Pushing Earth Climate Models to the Extremes

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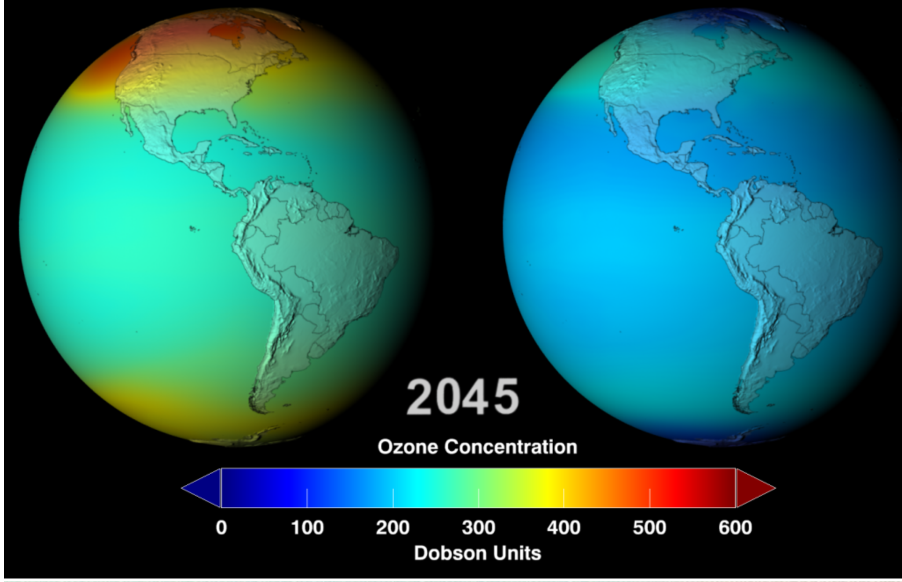
NASA/GSFC
Code 614



1906 San Francisco Earthquake
Painting by William Coulter
http://www.sfmuseum.org/1906/coulter.html

Introduction

Climate models are an excellent test bed to examine low frequency but high impact events and scenarios

Learn new things about the climate system

Could uncover subtle model problems

We will focus on 3 extremely large forcings:

1. Sulfate aerosol loading from a super-eruption

2. Black carbon aerosol from massive fires initiated by nuclear conflict

3. Unrestrained increase in CFCs – World Avoided

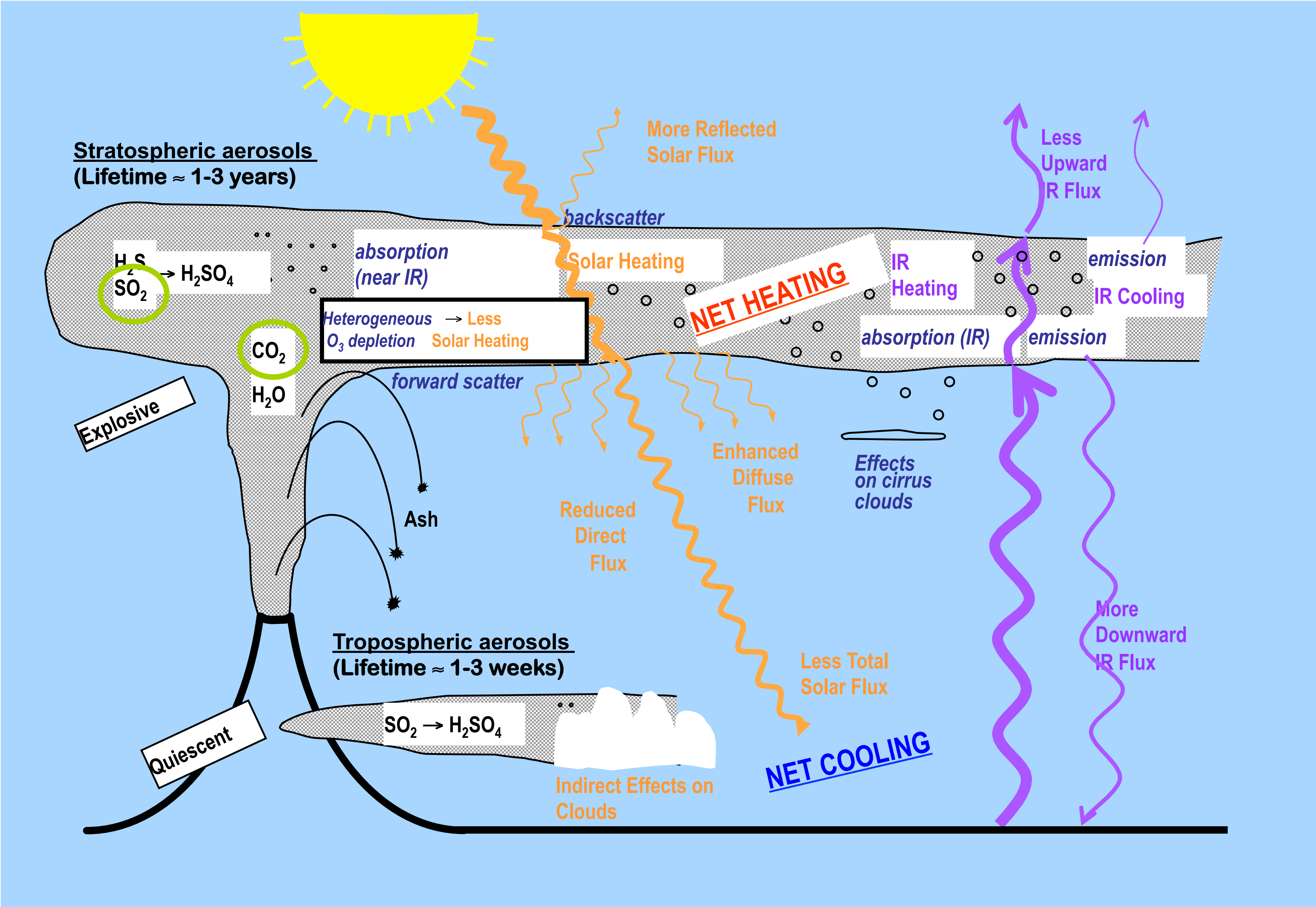


Diagram by Alan Robock

Model Configuration and Sulfate Properties

Work done in Collaboration with Alan Robock, Gera Stenchikov, and Drew Shindell

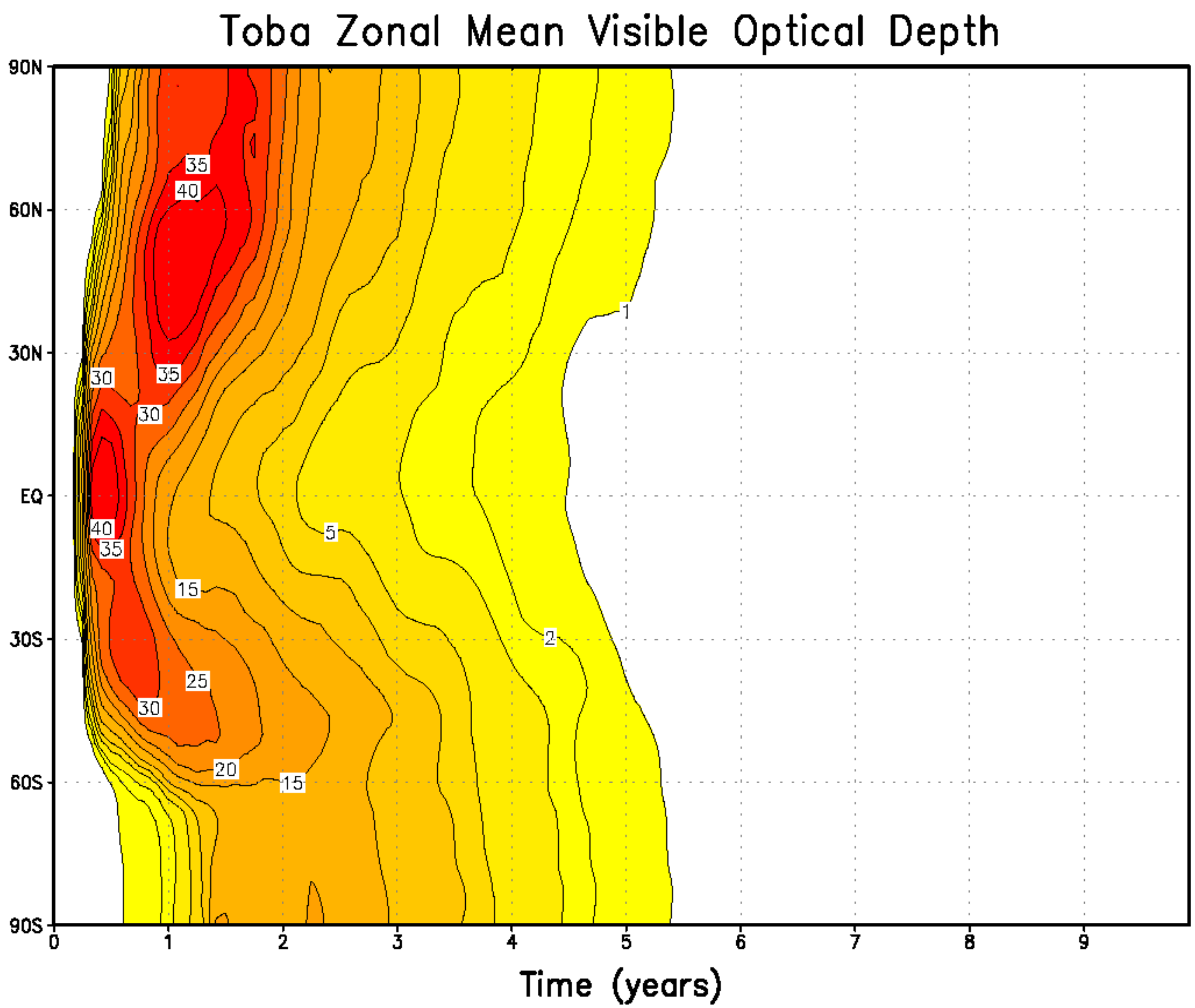
We use the NASA GISS ModelE AOGCM

- $4°\times5°$ horizontal resolution and 23 vertical levels in atmosphere 13 in ocean
- We ran a 30-yr control run and each volcanic run was 10 years
- Toba Super-eruption 74,000 years ago
- 0.67 to 18 Gt of SO_2 converts by OH into H_2SO_4 (injected from 24-32 km)
- 33 to 900 times larger than Pinatubo in June 1991 and injected over 7 days

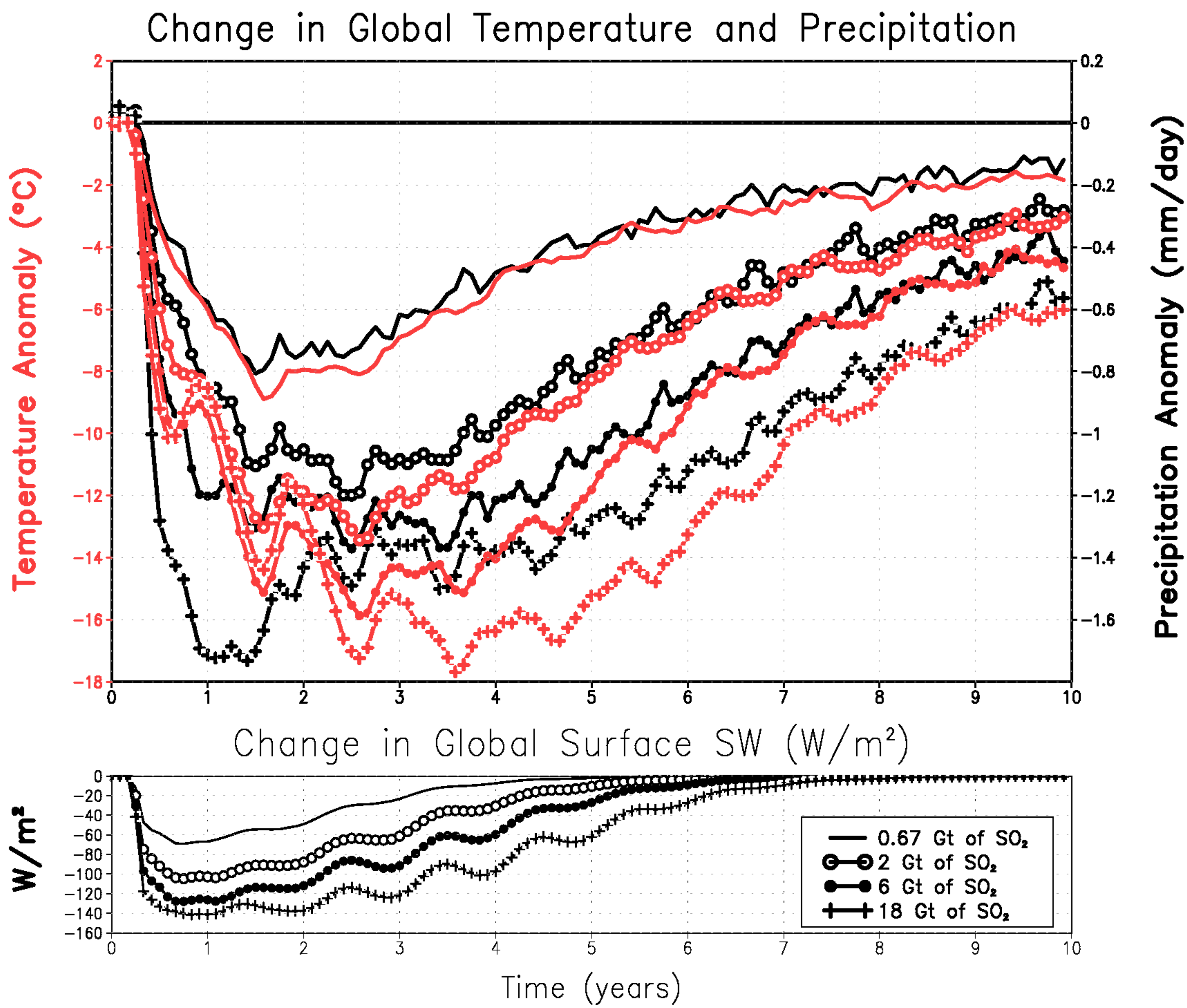
Properties of Sulfate Aerosol in Visible Band

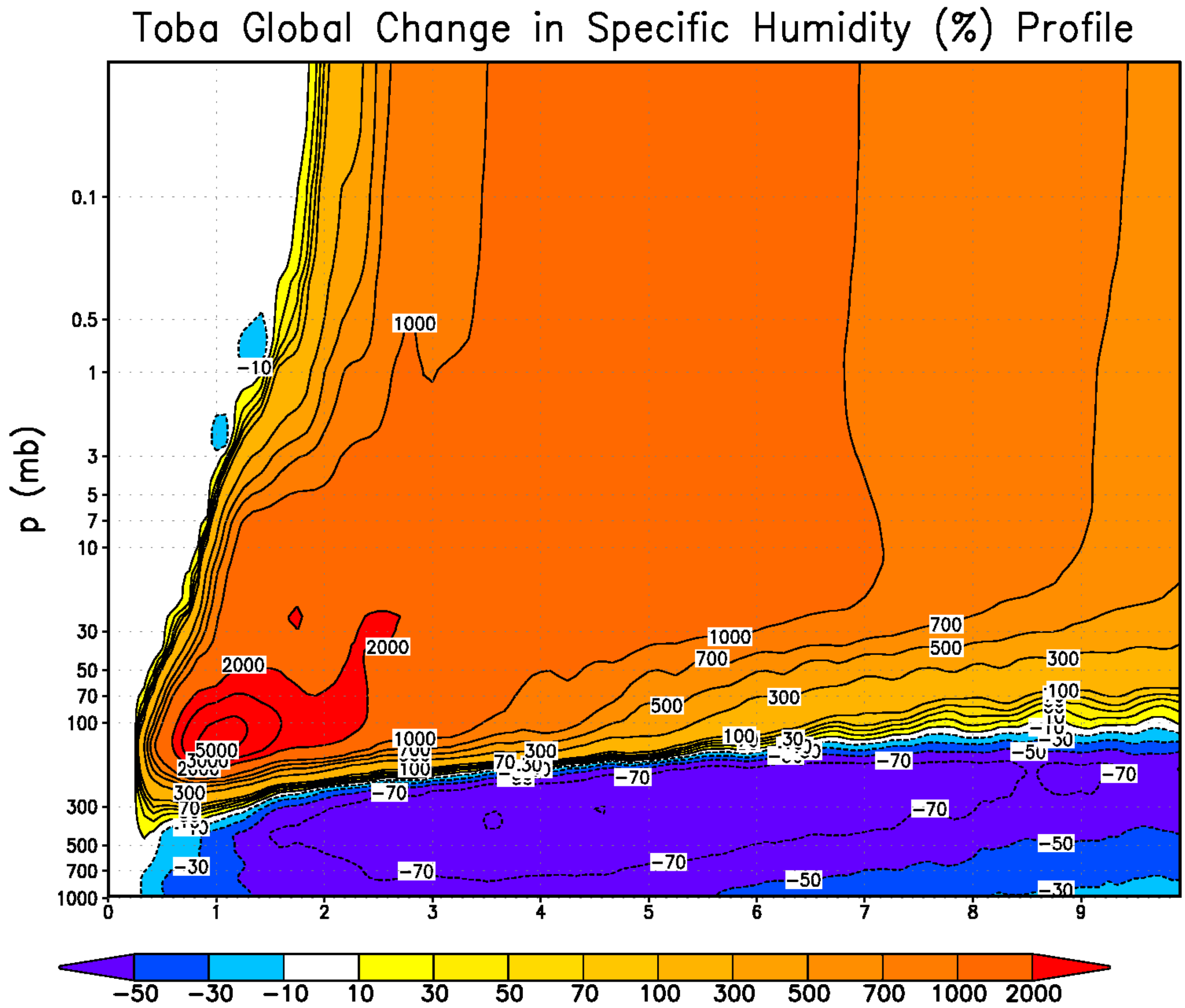
Size varies but an average aerosol has a 0.5 μm effective radius
2.62 m^2/g mass extinction coefficient
1 single scattering albedo
0 m^2/g mass absorption coefficient in visible but there is some absorption in Near-IR and Longwave

