Ozone Recovery: Impact of Carbon Dioxide and Nitrous Oxide

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GEOS CCM

The Goddard Chemistry Climate Model (GEOS CCM)

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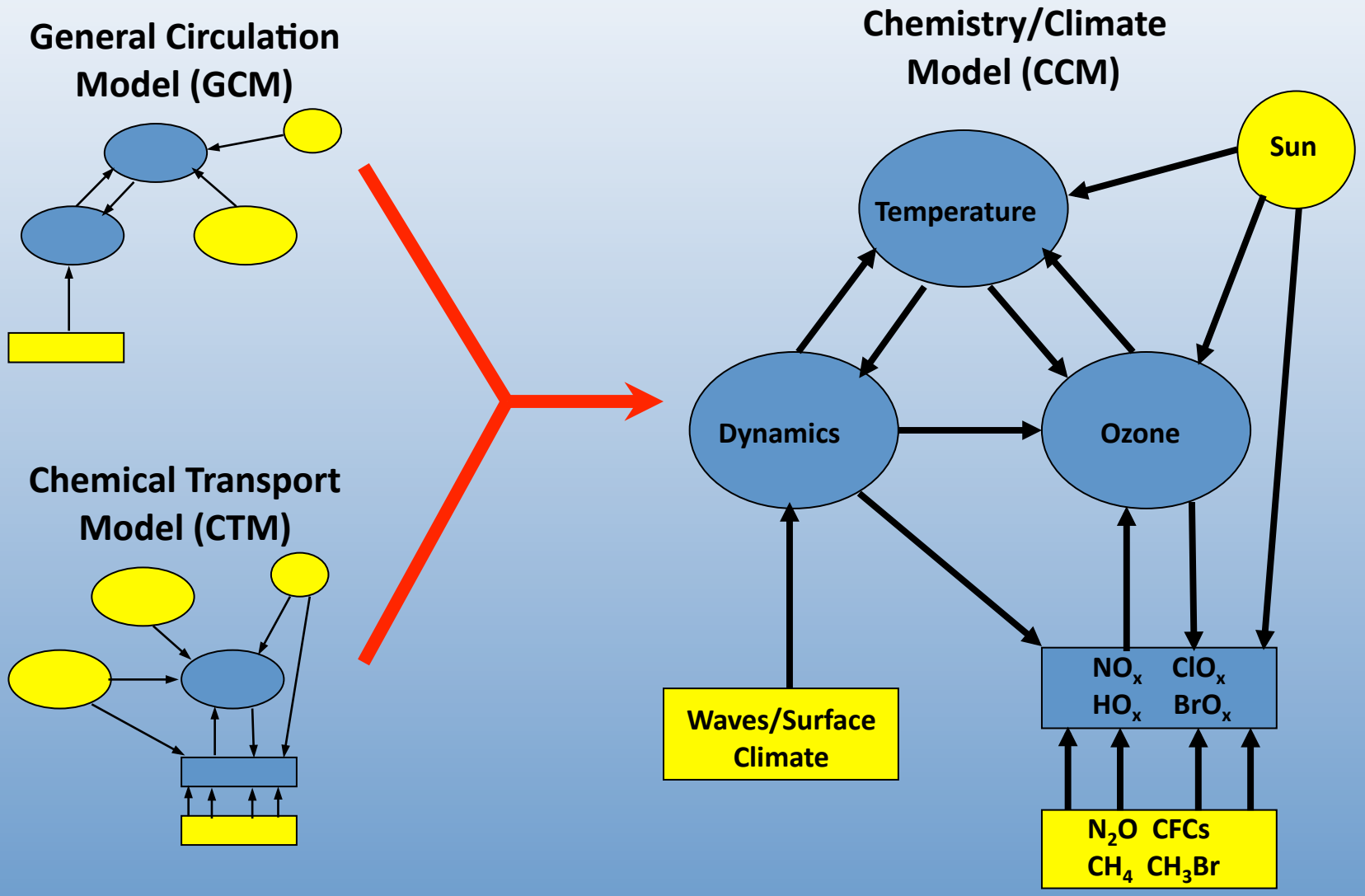
A joint project of the Goddard Atmospheric Chemistry and Dynamics Branch (ACDB) and the Global Modeling and Assimilation Office (GMAO)

We combine the atmospheric chemistry of the Goddard CTM and the GMI CTM with the atmospheric general circulation model(s) of GMAO into a coupled chemistry climate model

Funded by the NASA Modeling and Analysis Program (MAP)

Stratospheric Ozone/Chemistry/Climate System



What is GEOS CCM?

The GEOS CCM is a combination of the GEOS 4 or 5 AGCM and the stratospheric chemistry transport module from the Goddard CTM (Stratchem) or the GMI Combined troposphere-stratosphere CTM (Combo).

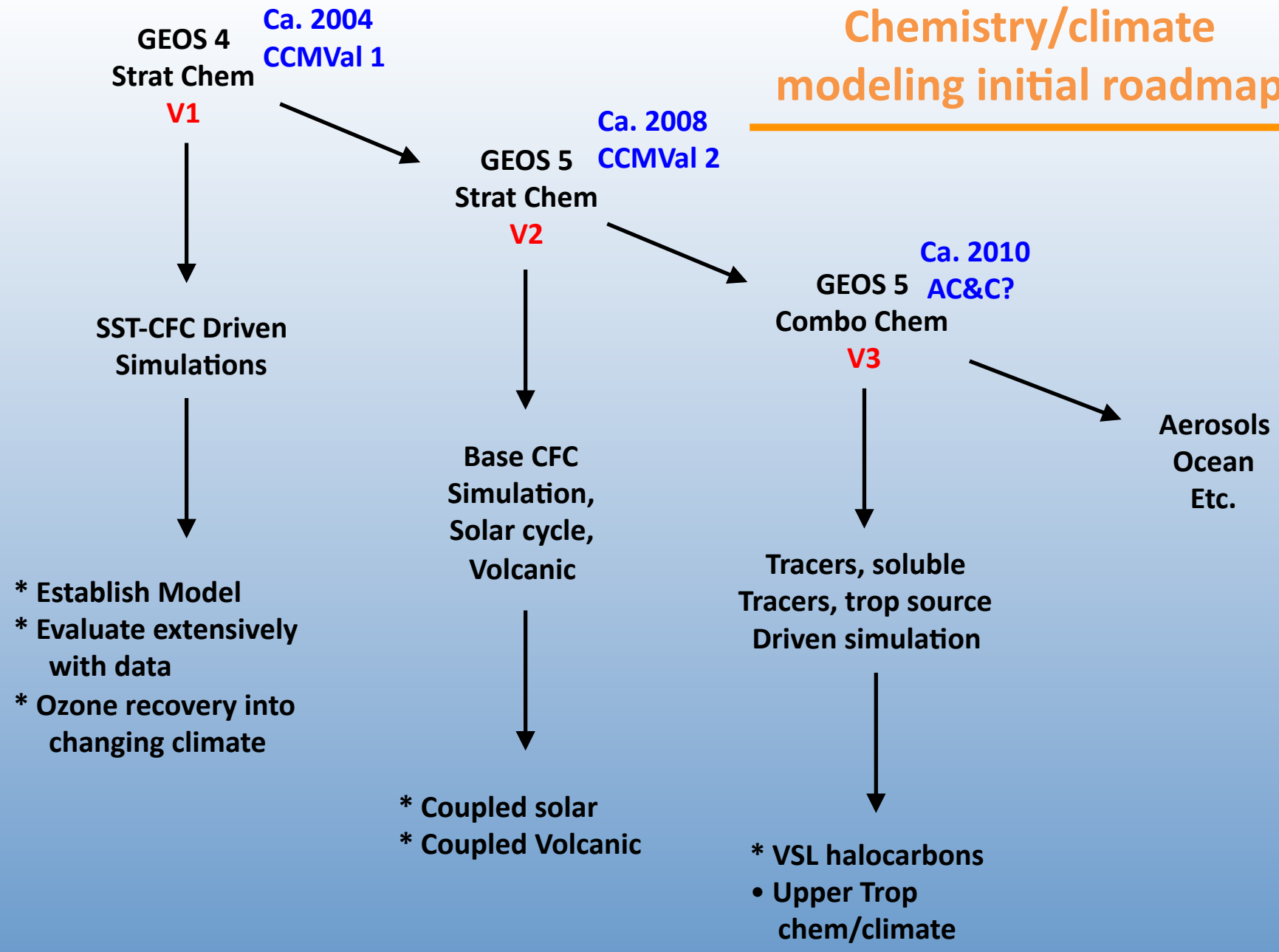
We have three versions in current use that are described below:

Version 1: GEOS 4 AGCM plus Stratchem
Version 2: GEOS 5 AGCM plus Stratchem
Version 3: GEOS 5 AGCM plus Combo chem

A version with Stratchem and the GOCART aerosol model is being tested for application to volcanic aerosols.

A future version is planned incorporating the GEOS 5 ocean-atmosphere GCM that is currently being tested by GMAO.

Chemistry/climate modeling initial roadmap

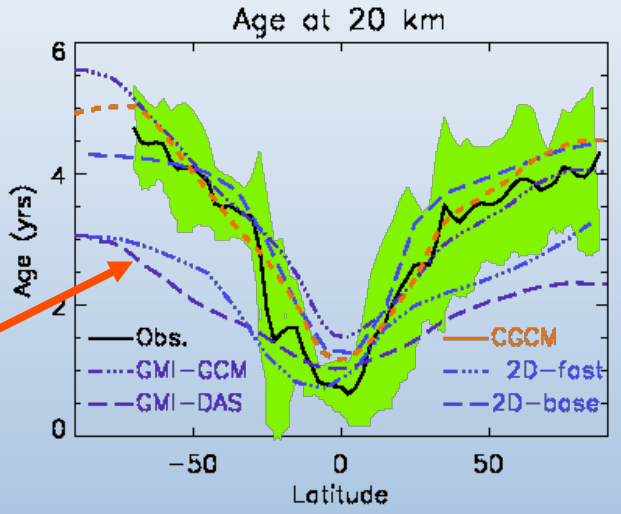


Some important aspects of the development of GEOSCCM

- CTMS and GCMs historically tended to have "fast" circulations and subsequent "young" age-of-air
- Compact tracer-tracer relationships were discovered in aircraft measurement campaigns; models had difficulty reproducing these relationships
- The development of finite-volume dynamical core (Lin and Rood, MWR, 1996) was developed to address tracer-tracer issue
- When applied to the dynamical core and the constituent transport, it solved many problems
  - compact tracer-tracer correlations
  - better balance between overturning circulation and isentropic mixing
  - slower circulation, increased age-of-air
  - better assimilations
  - vortex isolation, etc.

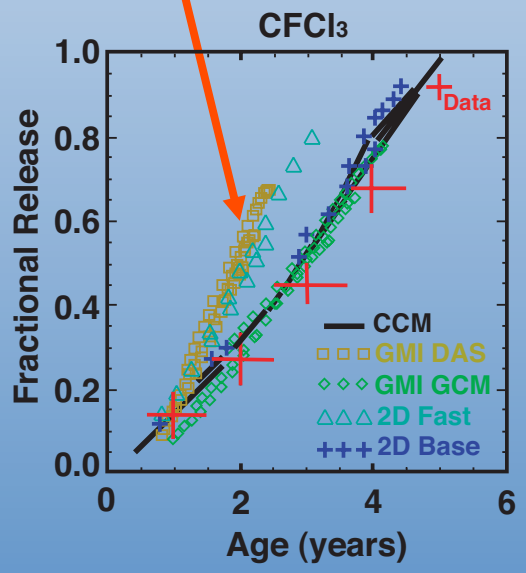
Critical Tests of Model Transport

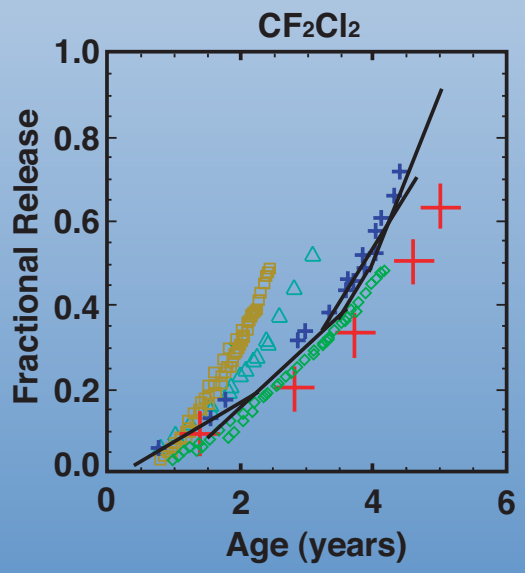
Combined mean age and fractional chlorine release constrain both age and age spectrum. Fast circulation models fail both. Some models may get mean age correct, but fail this fractional release test (Douglass et al. JGR 2009).



