Ozone Depletion, Greenhouse Gases, and the Special Case of Antarctic Climate Change

Susan Solomon, NOAA Senior Scientist
and co-chair, IPCC (2007) science report

1. Two historic papers and their importance to policy and science
2. Antarctic ozone depletion and Antarctic surface climate
3. Montreal helps Kyoto (a lot); connections to other policy considerations
4. Summary

Historic Paper #1: Molina and Rowland, Nature, 1974: CFCs are long-lived and deplete stratospheric ozone {CFC chemistry}

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.

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

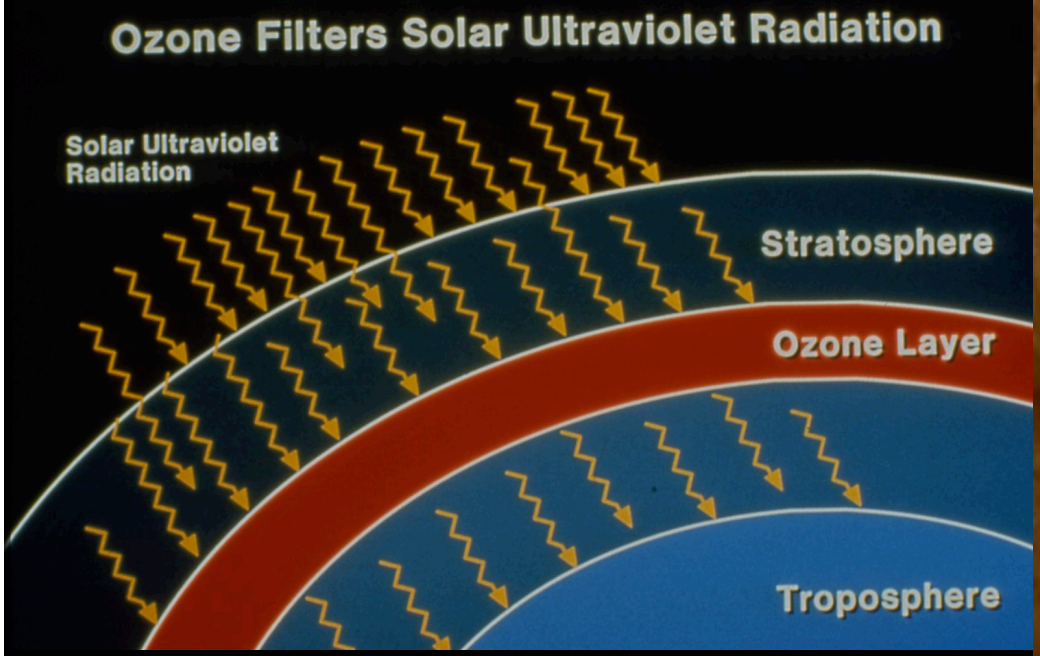
$$O + ClO \rightarrow Cl + O_2$$

Net: $O + O_3 \rightarrow 2O_2$

(Also: Stolarski and Cicerone)

Note: Reactions among gas molecules only.

Ozone And You, and Your World



What ozone does: The ozone layer protects life on the ground from DNA-damaging UV light.

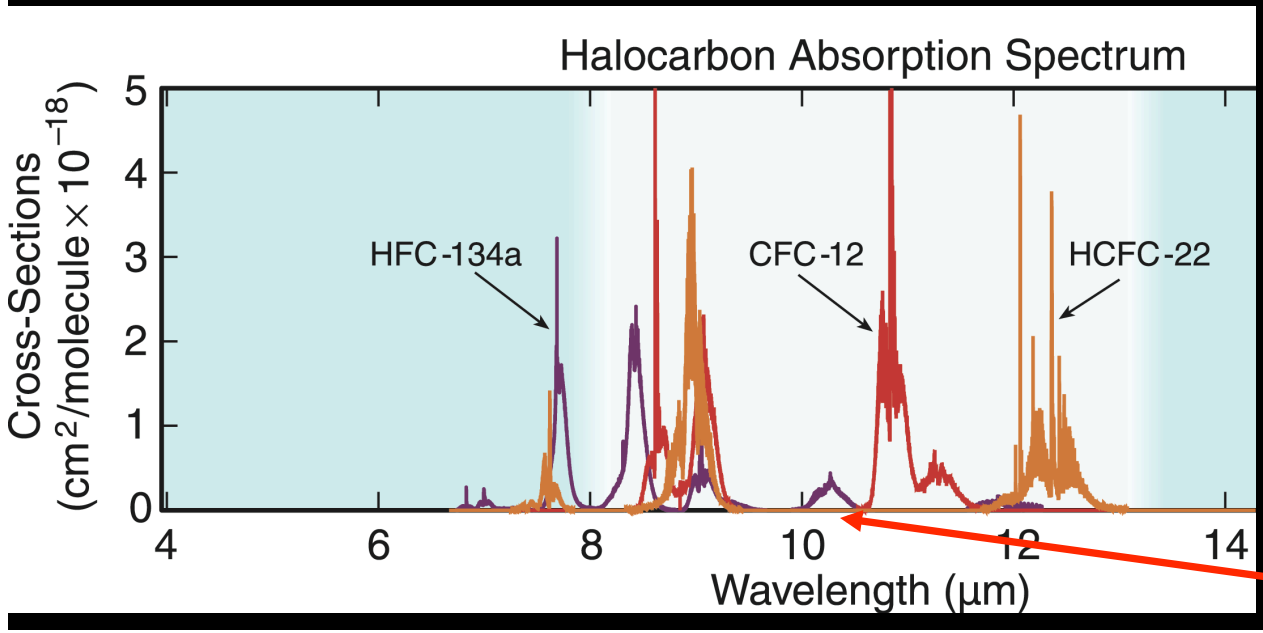
What ozone depletion doesn’t do: UV light doesn’t significantly contribute to the greenhouse effect, and ozone depletion doesn’t warm up the planet.

Historic Paper #2: CFCs are strong absorbers of infrared light, and *directly* contribute to global warming {CFC physics}

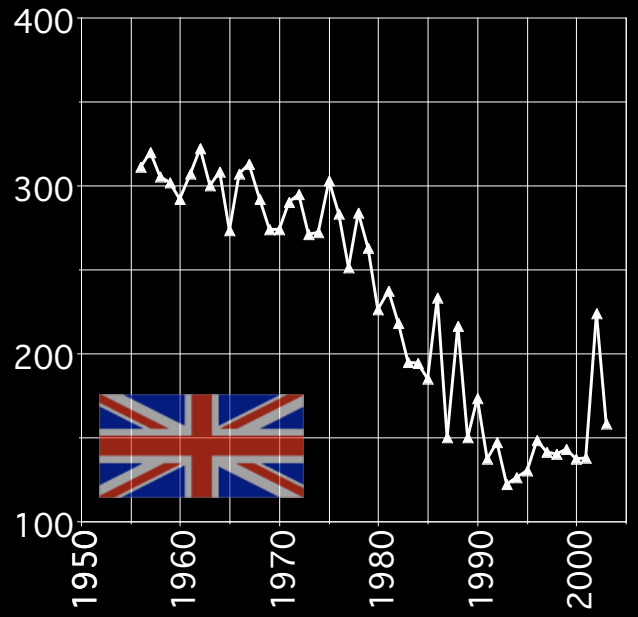
Greenhouse Effect Due to Chlorofluorocarbons: Climatic Implications

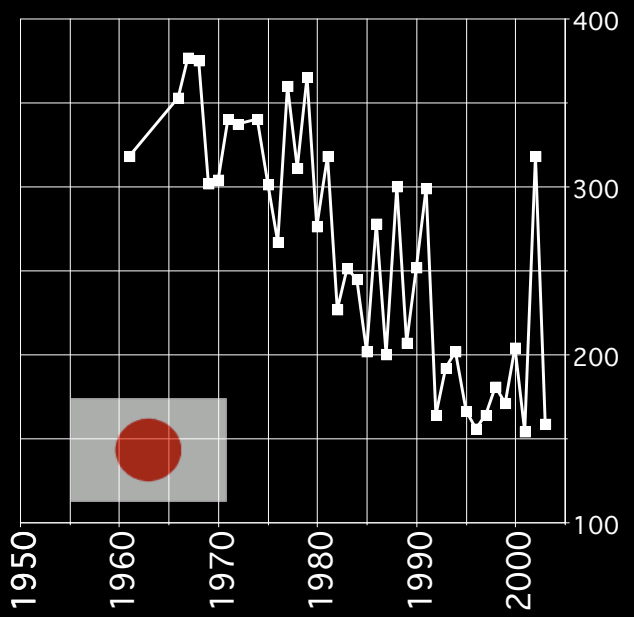
Abstract. *The infrared bands of chlorofluorocarbons and chlorocarbons enhance the atmospheric greenhouse effect. This enhancement may lead to an appreciable increase in the global surface temperature if the atmospheric concentrations of these compounds reach values of the order of 2 parts per billion.*

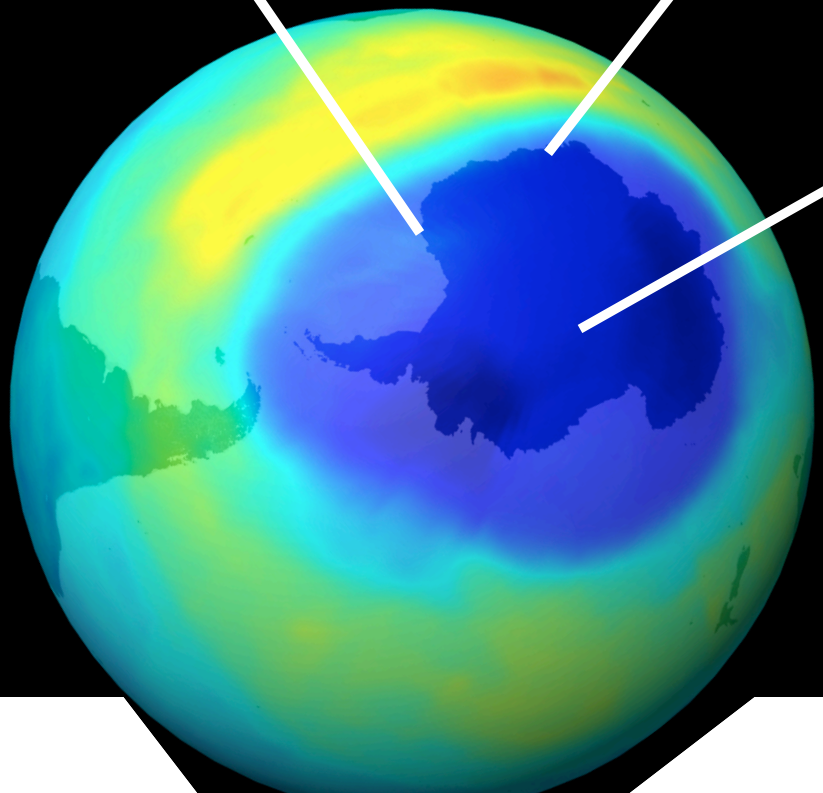
Ramanathan, Science, 1975.

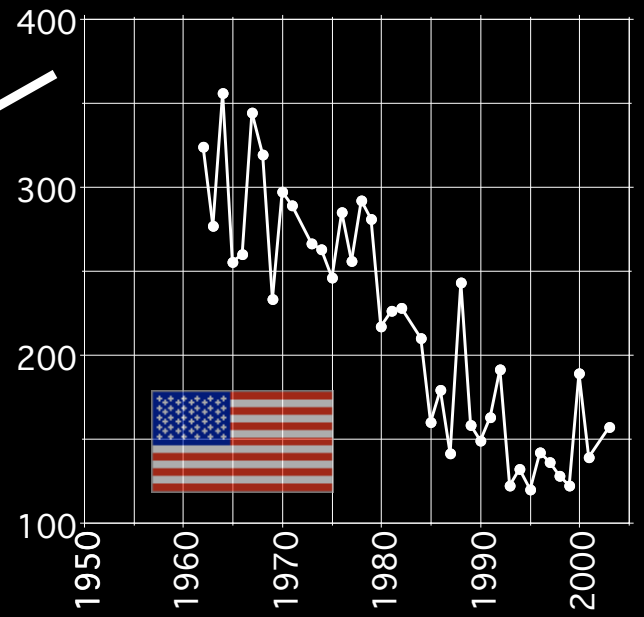


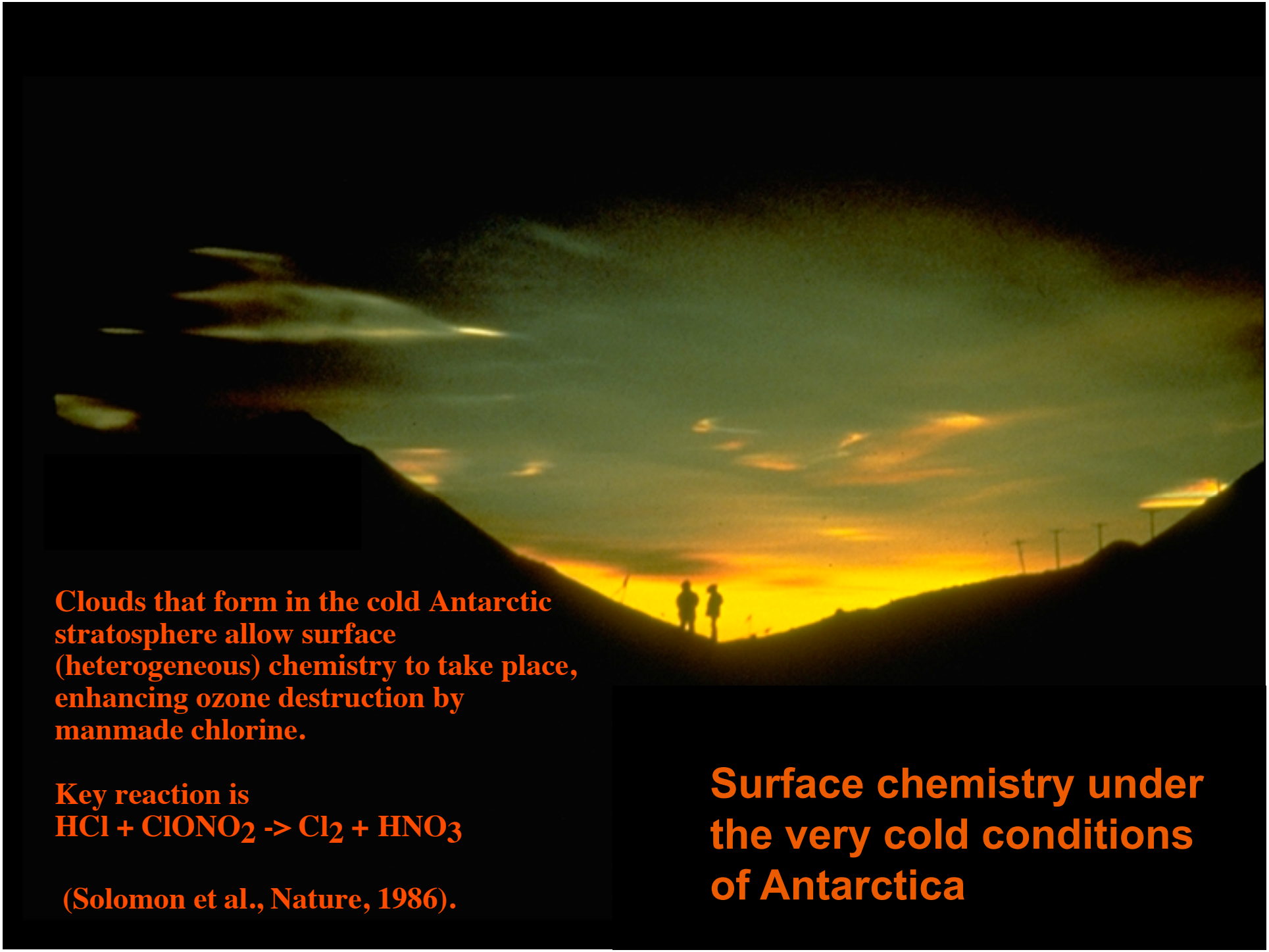
The Antarctic ozone hole









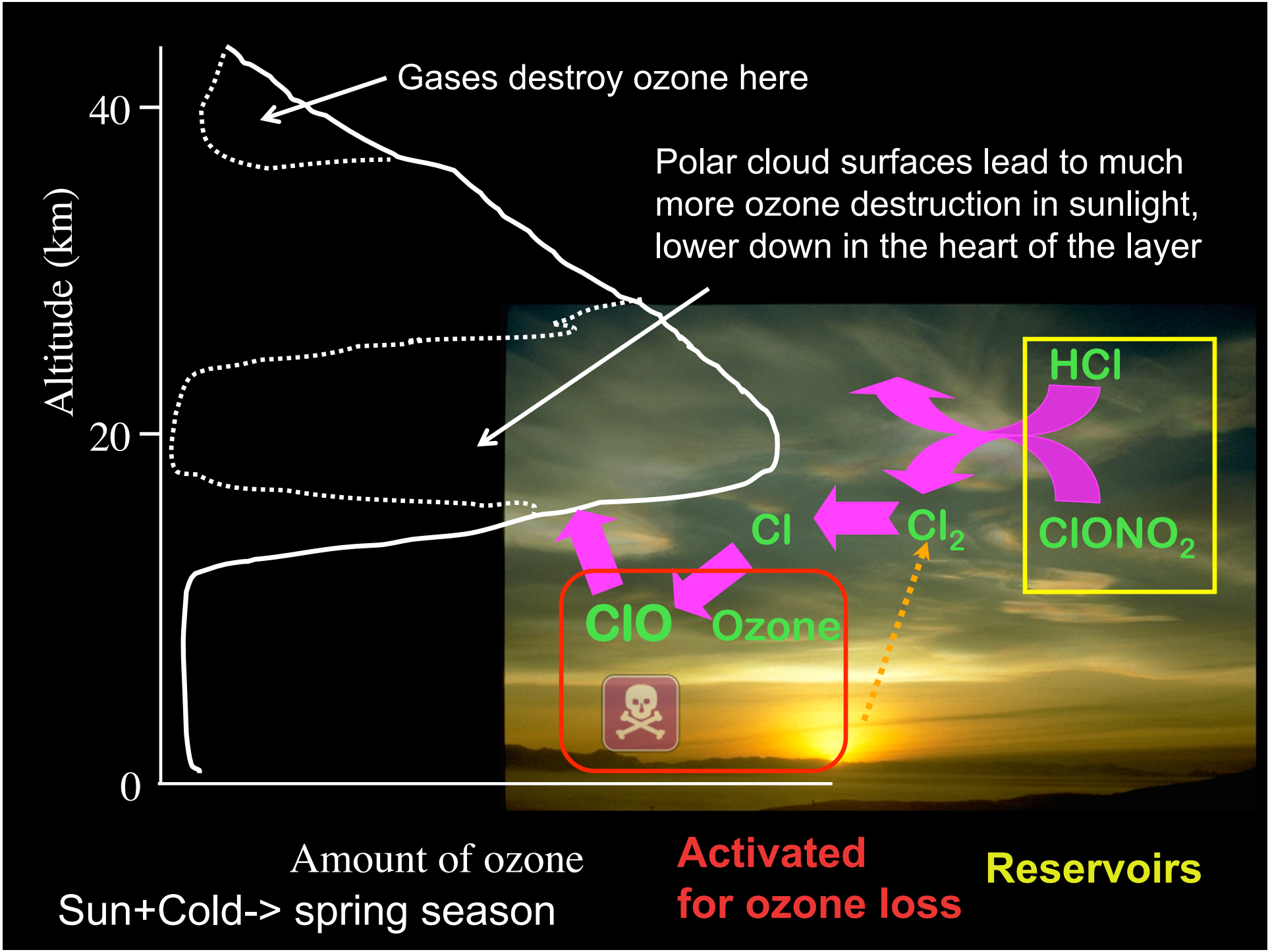


Clouds that form in the cold Antarctic stratosphere allow surface (heterogeneous) chemistry to take place, enhancing ozone destruction by manmade chlorine.