NASA GISS ModelE, 6 Gt of SO_2 or about 300x Pinatubo

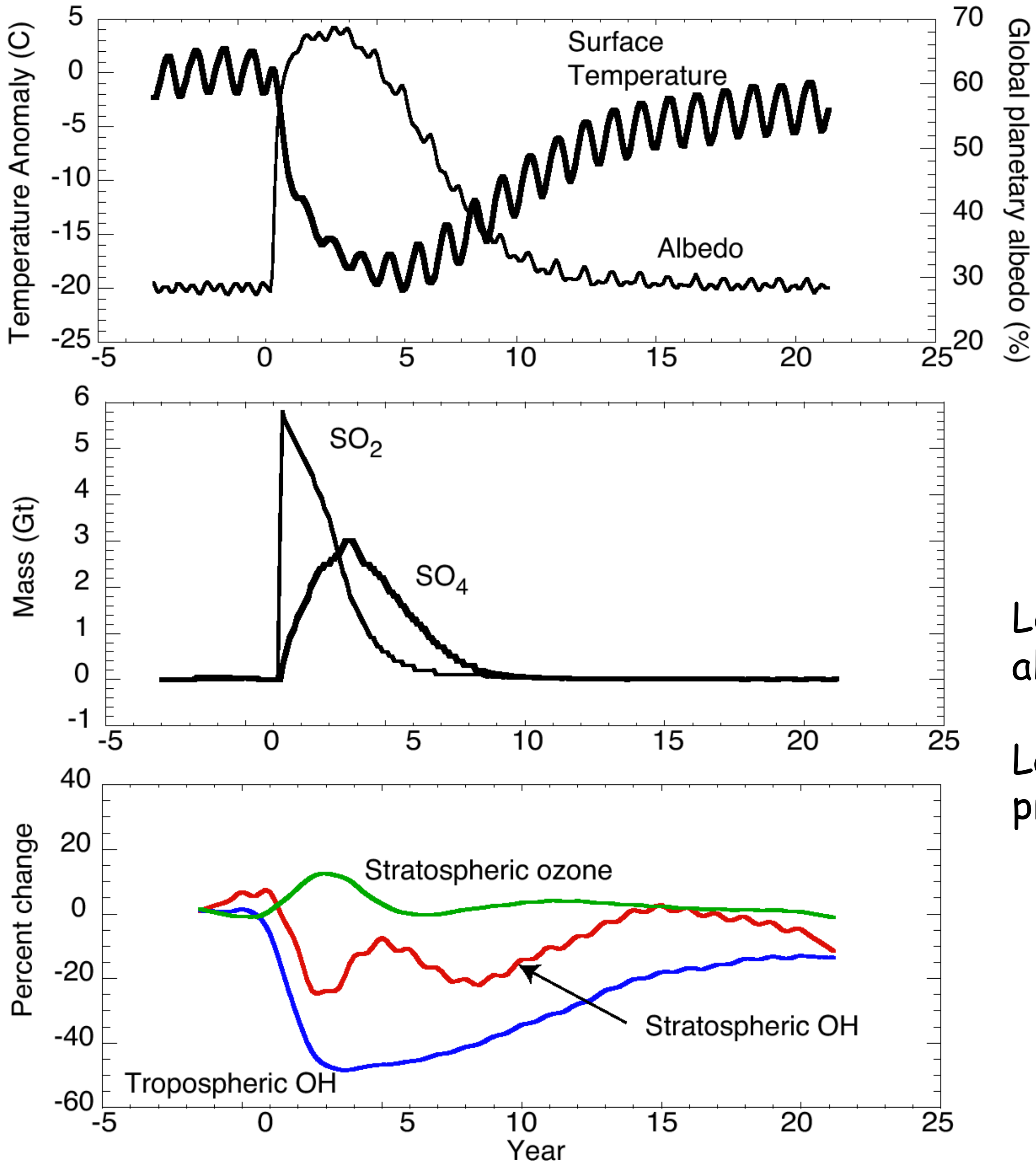


Optical Depths are about 2 orders of magnitude larger than Pinatubo


Change in Global Temperature and Precipitation
Temperature Anomaly (°C)
Precipitation Anomaly (mm/day)
Change in Global Surface SW (W/m²)
W/m²
Time (years)
0.67 Gt of SO₂
2 Gt of SO₂
6 Gt of SO₂
18 Gt of SO₂



NASA GISS ModelE, 300x Pinatubo



NASA GISS ModelE with stratospheric chemistry, 300x Pinatubo

Longer SO_2 lifetime when allowing OH to respond

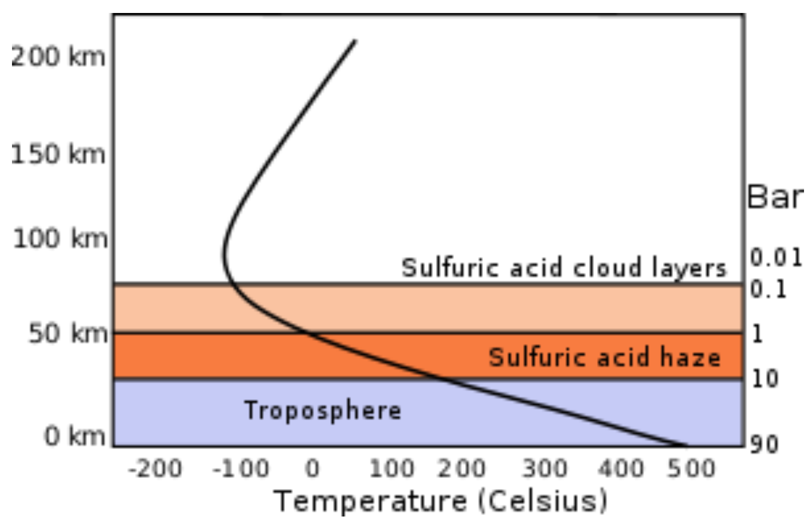
Large decrease in OH primarily from decreased UV

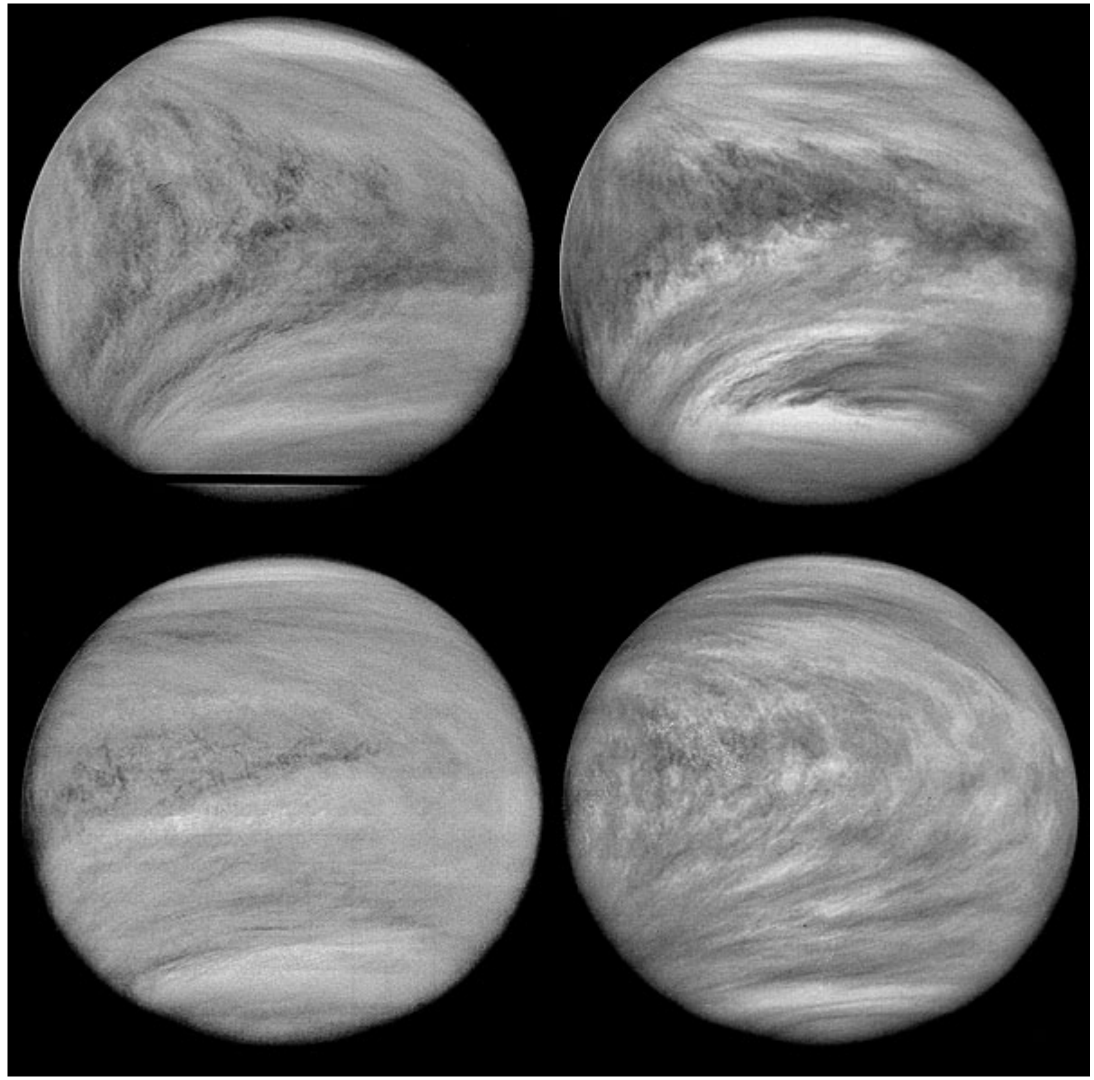
Superrotational Winds on Venus

Images over 4 Earth Days

Time it takes for superrotational winds to circle Venus

Large amounts of Sulfuric Acid in atmosphere

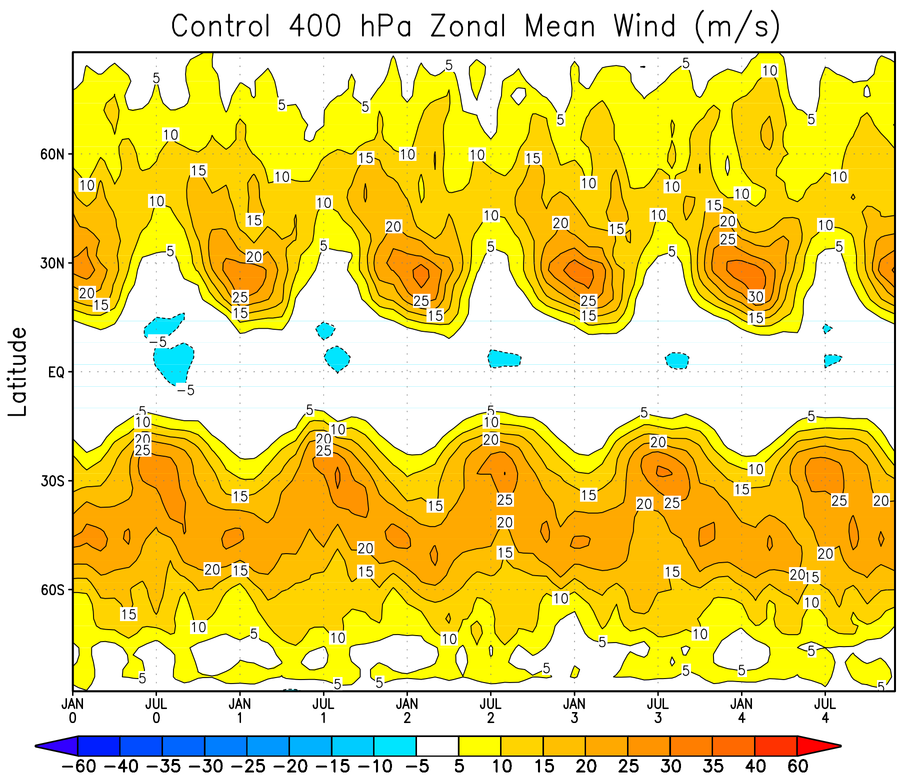


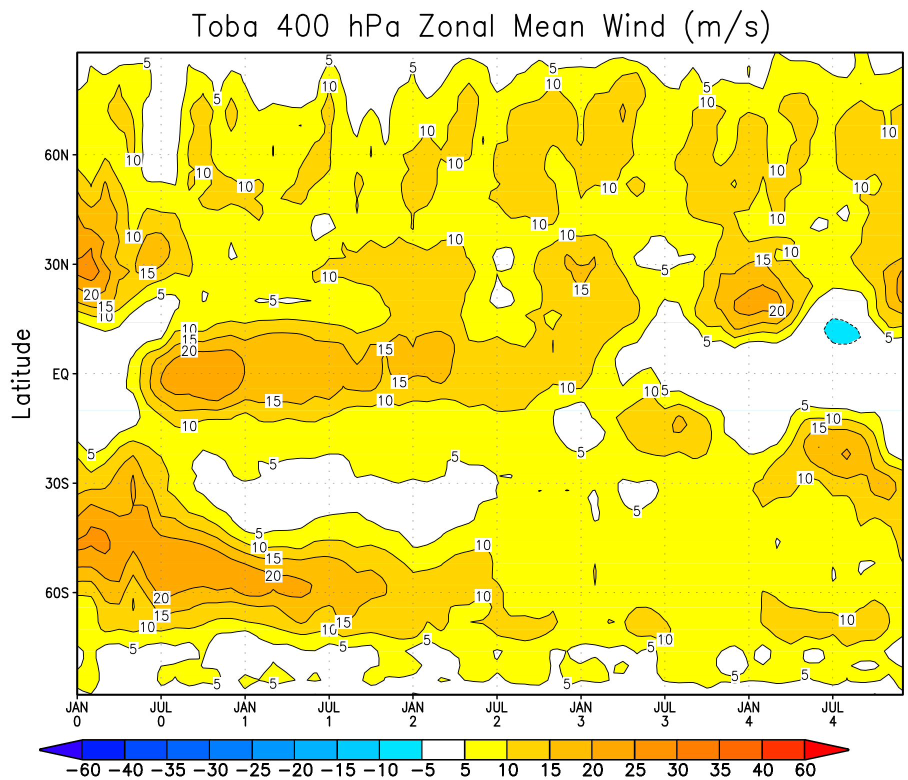


Pioneer Venus Orbiter 1979

Did Toba Induce Equatorial Superrotation on Earth?

Simulations using GISS ModelE produce equatorial superrotation shortly after the Toba eruption and are maintained for a couple years.