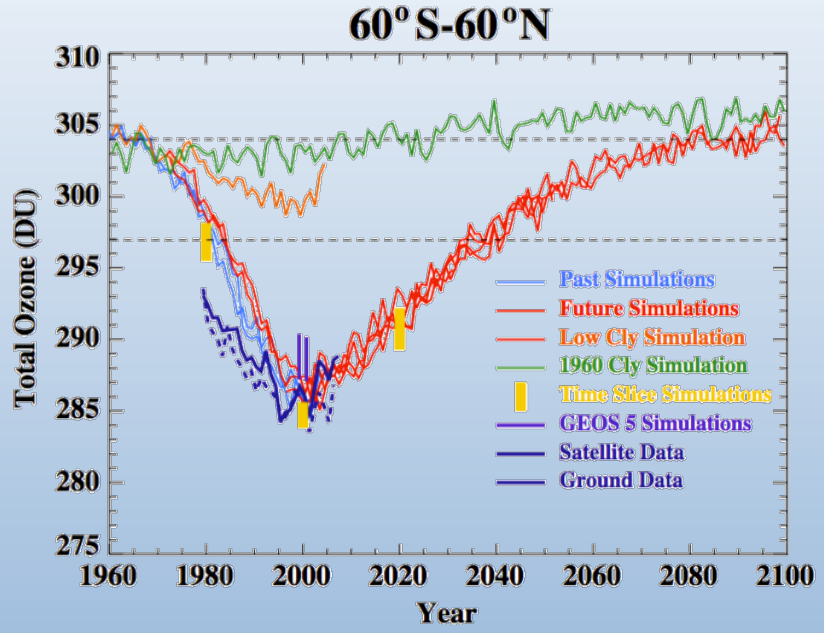
"Fast" circulation

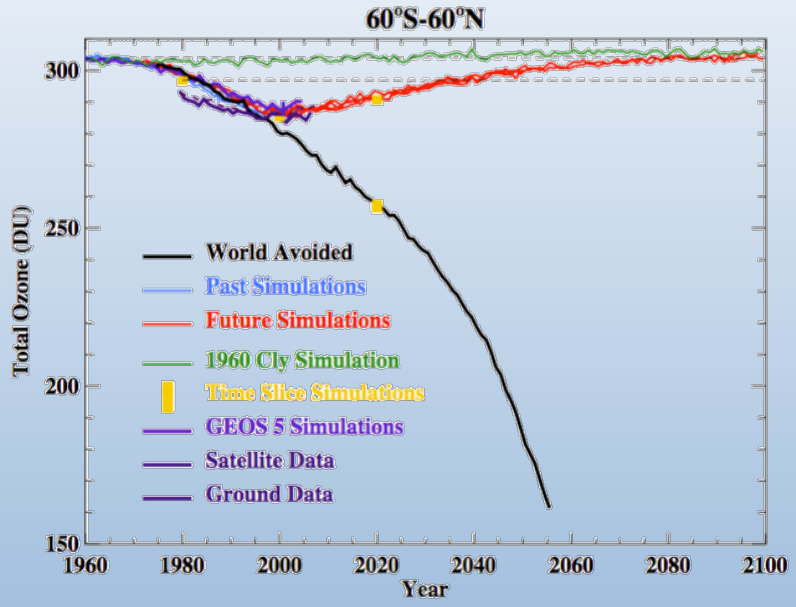
The "fast" circulation models shown are consistent with many of the published lifetimes for CFCs. Models that pass these tests tend to give longer lifetimes (e.g. ~55 years for $CFCl_3$).





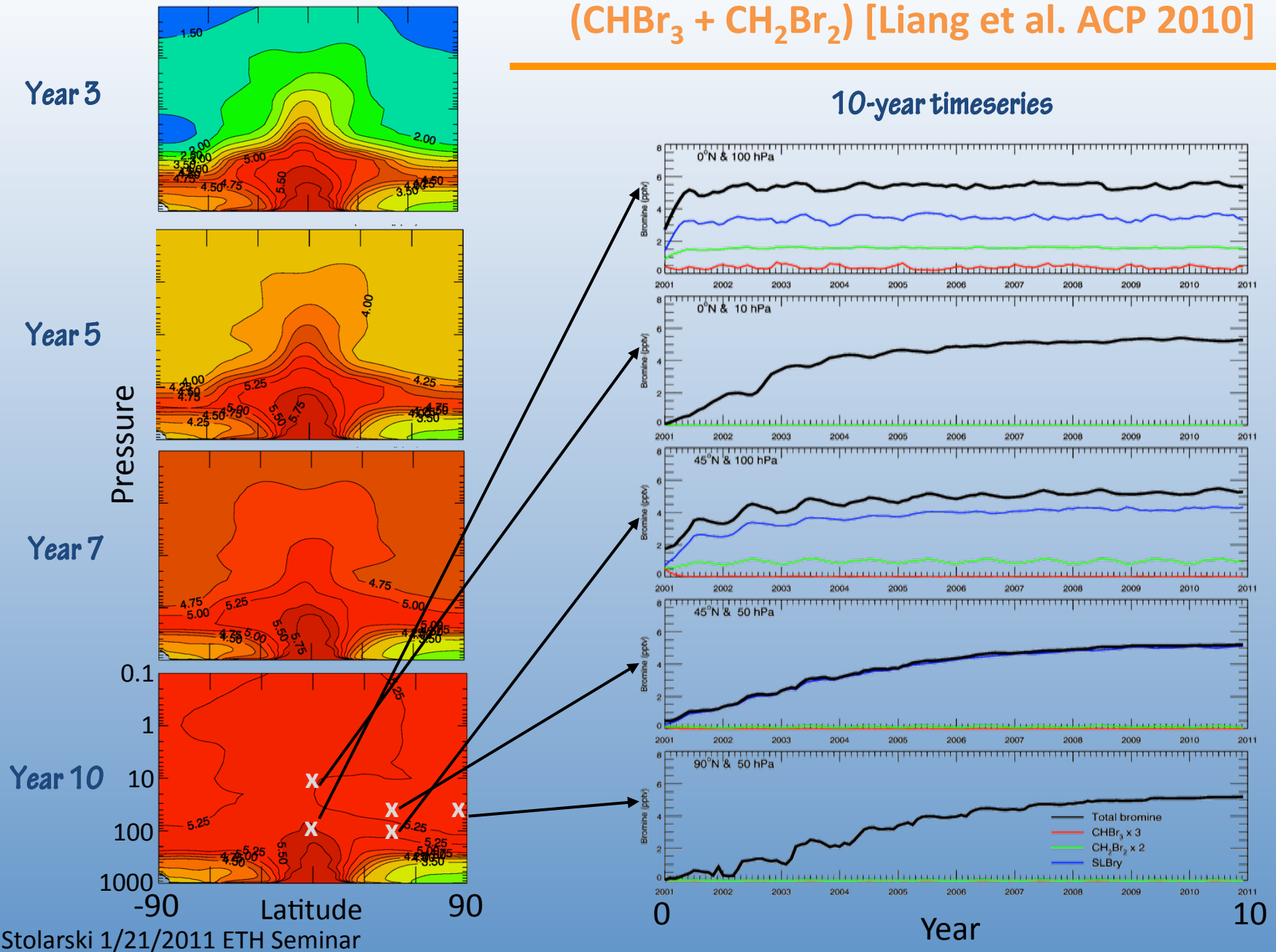
Numerous model simulations designed to separate the impact of various factors on stratospheric chemistry and Ozone





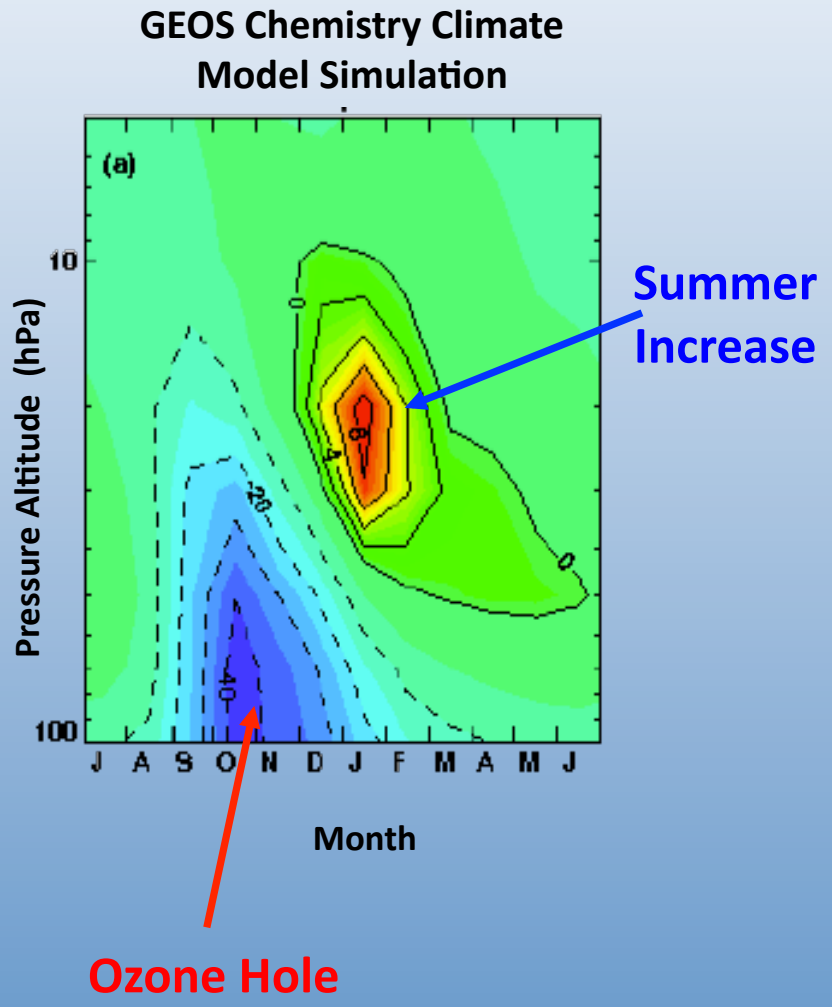
These are simulations with Version 1 of the model (evaluated in CCMVal simulation as reported in Eyring et al. [2006, 2007]. Version 2 has been evaluated in CCMVal 2. More than 1000 years of simulation are shown including a 1960 chlorine (no ODS) simulation extending from 1960 to 2100, and a "World-Avoided" simulation in which chlorine continued to increase to ~40ppbv.

