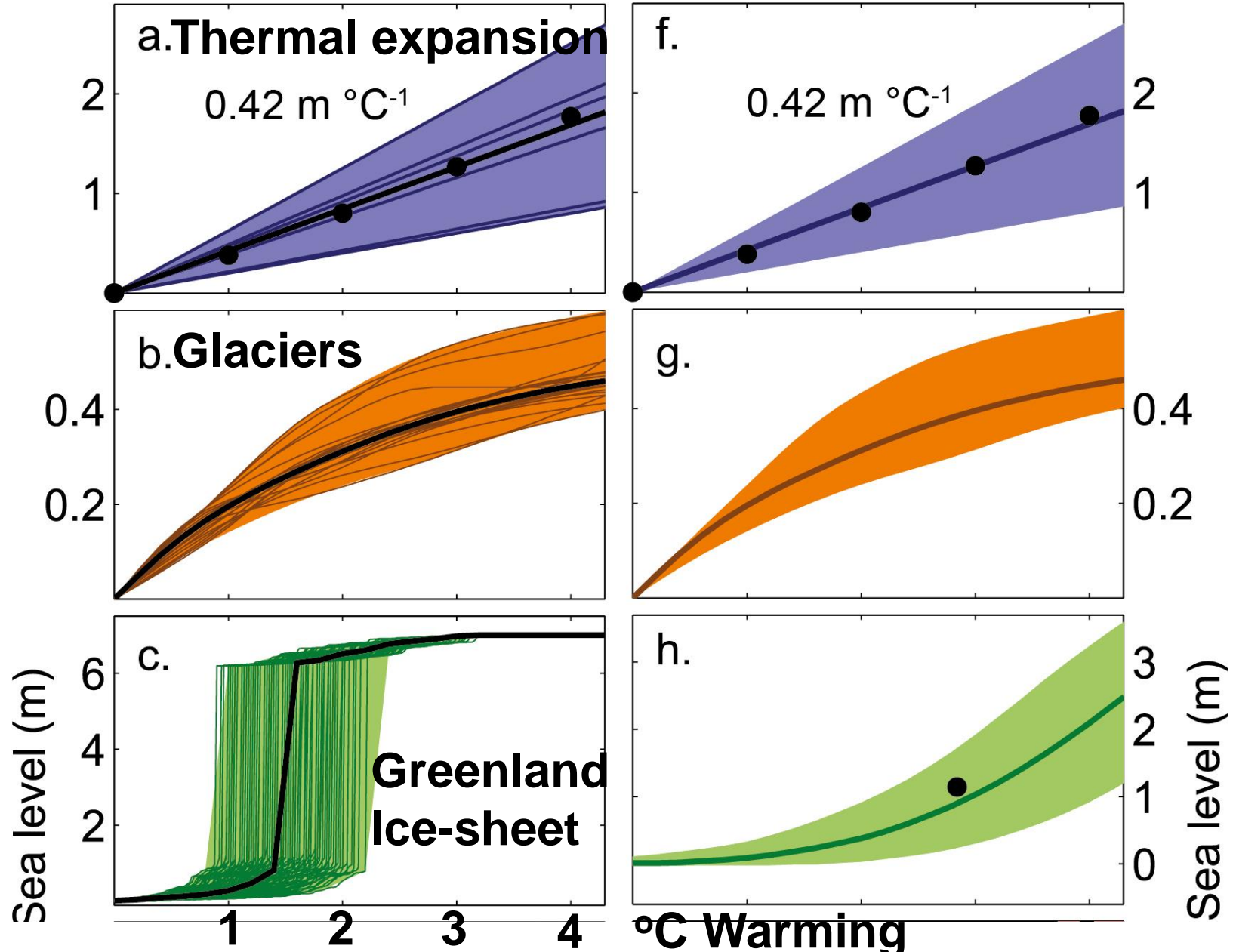
Eastern U.S. 1 m of sea level rise



Eastern U.S. 30 m of sea level rise



Multi-Millennial compared to 2000 yr Sea Level Rise

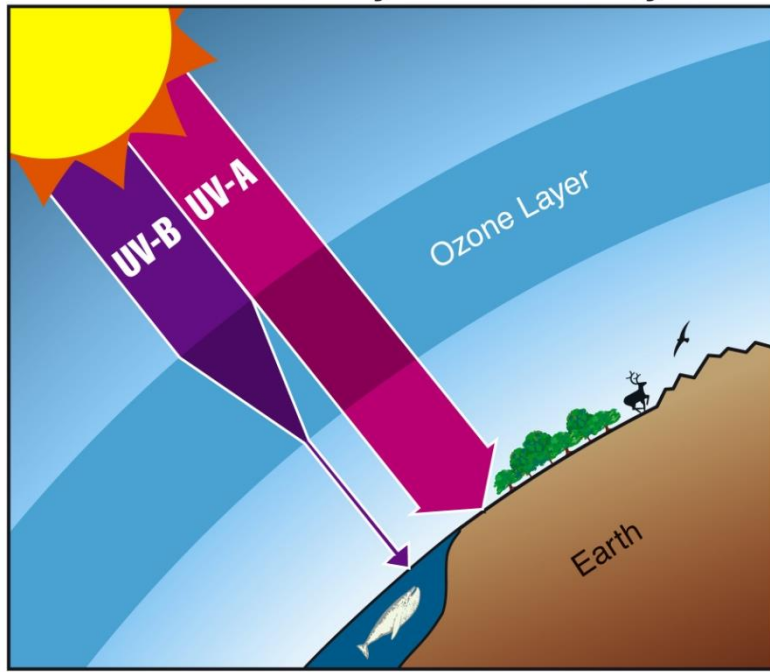


What can be done?



Stratospheric Ozone (O₃) Importance

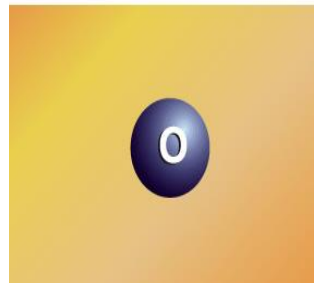
UV Protection by the Ozone Layer



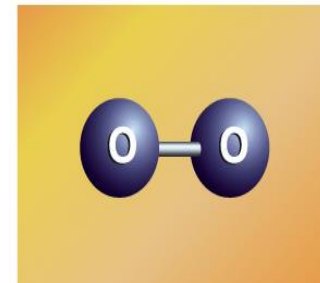
→ prevents exposure of terrestrial and surface water life to harmful UV radiation (causes DNA damage, skin cancer and loss of eyesite)

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

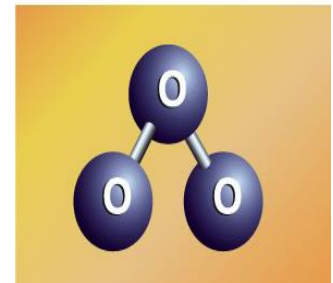
Oxygen
Atom (O)



Oxygen
Molecule (O₂)



Ozone
Molecule (O₃)



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!

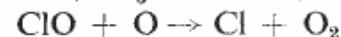
Stratospheric sink for chlorofluoromethanes : chlorine atomc-atalysed destruction of ozone

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 $\text{CFCl}_2 + \text{Cl}$ and to $\text{CF}_2\text{Cl} + \text{Cl}$ respectively, at altitudes of 20–40 km. Each of the reactions creates two odd-electron species—one Cl atom and one free radical. The dissociated chlorofluoromethanes can be traced to their ultimate sinks. An extensive catalytic chain reaction leads to the net destruction of O_3 and O occurs in the stratosphere.