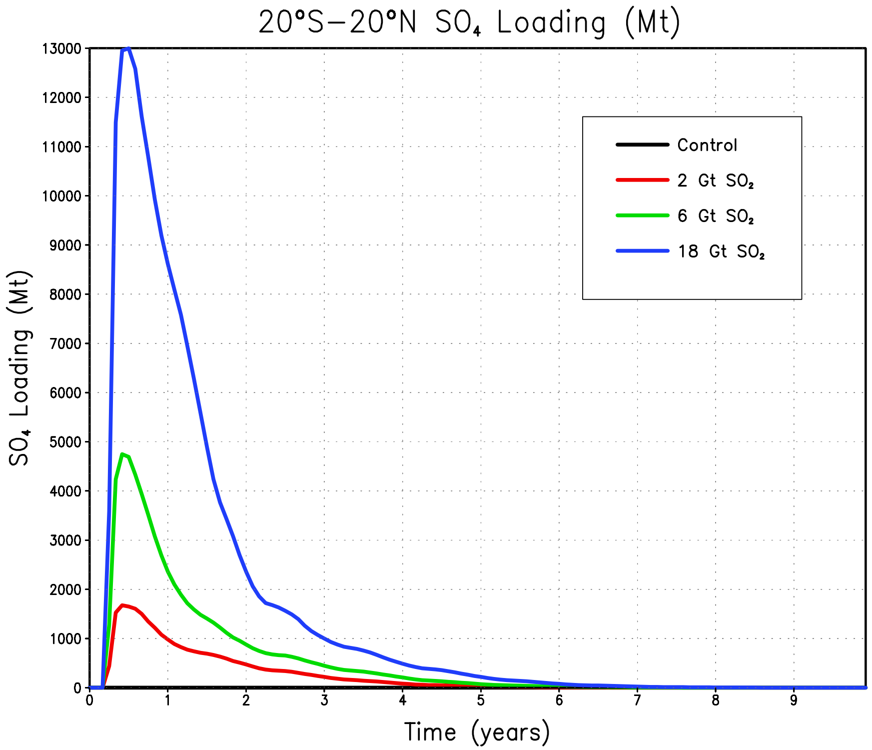


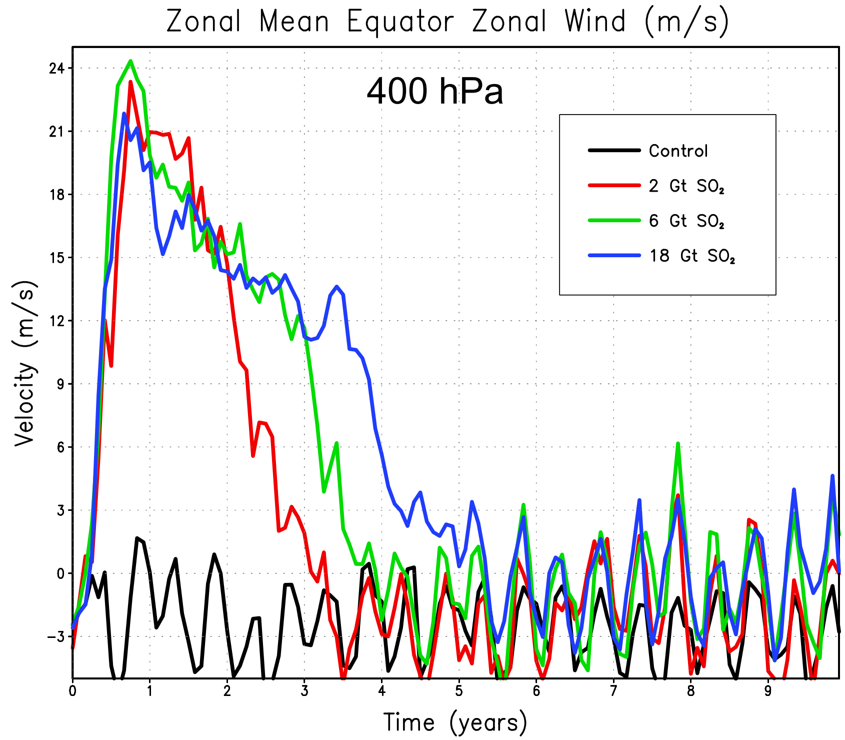


Zhu, Oman, Waugh, and Lloyd 2010

Sulfate Loading and Equatorial Superrotation

- All 3 scenarios produce similar peak winds
- But the length of time superrotation is maintained differs
- Suggest some critical loading necessary for maintaining this feature (~500 Mt)





Massive Fires from Nuclear War

- Crutzen and Birks, 1982 – first to point out massive fires would produce smoke that would change climate.
- Turco et al., 1983 – 1-D climate model predicting massive cooling from the resulting smoke – coined the term nuclear winter.
- Aleksandrov and Stenchikov, 1983 – first 3-D GCM of the climate impacts.
- A number of studies were conducted 1983-1985 some with results suggesting the original studies had overestimated the climate impacts.
- A few in the late 80s but very little since.
- But first we examine a regional nuclear conflict scenario

What would be the consequences of a regional nuclear war using 100 15-kt (Hiroshima-size) weapons?

Work done in Collaboration with Alan Robock, Gera Stenchikov, and Brian Toon

This would be only 0.03% in explosive yield of the current world arsenal.

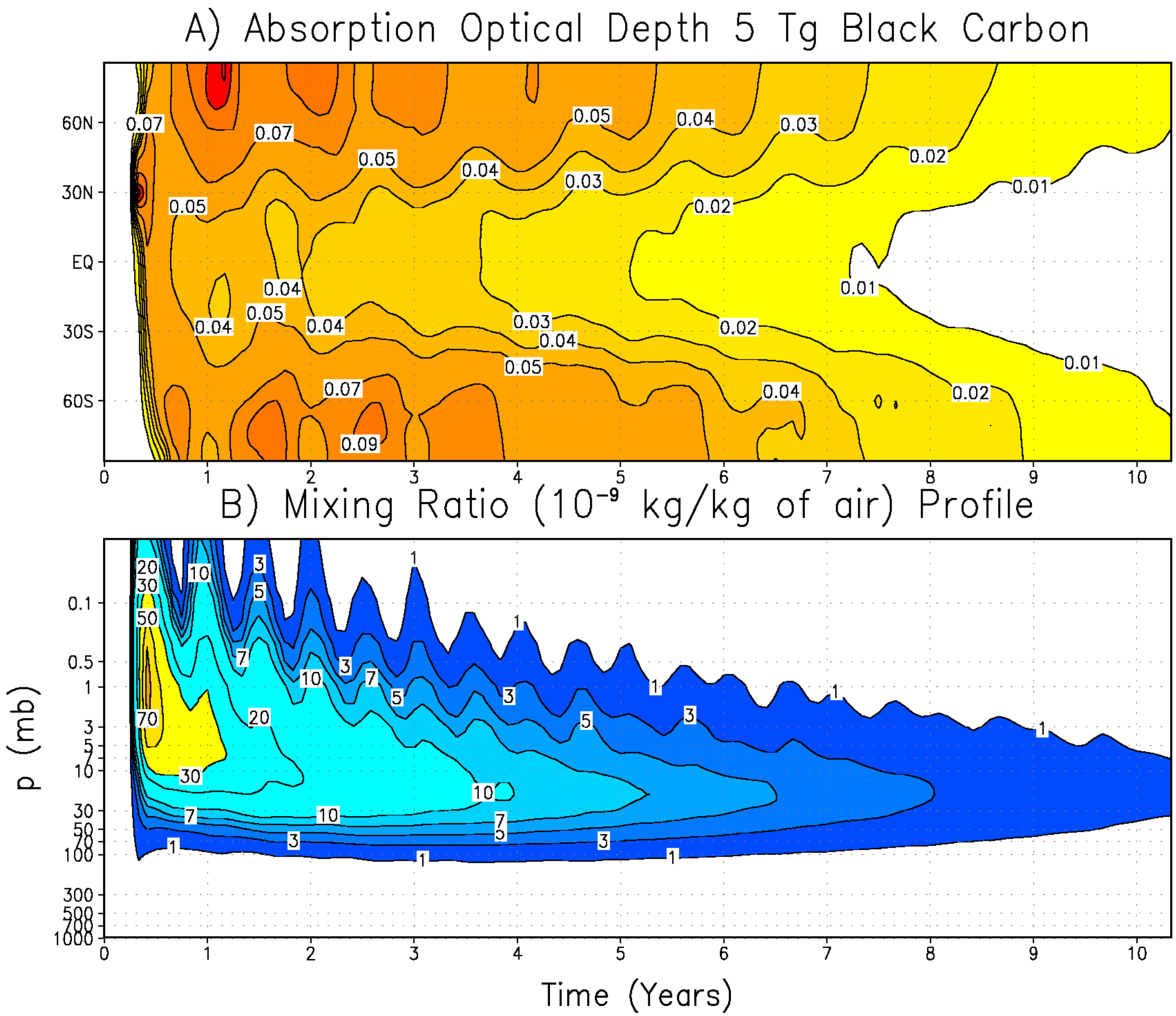
We use the NASA GISS ModelE AOGCM

- 4°x5° horizontal resolution and 23 vertical levels in atmosphere 13 in ocean
- 5 Tg of black carbon into the 300-150 mb layer (upper troposphere) over 1 grid box at 30°N, 70°E on May 15
- These are from estimates in Toon et al. 2007
- 30-yr control run
- 3-member ensemble for 10 yr
- BC optical properties – MEC 9 m^2/g and MAC 6.21 m^2/g

  SSA 0.31 and 0.1 μm radius

For a 5 Tg injection into the UT, the smoke would produce ~0.06 global absorption optical depth.

The “self lofting” BC quickly rises to a high altitude and has a 5-6 yr e-folding removal time, much longer than the 1 yr time for volcanic aerosols.

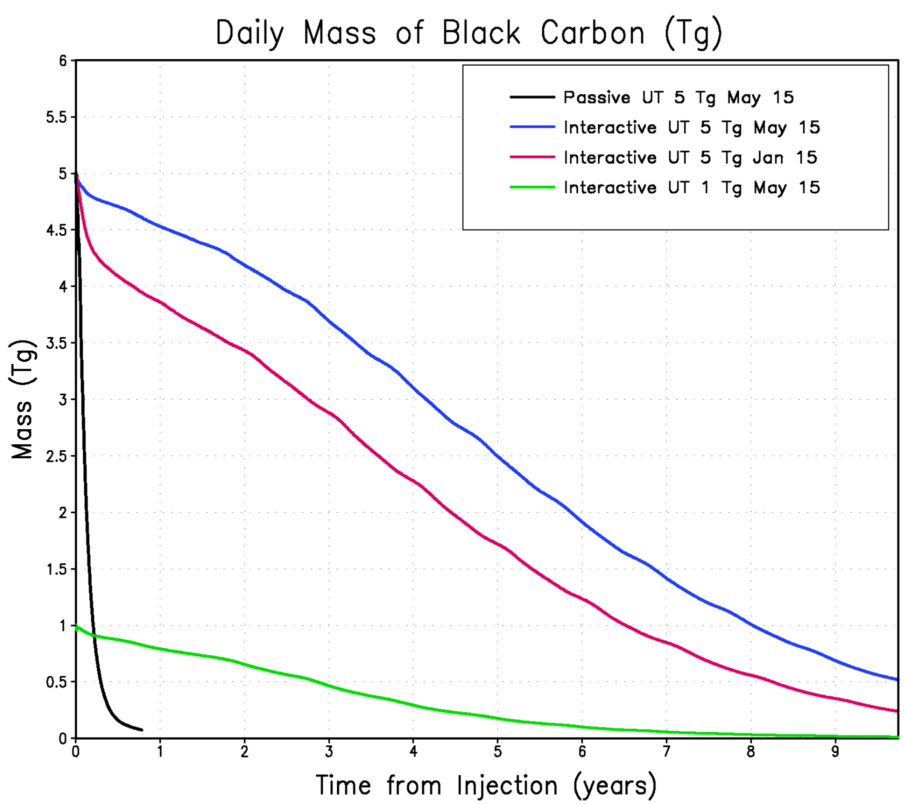


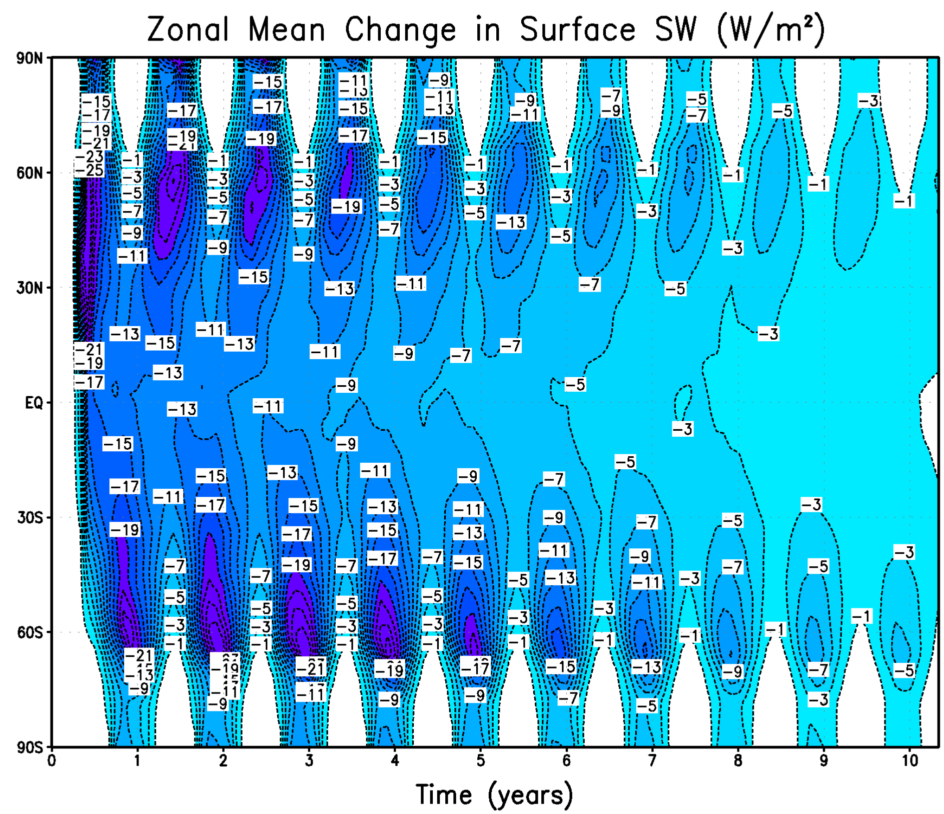
Daily mass loading of a few example cases - passive tracer is removed with e-folding time of 2 months

Jan. case has less lofting but only reduces lifetimes by about 20%

The rest of the figures correspond to the blue line (5 Tg UT May 15)

Very large changes in the surface SW radiation would occur with the largest anomalies over the mid-latitudes during the summer in the respective hemispheres.