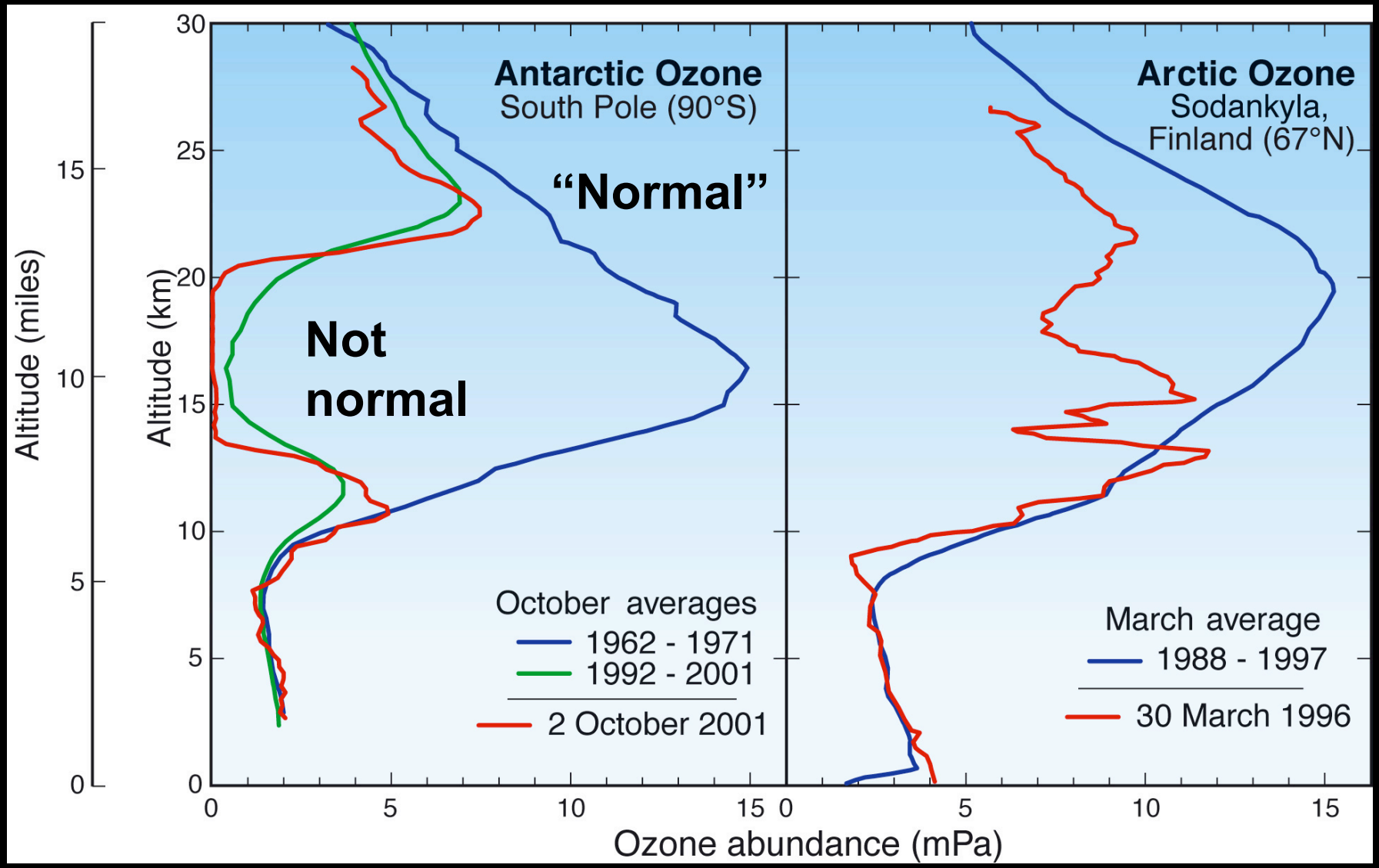
Key reaction is
$HCl + ClONO_2 \rightarrow Cl_2 + HNO_3$

(Solomon et al., Nature, 1986).

Surface chemistry under the very cold conditions of Antarctica

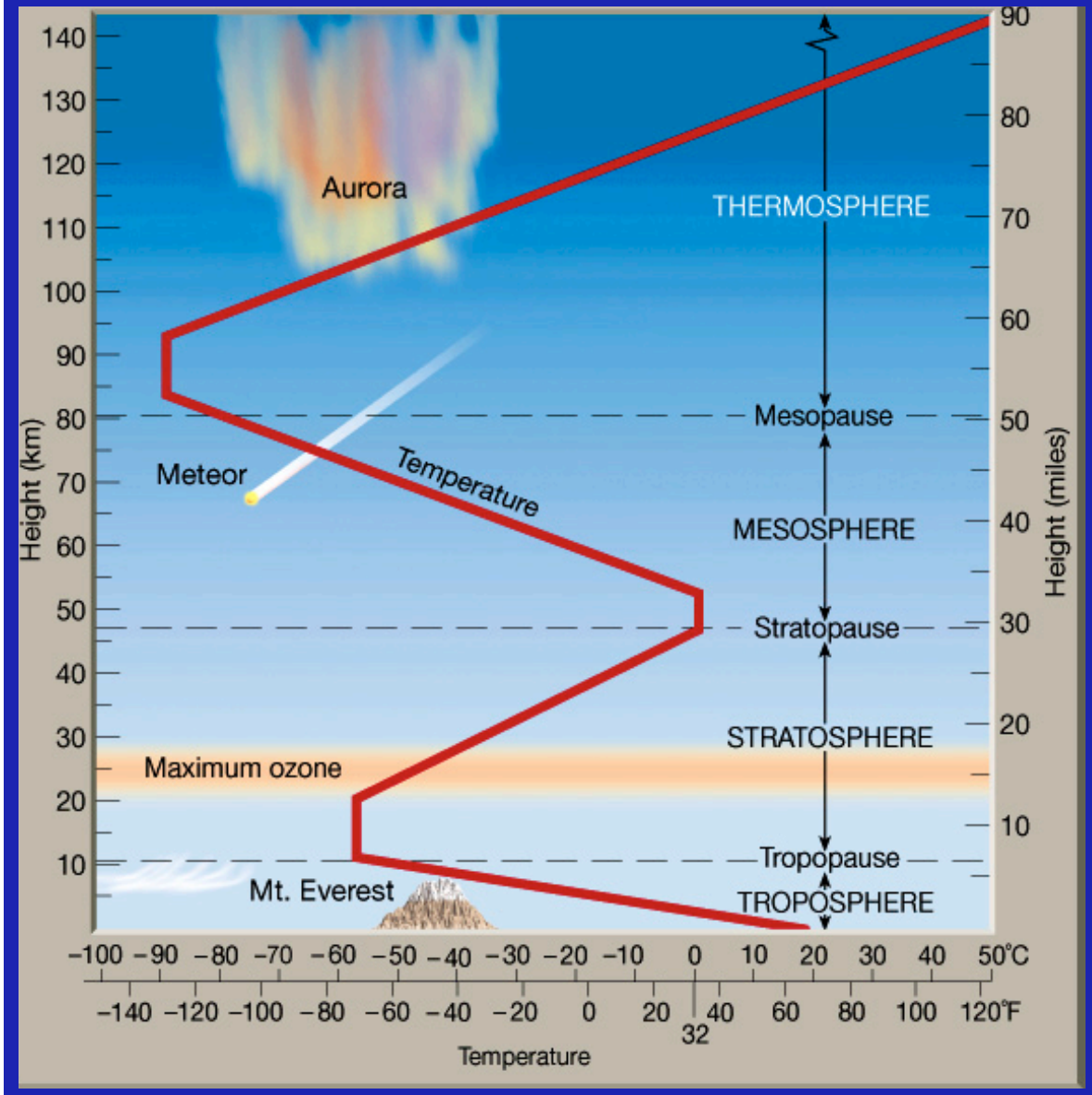

Gases destroy ozone here
Polar cloud surfaces lead to much more ozone destruction in sunlight, lower down in the heart of the layer
Altitude (km)
40
20
0
HCl
ClONO2
Cl
Cl2
ClO
Ozone
Amount of ozone
Sun+Cold-> spring season
Activated for ozone loss
Reservoirs

Poles Apart: How ozone used to be and how it is now



Ozone losses in the Arctic are much less severe than the Antarctic.

How does ozone depletion affect climate?



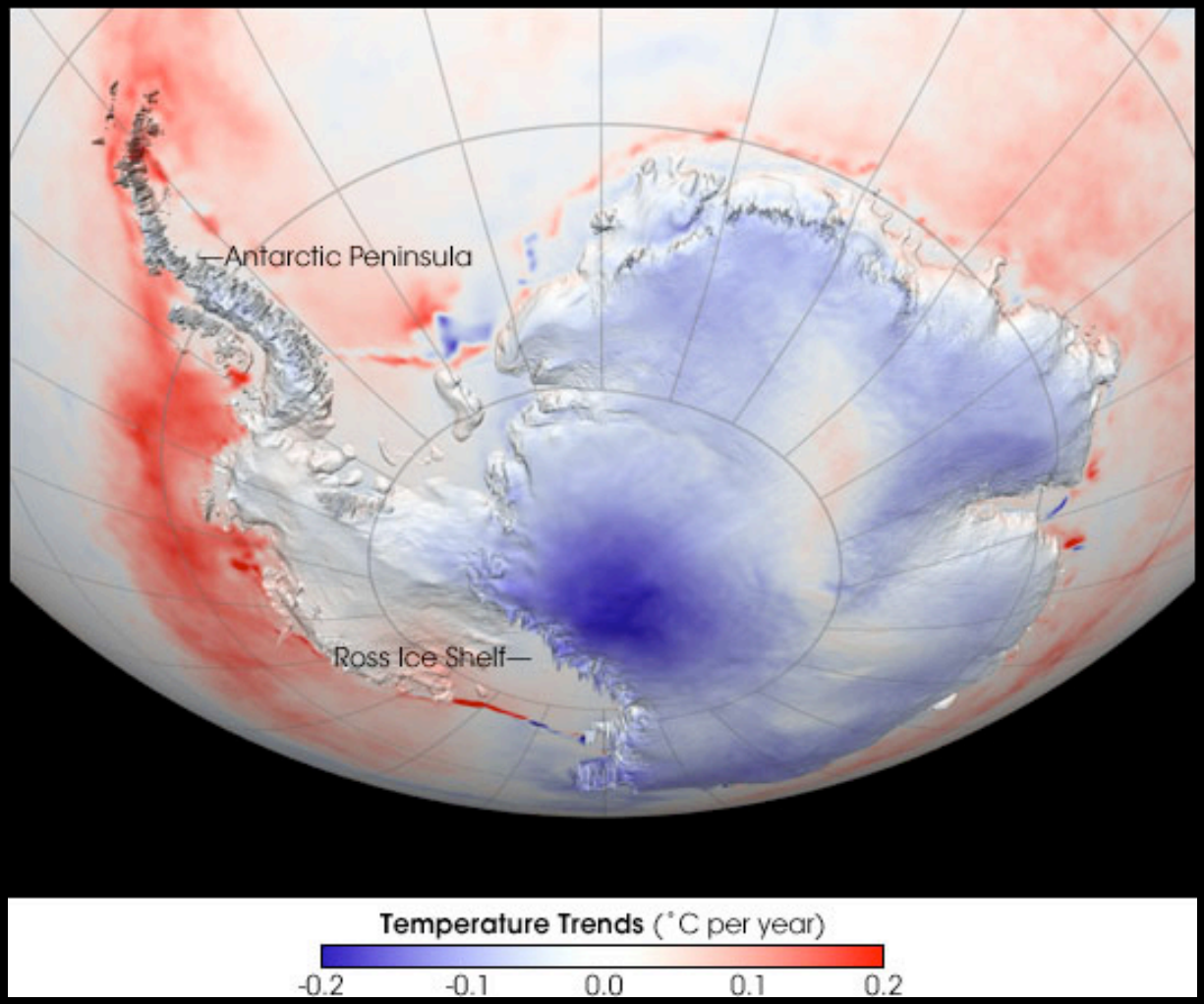
We would have no stratosphere if not for ozone.

Less ozone cools the stratosphere, which in turn can cool the troposphere (*indirect* climate effect of CFCs)

…

Can this cooling compete with warming of the troposphere and surface, due to CO_2 and other greenhouse gases?

Antarctic Surface Climate: Why So Different from the Rest of the World?

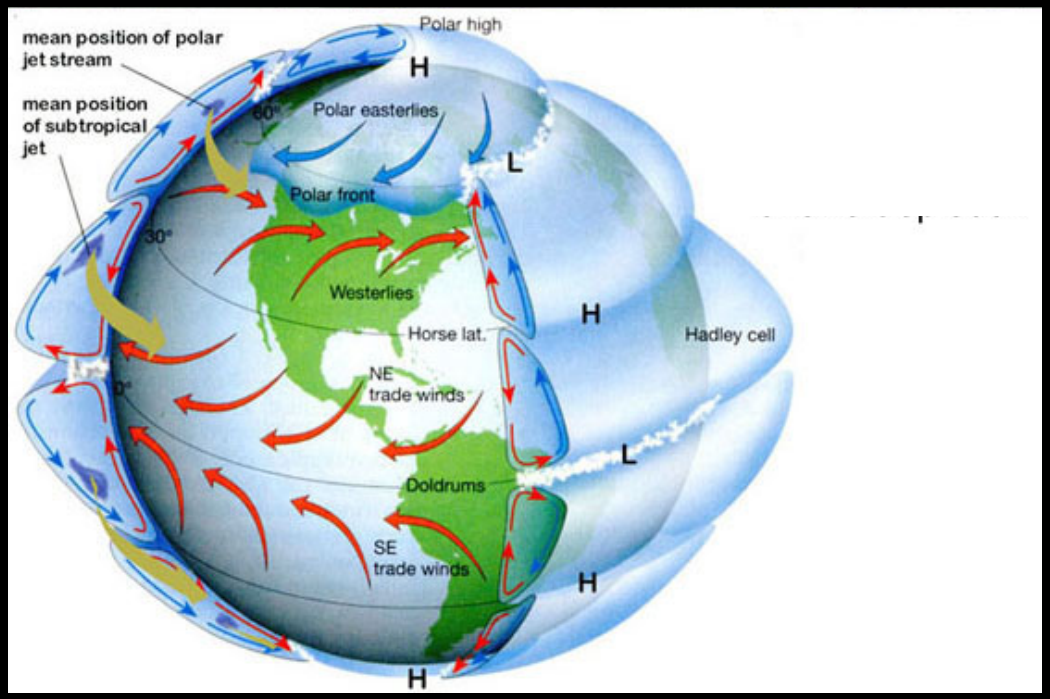


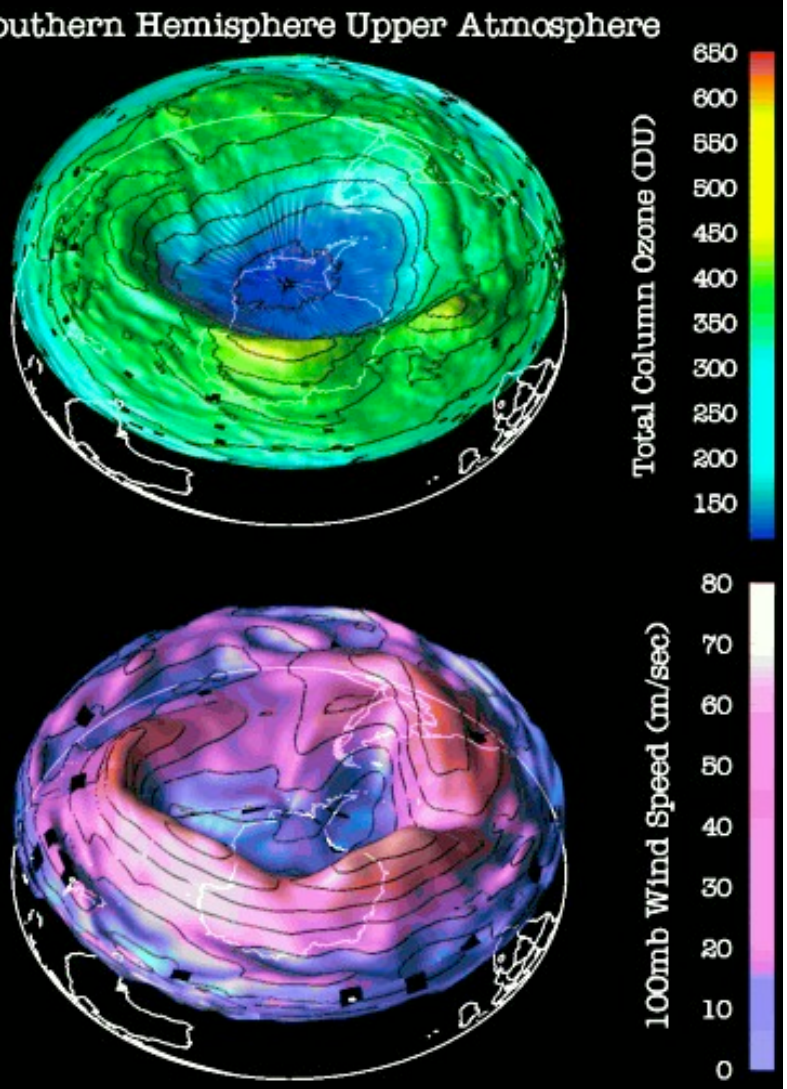
Summer skin temperature trends 1982-2004 from AVHRR

http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=17257

Ozone and Climate in the Vortex

A fundamental aspect of temperature, wind, and climate variability in the polar regions





Modes of Variability in the Stratosphere and Troposphere

Stratospheric Harbingers of Anomalous Weather Regimes

Mark P. Baldwin* and Timothy J. Dunkerton

Observations show that large variations in the strength of the stratospheric circulation, appearing first above ~50 kilometers, descend to the lowermost stratosphere and are followed by anomalous tropospheric weather regimes. During the 60 days after the onset of these events, average surface pressure maps resemble closely the Arctic Oscillation pattern. These stratospheric events also precede shifts in the probability distributions of extreme values of the Arctic and North Atlantic Oscillations, the location of storm tracks, and the local likelihood of mid-latitude storms. Our observations suggest that these stratospheric harbingers may be used as a predictor of tropospheric weather regimes.