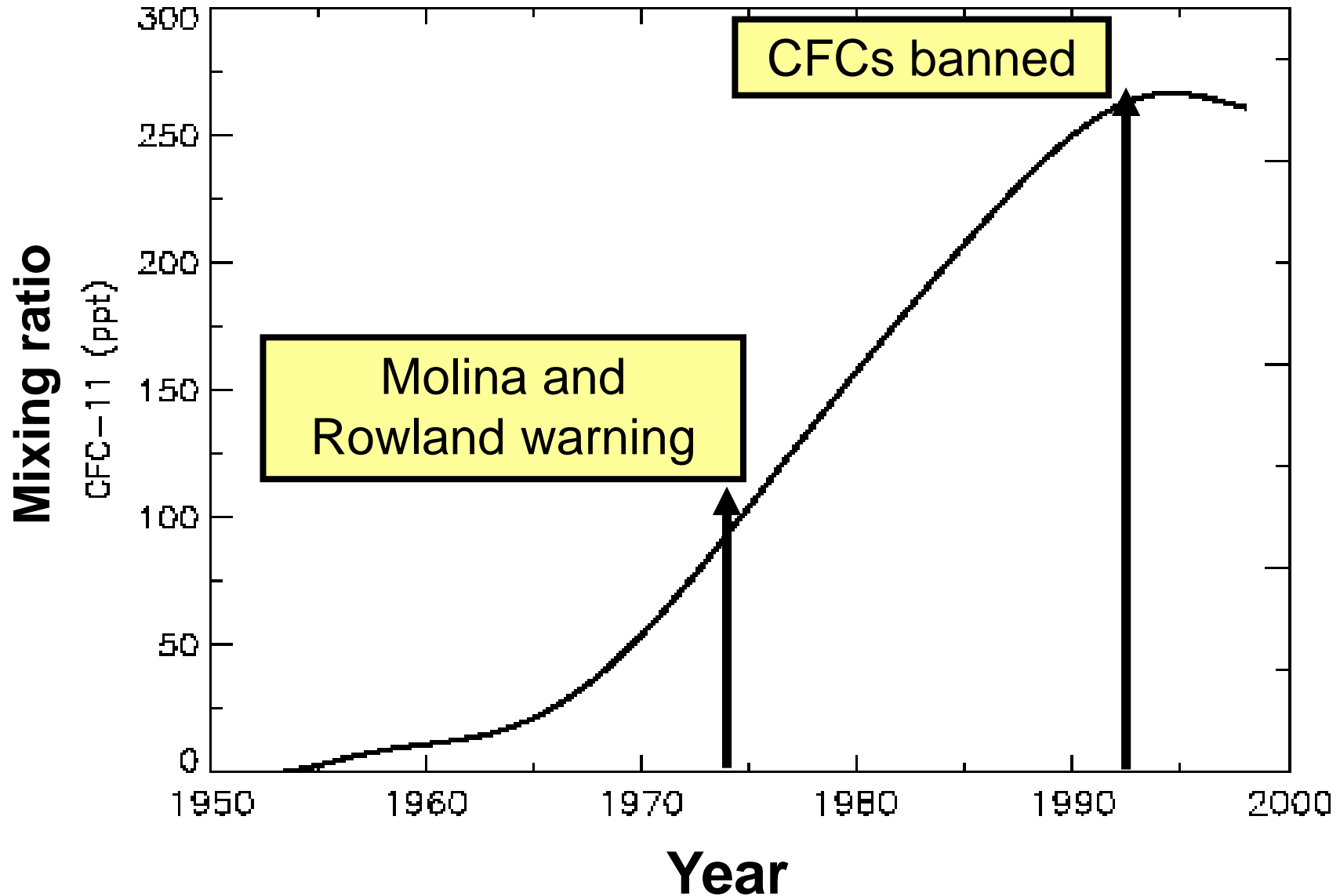


This has important chemical consequences. Under most conditions in the Earth's atmospheric ozone layer, (1) is faster than (2) because of the higher concentration of O_3 compared to O. (2) is slower of the reactions because there is a much lower concentration of O atoms.

Nature, June 28, 1974

Molina, Rowland, and Crutzen win Nobel Prize in 1994

CFC-11 Atmospheric Abundance

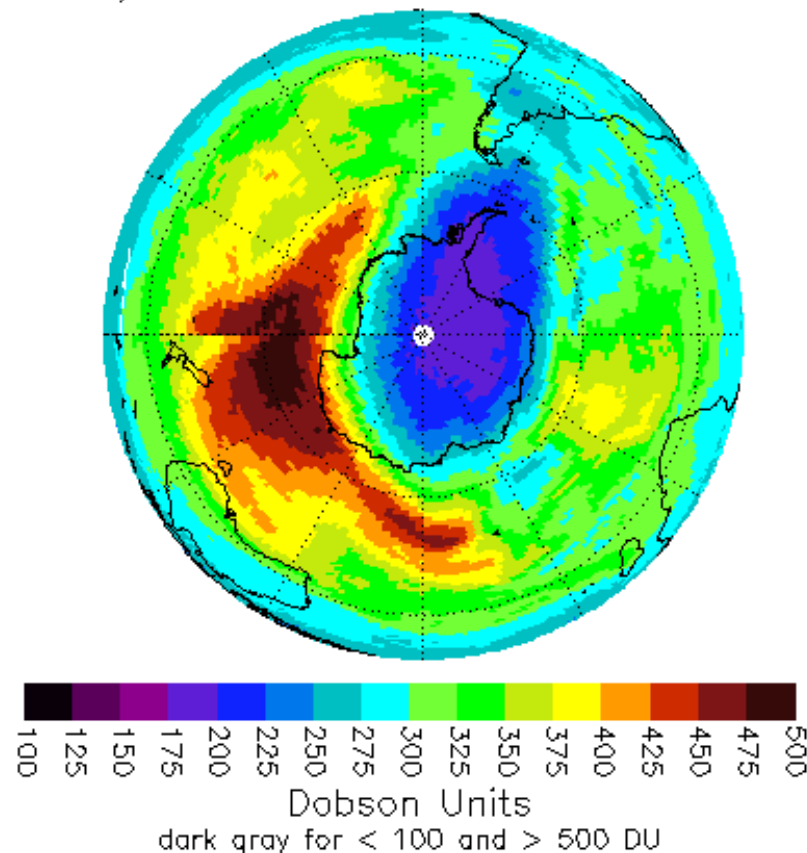


Discovery of Antarctic Ozone Hole



GEN:119/2004

IBUS-7/TOMS Total Ozone for Oct 3, 1983



GSFC/916



Reality was worse than the predictions!

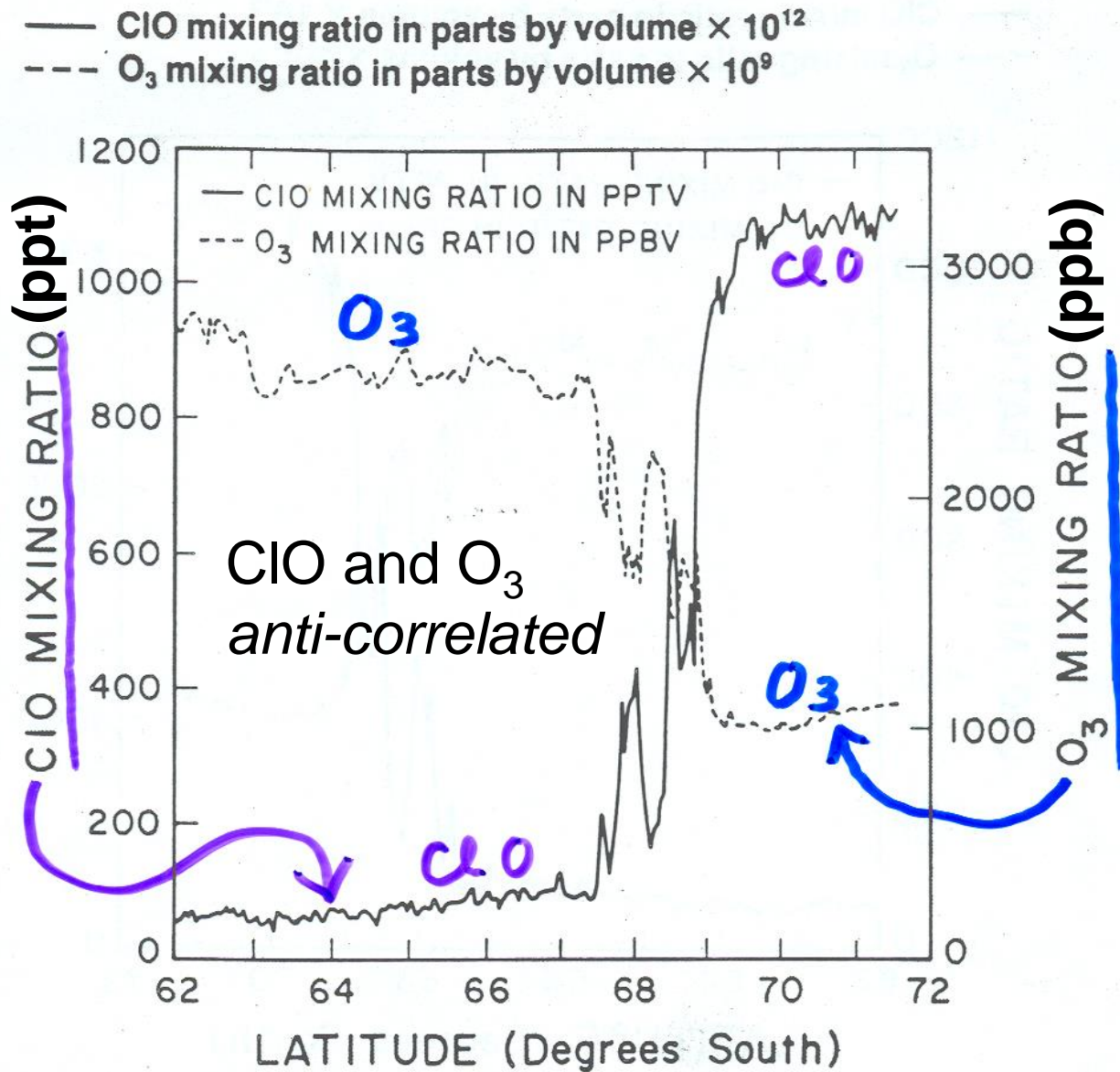
Antarctic Ozone Hole Theories



Also a real scientific debate

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

“Human Finger Prints”: Chlorine

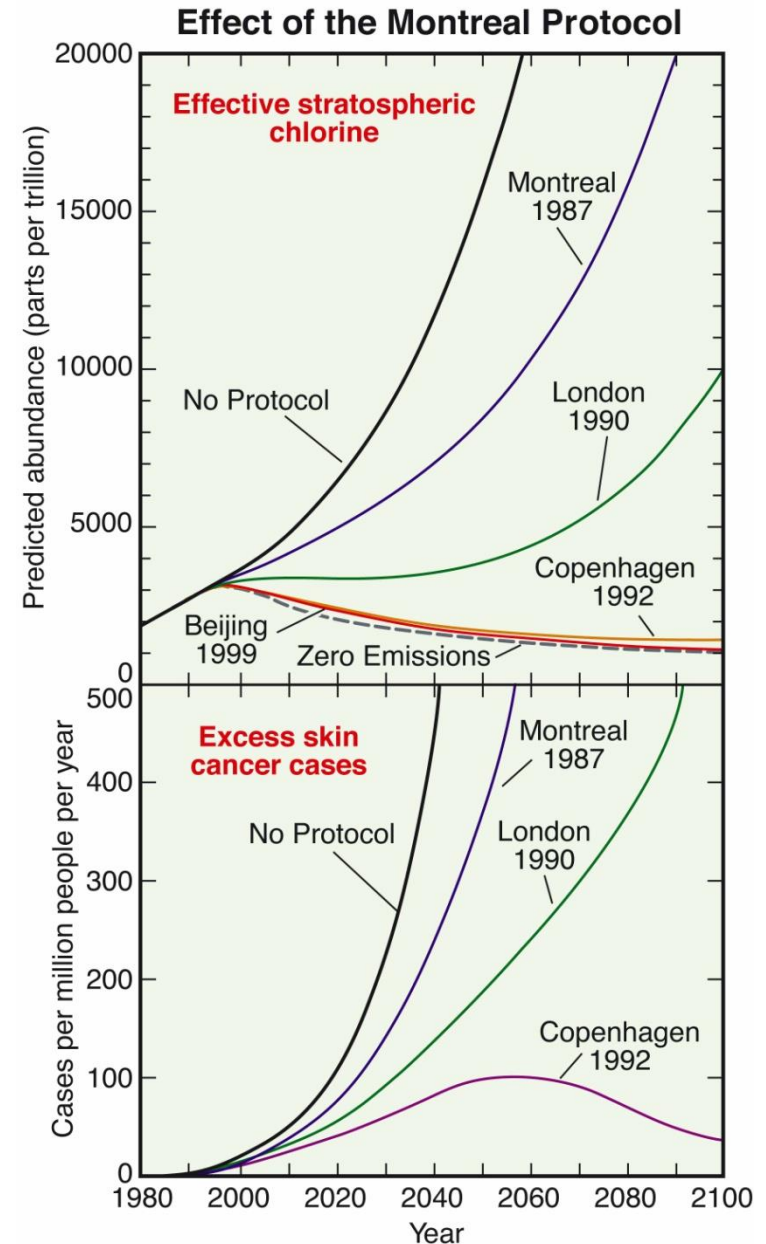


Montreal Protocol (Think “Paris Climate Accord”)