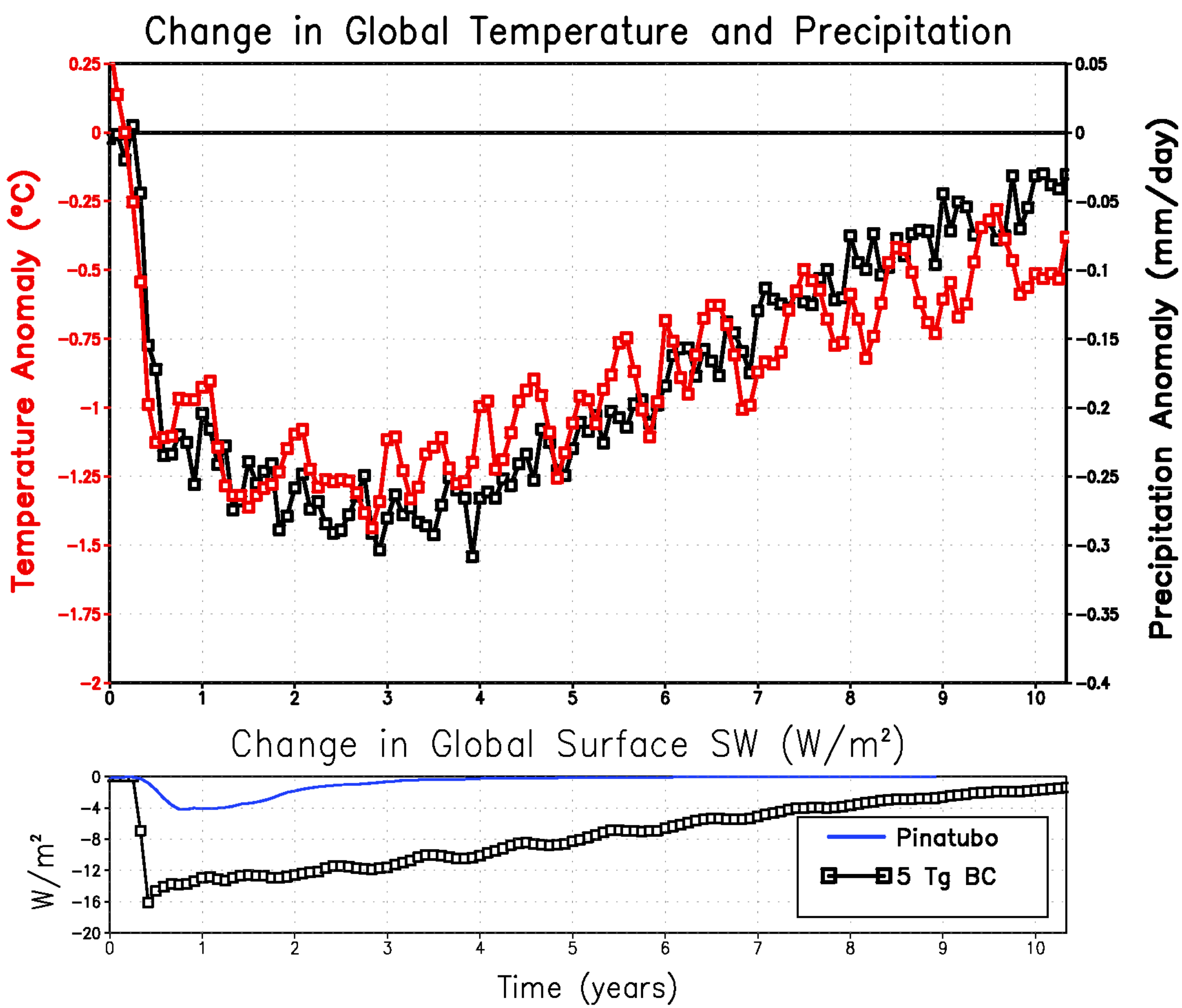


Global temperatures decrease 1.25°C for 2-3 years and after 10 years still -0.5°C

Precipitation decreases about 10% globally

The global change in surface SW would be -16 W/m² reducing to -8 W/m² after 5 years

4x larger than from Pinatubo and had a much shorter e-folding time

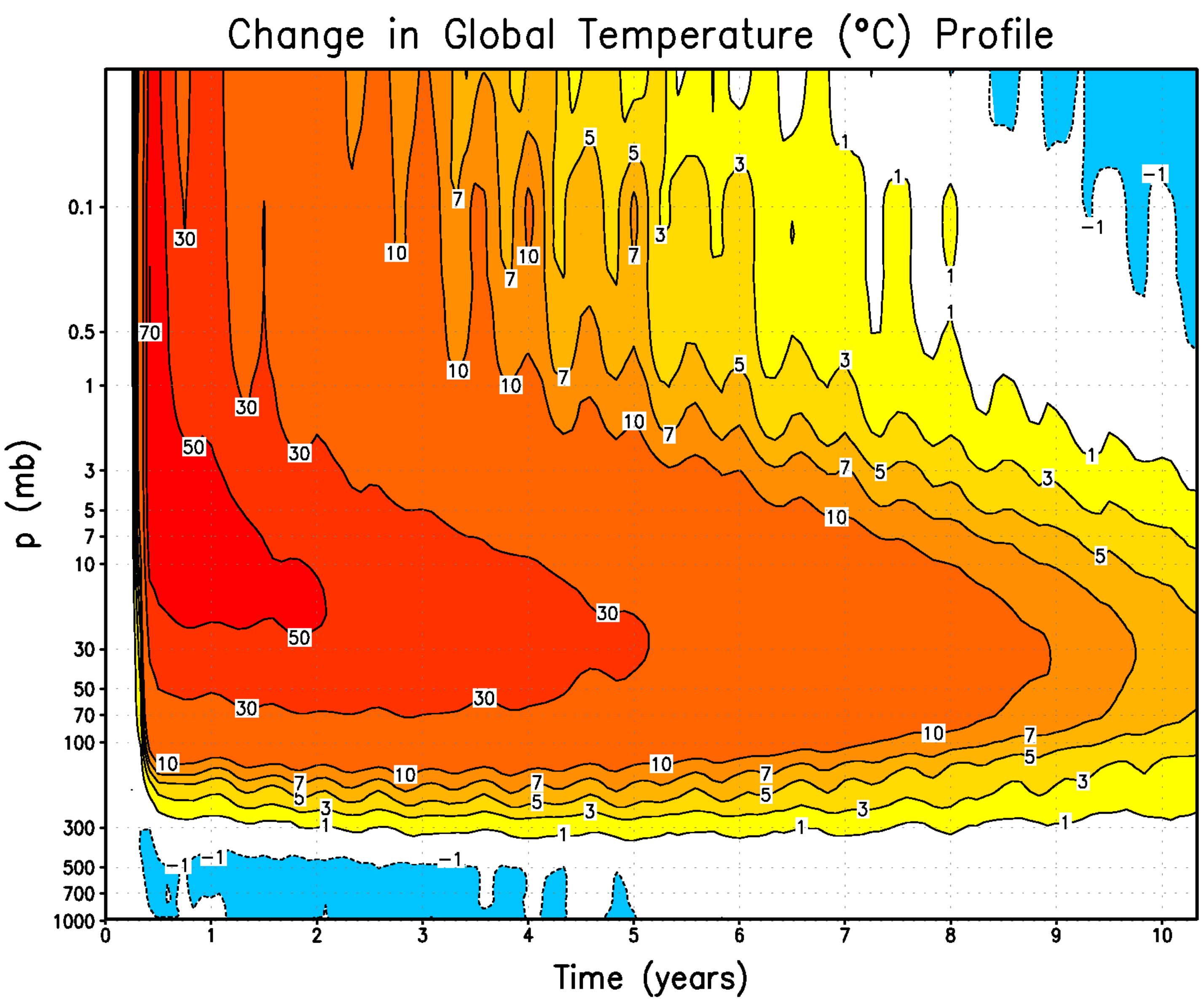


Heating of the stratosphere through the absorption of SW radiation would exceed 30-50°C for a couple years.

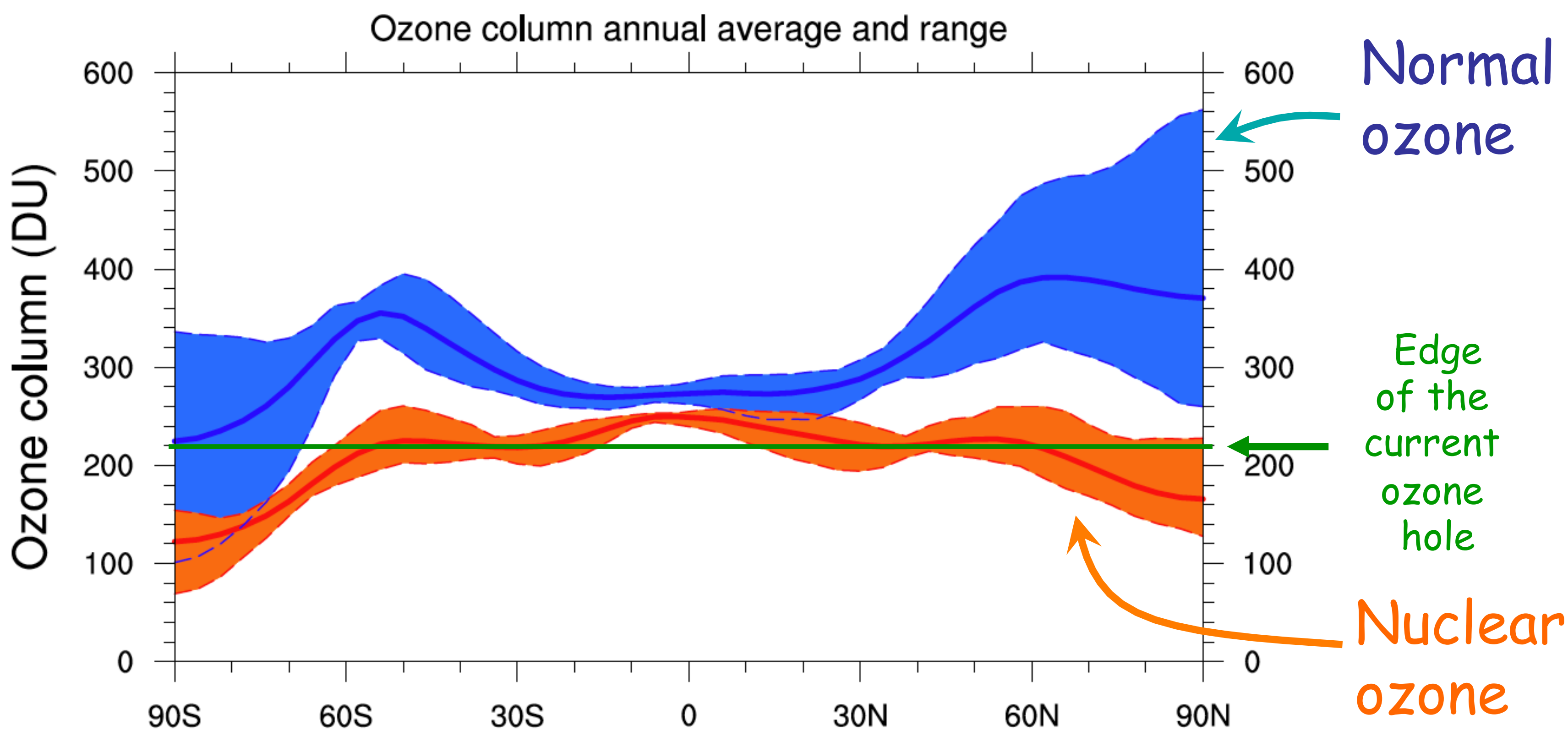
In the low to mid troposphere cooling of about 1°C occurs for about 4 years.

Strong heating of the tropical tropopause cold point will allow a significant increase in stratospheric water vapor.

Large ozone losses

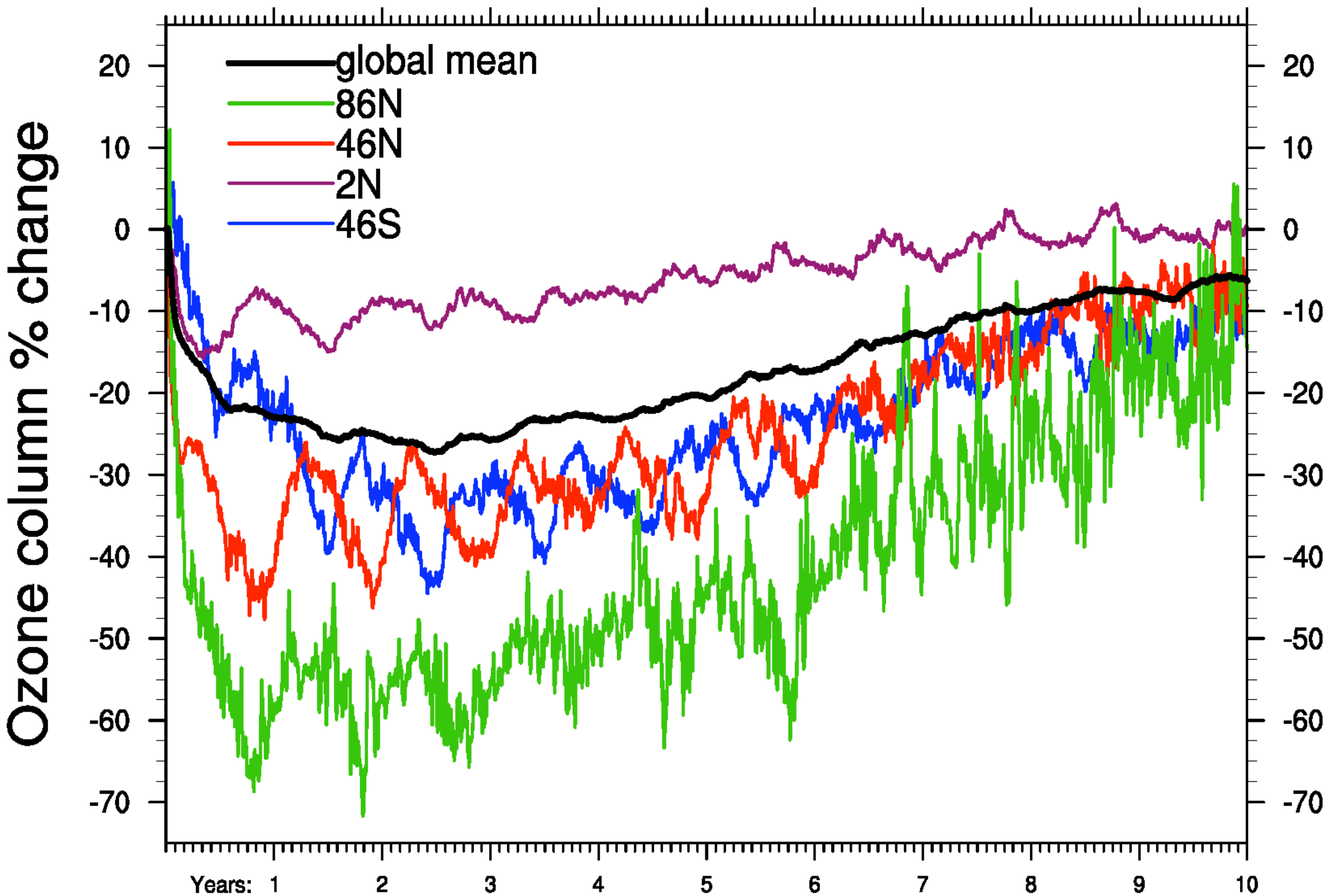


Ozone depletion 3 years after 5 Tg soot injection



Mills et al. (2008), *Proc. Nat. Acad. Sci.* using the WACCM model

Ozone depletion is large and long-lasting at all latitudes

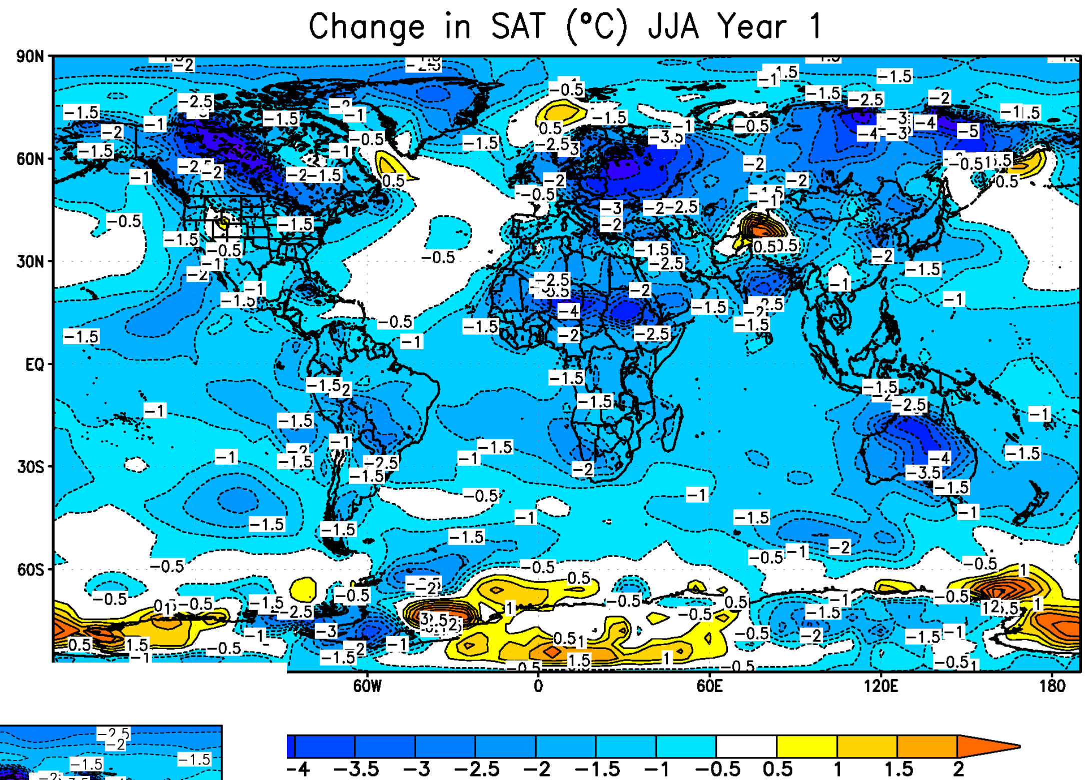


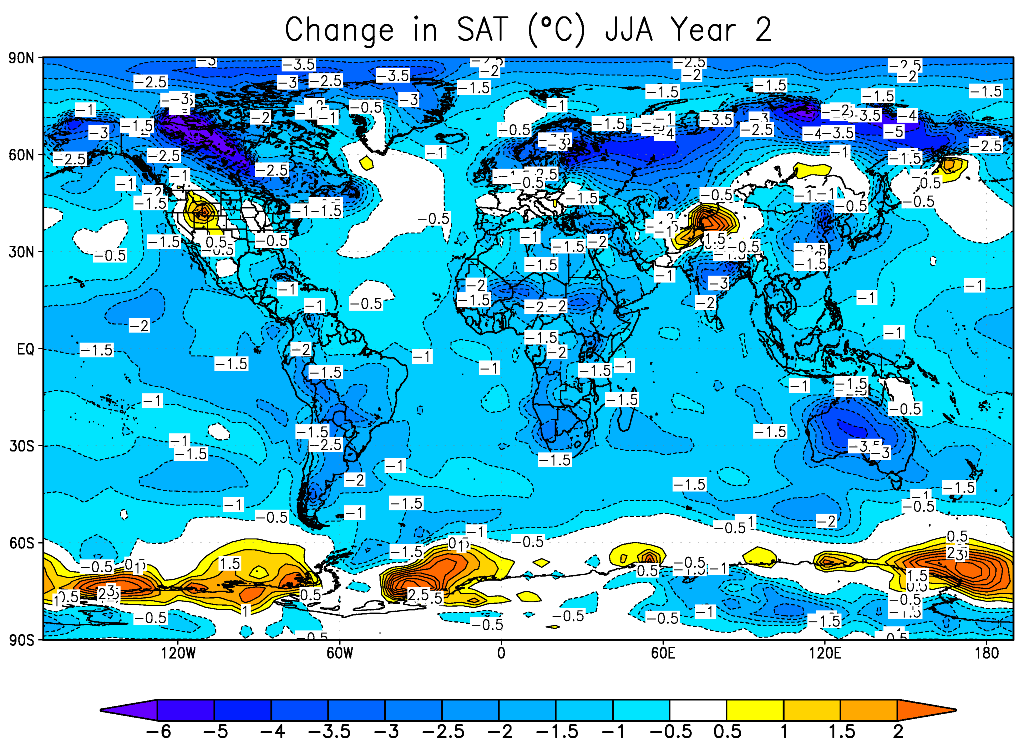
Mills et al. (2008), *Proc. Nat. Acad. Sci.*