Bromine from short-lived bromocarbons ($CHBr_3$ + CH_2Br_2) [Liang et al. ACP 2010]

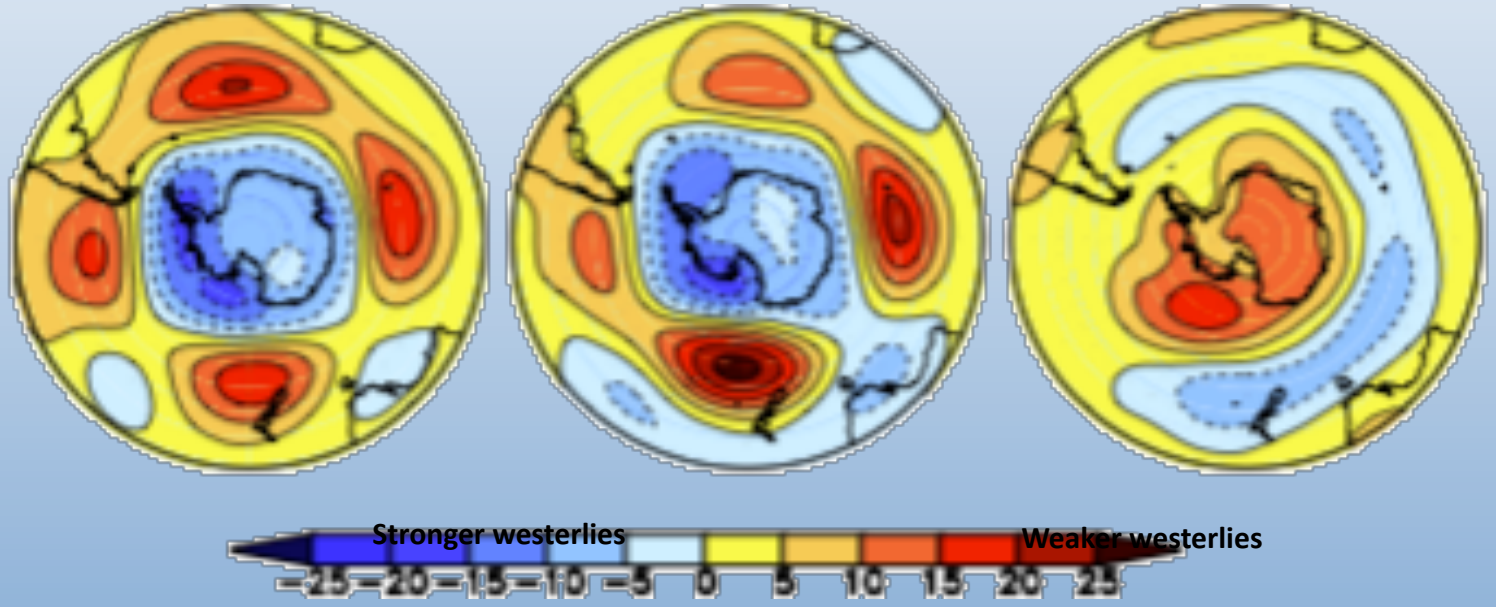


Ozone Increase in the Summertime Antarctic Stratosphere

- Ozone hole forms in the Antarctic Springtime lower stratosphere.
- Coupled chemistry-climate model indicates expected summertime increase in ozone over last 2 decades
- Uncoupled model does not show increase
- 25-year data set from SBUV series of satellites shows increase
- Tests the strength of feedback between ozone and climate in the stratosphere
- Future ozone profile measurements should show a decrease in summertime Antarctic ozone as the ozone hole recovers