Montreal, 1987: First legally binding international agreement

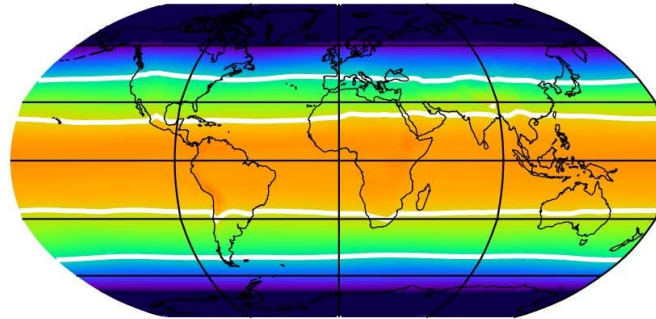
By 1992: a near complete ban on production and use of CFCs.

Replacements for CFCs, known as HCFCs, fairly easily implemented

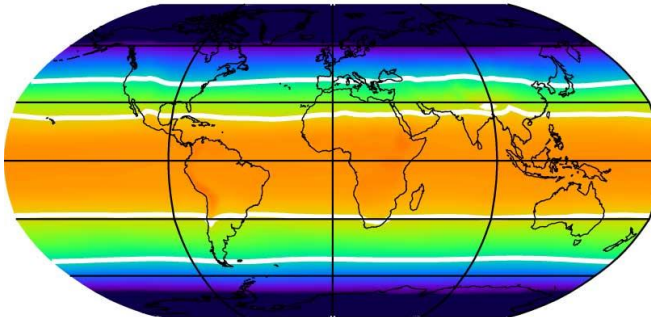


World Avoided: Health (Cancer and Cataracts)

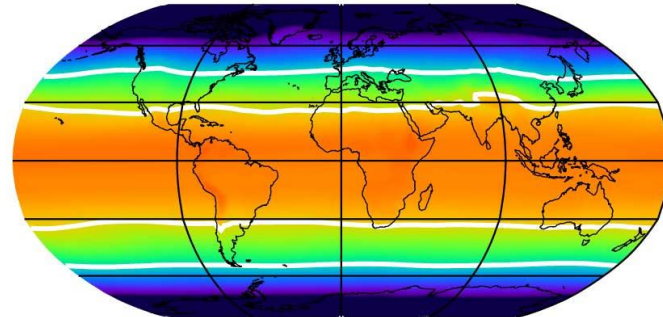
Mar 1975



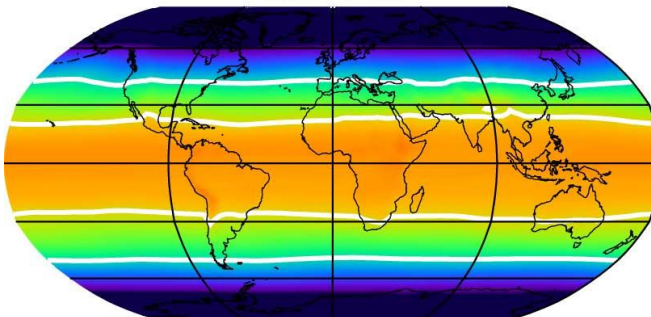
Expected Future
Mar 2020



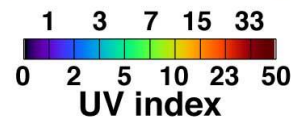
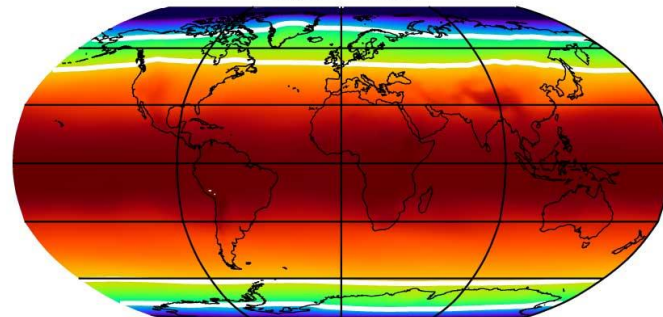
World Avoided
Mar 2020