JJA Surface Air Temperature Changes

Cooling is largest over landmasses up to 3-4°C

Warming over high mountain ranges from the black carbon aerosol





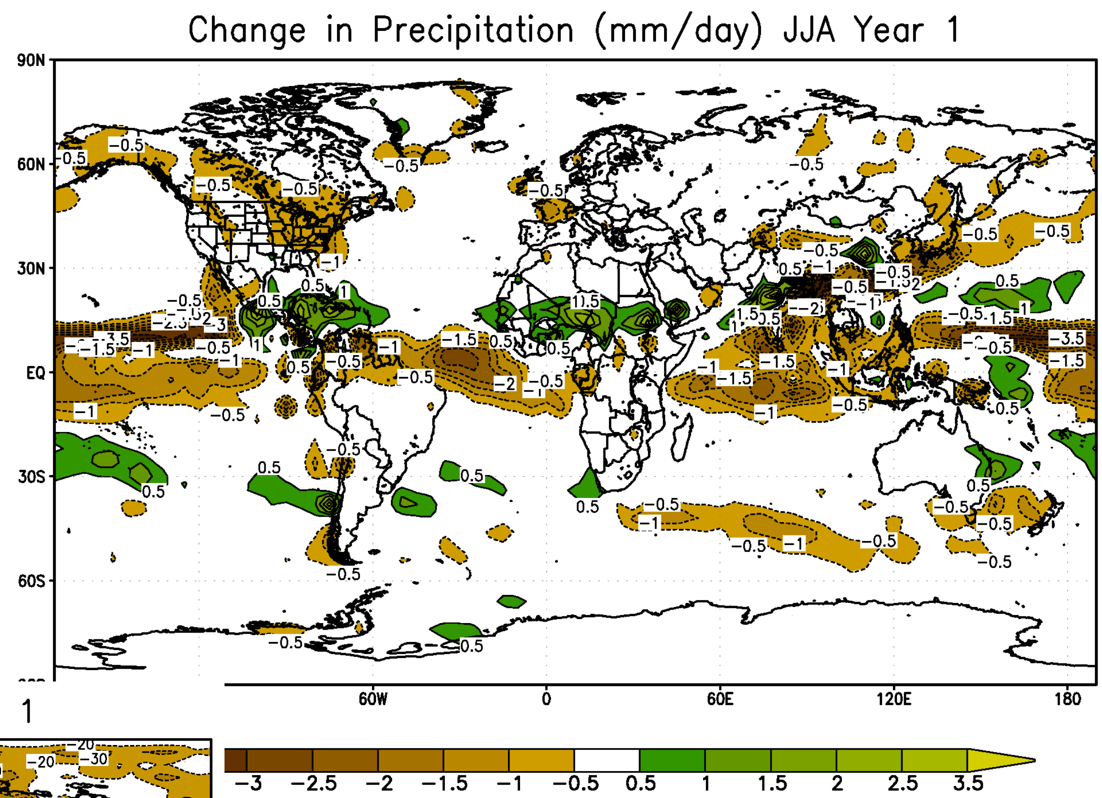
Again, we see warming surrounding Antarctica

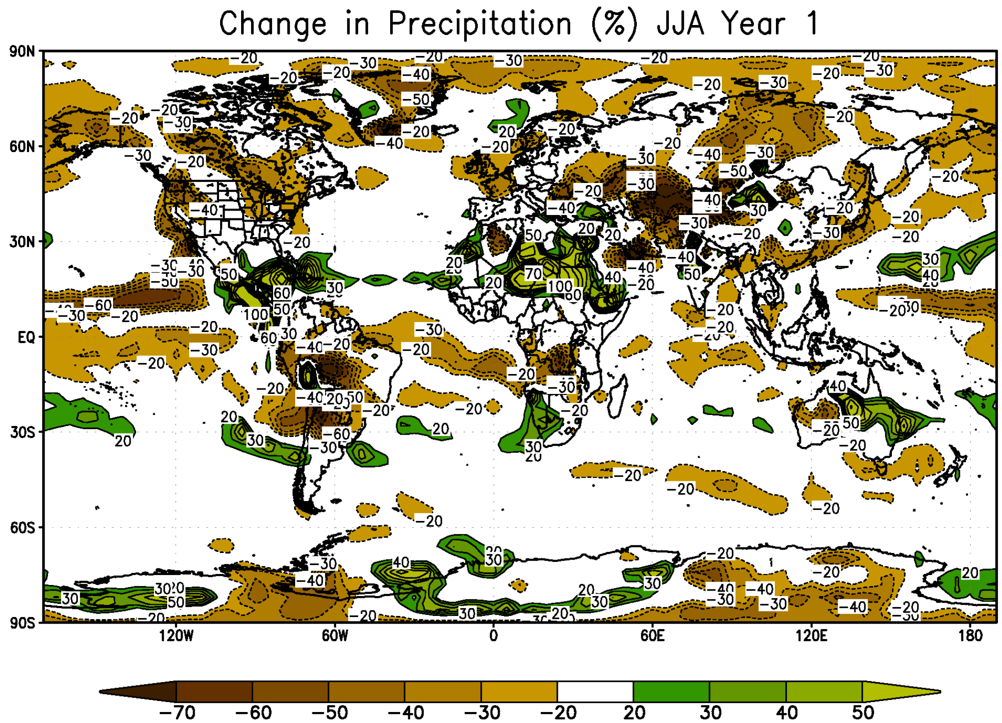
Weaker westerly winds at the surface produce a weaker oceanic circumpolar current and reduced upwelling

Large changes in precipitation are likely this example shows JJA about 1 year after injection.

Changes seem consistent with a weakening of the Hadley Cell circulation.

(mm/day) →





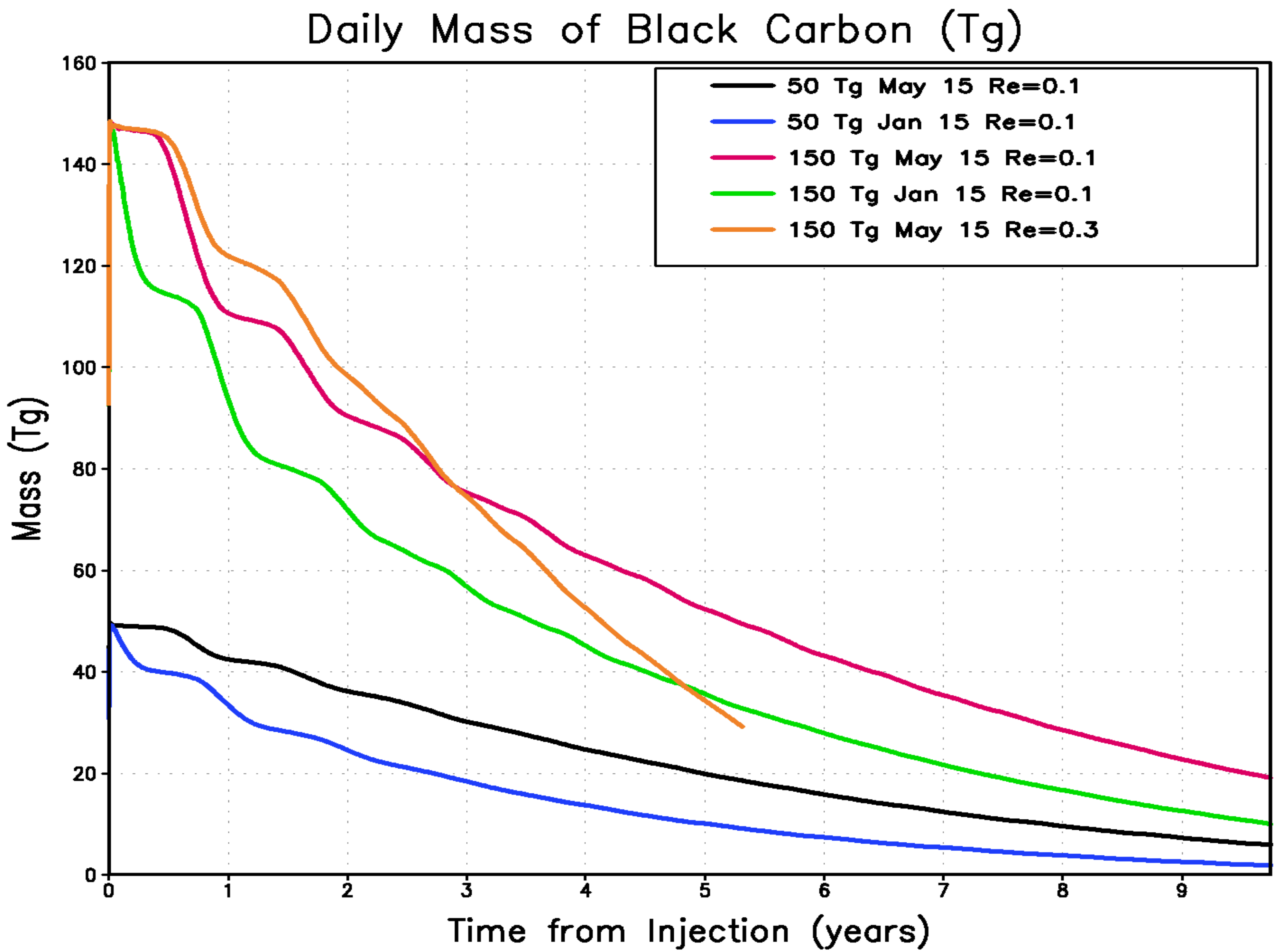
← (% change)

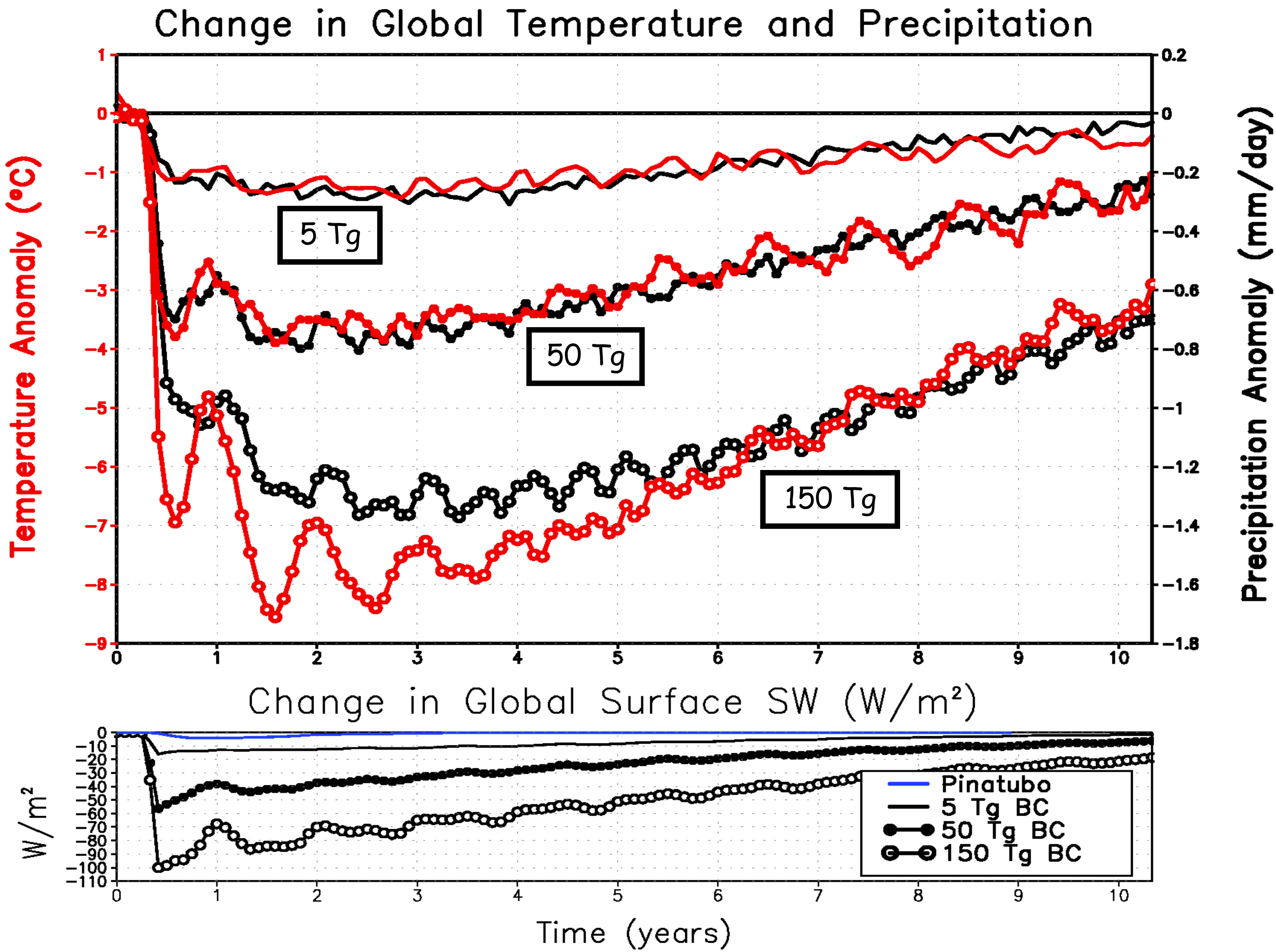
What would be the consequences of a full-scale nuclear war using the entire global arsenal?

This would be the same as the standard nuclear winter scenario of 20 years ago, and would produce 150 Tg of smoke, put into the atmosphere in the midlatitudes of the Northern Hemisphere.