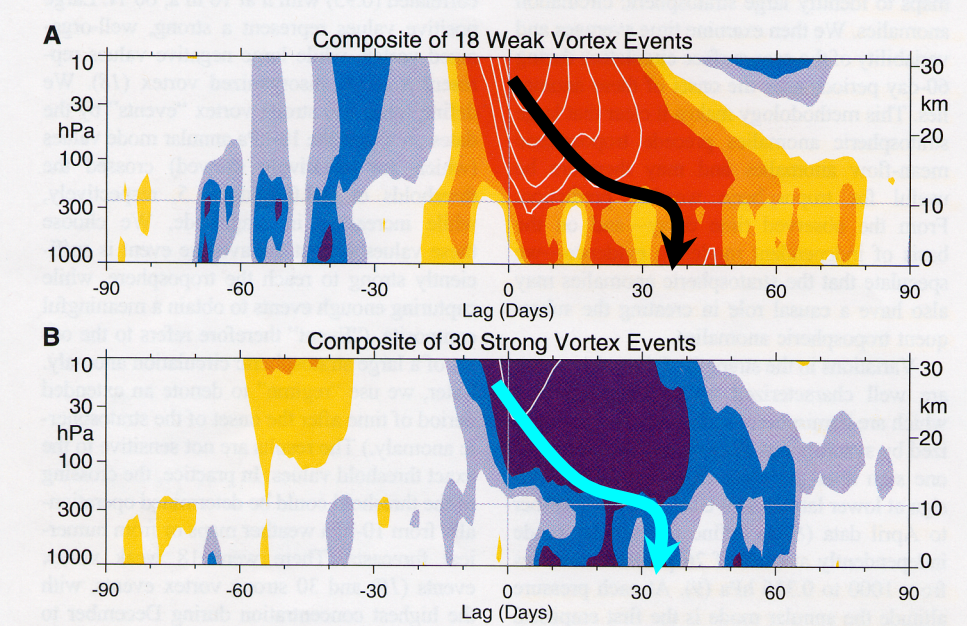


Fig. 2. Composites of time-height development of the northern annular mode for (**A**) 18 weak vortex events and (**B**) 30 strong vortex events. The events are determined by the dates on which the 10-hPa annular mode values cross –3.0 and +1.5, respectively. The indices are nondimensional; the contour interval for the color shading is 0.25, and 0.5 for the white contours. Values between −0.25 and 0.25 are unshaded. The thin horizontal lines indicate the approximate boundary between the troposphere and the stratosphere.

Weak vortex -> warmer, ‘floppier’

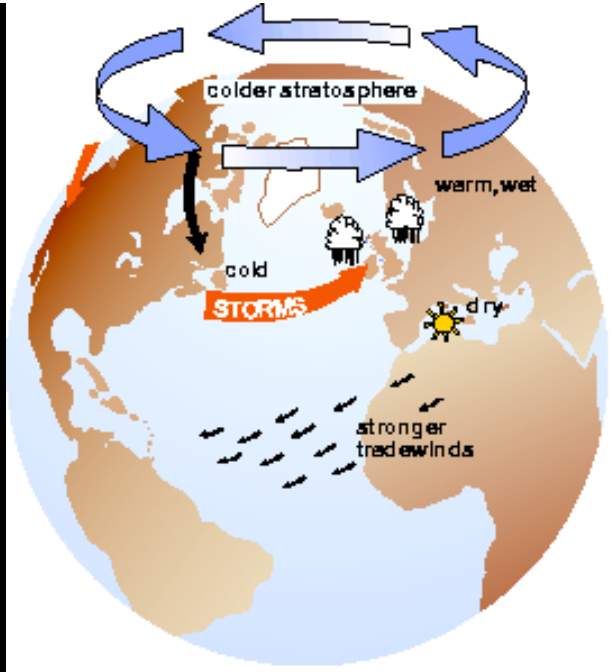
Strong vortex -> colder, ‘tighter’

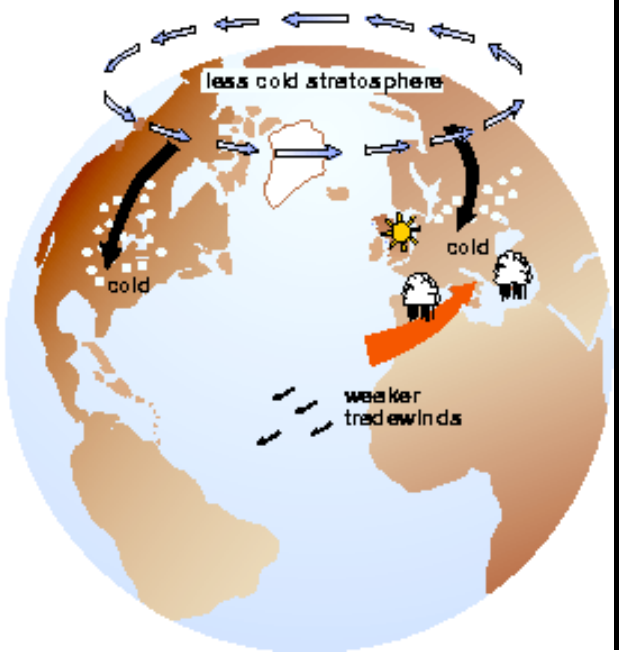
Connections of stratosphere/troposphere on seasonal time scales. What about long term?

The ‘classic’ factors that influence vortex tightness include sea surface temperatures and ‘natural noise’.

Could ‘new’ things also contribute: a changing stratosphere influencing the troposphere? If so, what about ozone depletion?

• Climate change: circulation changes (locally very important); radiation (global)

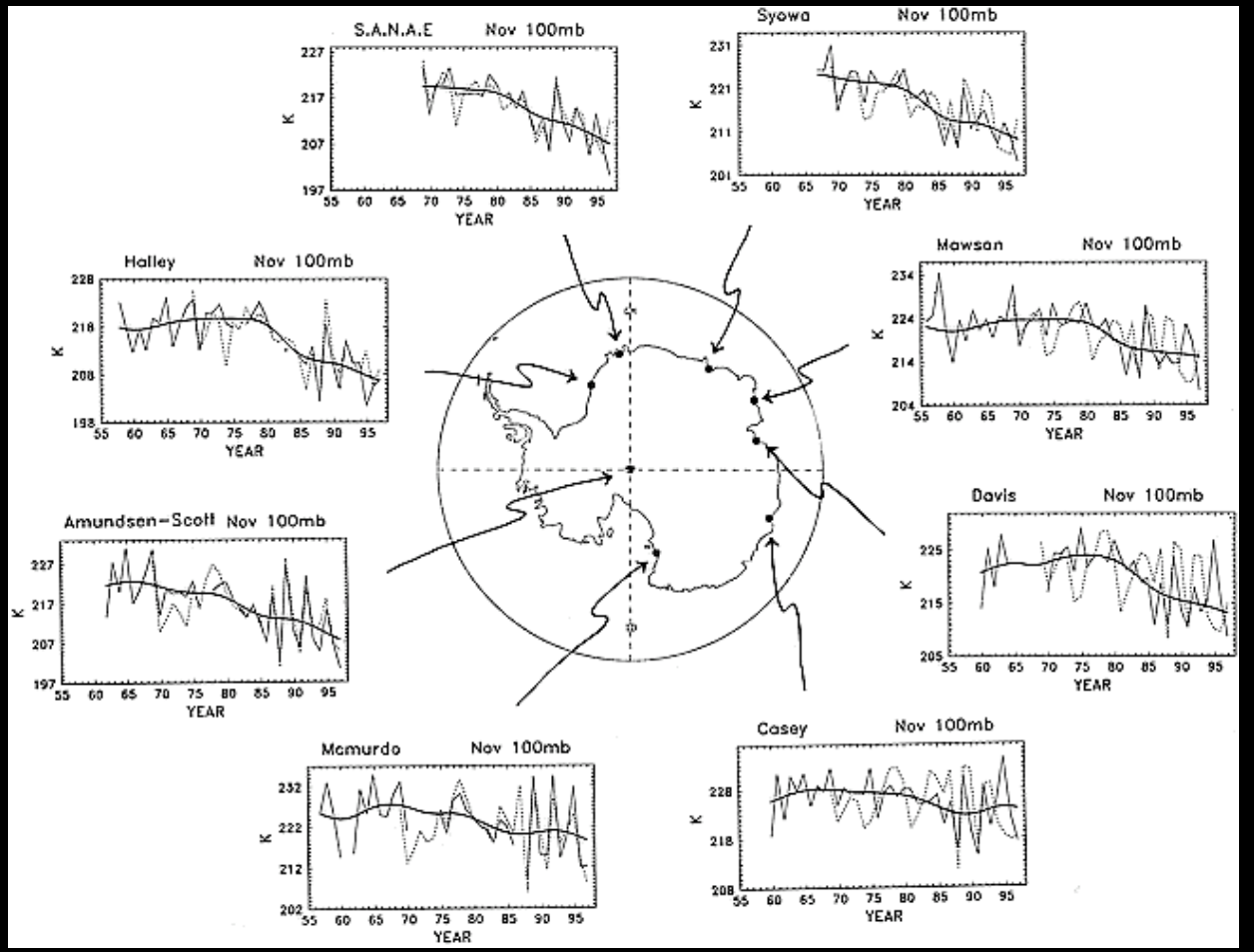




Ozone Hole Cools And Tightens The Antarctic Stratosphere

With so much less ozone, the Antarctic spring stratosphere gets much colder (5-10°C in November) and 'tighter', a remarkable change in stratospheric climate.

These cooling trends are very large…do they propagate down to affect the troposphere, and even surface climate?



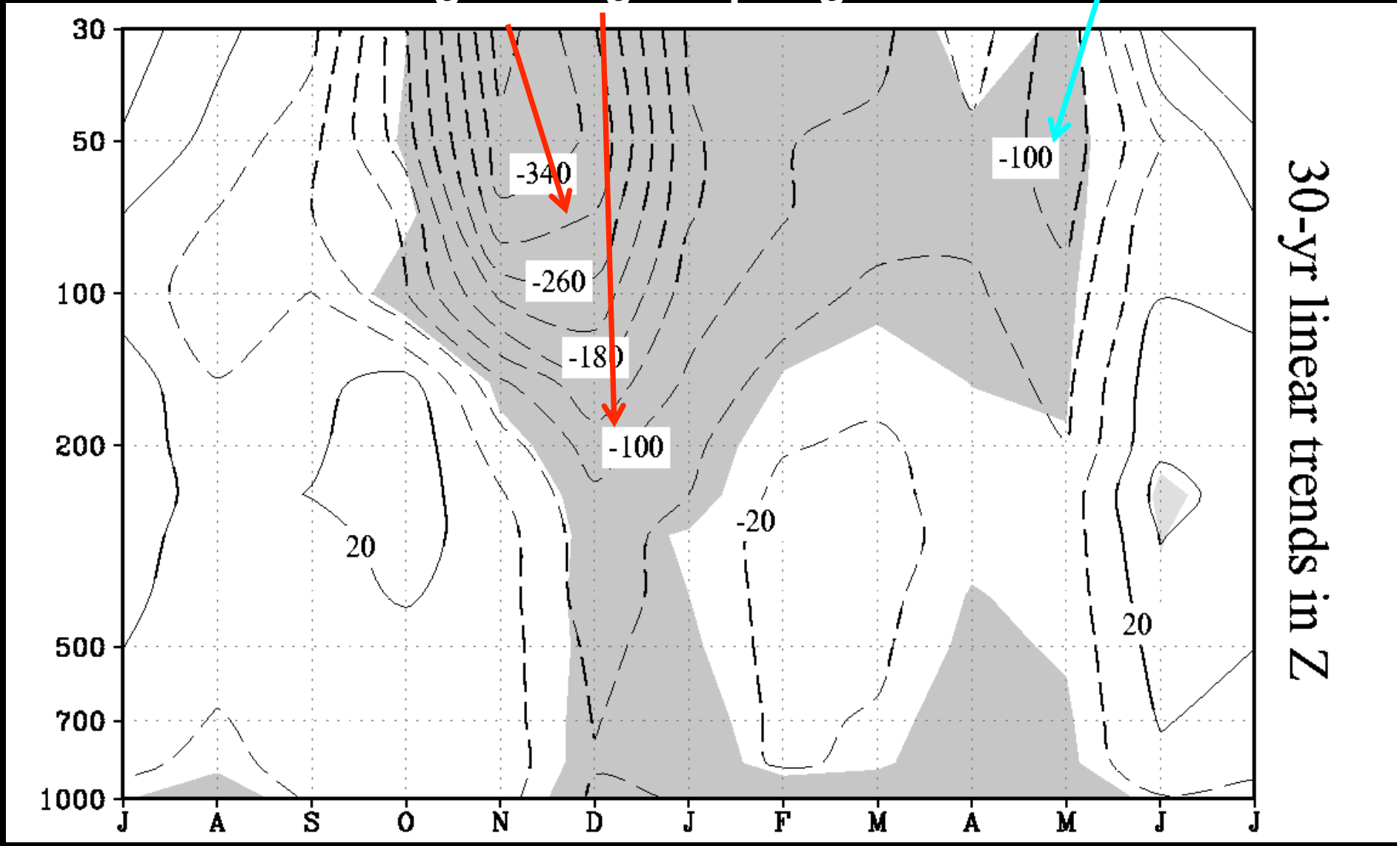
Randel and Wu

Recent SH climate change

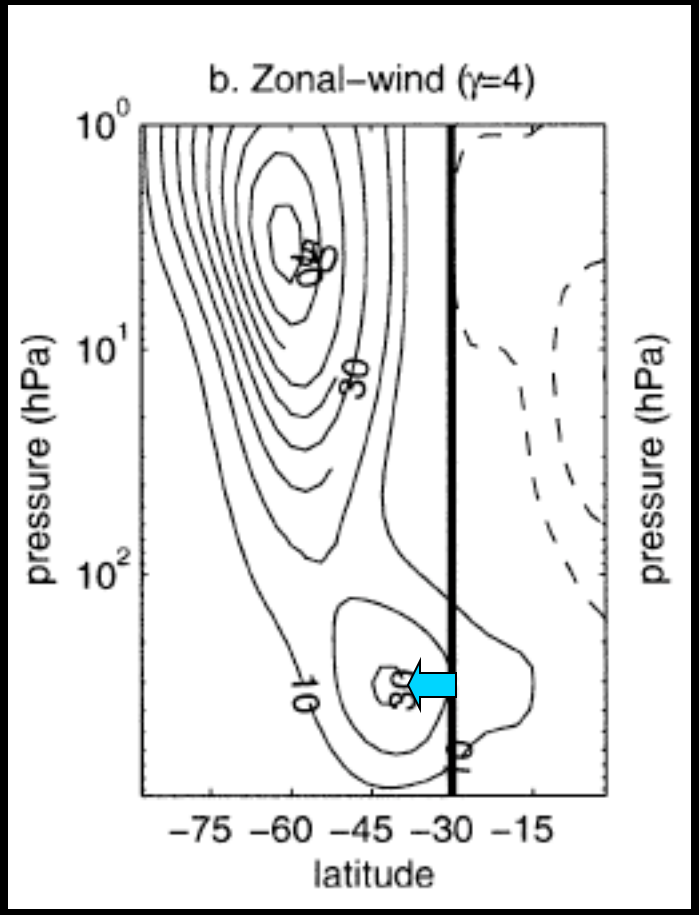
Thompson and Solomon, Science, 2002

Tightening in spring

And late fall



How Does the Fluid Dynamics Work? Still A Subject of Research…



Stratosphere–Troposphere Coupling in a Relatively Simple AGCM: The Role of Eddies

PAUL J. KUSHNER

NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

LORENZO M. POLVANI*

Department of Applied Physics and Applied Mathematics and the Department of Earth and Environmental Sciences, Columbia University, New York, New York