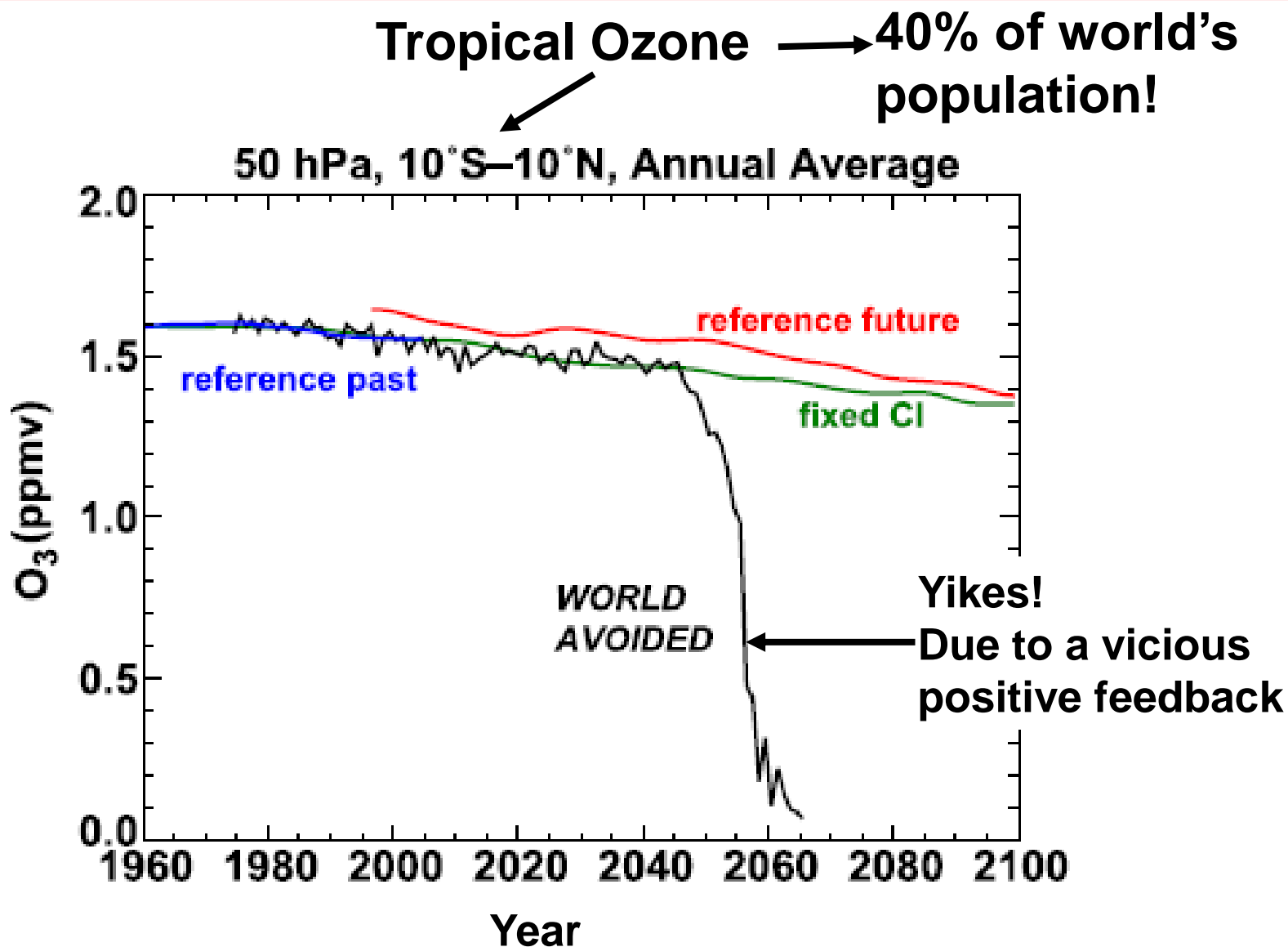
Mar 2065



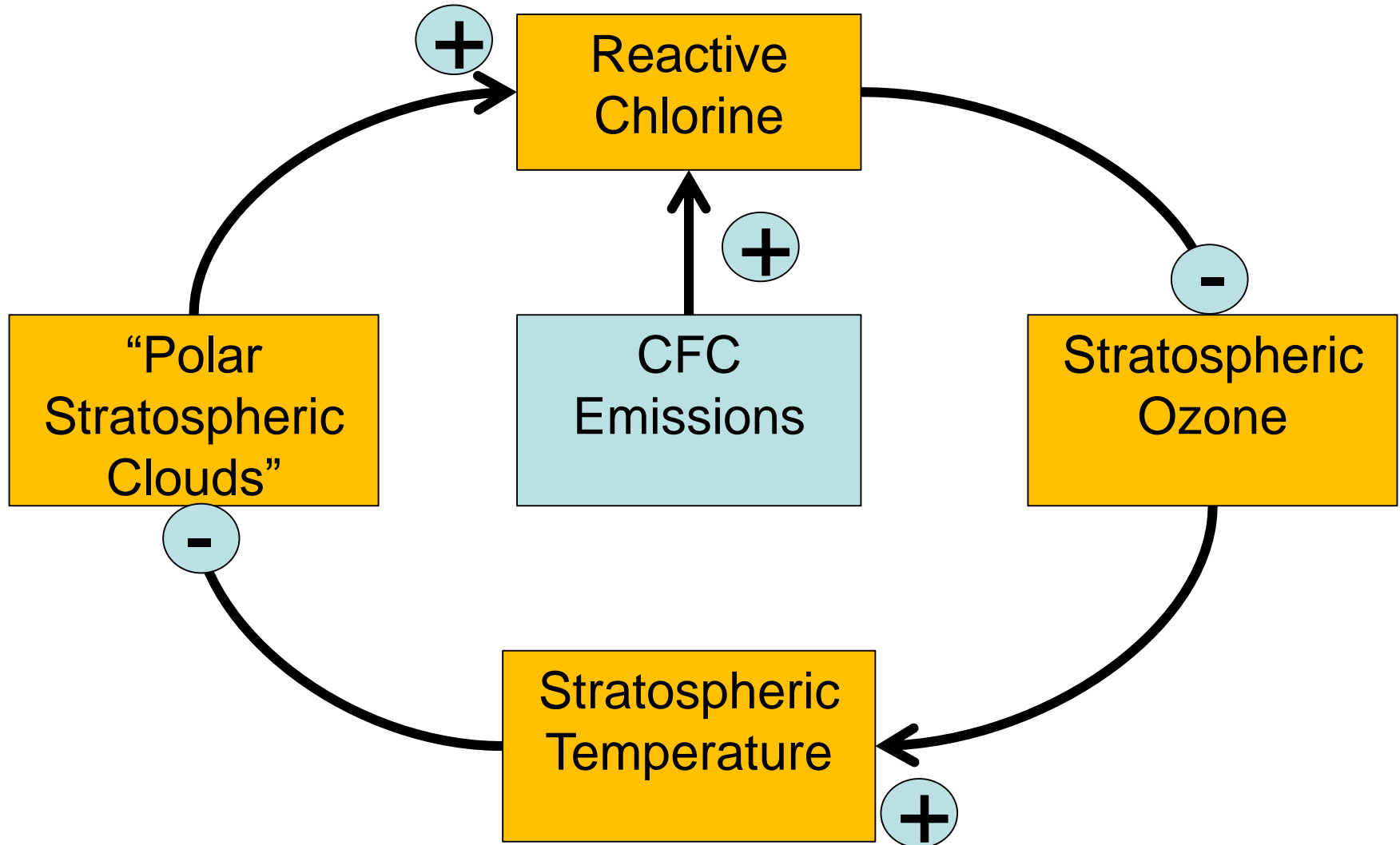
Mar 2065



Tipping Point Avoided

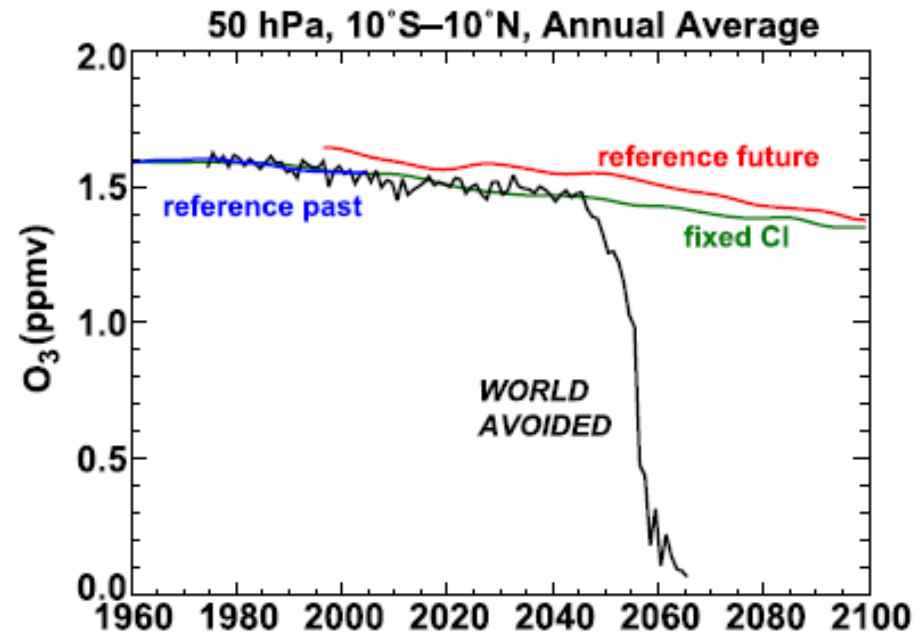


A Positive Feedback: CFC-Ozone Depletion-T



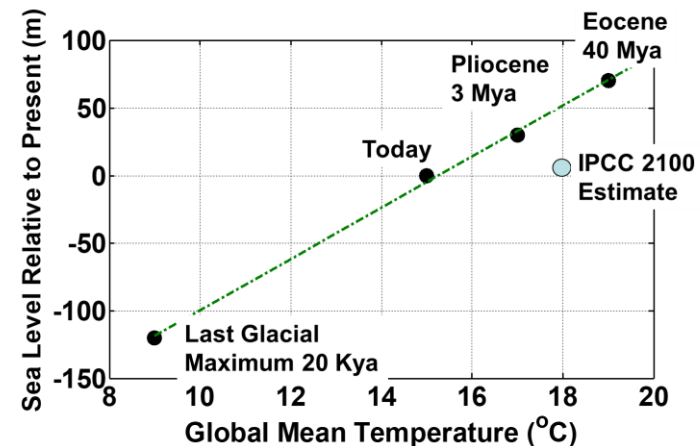
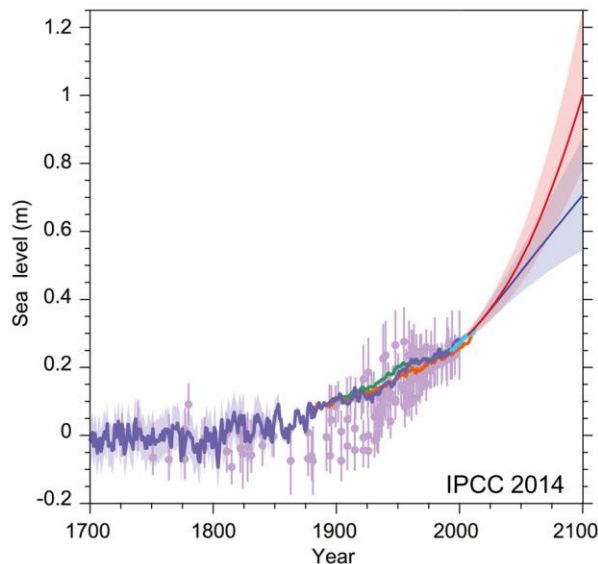
Ozone Depletion Problem vs Global Warming

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



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
- Scope of the ozone depletion problem would have been far worse than expected at time solutions were put into action
 - Are global warming predictions *too conservative* (e.g. sea level rise debate)? Or are climate scientists “*crying wolf*?”



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**
- **Scope of the ozone depletion problem would have been far worse than expected at time solutions were being sought and put into action**
 - **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**

Renewed CFC-11 Emissions?

LETTER

Nature 2019

<https://doi.org/10.1038/s41586-019-1193-4>

Increase in CFC-11 emissions from eastern China based on atmospheric observations

M. Rigby^{1,15}, S. Park^{2,15*}, T. Saito^{3,15}, L. M. Western^{1,15}, A. L. Redington^{4,15}, X. Fang^{5,15}, S. Henne⁶, A. J. Manning⁴, R. G. Prinn⁵, G. S. Dutton^{7,8}, P. J. Fraser⁹, A. L. Ganesan¹⁰, B. D. Hall⁷, C. M. Harth¹¹, J. Kim¹¹, K.-R. Kim², P. B. Krummel⁹, T. Lee², S. Li¹², Q. Liang¹³, M. F. Lunt¹⁴, S. A. Montzka⁷, J. Mühle¹¹, S. O'Doherty¹, M.-K. Park¹², S. Reimann⁶, P. K. Salameh¹¹, P. Simmonds¹, R. L. Tunnicliffe¹, R. F. Weiss¹¹, Y. Yokouchi³ & D. Young¹

The recovery of the stratospheric ozone layer relies on the continued decline in the atmospheric concentrations of ozone-depleting gases such as chlorofluorocarbons¹. The atmospheric concentration of trichlorofluoromethane (CFC-11), the second-most abundant chlorofluorocarbon, has declined substantially since the mid-1990s². A recently reported slowdown in the decline of the atmospheric concentration of CFC-11 after 2012, however, suggests that global emissions have increased^{3,4}. A concurrent increase in CFC-11 emissions from eastern Asia contributes to the global emission increase, but the location and magnitude of this regional source are unknown³. Here, using high-frequency atmospheric observations from Gosan, South Korea, and Hateruma, Japan, together with global monitoring data and atmospheric chemical transport model simulations, we investigate regional CFC-11 emissions from eastern Asia. We show that emissions from eastern mainland China are 7.0 ± 3.0 (± 1 standard deviation) gigagrams per year higher in 2014–2017 than in 2008–2012, and that the increase in emissions arises primarily around the northeastern provinces of Shandong and Hebei. This increase accounts for a substantial fraction (at least 40 to 60 per cent) of the global rise in CFC-11 emissions. We find no evidence for a significant increase in CFC-11 emissions from any other eastern Asian countries or other regions of the world where there are available data for the detection of regional emissions. The attribution of any remaining fraction of the global CFC-11 emission rise to other regions is limited by the sparsity of long-term measurements of sufficient frequency near potentially emissive regions. Several considerations suggest that the increase in CFC-11 emissions from eastern mainland China is likely to be the result of new production and use, which is inconsistent with the Montreal Protocol agreement to phase out global chlorofluorocarbon production by 2010.

have contributed to the slow-down, an increase in northern hemispheric emissions is required, starting after 2012, to explain most of these observed changes³.