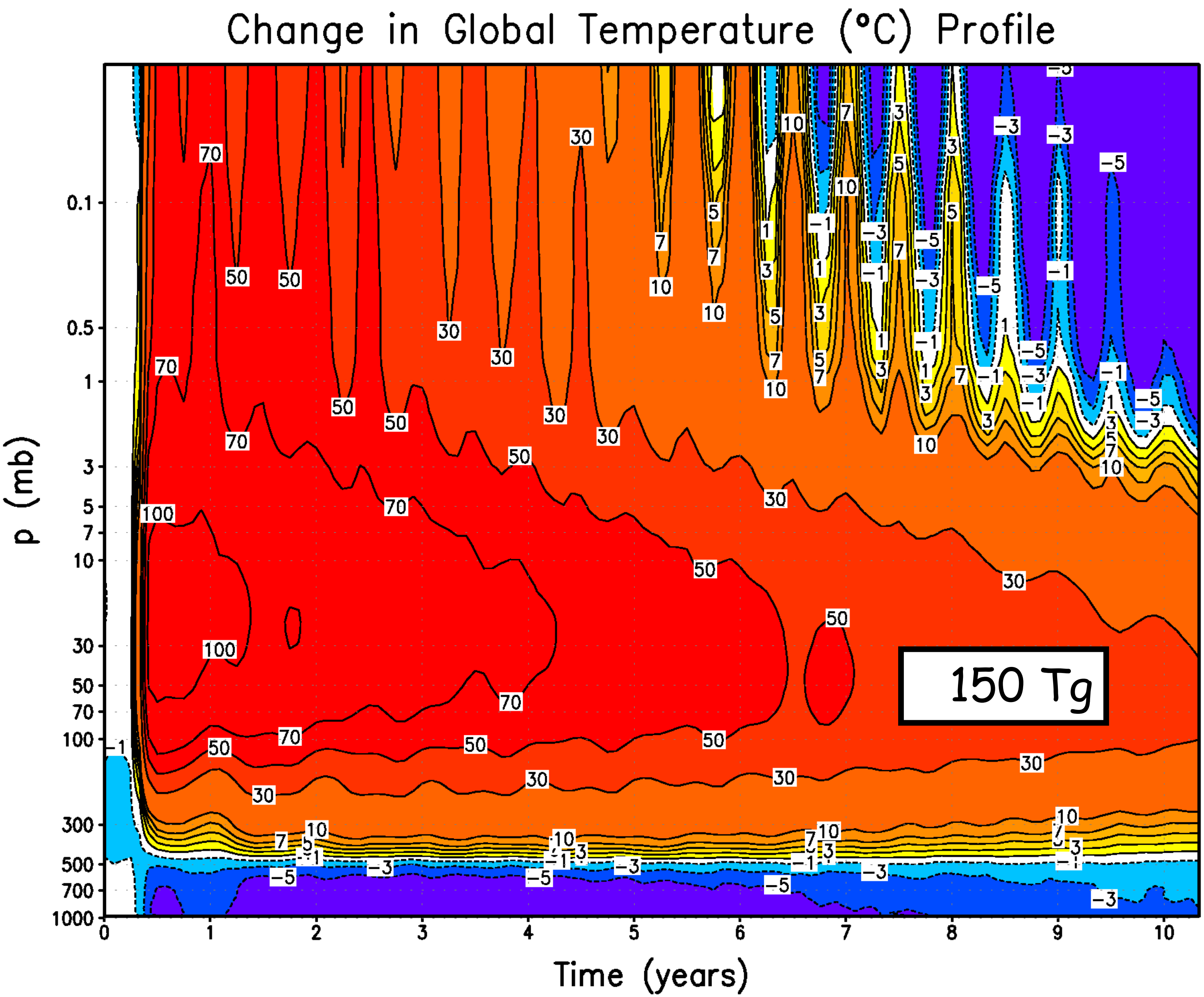
We again use the NASA GISS ModelE AOGCM.

- 150 Tg of smoke into the 300-150 mb layer (upper troposphere) over the US and Russia starting on May 15
- Also, a 50 Tg of smoke case was simulated
- 30-yr control run
- 1 10-yr calculation for each case
- BC optical properties – MEC 5.5 m^2/g and MAC 2 m^2/g
  SSA 0.64 and 0.1 μm radius

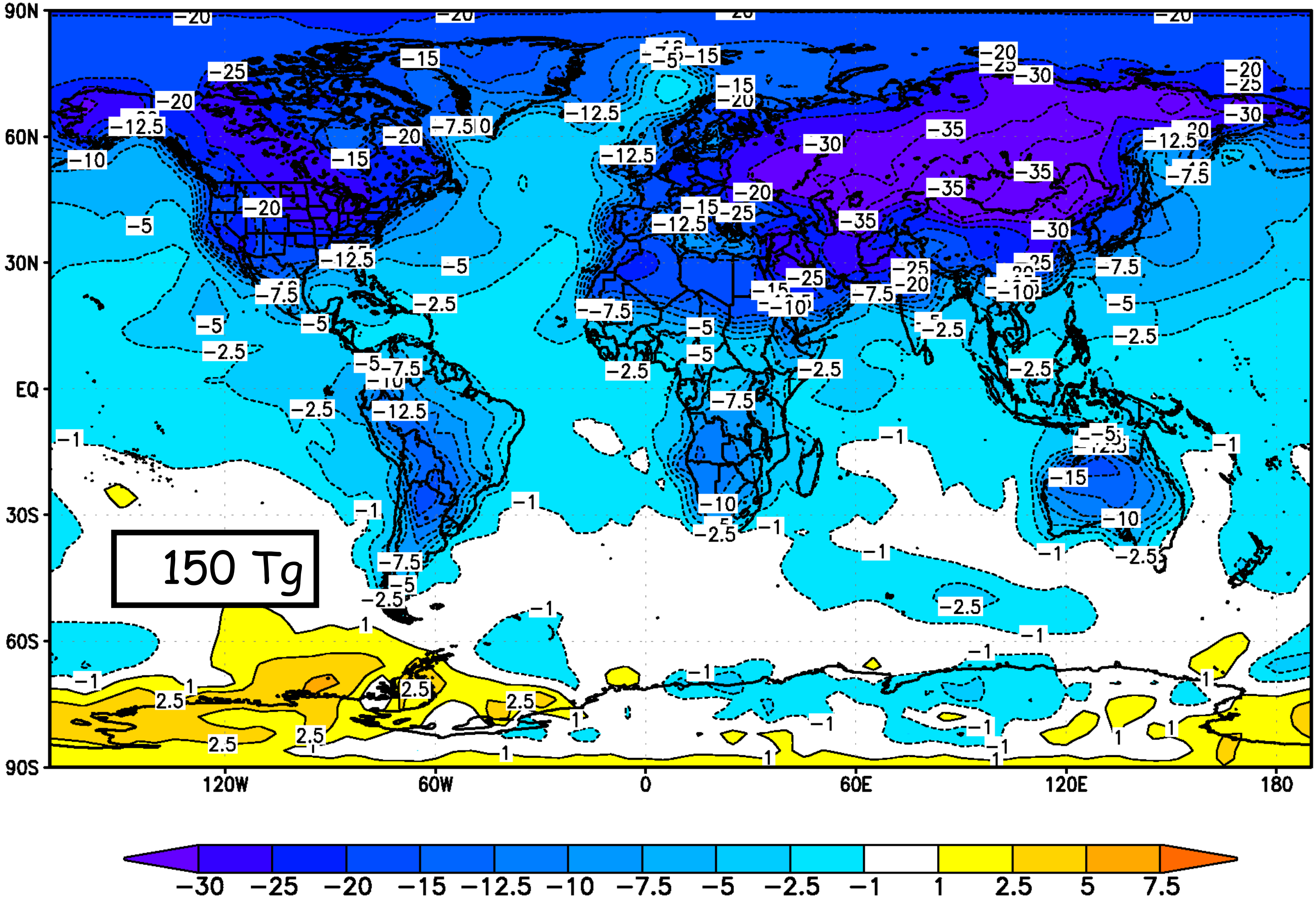

Daily Mass of Black Carbon (Tg)
50 Tg May 15 Re=0.1
50 Tg Jan 15 Re=0.1
150 Tg May 15 Re=0.1
150 Tg Jan 15 Re=0.1
150 Tg May 15 Re=0.3
Mass (Tg)
0
20
40
60
80
100
120
140
160
0
1
2
3
4
5
6
7
8
9
Time from Injection (years)



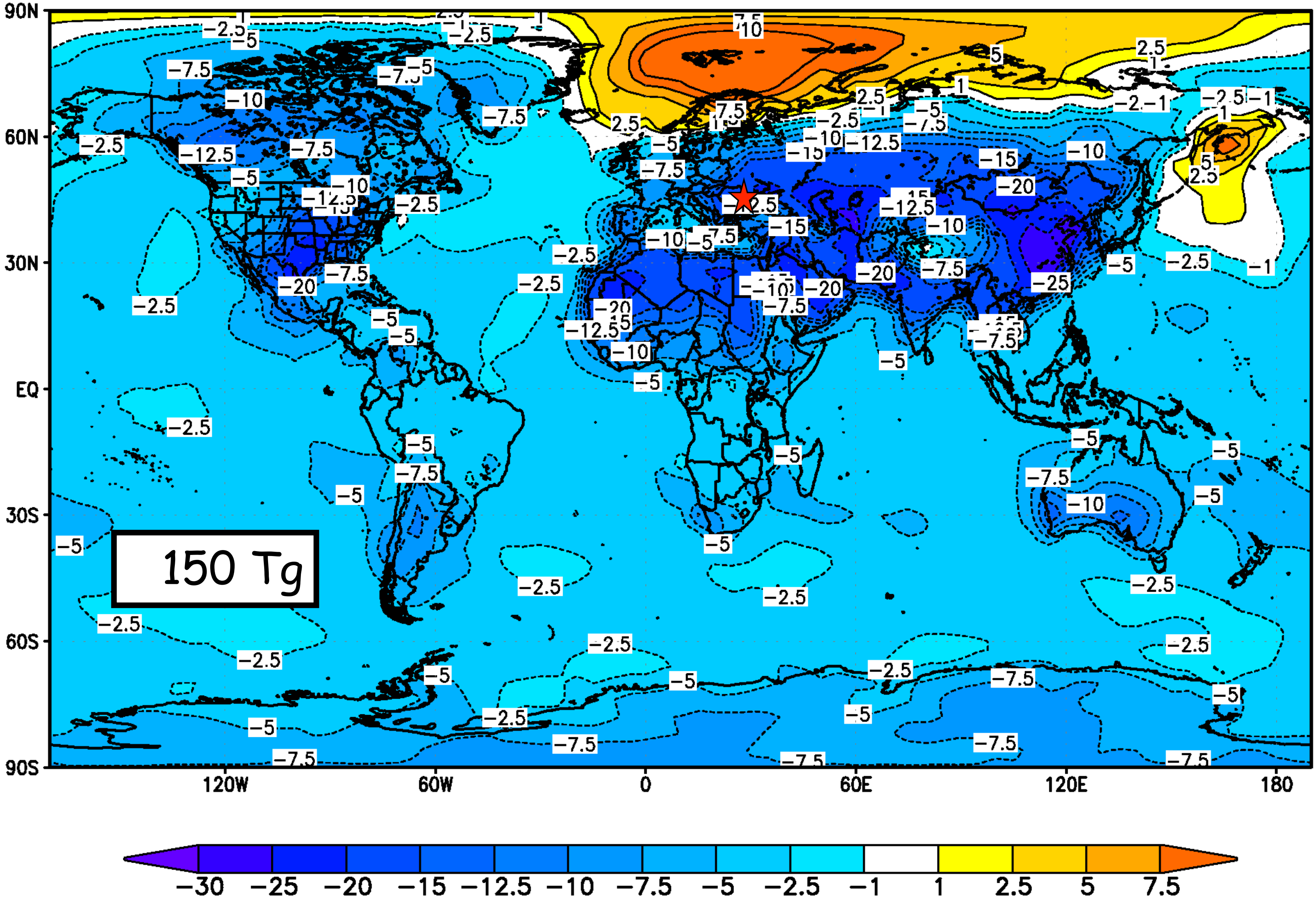
Change in Global Temperature and Precipitation
Temperature Anomaly (°C)
Precipitation Anomaly (mm/day)
5 Tg
50 Tg
150 Tg
Change in Global Surface SW (W/m²)
W/m²
Pinatubo
5 Tg BC
50 Tg BC
150 Tg BC
Time (years)

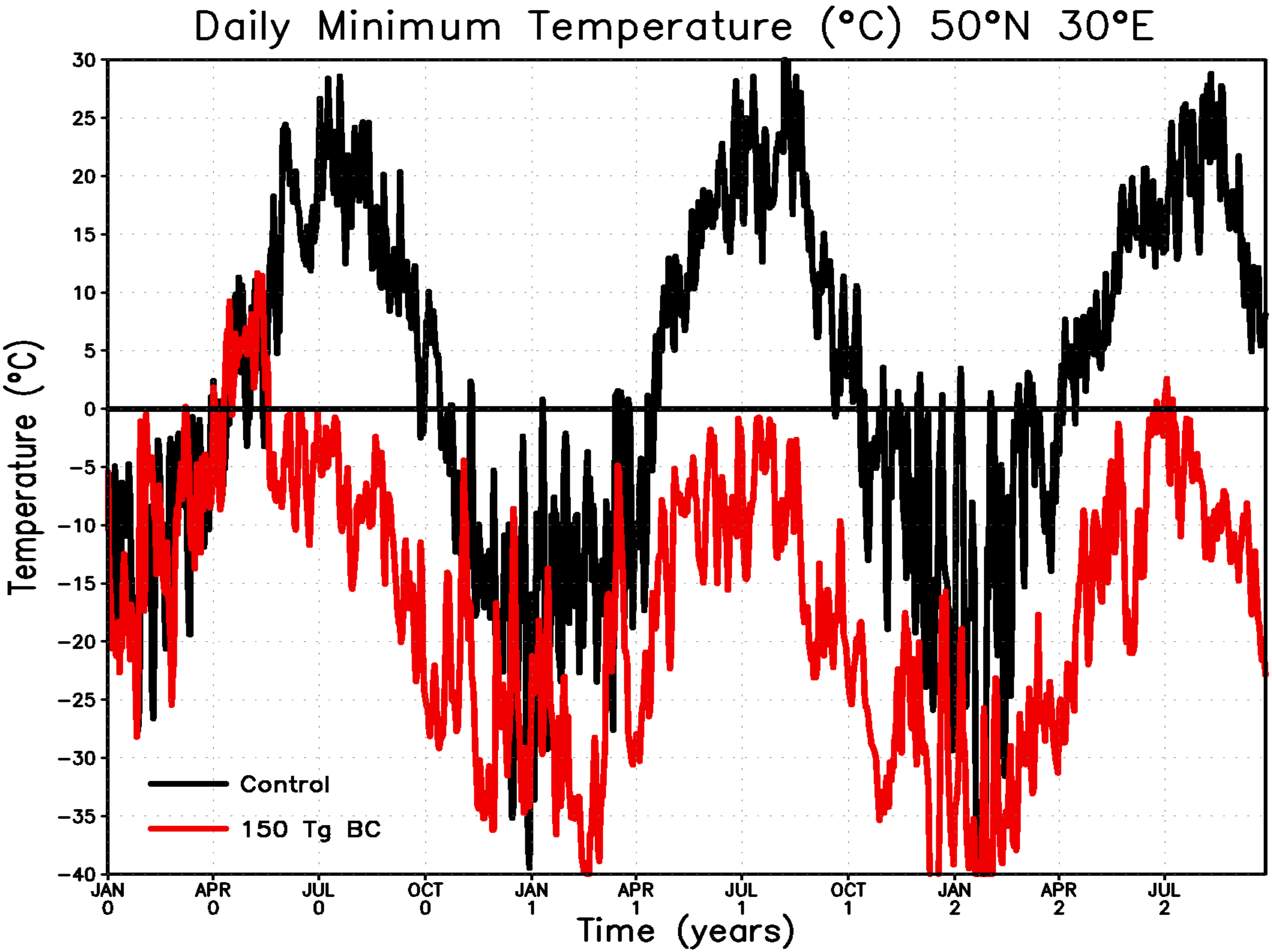

Change in Global Temperature (°C) Profile
p (mb)
Time (years)
150 Tg

Change in SAT (°C) JJA Year 0

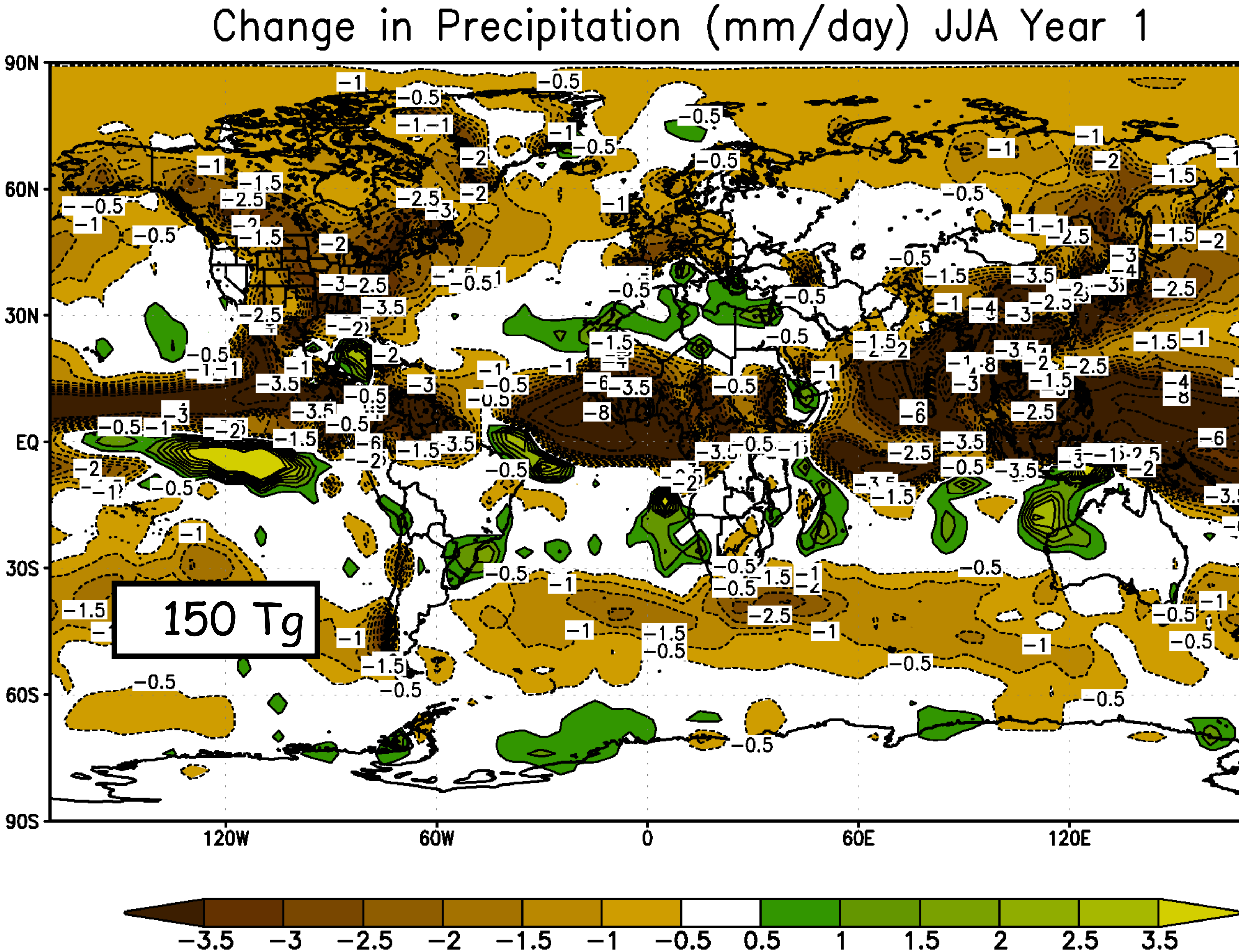


Change in SAT (°C) DJF Year 0-1





Daily Minimum Temperature (°C) 50°N 30°E
Temperature (°C)
30
25
20
15
10
5
0
−5
−10
−15
−20
−25
−30
−35
−40
Control
150 Tg BC
JAN 0
APR 0
JUL 0
OCT 0
JAN 1
APR 1
JUL 1
OCT 1
JAN 2
APR 2
JUL 2
Time (years)