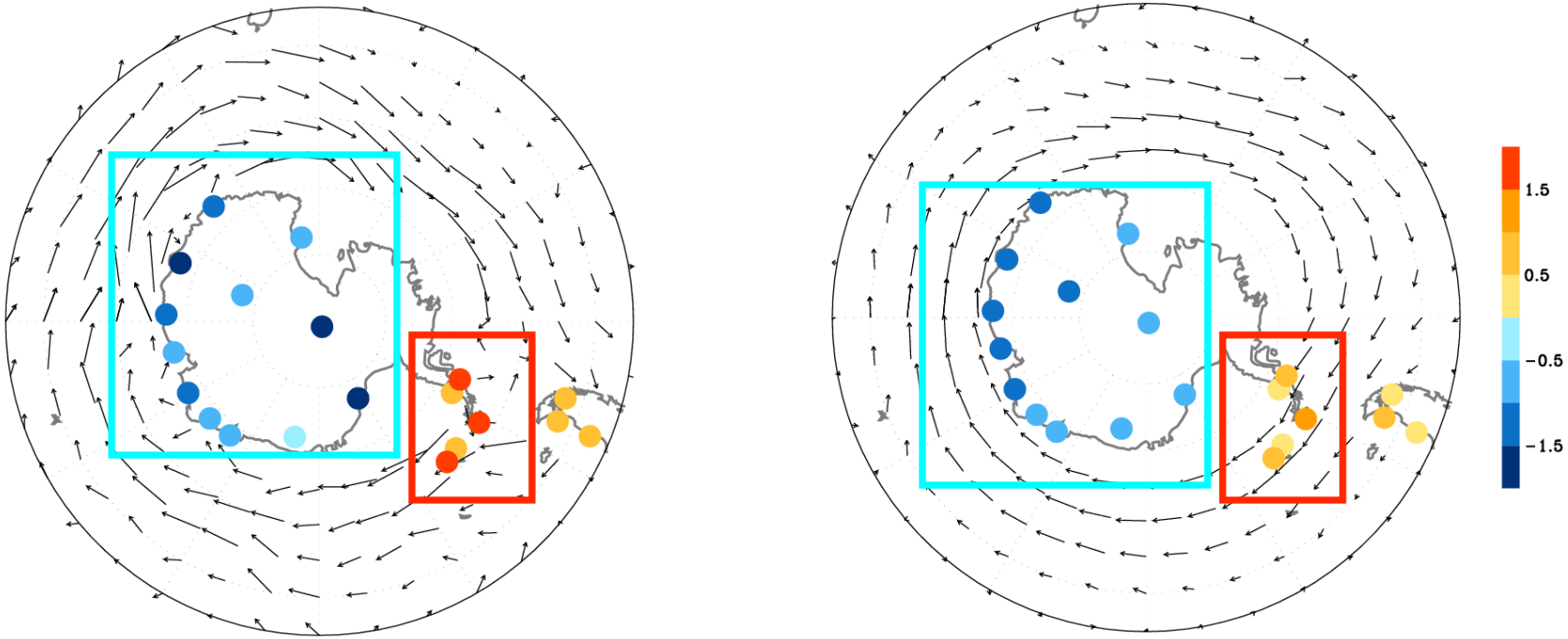
(Manuscript received 16 January 2003, in final form 29 July 2003)

- Position of the jet moves as polar stratosphere cools?
- "Downward control": change in the stratosphere moves down to the lower atmosphere through conservation of mass/momentum.
- More complex models?
- Initiation and/or amplification by coupling through eddies (waves); downward control with eddy feedback?

Recent surface climate trends and the vortex

Total trends

Congruent with SAM



Recent trends in surface temperature and wind (Dec-May 1969-2000).
Stronger vortex: cold air stays bottled up in the vortex, so the plateau gets colder while the peninsula gets warmer

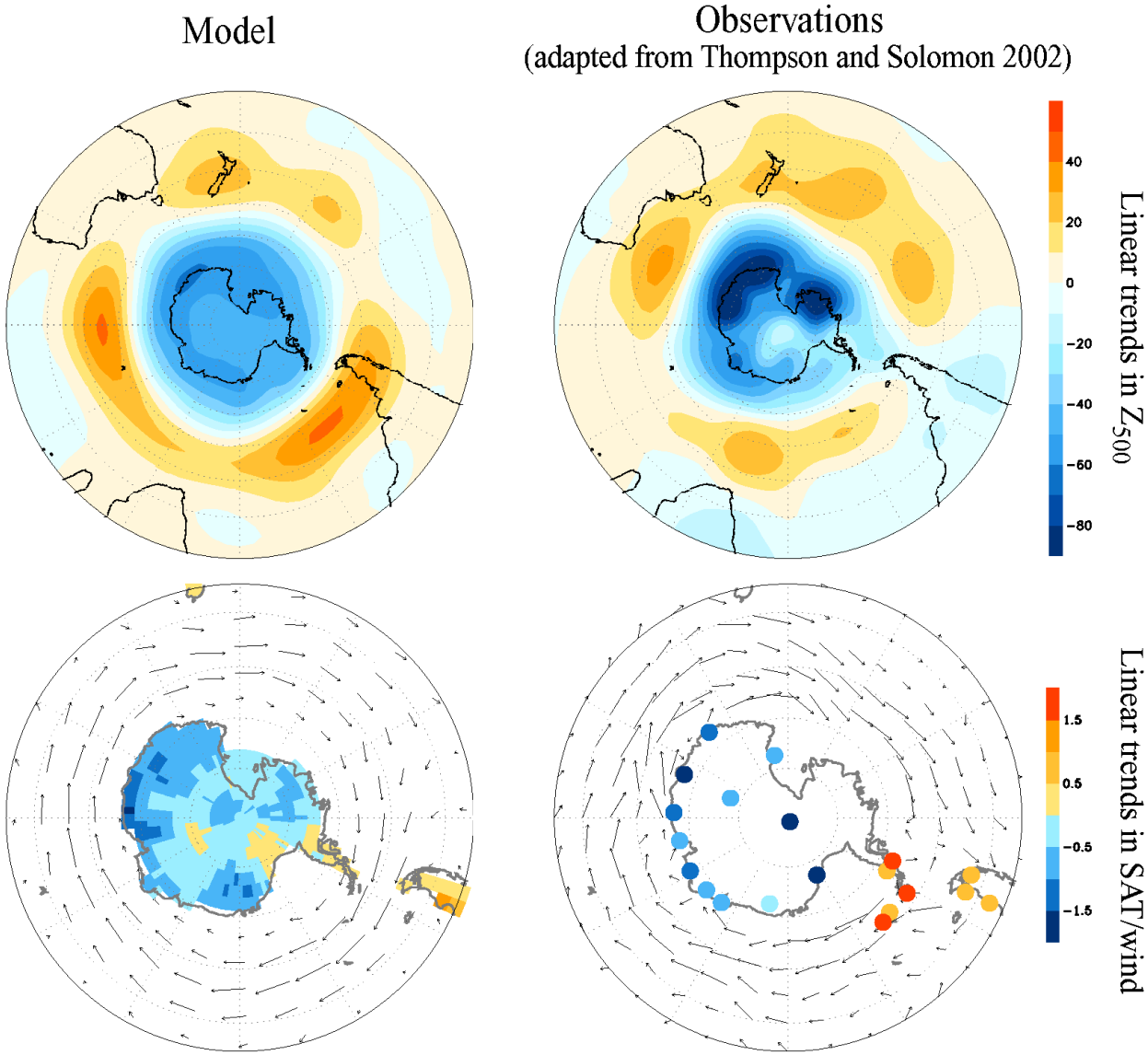
Thompson and Solomon Science 2002

Model/Measurement Comparison

Hadley Center GCM forced with obsvd ozone depletion

(Gillett and Thompson, 2003).

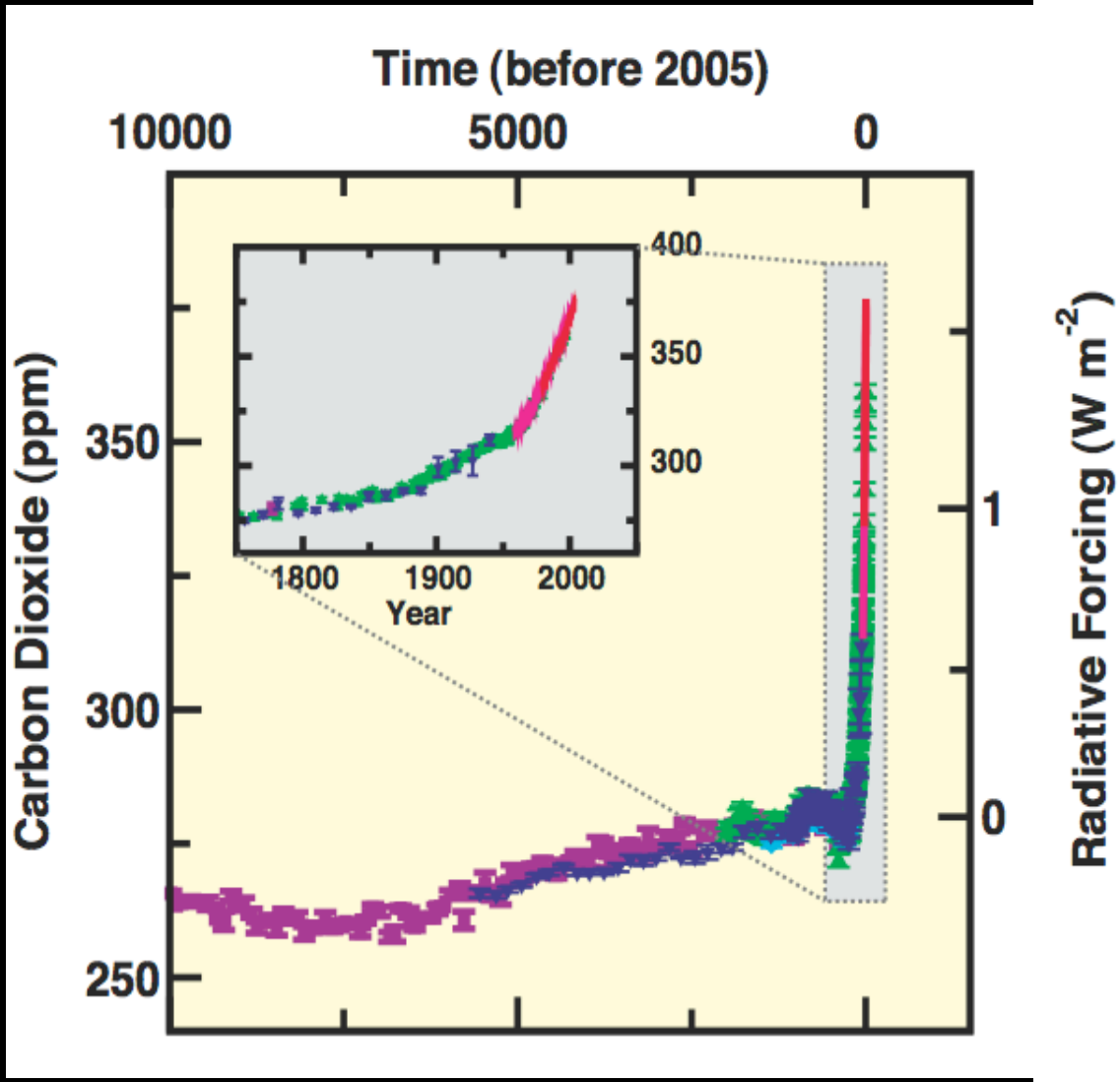
{GHGs can also contribute to strengthening the vortex, but ozone has a much bigger effect.}



Human Drivers of Climate Change: Unprecedented

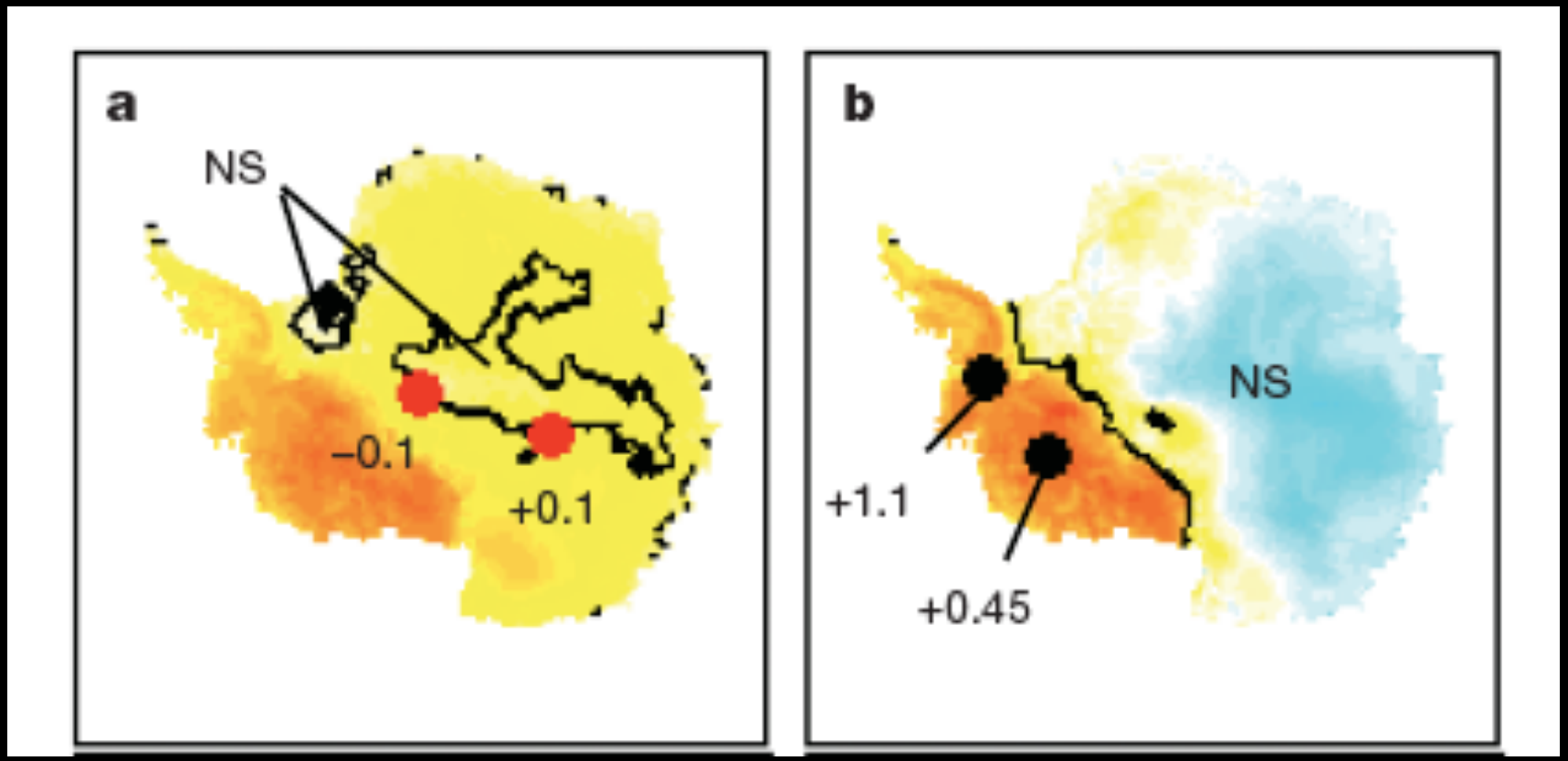
CARBON DIOXIDE

- A critical greenhouse gas.
- Dramatic increase in industrial era, 'forcing' climate change. Carbon dioxide is the dominant forcing agent.
- Higher concentration than for more than 600,000 years.



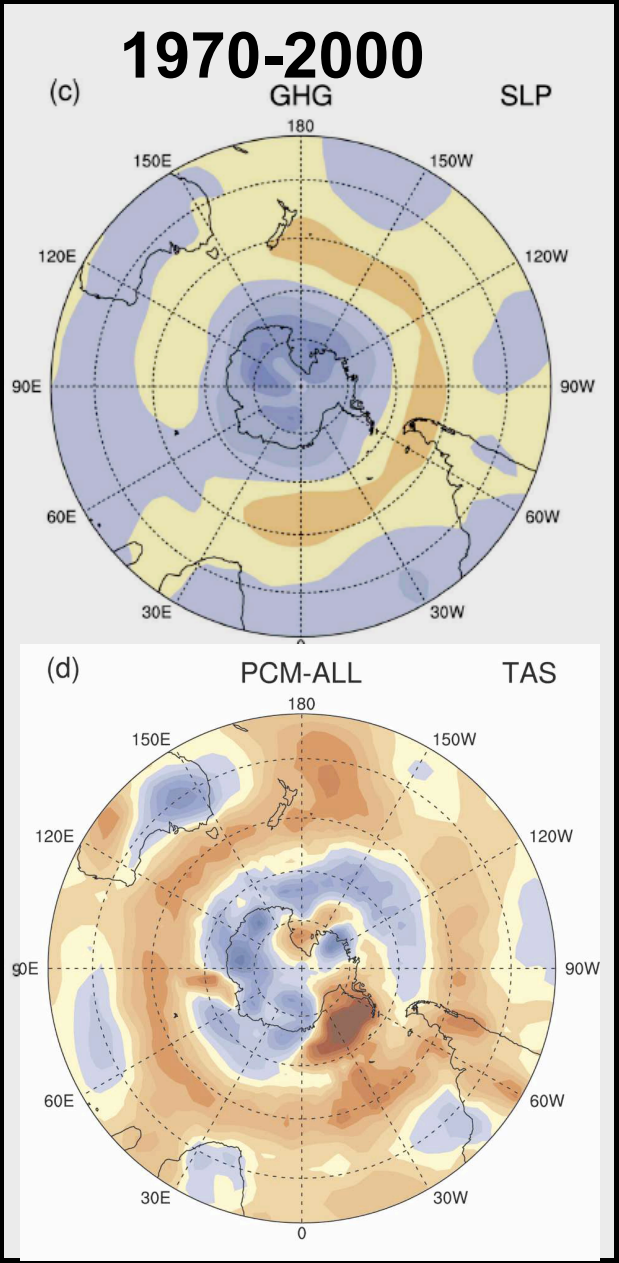
Statistical "Reconstruction" of the Past: Antarctic Warming Due to CO_2 Before The Ozone Hole

1957-2006, annual avg **1969-2000, annual avg**



Steig et al., Nature, 2009

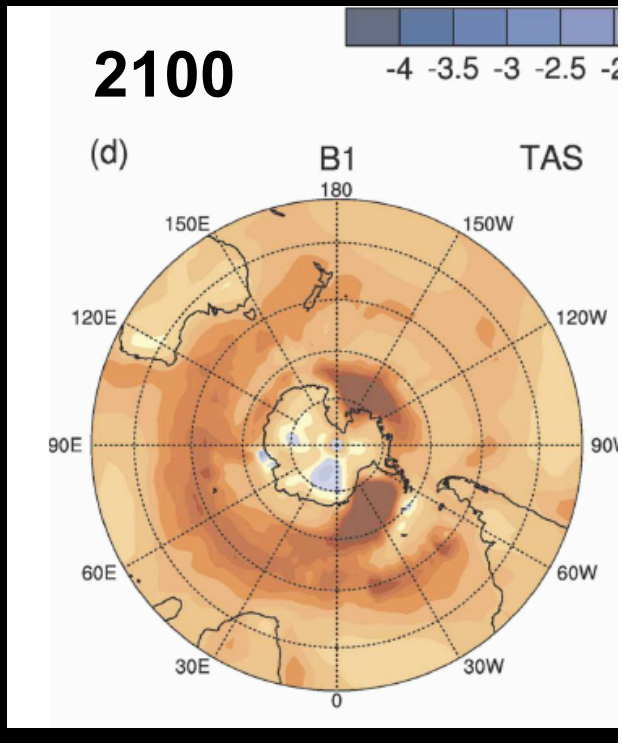
Past and Future Antarctic Temperatures in the NCAR PCM



Past: O_3 vs CO_2 similar to Hadley center model.