High-frequency atmospheric CFC-11 mole fraction data from the AGAGE network⁴ and Japanese National Institute for Environmental Studies (NIES)⁵ show signals that are consistent with a continuing decline in CFC-11 emissions from Europe, North America and Australia in recent years, but a rise from eastern Asia since 2012 (Fig. 1; Extended Data Fig. 1). In these datasets, enhancements above the hemispheric background mole fractions are observed when plumes from nearby sources impinge on the measurement stations. For the AGAGE stations in Europe, the west coast of North America, Australia and more remote locations, the magnitudes of above-baseline events are relatively small and have declined throughout the study period (2008–2017, inclusive), indicating that emissions near these sites have dropped. A decline in emissions from the continental United States has also been inferred over the 2008 to 2014 period with independent NOAA data⁶. By contrast, observations at Hateruma, Japan (see Extended Data Fig. 2 for location), show persistent above-baseline events throughout 2008–2017, which have not declined substantially or may have increased, and data from Gosan, South Korea, show a strong increase in the magnitude of these events after 2012 (Fig. 1). We focus our analysis on eastern Asia because the existing measurement networks only show an increase in the magnitude of above-baseline events in this region. A qualitative emissions increase from somewhere in this region was also indicated in NOAA data from Hawaii³.

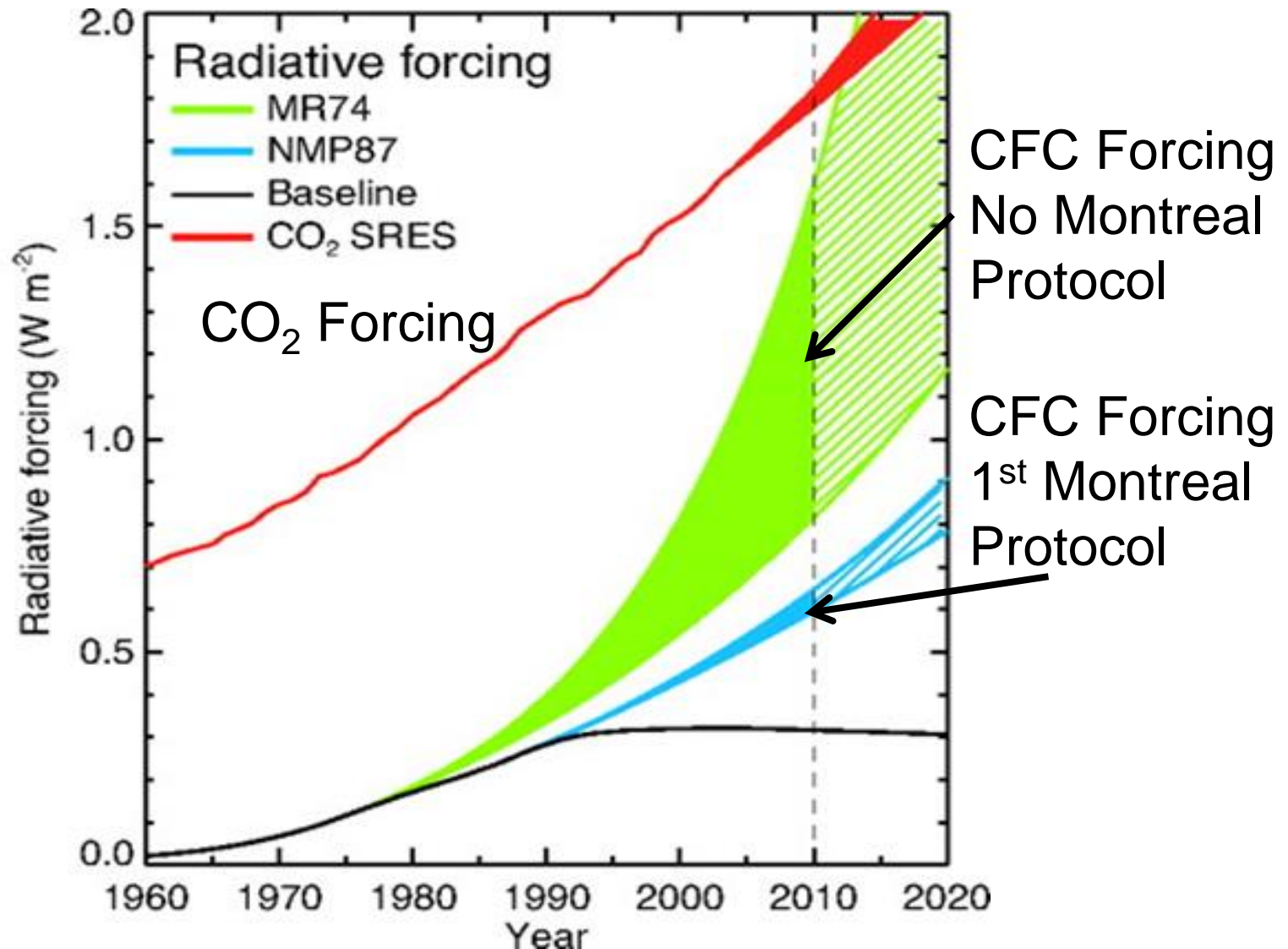
To quantify emissions from eastern Asian countries, atmospheric observation-based ‘inverse’ or ‘top-down’ estimates were carried out with CFC-11 measurements from Gosan and Hateruma observations using two atmospheric chemical transport models and four statistical methods (see Methods). Previous top-down studies in this region

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**
- **Scope of the ozone depletion problem would have been far worse than expected at time solutions were being sought and put into action**
 - **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**

An Ozone Depletion – Global Warming Connection

CFCs are potent Greenhouse Gases!