Change in Precipitation (mm/day) JJA Year 1
90N
60N
30N
EQ
30S
60S
90S
120W
60W
0
60E
120E
180
150 Tg
−3.5
−3
−2.5
−2
−1.5
−1
−0.5
0.5
1
1.5
2
2.5
3.5

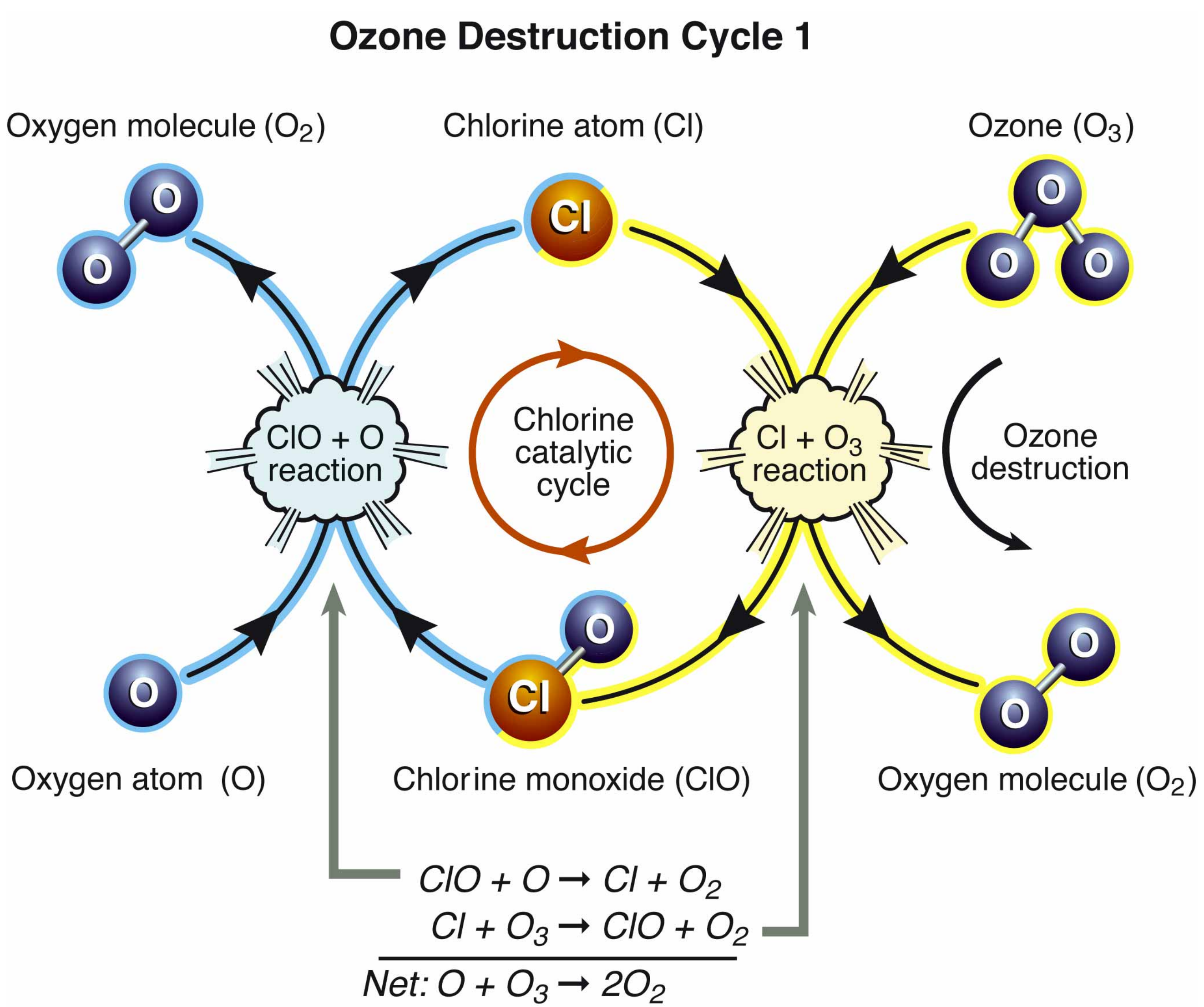
The World Avoided
What would have happened to our atmosphere if CFCs had not been regulated?

Work done in collaboration with Paul Newman and others in Code 614

Why do a simulation like this?

- Accountability: Scientists predicted massive ozone losses, actions were taken, and losses were mitigated. Do the state-of-the-art models justify the claimed large losses?
- Provides a reasonable baseline for assessing the impact of international agreements on ozone, UV impacts, and climate change
- Gives an indication of unforeseen impacts on atmosphere of large ozone losses
- Provides an extreme condition test for the models - pushing to an extreme oftentimes uncovers subtle problems

Chlorine Catalytic Destruction



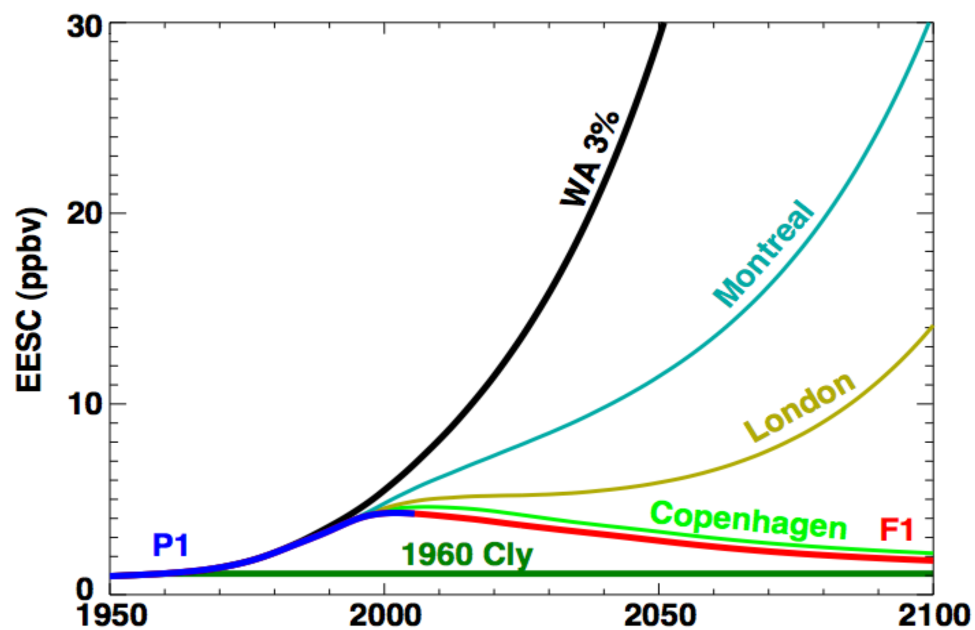
We use the NASA Goddard Earth Observing System (GEOS) Chemistry Climate Model (CCM)

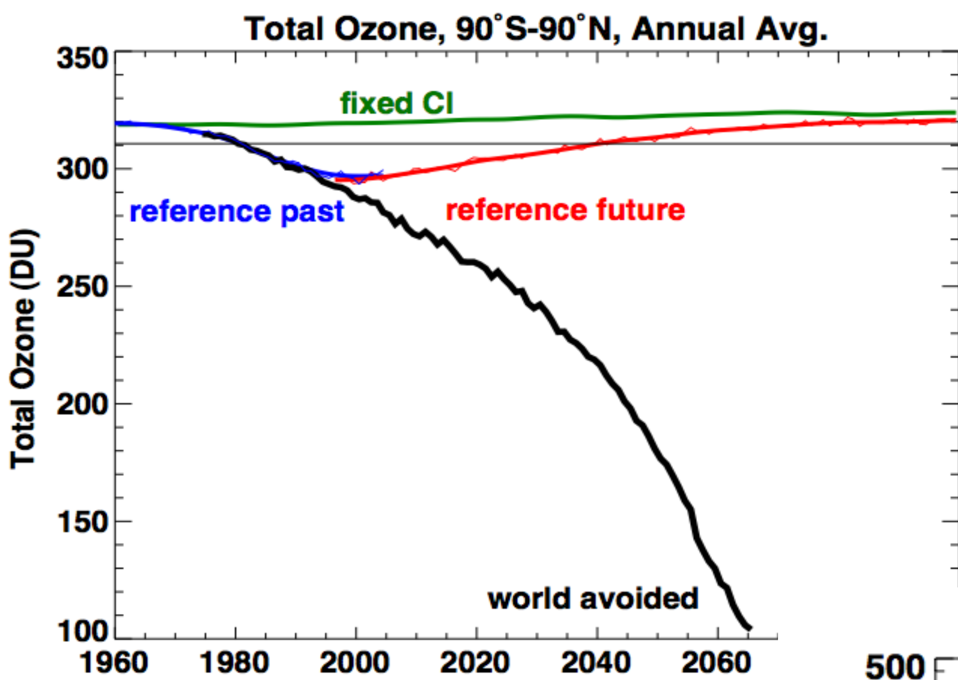
- 2°x2.5° horizontal resolution and 72 vertical levels
- Used NMR74 scenario which is a 3% per yr increase in halogens
- Interactive Stratospheric Chemistry
- Simulation run from 1974 to 2075

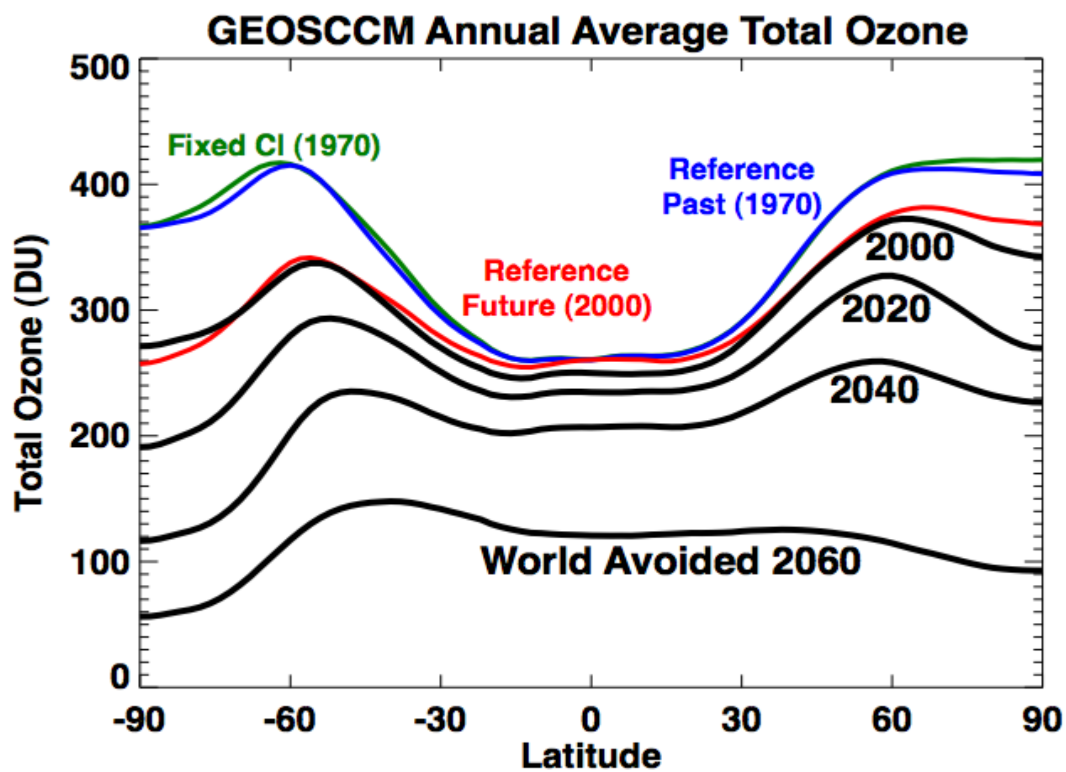
EESC = Effective Equivalent Stratospheric Chlorine

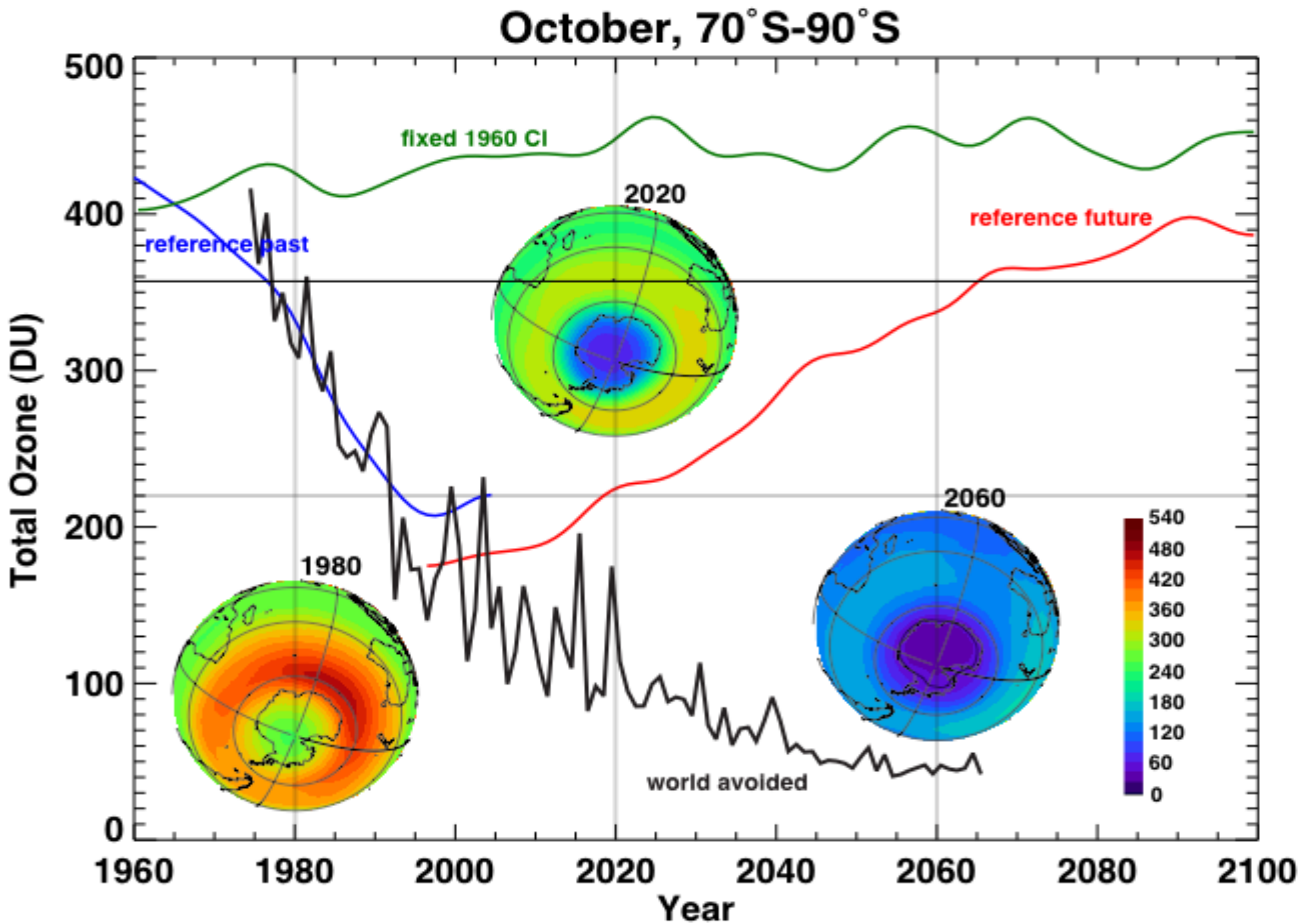
Takes into account both Chlorine and Bromine