Future: ozone recovers, and the direct warming due to GHGs becomes stronger (even for modest emissions)

Antarctica stops cooling and warms…



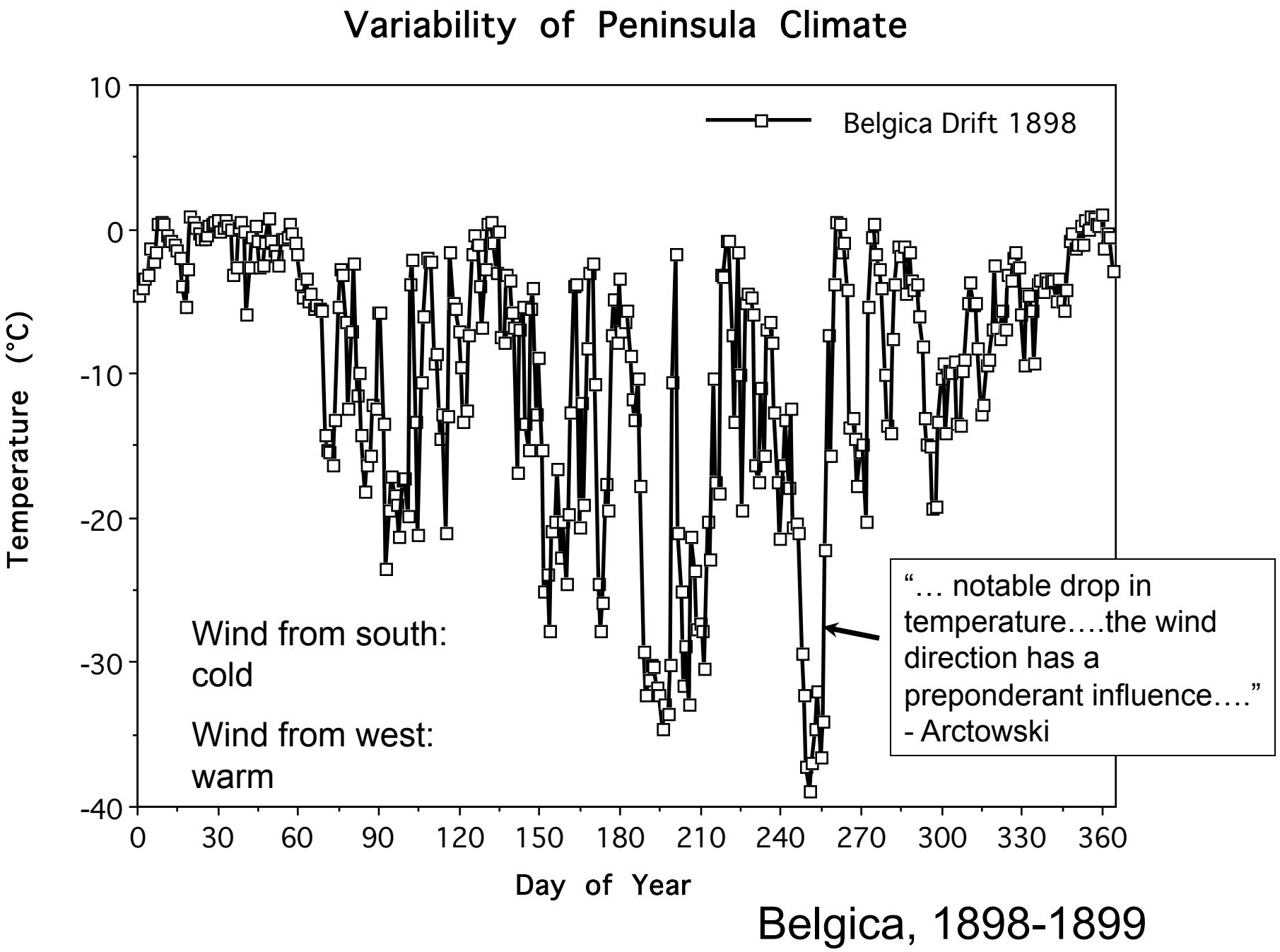
Arblaster and Meehl, J. Clim., 2006

History and Impacts: The Belgian Antarctic Expedition 1898

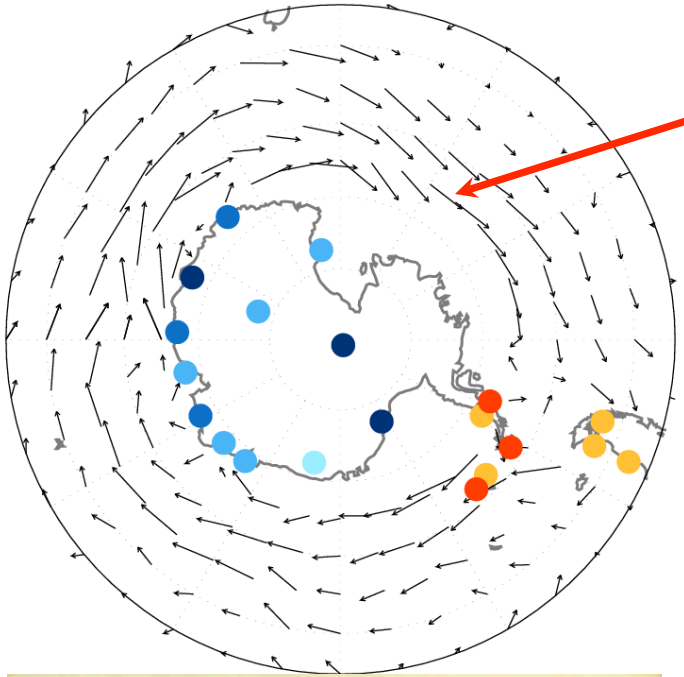
Captain Adrien de Gerlache de Gomery,

Age 29

March 3: “What poet has ever sung of the splendour of the polar world…we were held spellbound by this spectacle…..a dazzling dreamscape….”

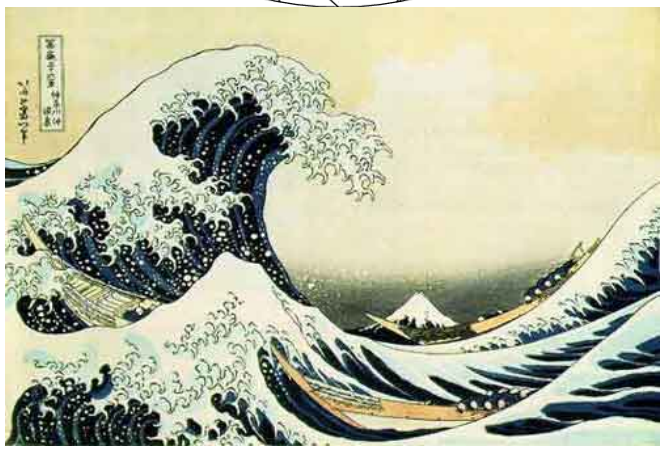

Variability of Peninsula Climate
Belgica Drift 1898
Temperature (°C)
10
0
-10
-20
-30
-40
0
30
60
90
120
150
180
210
240
270
300
330
360
Day of Year
Wind from south: cold
Wind from west: warm
"… notable drop in temperature….the wind direction has a preponderant influence…."
- Arctowski
Belgica, 1898-1899

Impacts: Winds And Ozone, and Climate Variability and Carbon



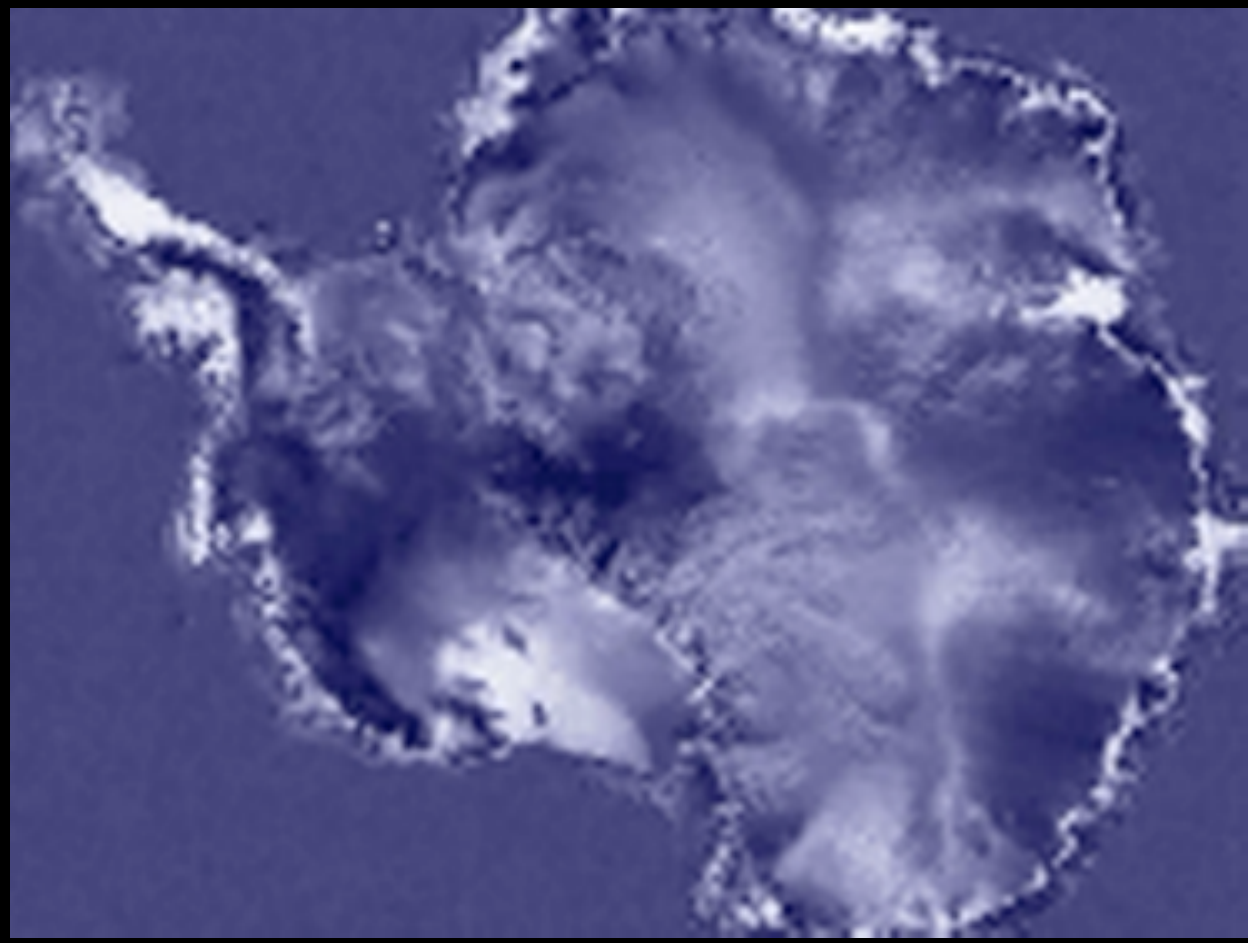
Stronger avg westerlies

Links to Australian drought?



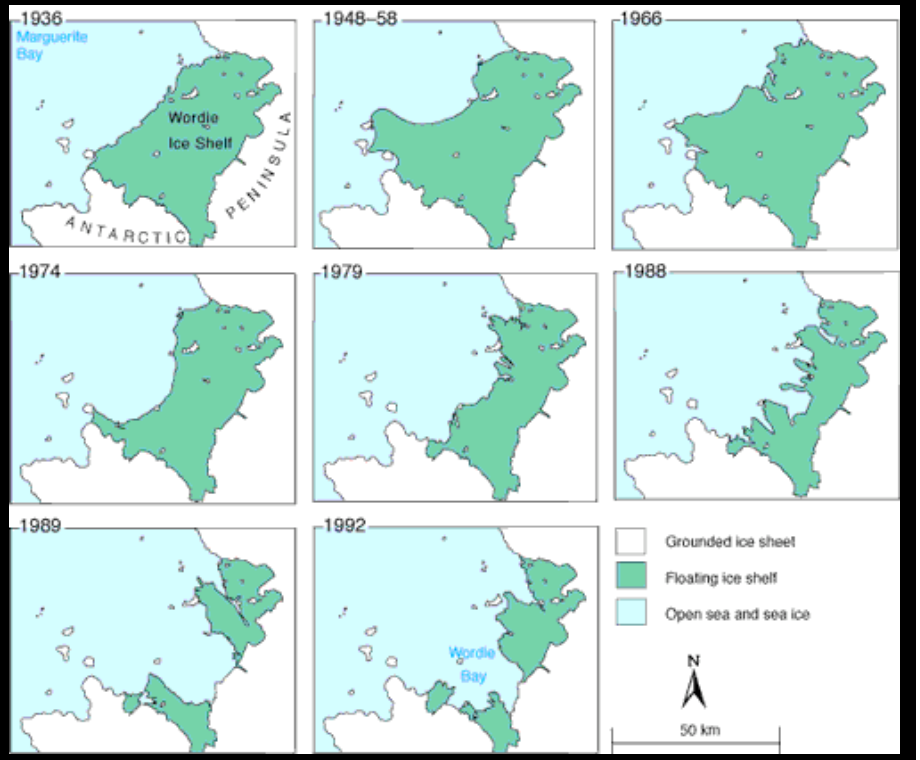
How do changes in wind stress affect ocean circulation and carbon and heat transport?

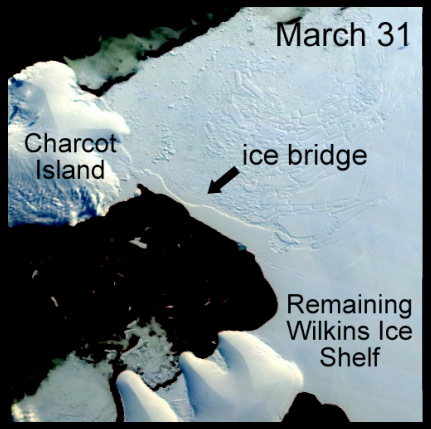
Impact: Ice shelves and glaciers in the Antarctic east peninsula region are changing in dramatic ways due at least in part to the extreme summer warmth……So is this linked to ozone loss, as well as GHGs?