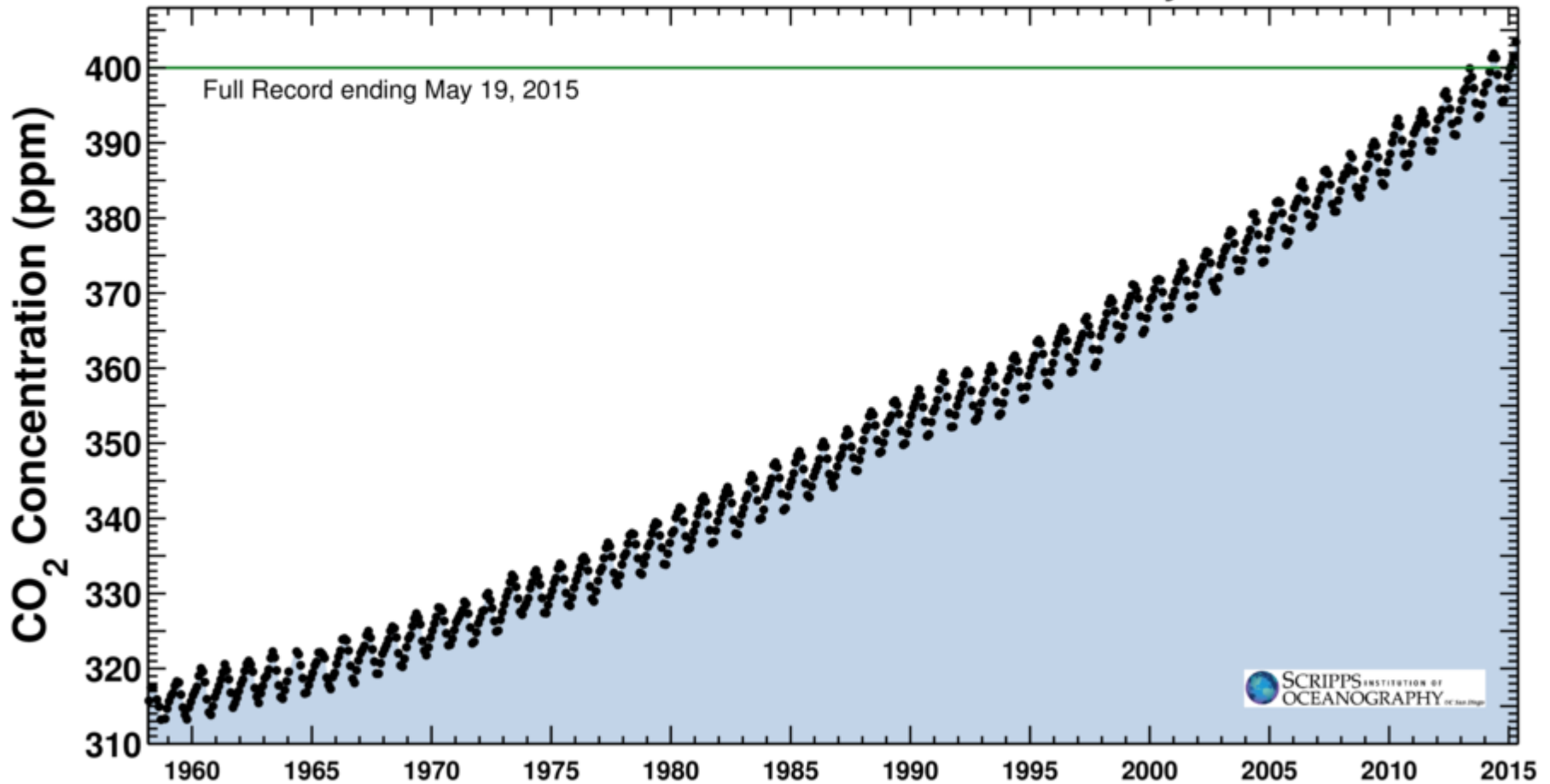


Anthropogenic GHG Forcing

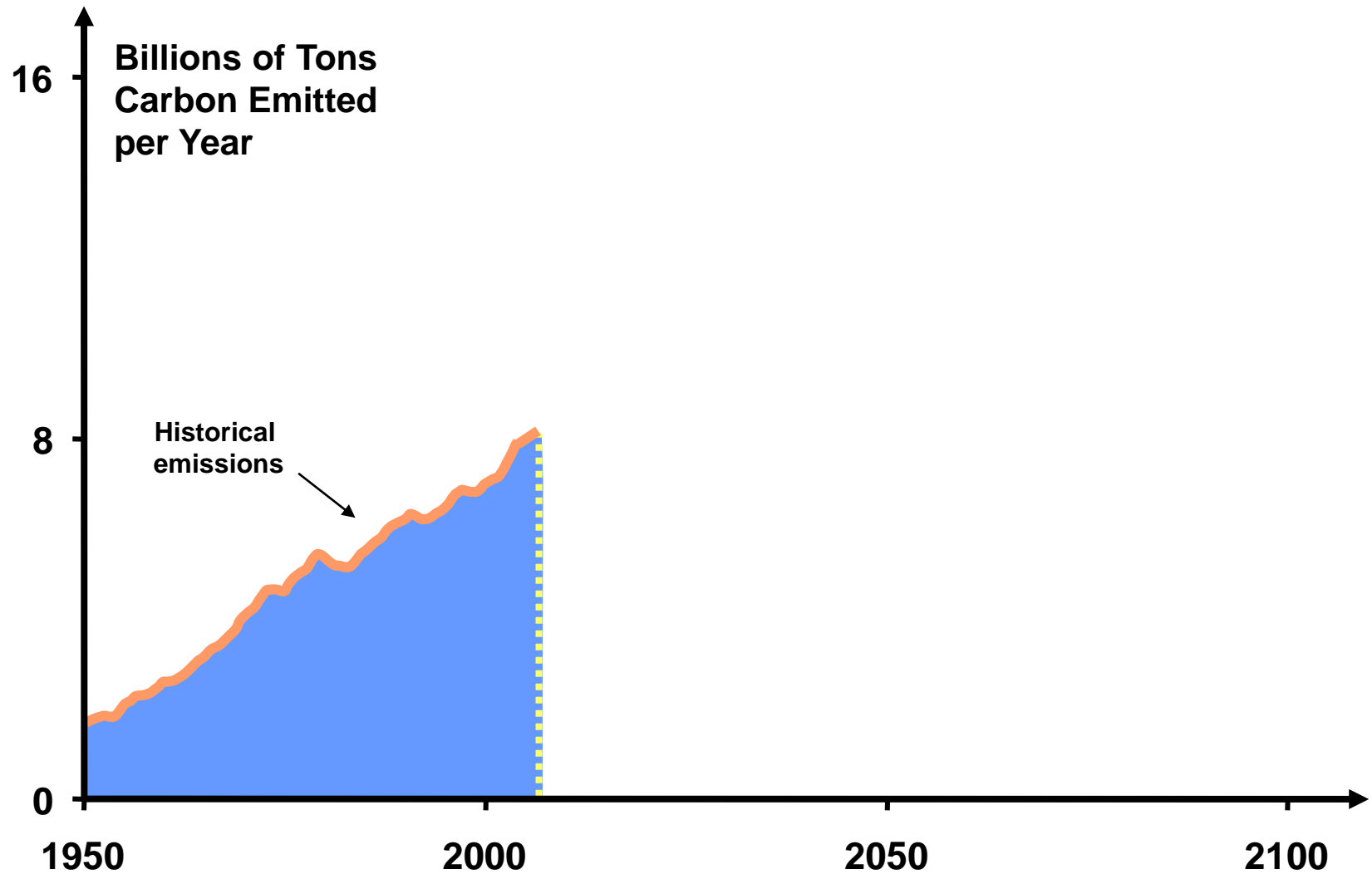
Latest CO₂ reading
May 19, 2015

403.88 ppm

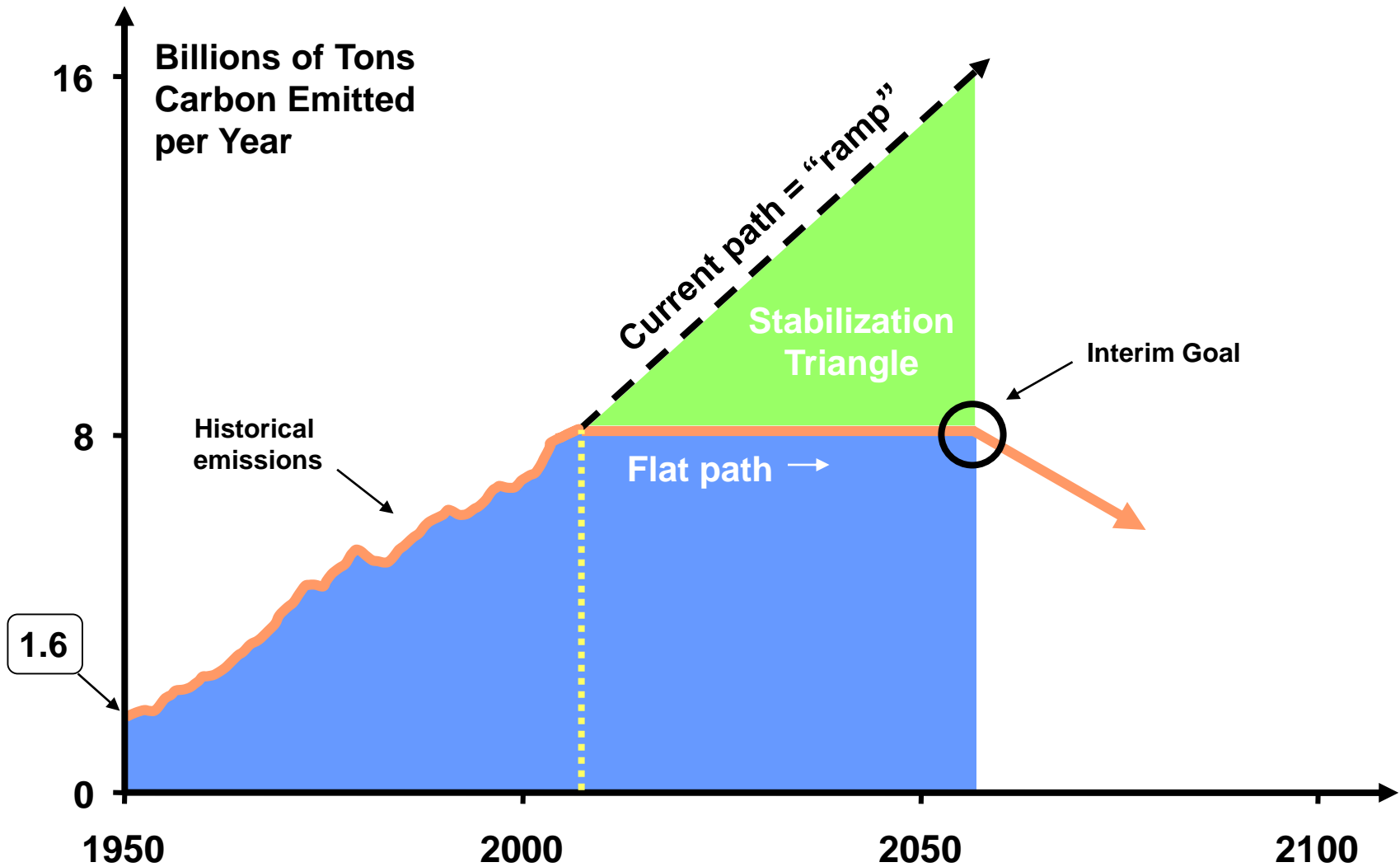
Carbon dioxide concentration at Mauna Loa Observatory