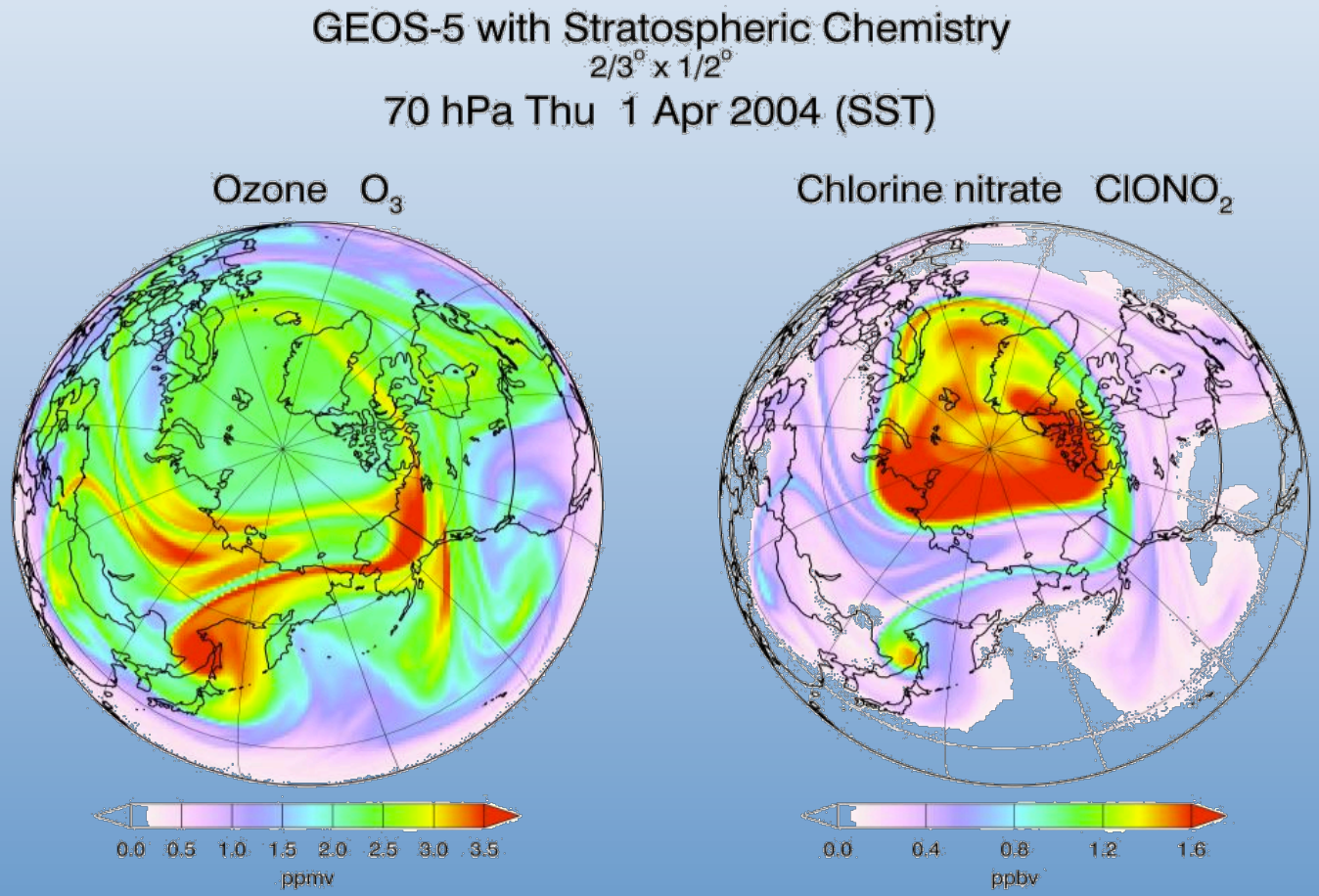


Polar ozone changes have an impact on the Southern Annular Mode



Linear trend (1960-2000) in the 500-hPa Southern Annular Mode in DJF for runs P1 (left), P2 (center) and CFC1960 (right). CFCs are fixed at 1960 values in CFC1960, but grow according to established scenarios in P1 and P2. (from Perlwitz, et al. JGR, 2008)

Version 2 of the model (GEOS 5 + stratchem) has been used in the GMAO forecast system at 2/3 by 1/2 degree resolution for aircraft mission support

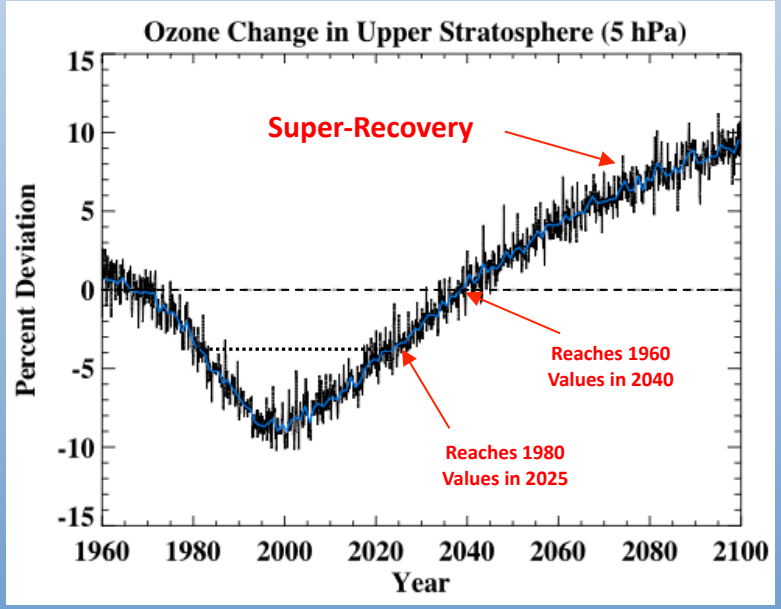


Ozone recovery

"Super-Recovery" of Ozone in the Upper Stratosphere

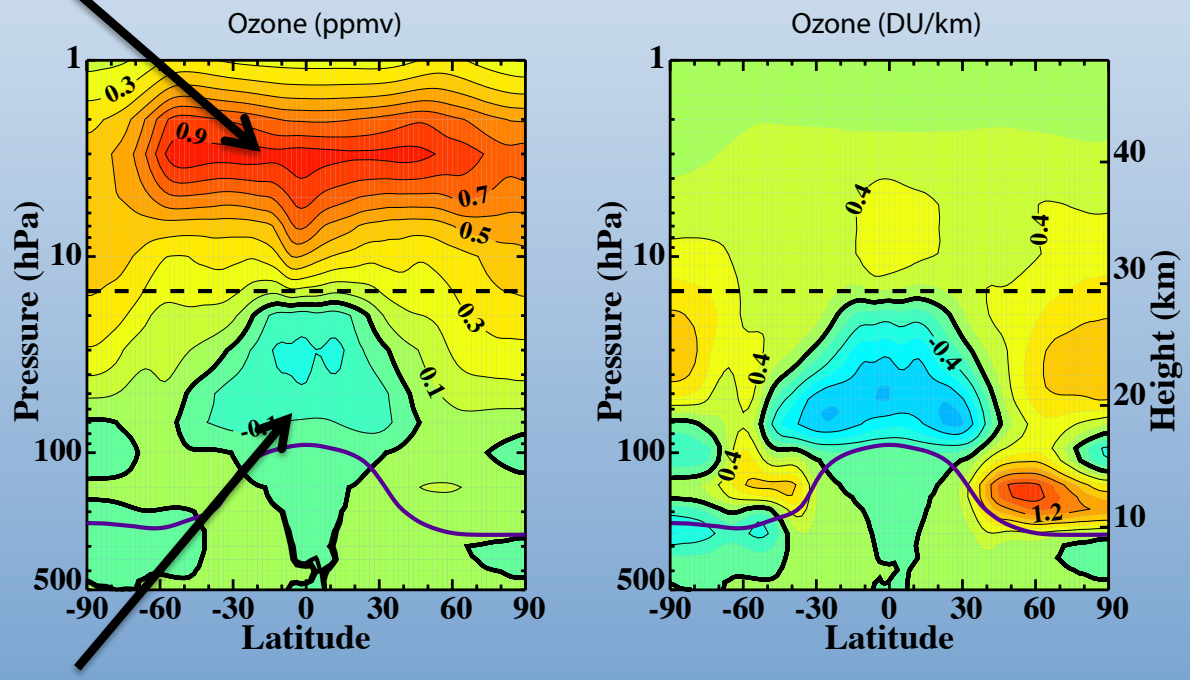
- **Ozone is expected to recover to its pre-1980 concentrations as CFCs are removed from the atmosphere in accordance with the Montreal Protocol**
- **Continued increases in greenhouse gases (esp. CO_2) will continue to cool the stratosphere**
- **Temperature decreases will slow natural ozone loss rates and lead to an increase in ozone**
- **This effect is know as "super-recovery"**

Results from simulations by the Goddard Chemistry Climate model (GEOS CCM)