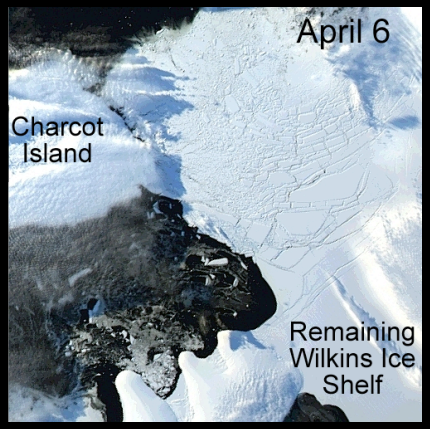


Rapid collapse of Larsen-B

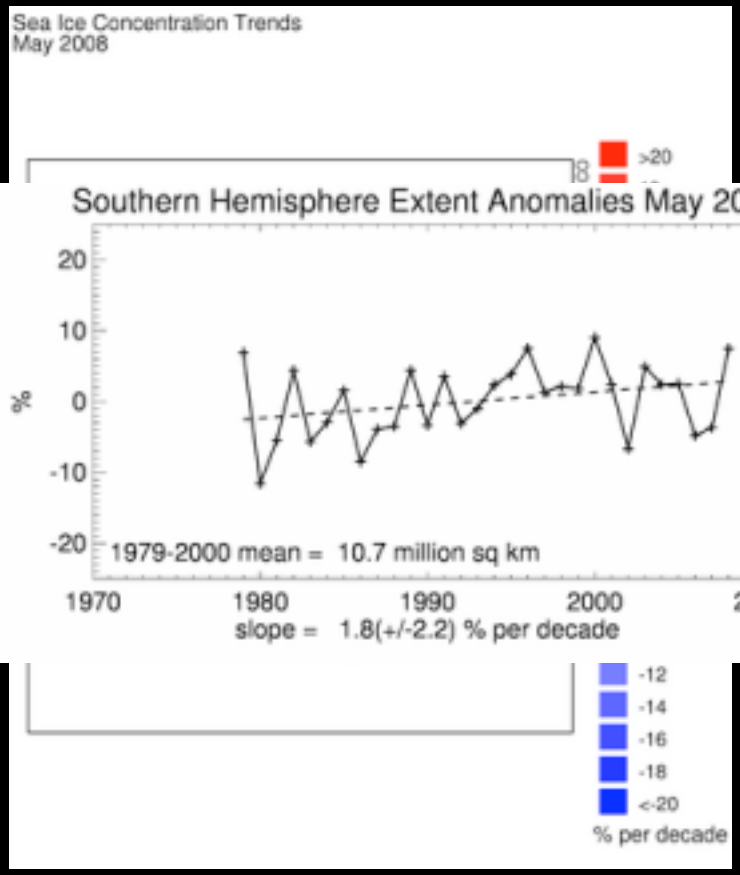
Vanishing Antarctic Ice Shelves: Changing the Geography of Our Planet

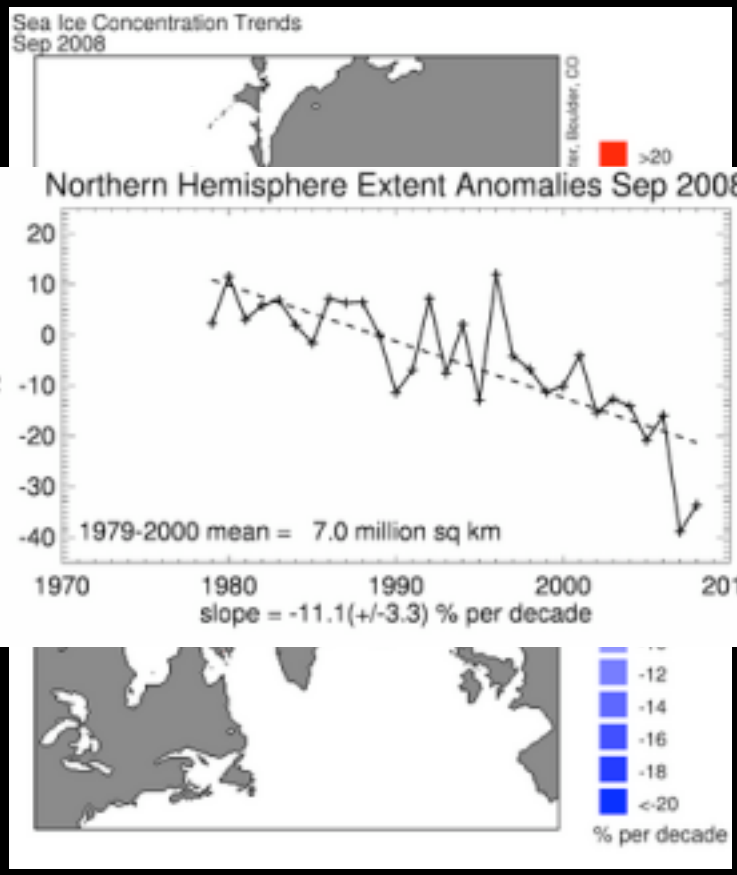






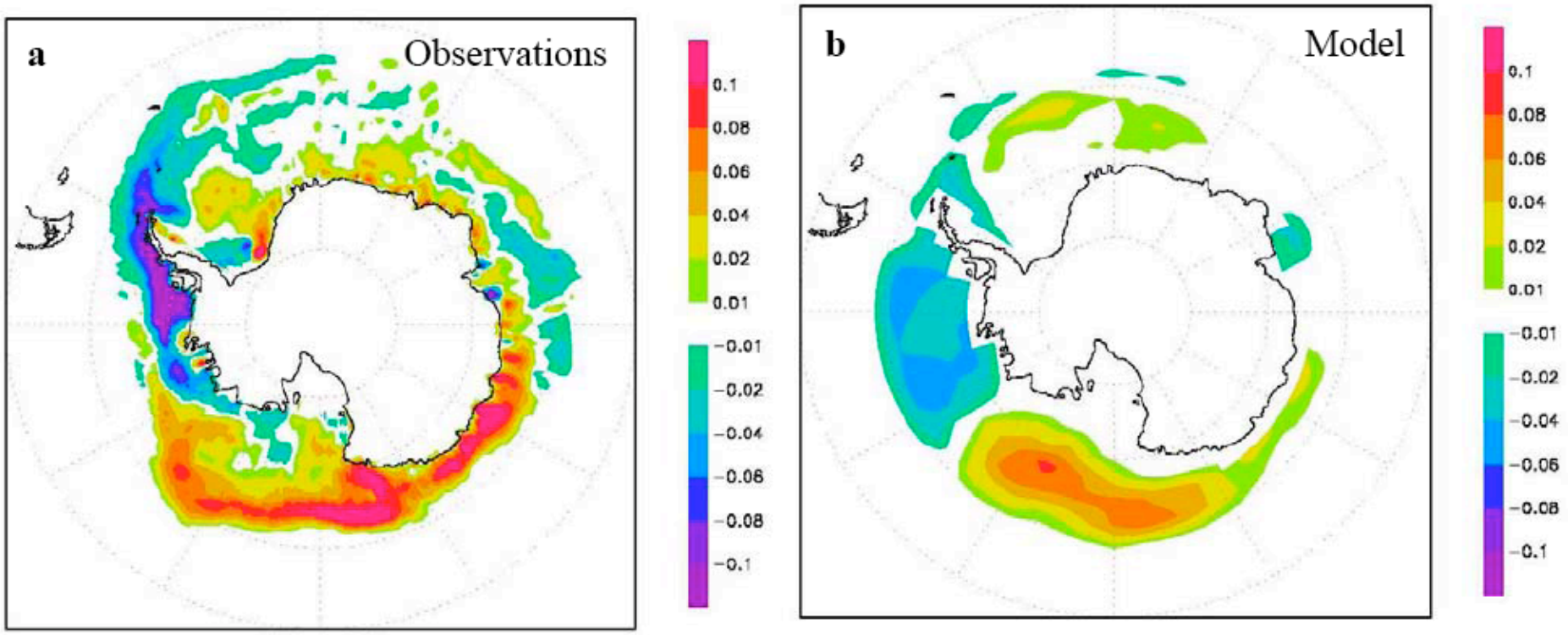
Impacts: The Puzzle Of Arctic and Antarctic Sea Ice Trends





Overall trends very different. Ozone and SAM has affected the air temperatures and circulation patterns in SH summer/ fall. Is this affecting sea ice?

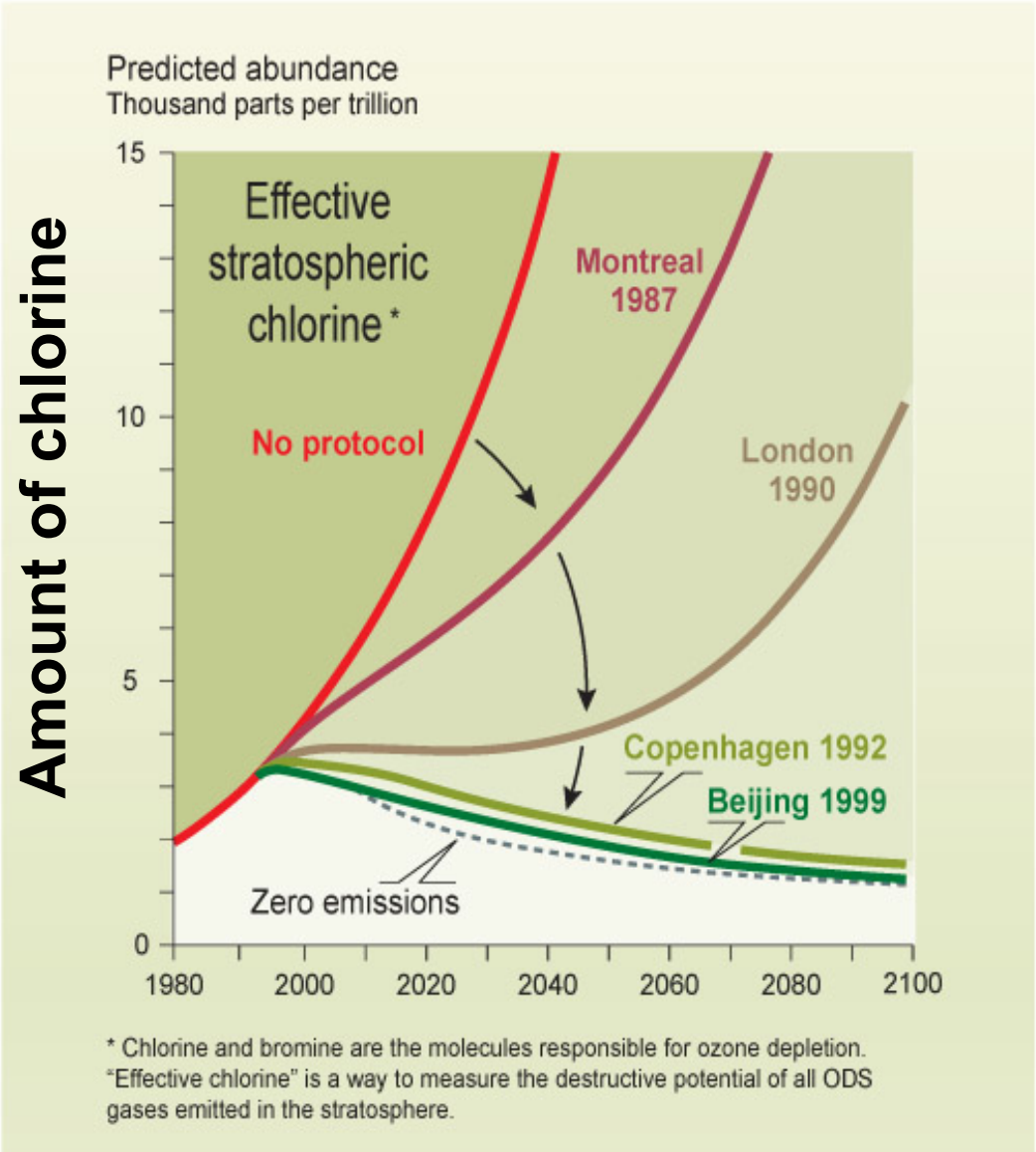
Arctic and Antarctic sea ice trends for 1980-2000 vs model with data assimilation to capture SAM trends:



Goosse et al, Clim. Dyn., 2009; also Turner et al., GRL 2009

Increases in sea ice extent driven by SAM changes 1980-2000 (circulation, ozone?). Model also shows decreases for 1950-1980 (warming, GHG?).

THE EFFECTS OF THE MONTREAL PROTOCOL AMENDMENTS AND THEIR PHASE-OUT SCHEDULES



Concern about ozone depletion led the nations of the world to agree to a Montreal Protocol to freeze and then phaseout CFC emissions.

Quotations About Negotiations, From A Book By A Participant

"Skepticism about the …..theory and minimizing of possible harmful effects marked the official **XXXX** position."

"The **YYYY** government based its position and tactics largely on the self-serving data and contentions of….big companies."

"The **ZZZZ** government and its allies introduced a resolution…..for arriving at a legally binding control protocol."

Quotations About Negotiations, From A Book By A Participant

"Skepticism about the….theory and minimizing of possible harmful effects marked the official **UK** position."

"The **European Commission** government based its position and tactics largely on the self-serving data and contentions of….big companies."

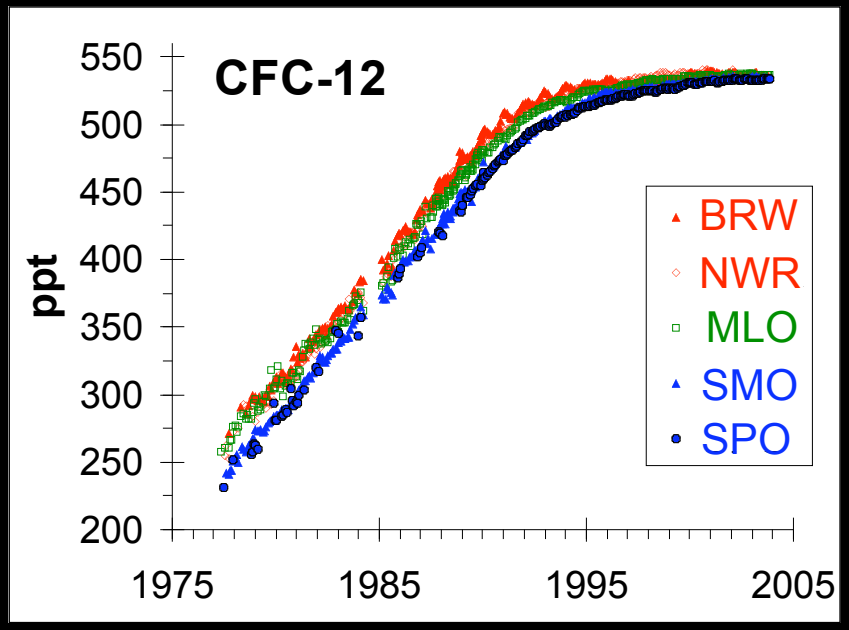
"The **US** government and its allies introduced a resolution…..for arriving at a legally binding control protocol."

Benedick, Ozone Diplomacy

The United States was the world leader on the Montreal Protocol to protect the ozone layer (in 1987).

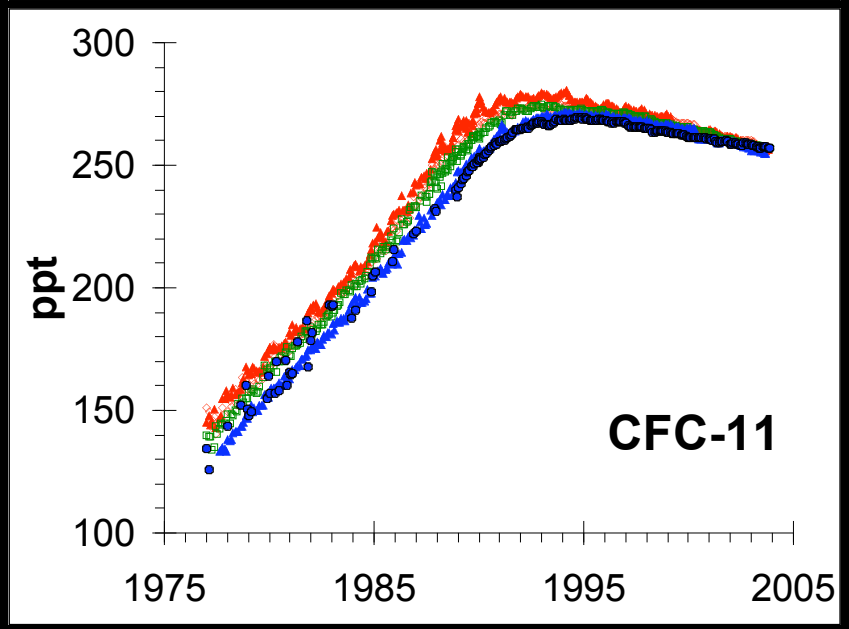
It Took A Village: Science Matters, The Governments Matter, We The People Matter, Industry Matters….

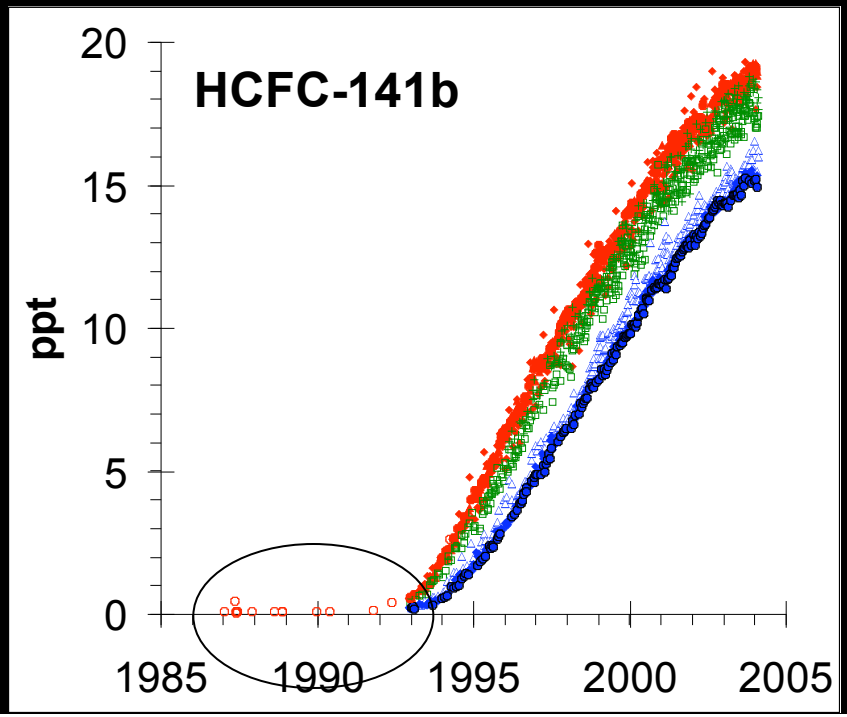
Effect on Concentrations



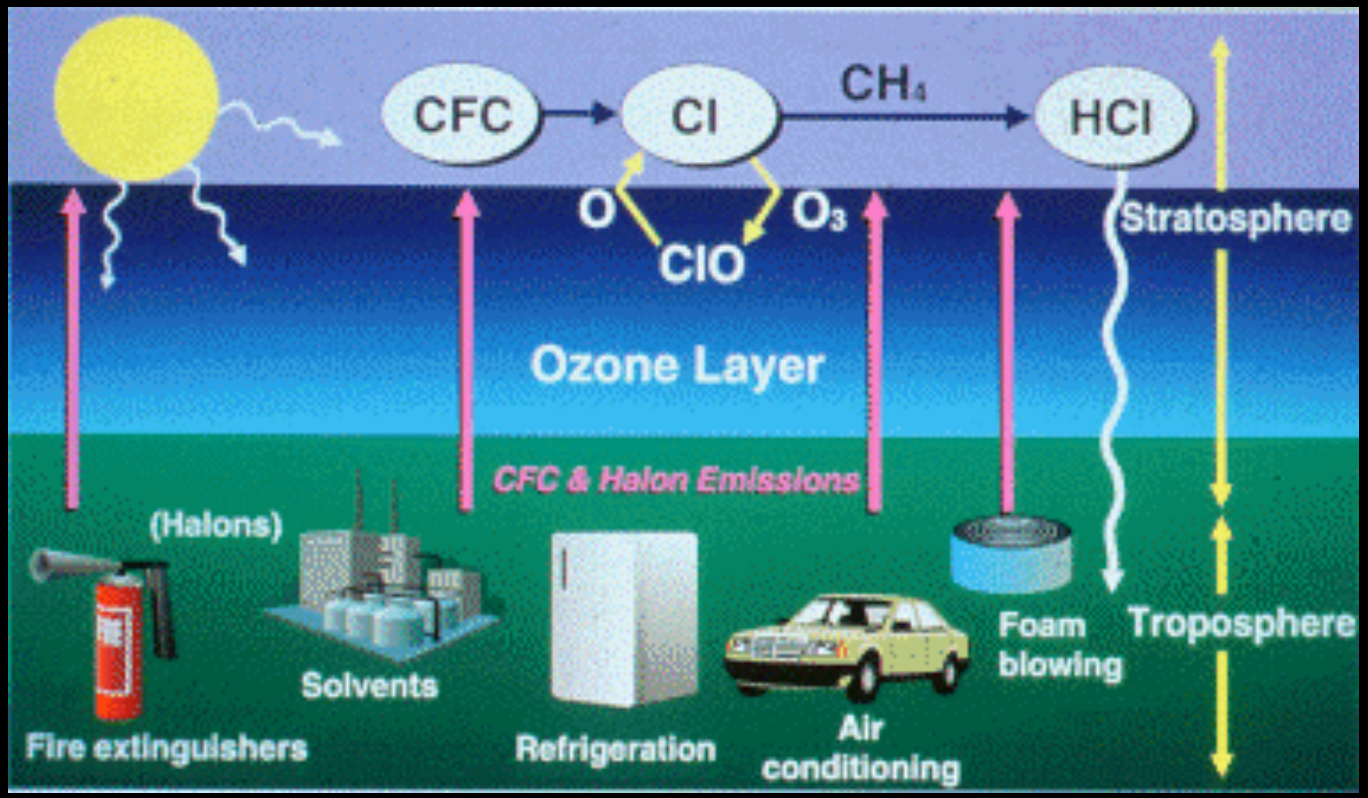
CFCs are well measured; they are starting to slowly decline…. (long lifetimes means a slow decay so ozone holes will happen until about 2050).