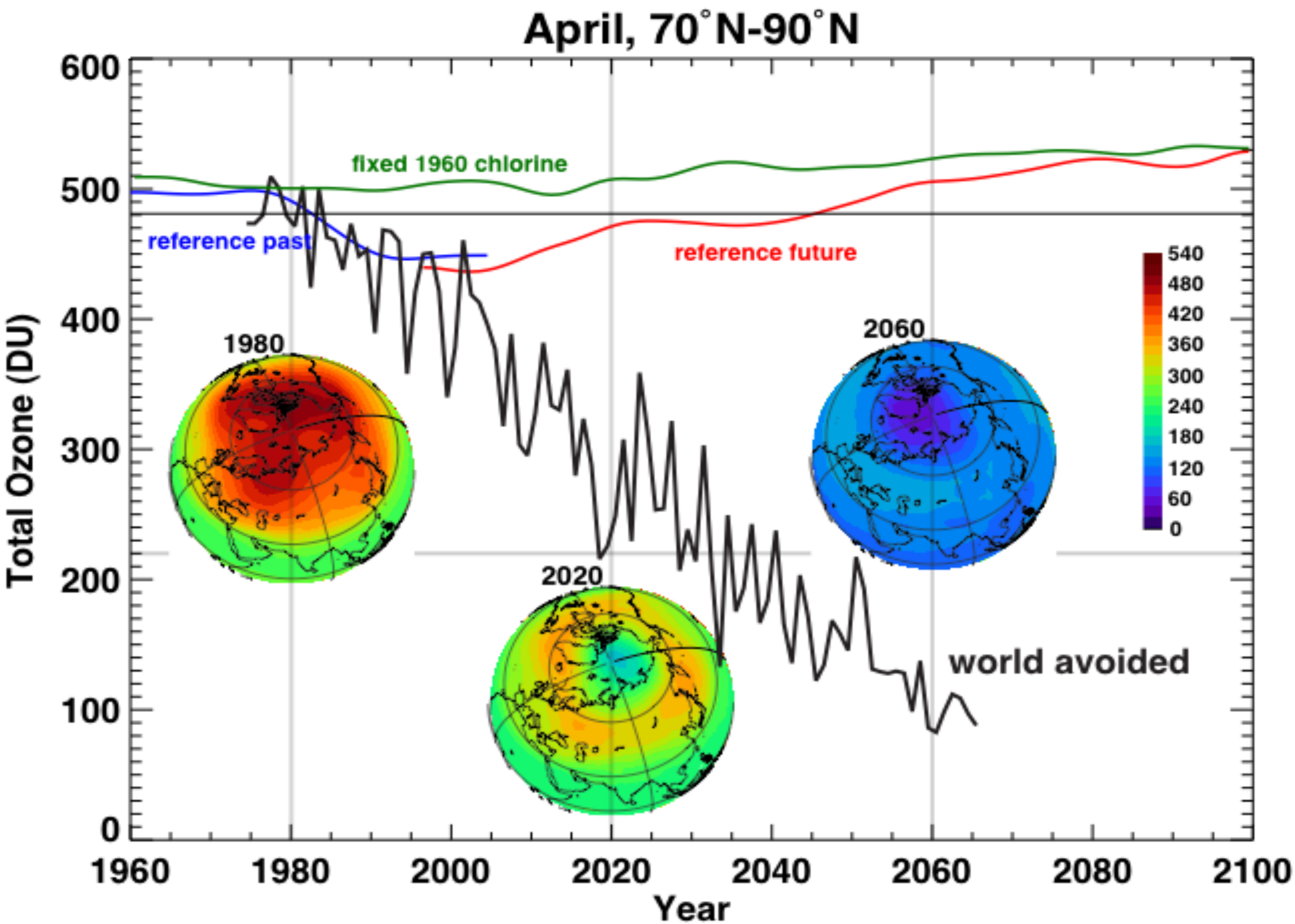
Halogen Scenarios




Total Ozone, 90˚S-90˚N, Annual Avg.
Total Ozone (DU)
350
300
250
200
150
100
1960
1980
2000
2020
2040
2060
fixed Cl
reference past
reference future
world avoided


GEOSCCM Annual Average Total Ozone
Total Ozone (DU)
500
400
300
200
100
0
-90
-60
-30
0
30
60
90
Latitude
Fixed Cl (1970)
Reference
Past (1970)
Reference
Future (2000)
2000
2020
2040
World Avoided 2060

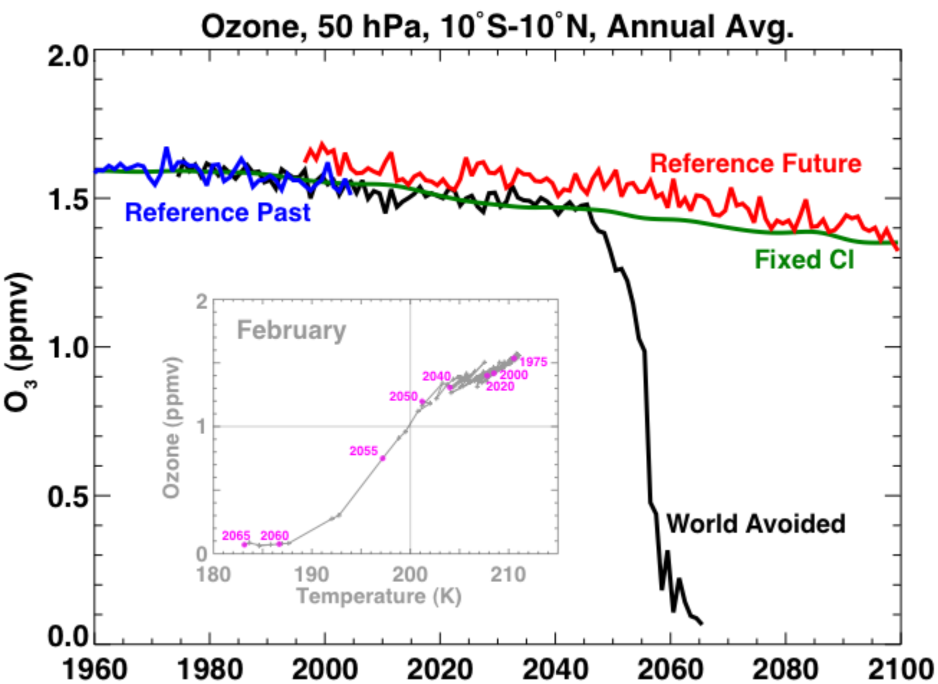

October, 70˚S-90˚S
500
400
300
200
100
0
Total Ozone (DU)
1960
1980
2000
2020
2040
2060
2080
2100
Year
fixed 1960 Cl
reference past
reference future
world avoided
1980
2020
2060
540
480
420
360
300
240
180
120
60
0

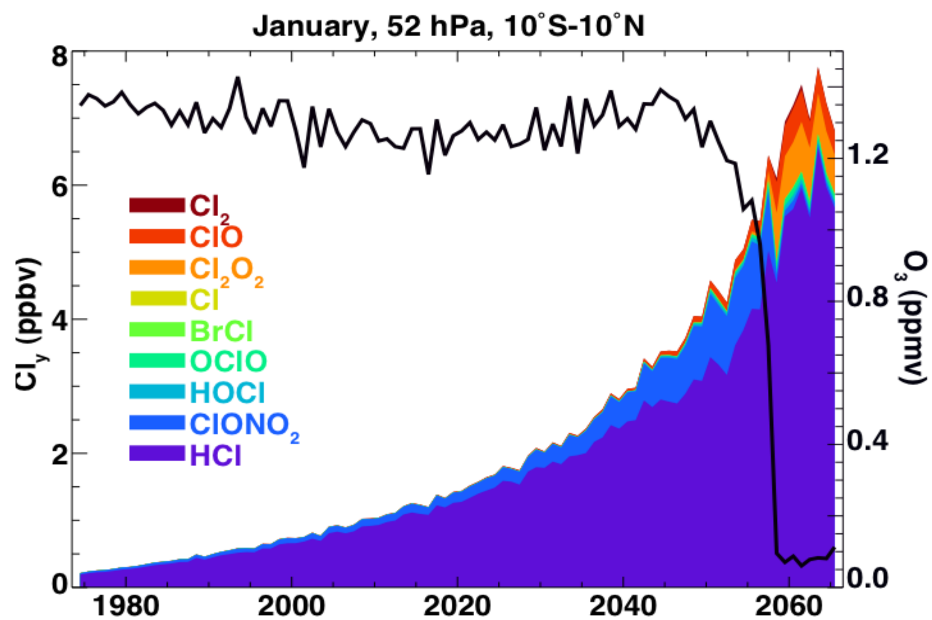

April, 70°N-90°N
Total Ozone (DU)
Year
fixed 1960 chlorine
reference past
reference future
world avoided
1980
2020
2060
540
480
420
360
300
240
180
120
60
0
600
500
400
300
200
100
0
1960
1980
2000
2020
2040
2060
2080
2100

Tropical Collapse of Lower Stratospheric Ozone

Polar-type stratospheric chemistry starts to occur in the tropics.

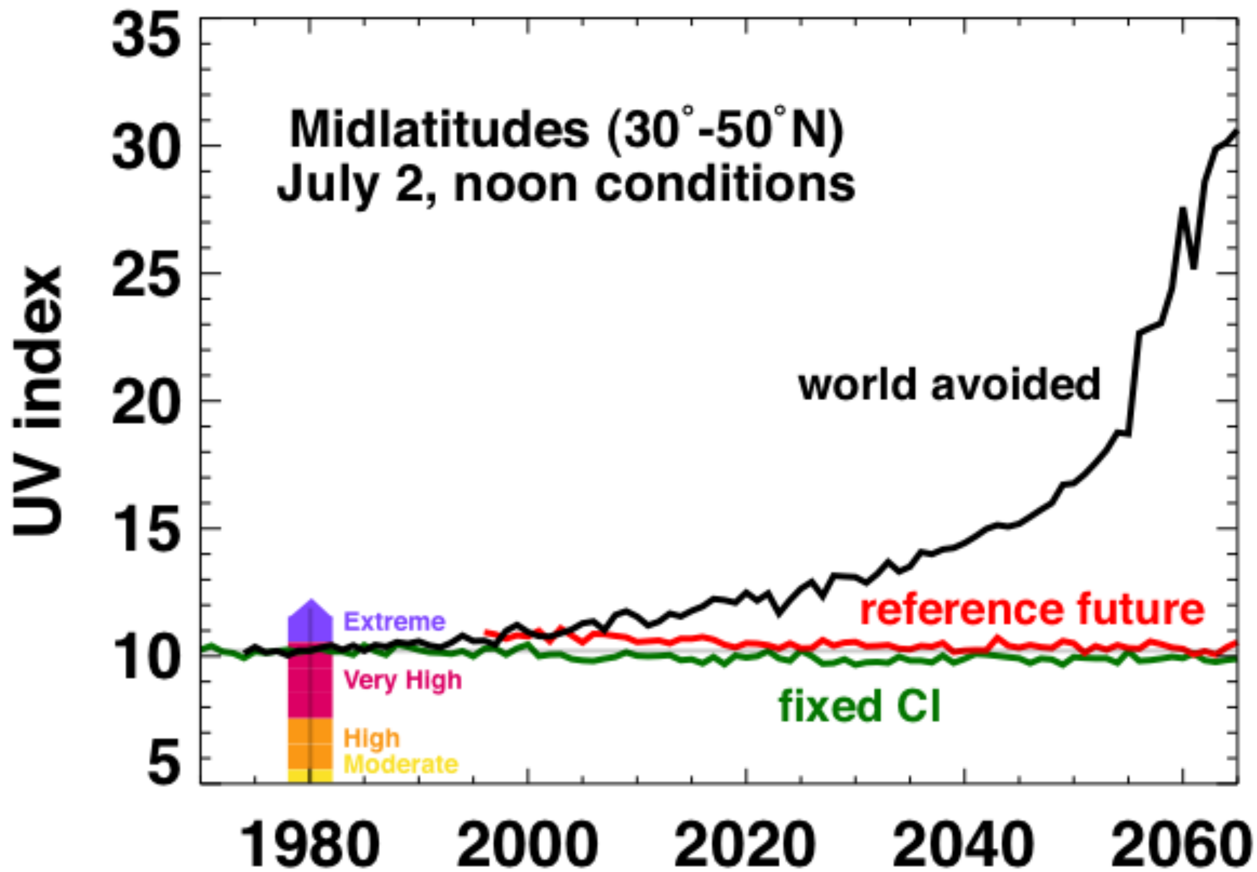
In the mid 2050s tropical lower stratospheric ozone drops to near zero.





Very Large Increase in Ultraviolet Radiation Reaching the Surface

Sunburn could occur within minutes of exposure



Summary

Extreme forcings of the Climate System can be useful on several levels

•Learn new things about the climate system
Strat. H_2O increase and eq. superrotation from **Super Eruptions**
Strong self lofting of BC from massive fires in a **Nuclear Conflict**
Possible tropical ozone collapse from high CFC's in the **World Avoided**

• Revisiting older problems with new more comprehensive models
Nuclear Winter

•To test paths not taken because of some action for accountability
World Avoided

Papers Published on this work

Robock, A., C. M. Ammann, L. Oman, D. Shindell, S. Levis, and G. Stenchikov, 2009: Did the Toba volcanic eruption of ~74k BP produce widespread glaciation? *J. Geophys. Res.*, 114, doi: 10.1029/2008JD011652.

Zhu, X., L. D. Oman, D. W. Waugh, and S. A. Lloyd, 2010: Equatorial Superrotation on Earth Induced by Optically Thick Dust Clouds, *Johns Hopkins APL Technical Digest*, 28, 3, 240-241.

Robock, A., L. Oman, G. L. Stenchikov, O. B. Toon, C. Bardeen, and R. P. Turco, 2007: Climatic consequences of regional nuclear conflicts. *Atm. Chem. Phys.*, 7, 2003-2012.

Robock, A., L. Oman, and G. L. Stenchikov, 2007: Nuclear winter revisited with a modern climate model and current nuclear arsenals: Still catastrophic consequences. *J. Geophys. Res.*, 112, D13107, doi: 10.1029/2006JD008235.

Toon, O. B., A. Robock, R. P. Turco, C. Bardeen, L. Oman, and G. L. Stenchikov, 2007: Consequences of regional-scale nuclear conflicts. *Science*, 315, 1224-1225.

Toon, O. B., R. P. Turco, A. Robock, C. Bardeen, L. Oman, and G. L. Stenchikov, 2007: Atmospheric effects and societal consequences of regional scale nuclear conflicts and acts of individual nuclear terrorism. *Atm. Chem. Phys.*, 7, 1973-2002.

Robock, A., O. B. Toon, R. P. Turco, L. Oman, G. L. Stenchikov, and C. Bardeen, 2007: The continuing environmental threat of nuclear weapons: Integrated policy responses needed. *EOS*, 88, 228, 231, doi: 10.1029/2007ES001816.

Newman, P. A., L. D. Oman, A. R. Douglass, E. L. Fleming, S. M. Frith, M. M. Hurwitz, S. R. Kawa, C. H. Jackman, N. A. Krotkov, E. R. Nash, J. E. Nielsen, S. Pawson, R. S. Stolarski, and G. J. M. Velders, 2009: What would have happened to the ozone layer if chlorofluorocarbons (CFCs) had not been regulated?, *Atmos. Chem. Phys.*, 9, 2113-2128.