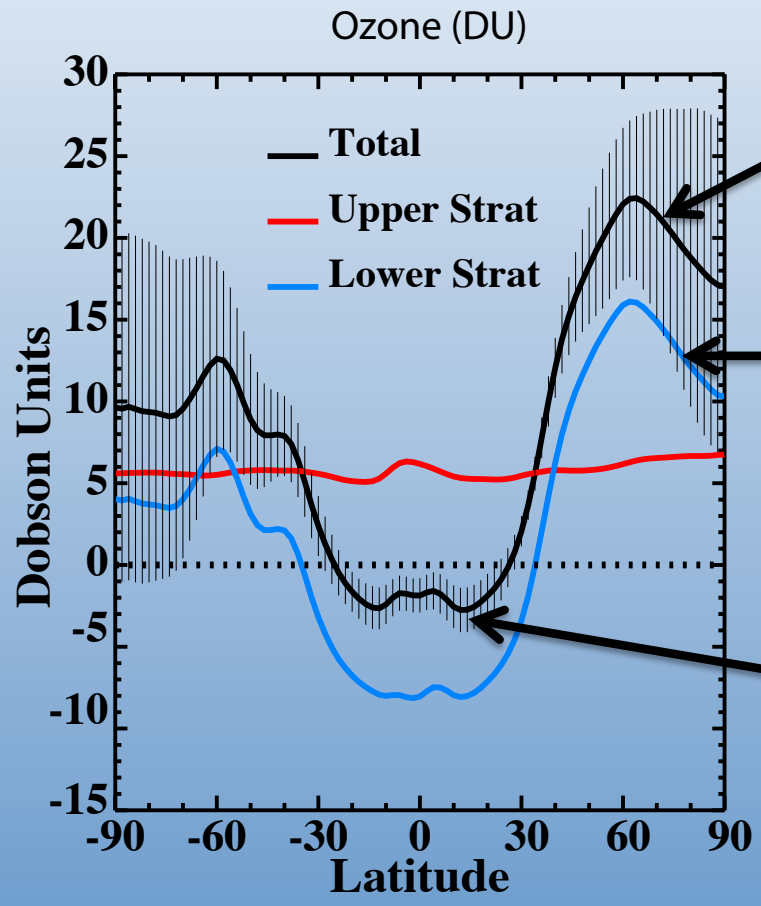
CCM Simulation of ozone when chlorine is returned to 1980 values

Ozone Response to cooling in upper stratosphere



Ozone Response to circulation change in lower stratosphere

Impact of ozone changes due to GHGs on column ozone



20 DU increase to unprecedented high values of ozone in mid-latitudes and polar regions

Latitude-dependent lower stratospheric signature yields near-zero global average change

Under-recovery in tropics (very little change there due to CFCs)

Nitrous oxide

Odd Nitrogen (NO_y) is produced by the reaction of $O(^1D)$ with Nitrous Oxide (N_2O) and destroyed by the reaction of N atoms with NO.

Definition of NO_y

$$NO_y = N + NO + NO_2 + NO_3 + 2*N_2O_5 + HNO_3 + HO_2NO_2 + ClNO_3 + BrNO_3$$

Production of NO_y

$$O(^1D) + N_2O \rightarrow NO + NO$$

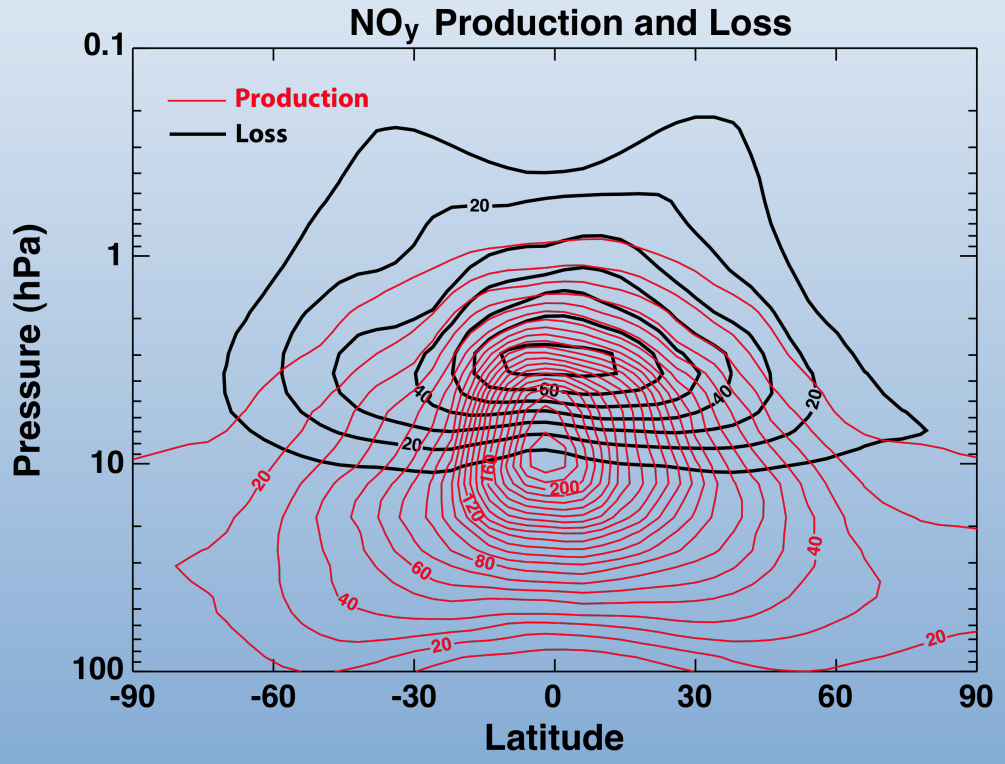
Loss of NO_y

$$N(^4S) + NO \rightarrow N_2 + O$$

NO_y Production is balanced by loss and transport to the troposphere

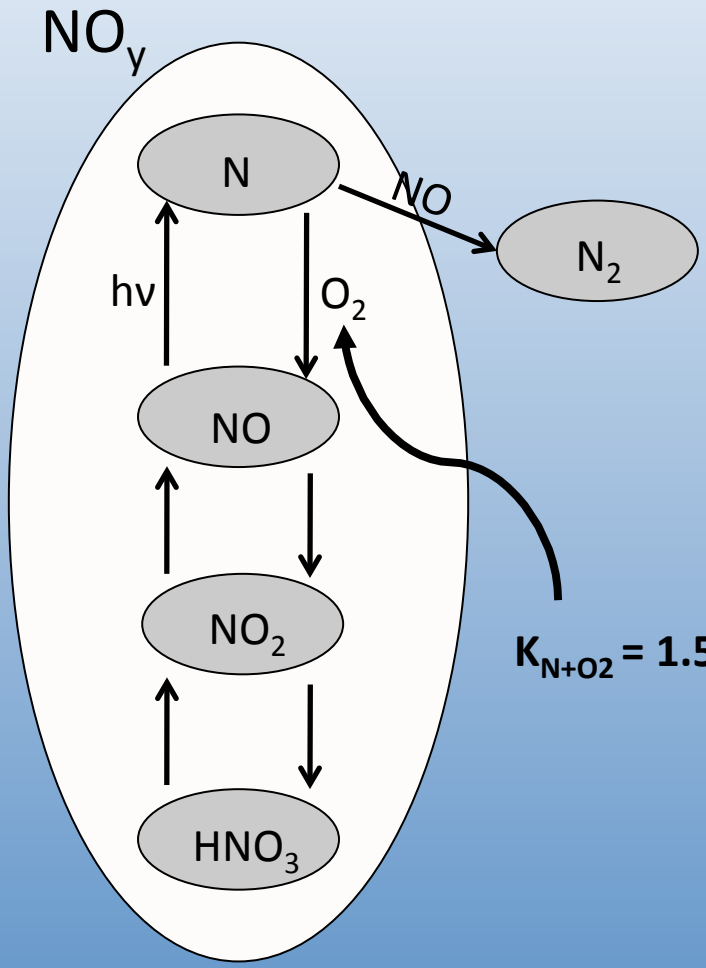
Chemical Loss occurs in the upper stratosphere above ~10 hPa.