Substitutes are building up…..



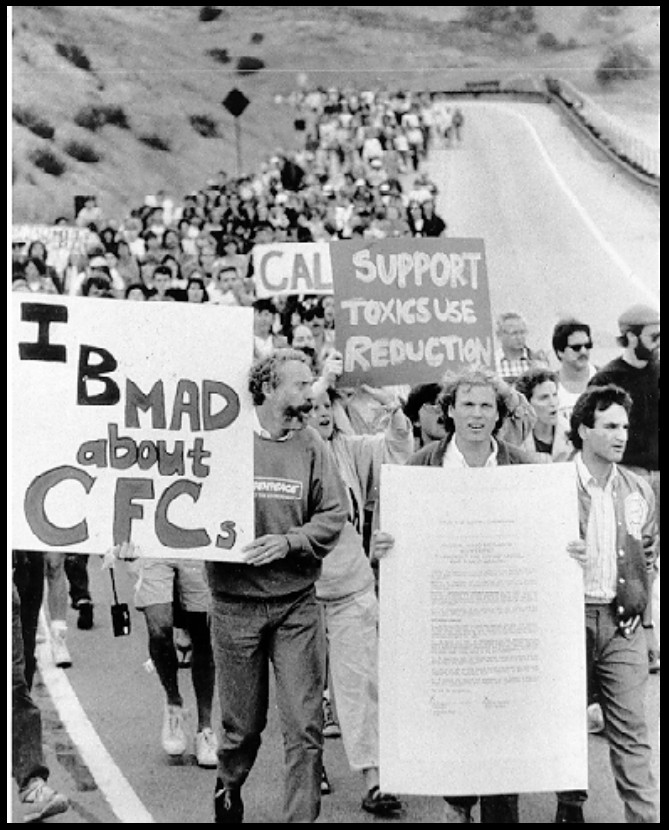


Many Different Sectors Used Ozone Depleting Substances



+ small use in medical applications such as asthma inhalers, specialty electronics etching, etc.

How to Replace CFCs?

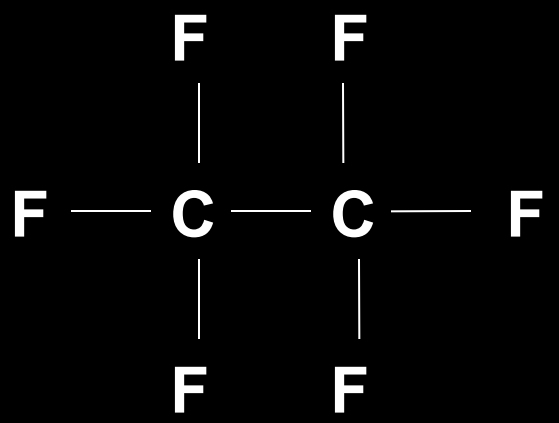


Atmospheric Lifetimes of Long-Lived Halogenated Species

A. R. Ravishankara, S. Solomon, A. A. Turnipseed, R. F. Warren*

The atmospheric lifetimes of the fluorinated gases CF_4, C_2F_6, c-C_4F_8, $(CF_3)_2$c-C_4F_6, C_5F_{12}, C_6F_{14}, C_2F_5Cl, $C_2F_4Cl_2$, CF_3Cl, and SF_6 are of concern because of the effects that these long-lived compounds acting as greenhouse gases can have on global climate. The possible atmospheric loss processes of these gases were assessed by determining the rate coefficients for the reactions of these gases with $O(^1D)$, H, and OH and the absorption cross sections at 121.6 nanometers in the laboratory and using these data as input to a two-dimensional atmospheric model. The lifetimes of all the studied perfluoro compounds are >2000 years, and those of CF_3Cl, CF_3CF_2Cl, and CF_2ClCF_2Cl are >300 years. If released into the atmosphere, these molecules will accumulate and their effects will persist for centuries or millennia.

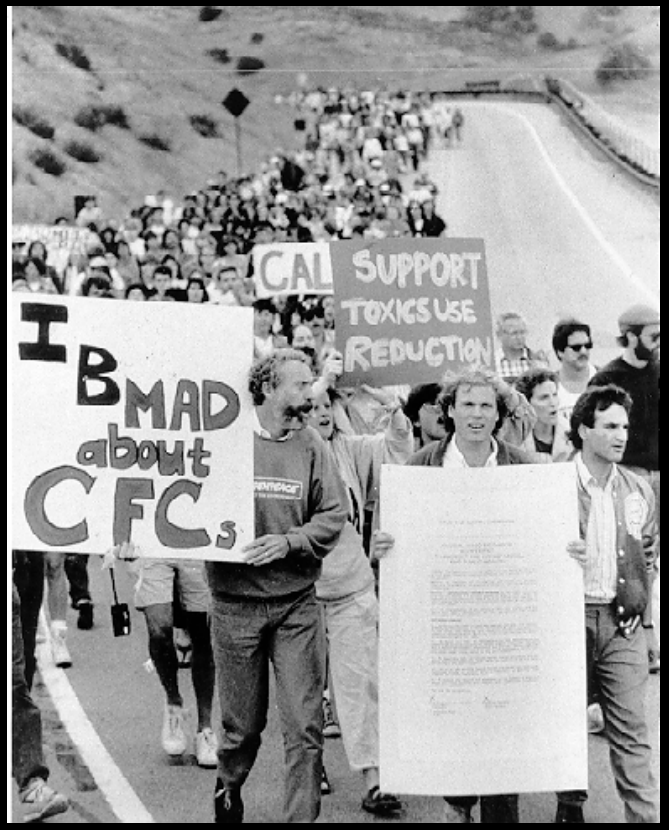
What about a PFC, C_2F_6? No chlorine, so no ozone loss, and some nice chemical properties….

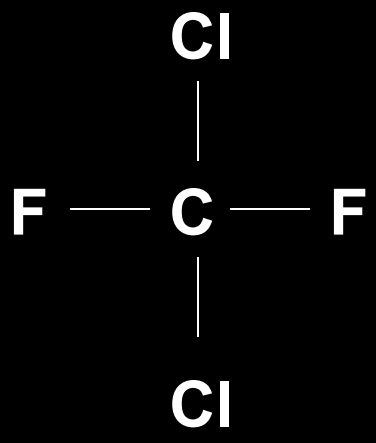


Lifetime in the atmosphere ≈10000 yrs and it's a strong GHG.

Bad idea.

How to Replace CFCs?

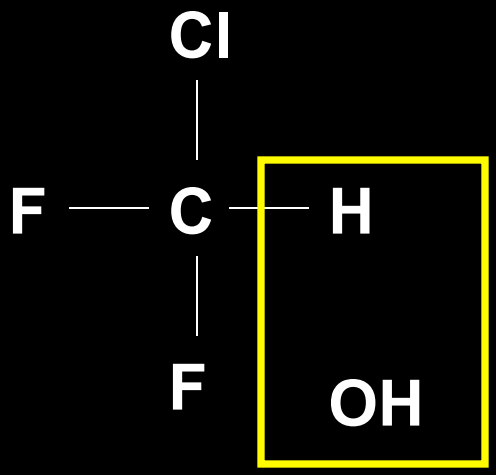




CFC-12

CF_2Cl_2

What about HCFCs?

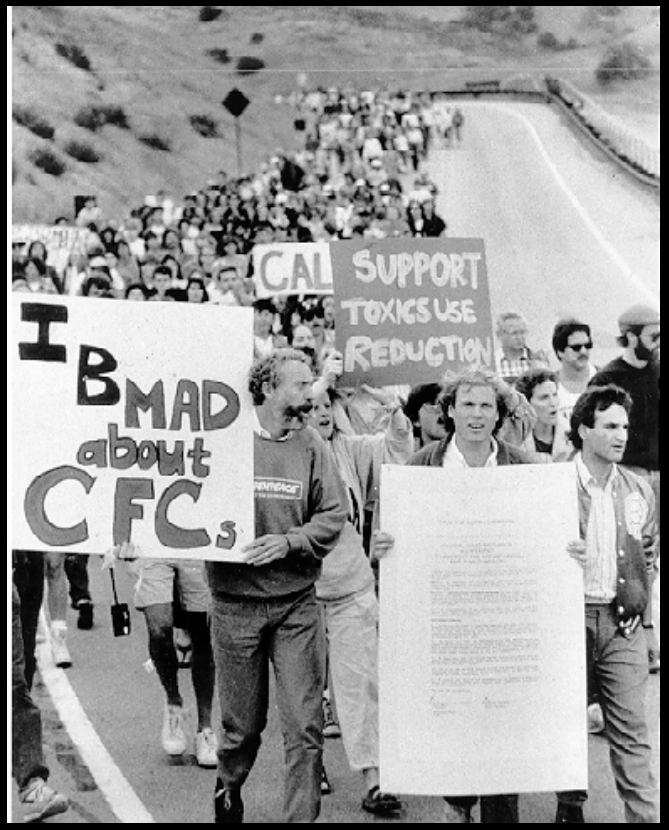


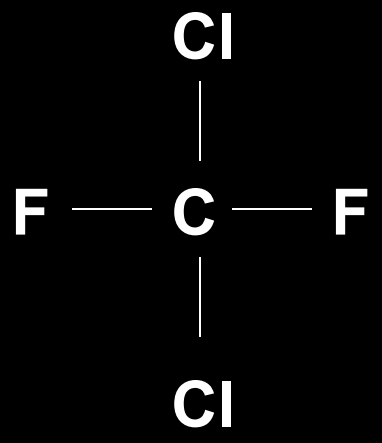
HCFC-22

Lifetime in the atmosphere ≈12 yrs

Per lb effect on ozone only 5% of CFC-12.

How to Replace CFCs?



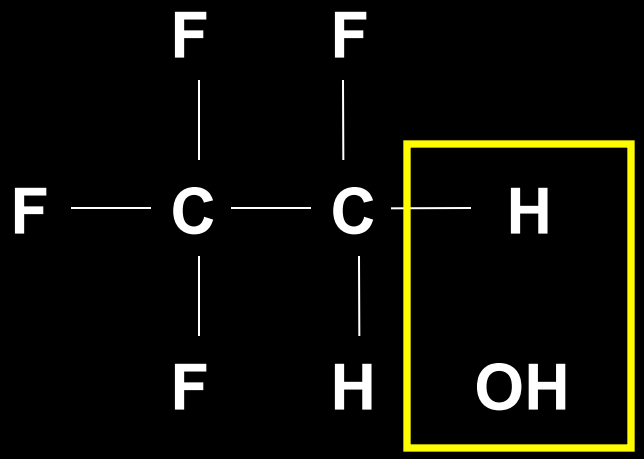


CFC-12

CF_2Cl_2

What about HFCs?

No chlorine, so no ozone loss….



HFC-134a

Lifetime

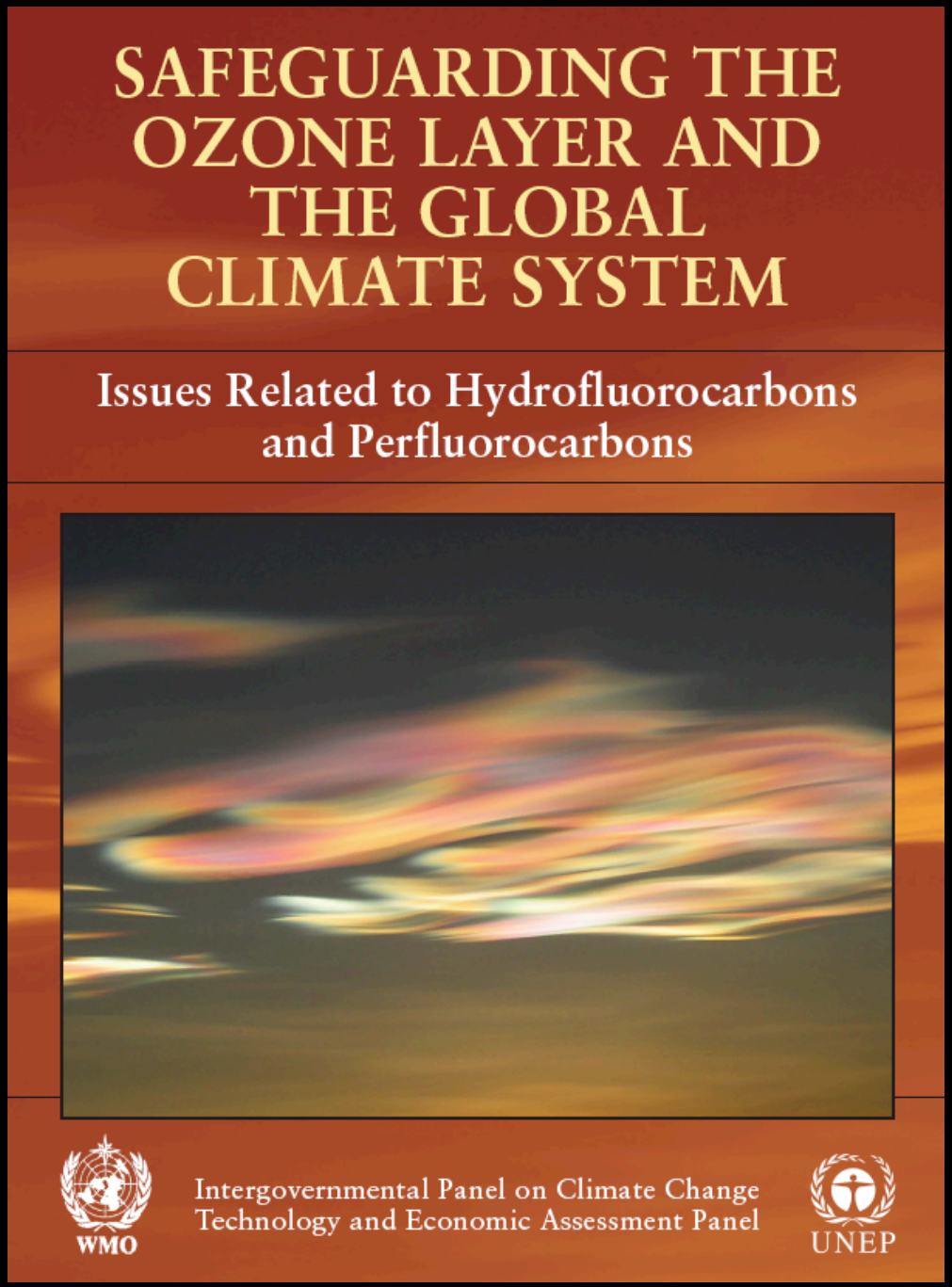
≈14 yrs

Intersection of the Montreal and Kyoto Protocols

- The Montreal Protocol controls the production and consumption of Ozone Depleting Substances including CFCs and HCFCs
- The Kyoto Protocol controls the emissions of a basket of greenhouse gases including HFCs and PFCs
- Ozone Depleting Substances are also potent greenhouse gases. Most substitutes have less potential to affect climate, and some have none.
- Substitutes can lead to a 'win-win' for both climate and ozone.

Substance	GWP	ODP
CFC-12	10890	1
HCFC-22	1810	0.05
HFC-134a	1430	0
HFC-152	53	0
Organics	0	0
Lemon juice	0	0

ODP and GWP indices: per-lb effect of these molecules for ozone loss or climate change over a given time (100 years) relative to a reference gas (CFC-11 for ODP, CO_2 for GWP).