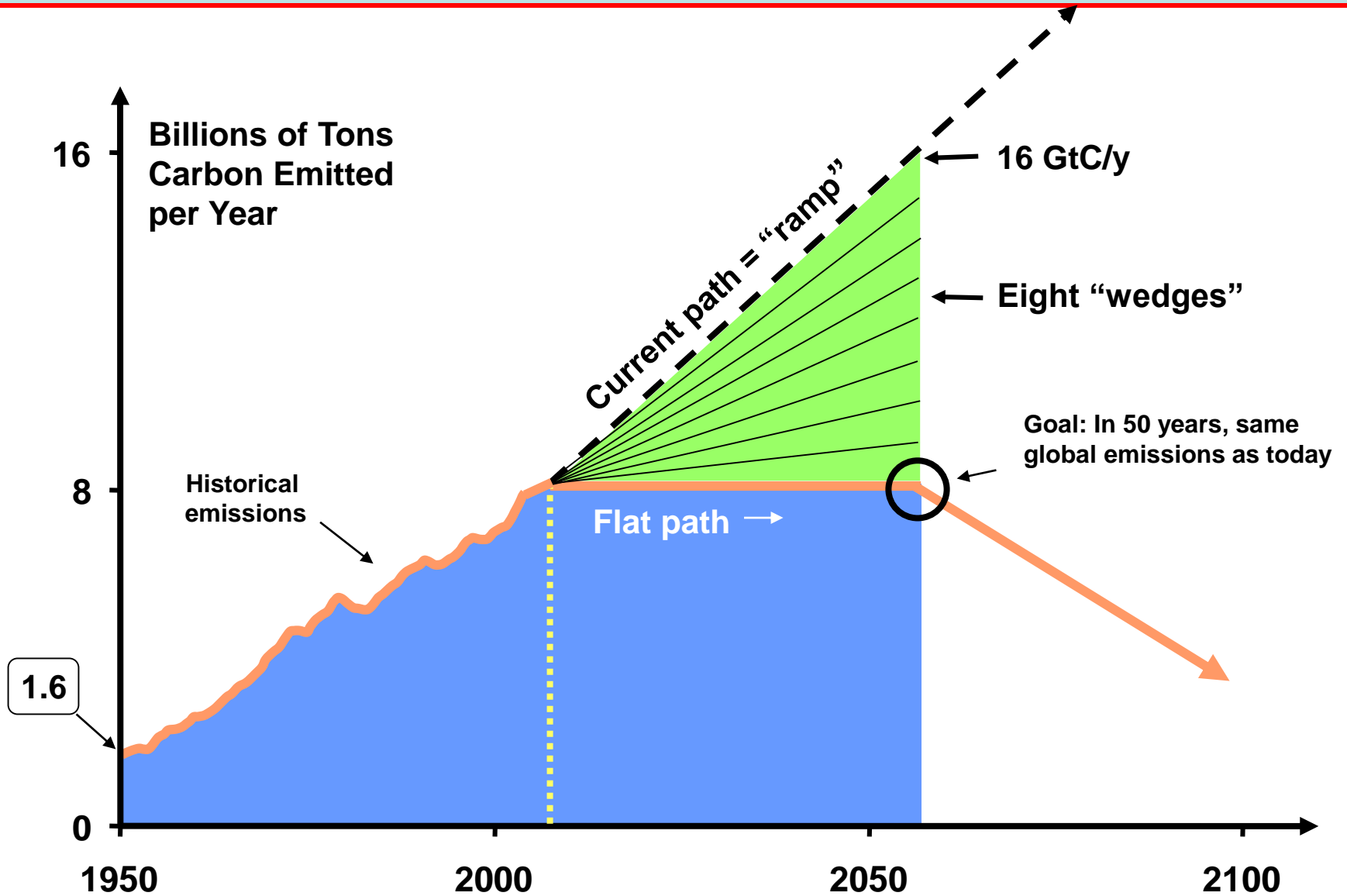
Historical Emissions



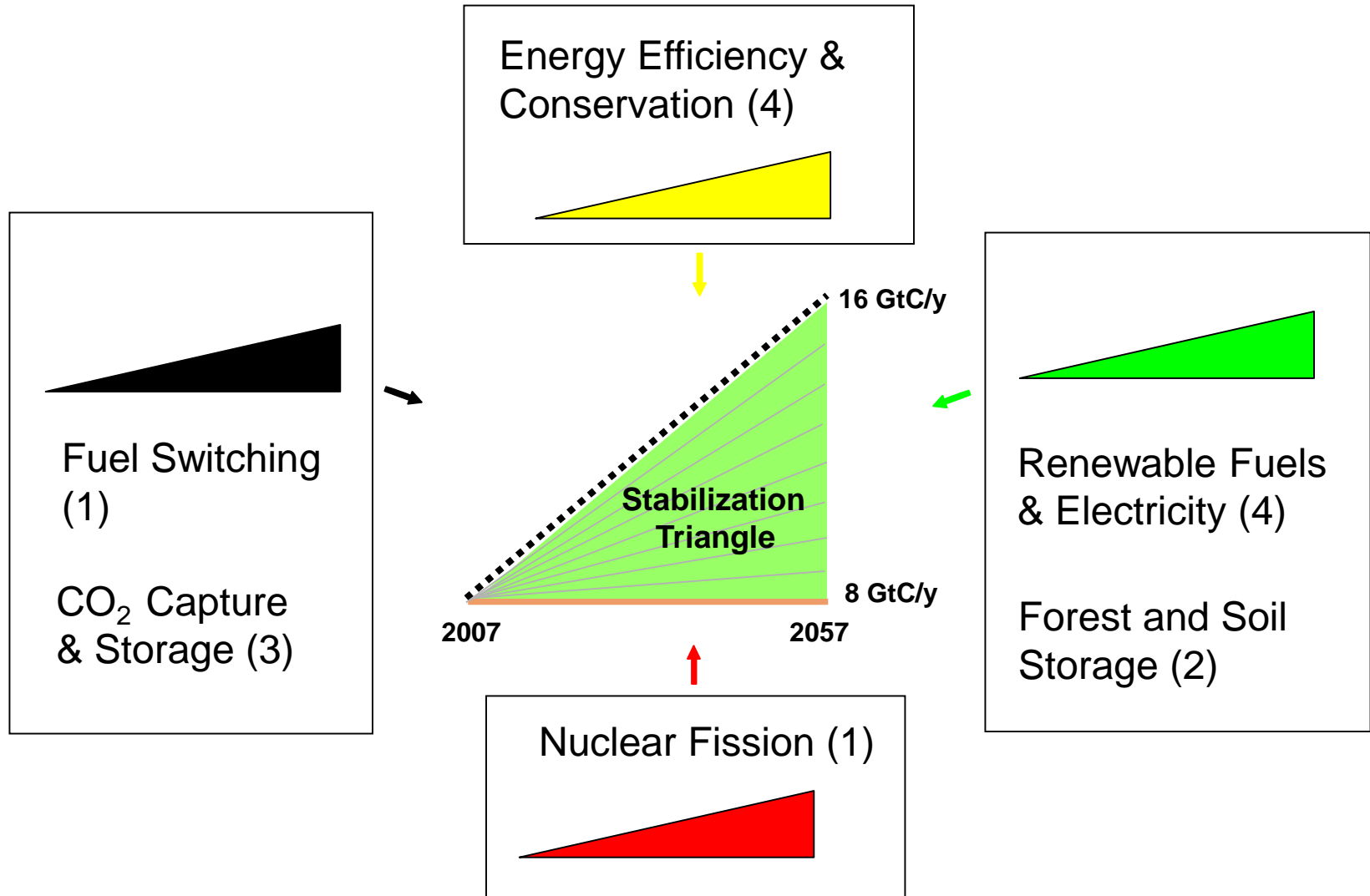
The Stabilization Triangle



Stabilization Wedges



15 Wedge Strategies in 4 Categories



See [Carbon Mitigation Initiative](#)

Alternative to the Wedges Approach: Geo-engineering?



Solar Radiation Management
--increase albedo to offset GHG warming

Carbon capture
--actively scrub CO₂ from the atmosphere

Geo-engineering: Particles in Stratosphere

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



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. Coleman¹

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 CO₂ concentrations.

Estimates: Need 1 – 5 Tg S/yr to negate doubled CO₂

Geo-engineering: Particles in Stratosphere



**~20 Tg S in
stratosphere**



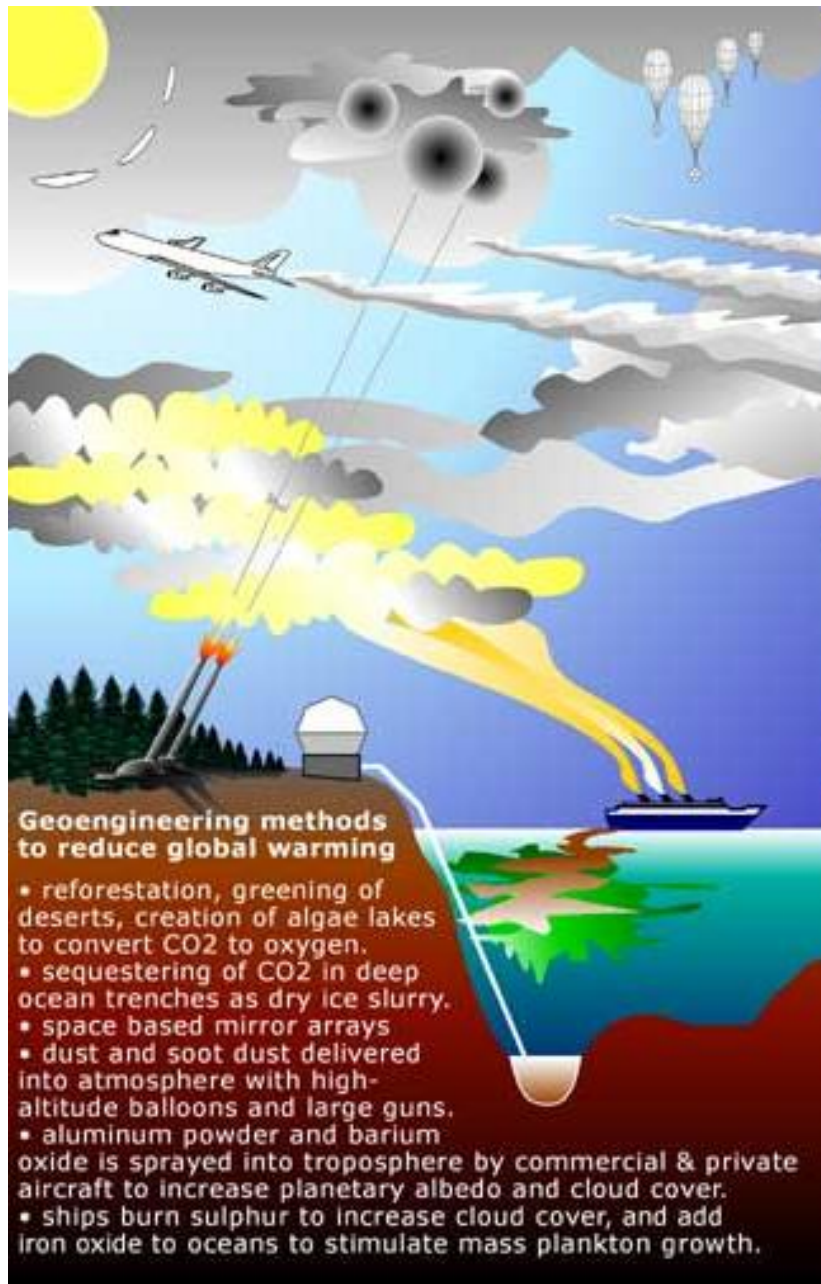
Need Mt.
Pinatubo every 2-
4 years...