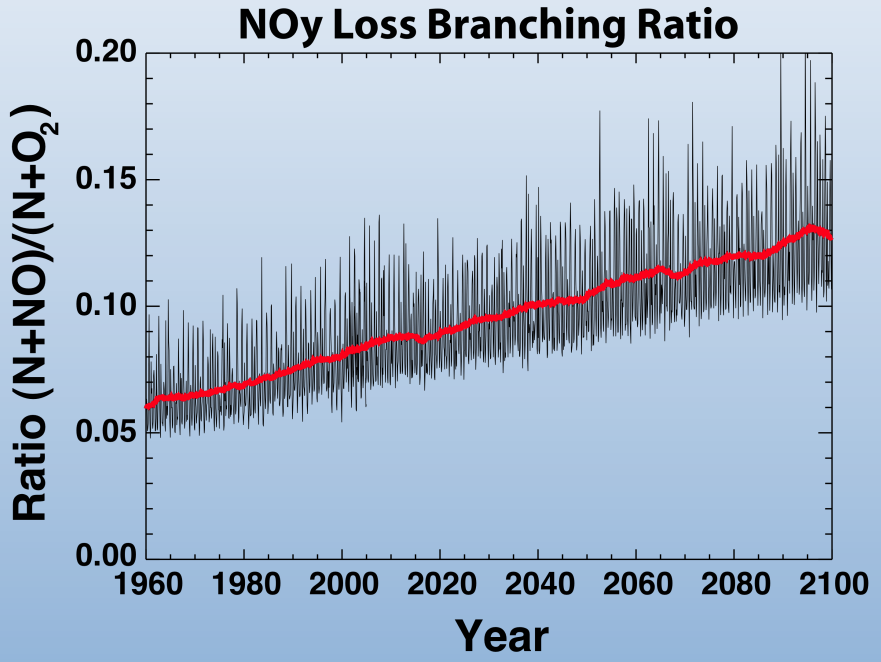
Chemical Loss is about 30-40% of total loss: transport to the troposphere is 60-70%.



In-situ chemical loss of NO_y makes it different from Cl_y

N atoms, formed by photolysis of NO, can either reform NO or can react with NO to remove NO_y





$K_{N+O2} = 1.5 \times 10^{-11} EXP(-3600/T)$

The branching ratio is strongly temperature dependent: low temperatures → more NO_y loss

Climate change affects NO_y impact on ozone

$$\Delta O3 = \frac{\partial O3}{\partial NOy} \Delta NOy$$

NO_y leads to ozone loss

$$NOy = NOy\,(N2O, T)$$

NO_y is a function of both N_2O and Temperature

$$\Delta NOy = \frac{\partial NOy}{\partial N2O} \Delta N2O + \frac{\partial NOy}{\partial T} \Delta T$$

The change in NO_y (and ozone) thus depends on both N_2O and Temperature

$$\Delta O3 = \frac{\partial O3}{\partial NOy}\frac{\partial NOy}{\partial N2O} \Delta N2O + \frac{\partial O3}{\partial NOy}\frac{\partial NOy}{\partial T} \Delta T$$

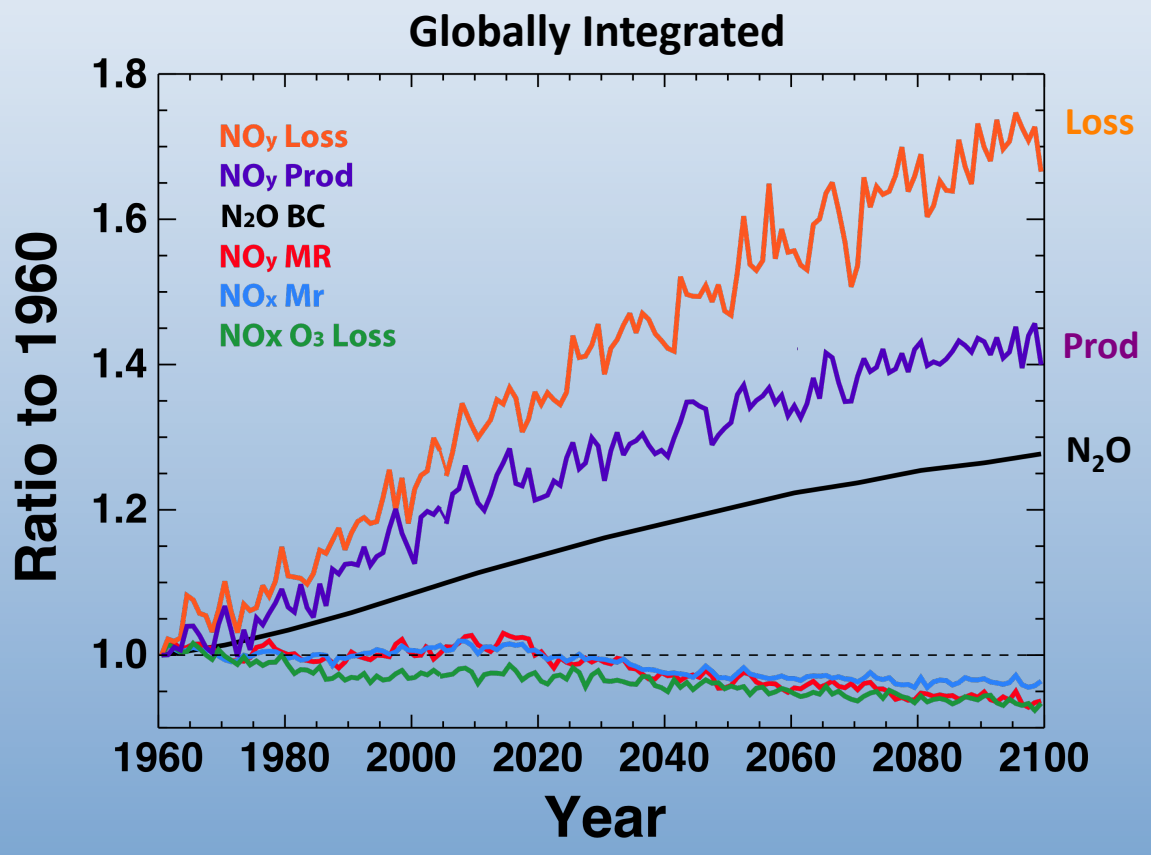
The ODP is the ratio of this term to the equivalent term for CFC-11

Simulation with 25% increase in N_2O yields 40% increase in NO_y production and 70% increase in NO_y loss

Production increases due to speed up of circulation pushing N_2O to higher altitude