IPCC (2005)

Joint IPCC WG1/WG3/ TEAP

Solomon, co-chair IPCC Working Group One

GWP-Weighted Emissions

Combined CO_2-eq from halocarbons:

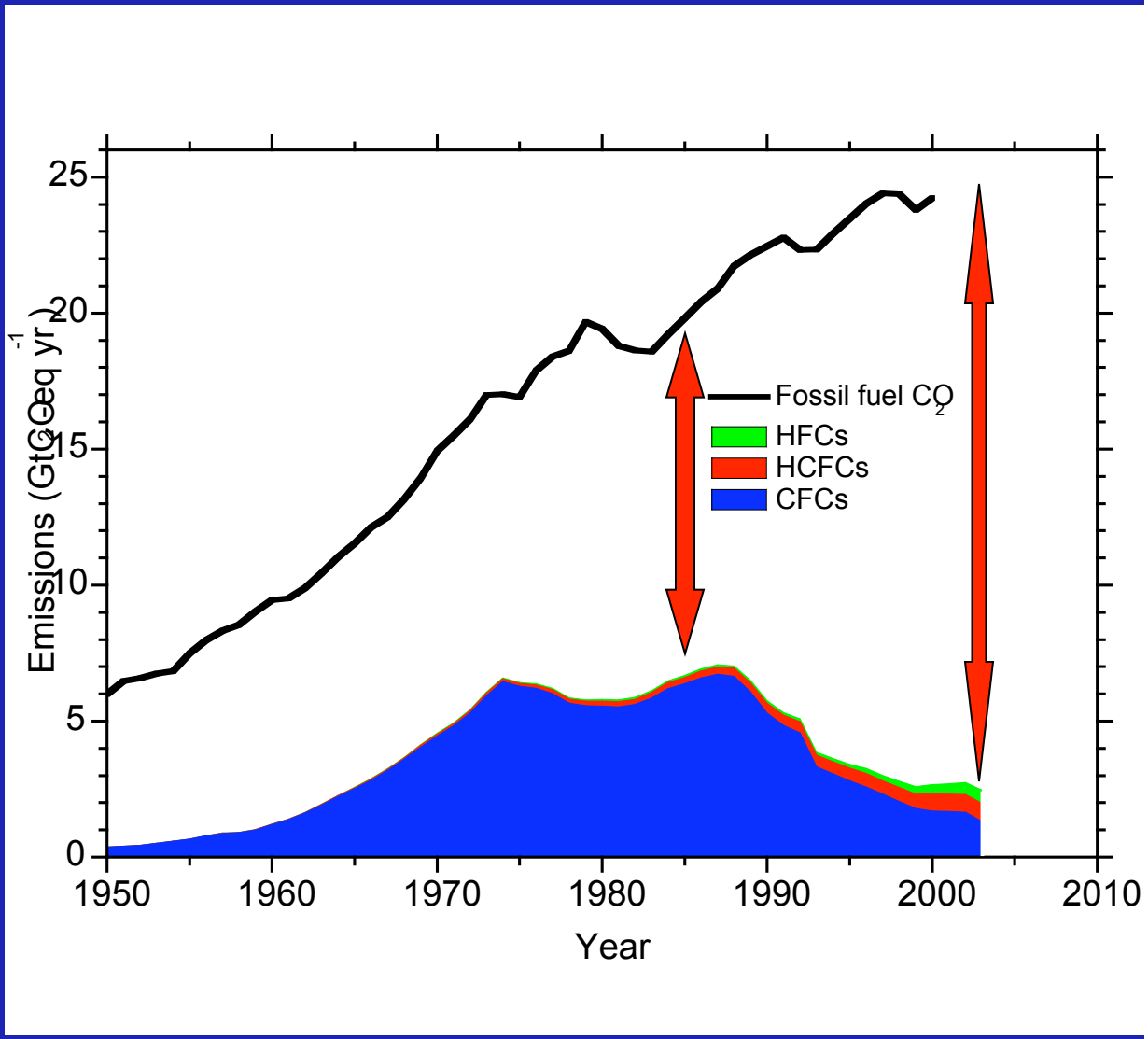
~7.5 Gt near 1990, about 33% of that year's CO_2 emissions from global fossil fuel burning.

2002 breakdown:

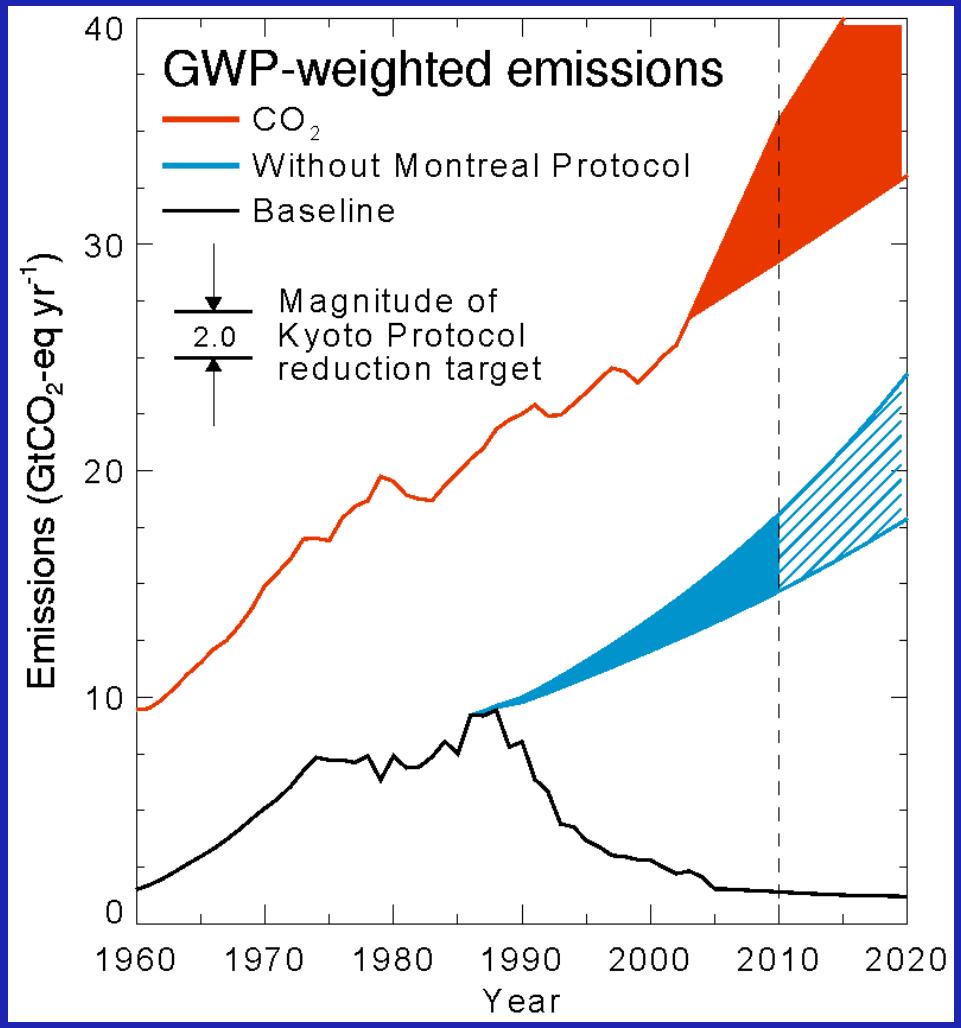
1.5-1.9 Gt for CFCs;

0.53-0.56 Gt for HCFCs;

0.36 Gt for HFCs



Benefits of Montreal Protocol for Climate



Velders et al., PNAS, 2007

CO_2 emissions

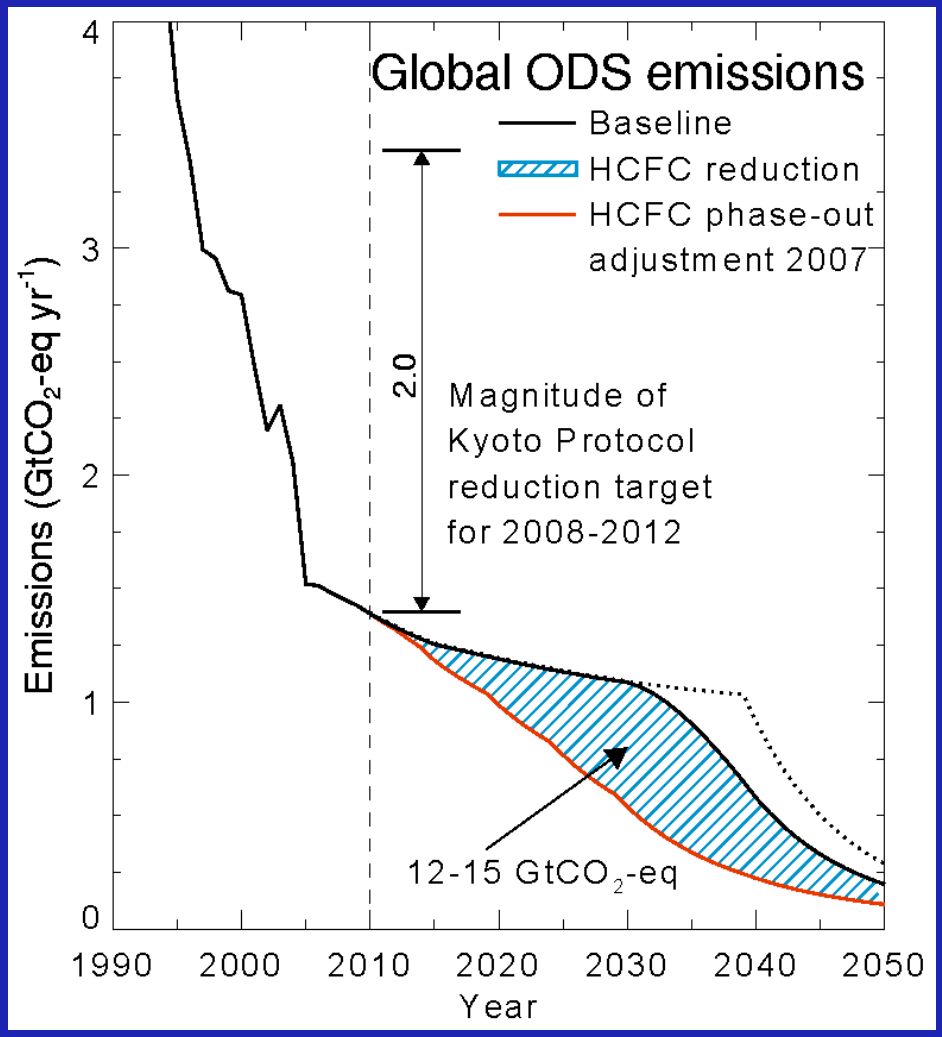
World avoided by the Montreal Protocol?

Reduction Montreal Protocol of ~11 $GtCO_2$-eq/yr

➔5-6 times global Kyoto target

Role of ozone depletion cooling due to CFCs? Could reduce this by perhaps a third but….

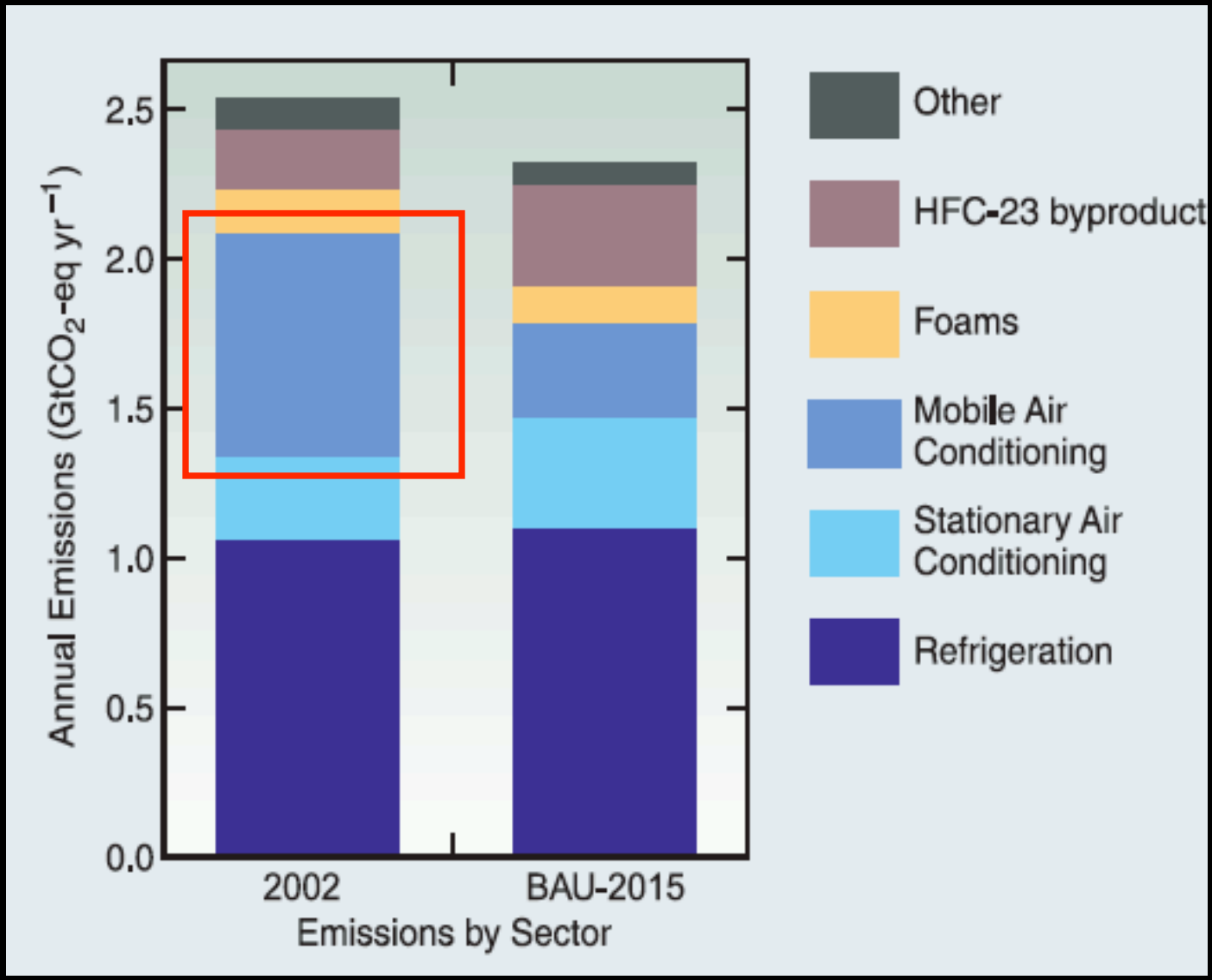
Montreal Sep 2007 adjustment: HCFC early phase-out



Reduction in emissions:

- HCFCs 'transition' speedup
- 12-15 $GtCO_2$-eq potential reduction if HCFCs and HFC-134a replaced with low-GWP alternatives or reduced through conservation/recycling.

Halocarbon (CFC, HCFC, and HFC) Emissions by Sector



Some Auto Air Conditioner HFC Mitigation Options

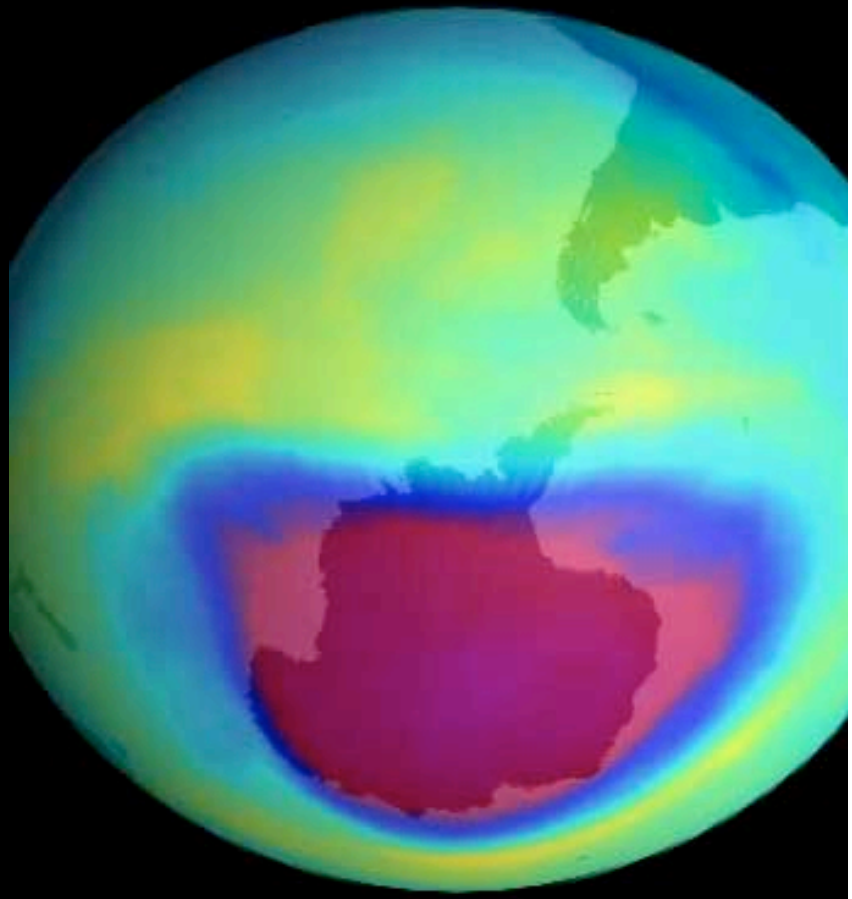
- **One option is to stop 'do-it-yourself' cans; save more than 50% of the emissions from those recharges.**
- **'Enhanced' systems with tighter hoses, compressors, and valves, at a cost of $24-36/vehicle, and a savings of over 60%.**
- **Improved 'end of life' recovery and recycling.**
- **Switch to lower-GWP refrigerants? HFC-152a?**

Conclusions:

The ozone hole has affected the climate of Antarctica in a surprising way: contributed to local cooling on the plateau and local warming on the peninsula in summer/fall. CO_2 also warms…

Actions taken to deal with ozone depletion and CFCs (the Montreal Protocol) have had large effects on reducing climate forcing - bigger than the Kyoto Protocol.

Some more reduction of climate forcing through CFC, HCFC, and HFC-134a reduction is possible (and would be significant).



September 24, 2001