Marine Cloud Brightening

- <https://twitter.com/i/status/1121455609465974786>



Various Geo-engineering Schemes



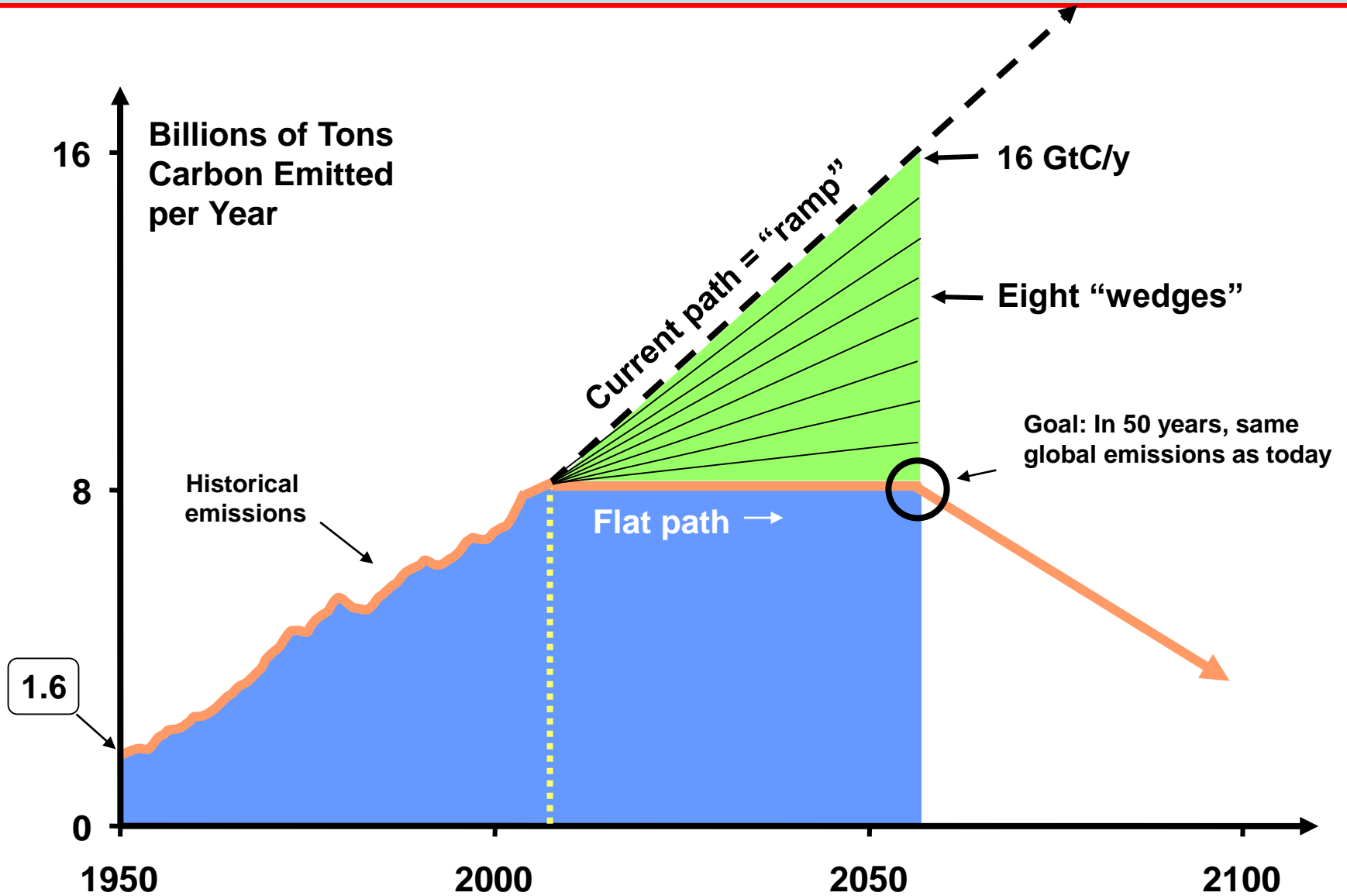
What laws and treaties exist or are needed?

Who will control the desired climate?

What happens if there is an interruption in the scheme (CO₂ still increasing)?

Global average T is not the only problem associated with increasing CO₂, what about those?

Stabilization Wedges



A Global Problem Requires a Global Solution



United Nations
Framework Convention on
Climate Change

UNFCCC Google Search



Home CDM JI CC:iNet TT:Clear

Your location: Home

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Get News
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Bodies

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<< previous MEETINGS next >>



Bonn Climate Change Conference - June 2015

COP 21 / CMP 11
Host country website



PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

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

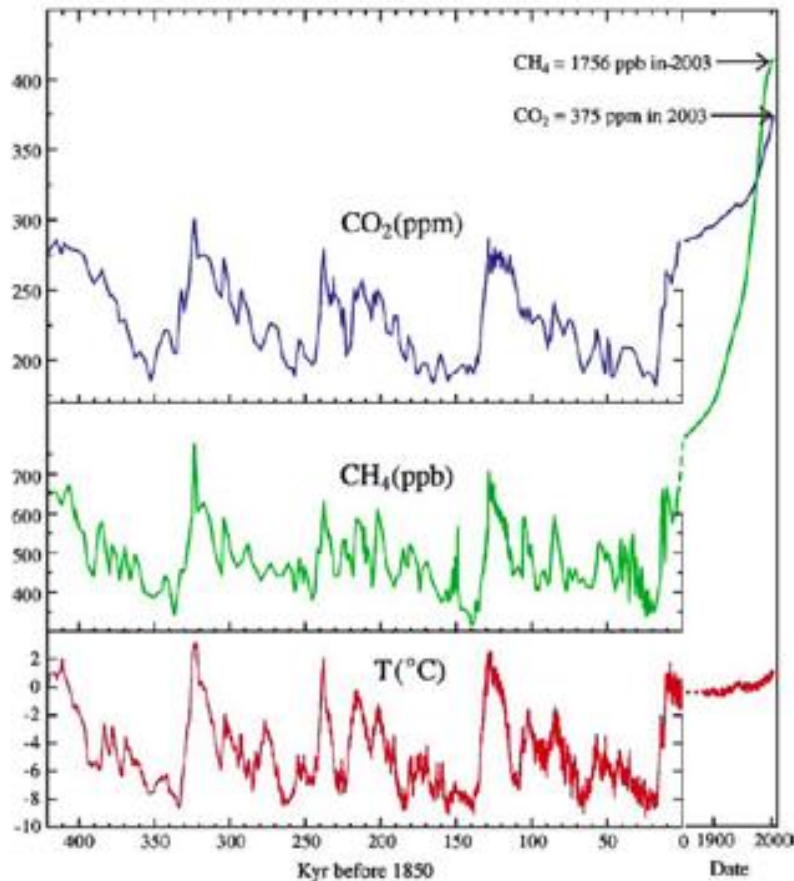
New York Times: Climate Deal Needs a Big Stick, Eduardo Porter

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

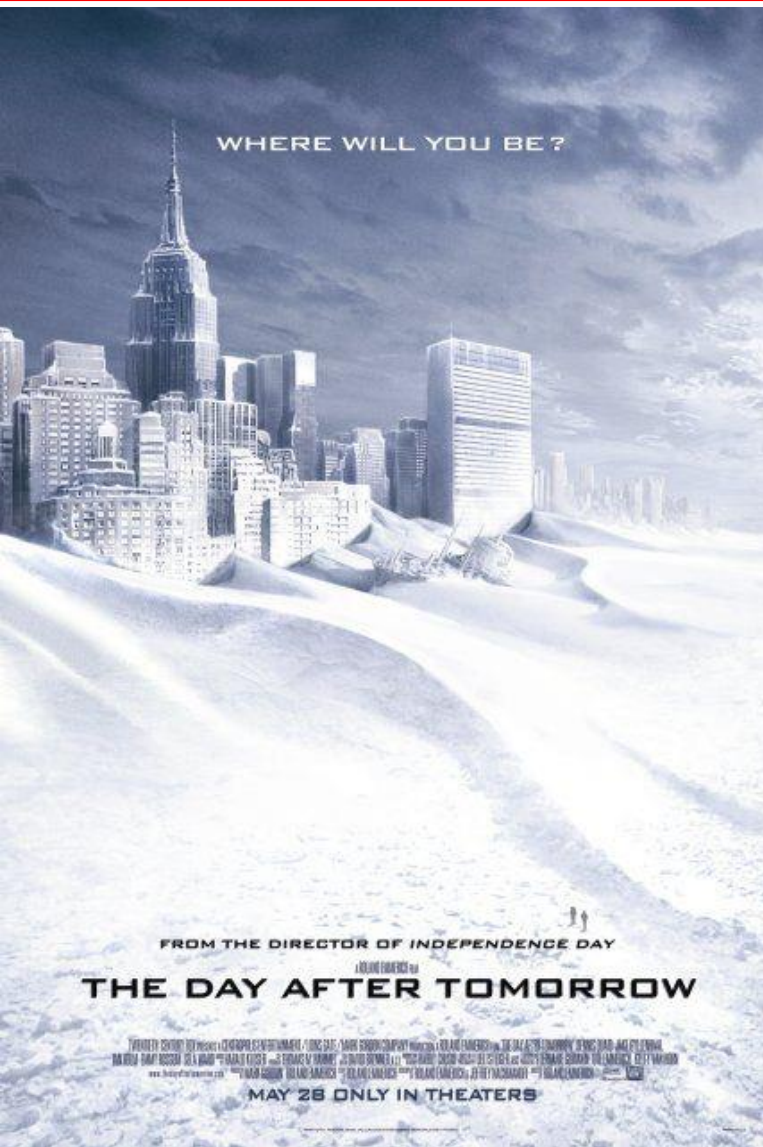


1. Introduce you to climate science and the scientific method

2. Give you tools to understand and critically evaluate 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=3EOa_6OPMR8

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