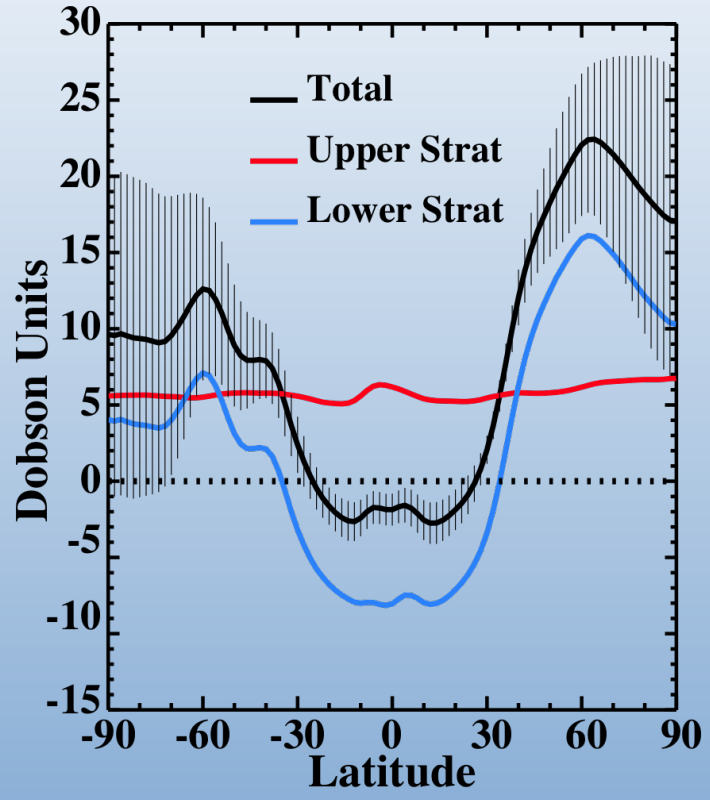
Loss increases due to cooling of upper stratosphere from increased radiation to space by CO_2

Net result is slight decrease in NO_y, NO_x, and ozone loss despite the increase in N_2O.



Simulations done using the GEOS CCM (Goddard Earth Observation System Chemistry Climate Model

What would happen if we could limit N_2O?



Reducing N_2O in 2100 would lead to greater super-recovery in the extra-tropics and perhaps a full recovery (or more) in the tropics

(but we have no quantitative estimates!)

Models (e.g. Li et al. *Atmos. Chem. Phys.*, 9, 2207-2213, 2009) simulate a "super-recovery" of ozone at mid and high latitudes and a slight under recovery in the tropics.

Conclusions (Nitrous Oxide)

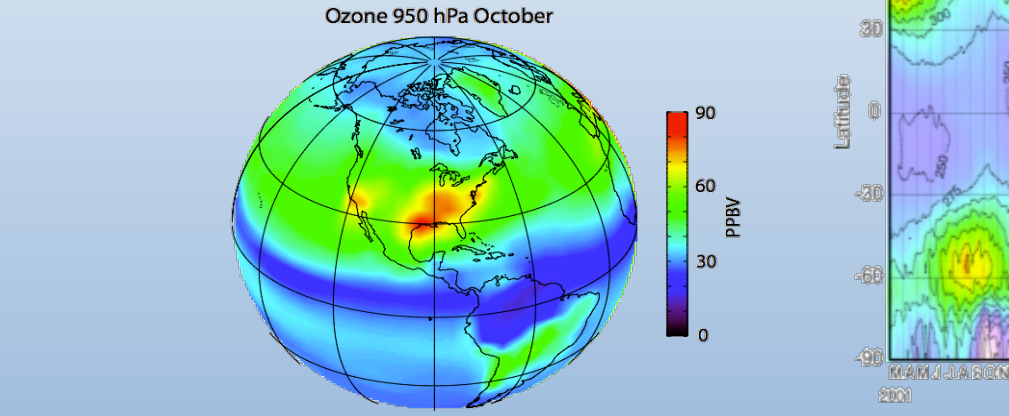
- In our model simulation, a 25% increase in N_2O coupled with a projected CO_2 increase led to a **slight decrease** in the ozone loss due to nitrogen oxides.

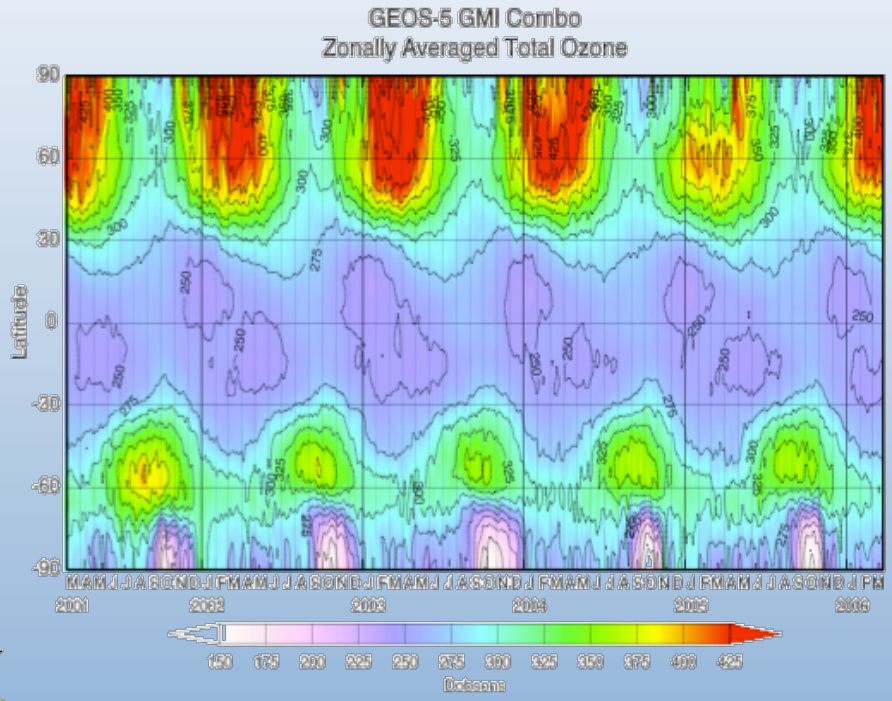
- **Increased N_2O, by itself, would lead to increased O_3 loss**
  - **CO_2-induced cooling of the stratosphere increases O_3 through decreasing loss rates**
  - **CO_2-induced cooling of the stratosphere also reduces the amount of NO_y produced from N_2O**

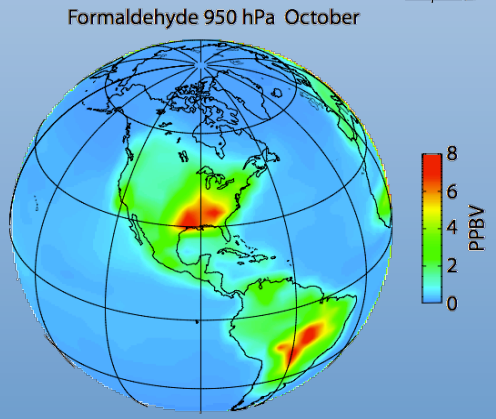
- **The calculation of the impact of N_2O on ozone is significantly complicated by climate change**

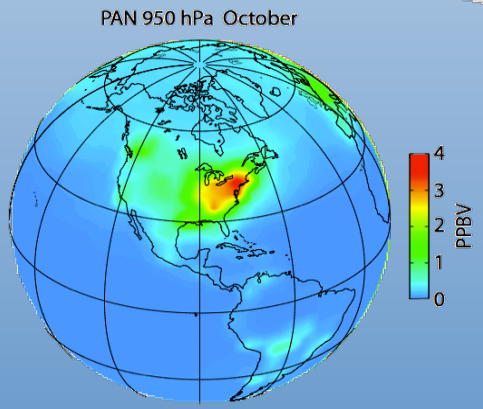
Future directions of GEOSCCM: Tropospheric chemistry changes and surface interactions

Version 3 of the model (GEOS 5 + Combo chem) is being tested for simulations of the combined troposphere and stratospheric chemistry





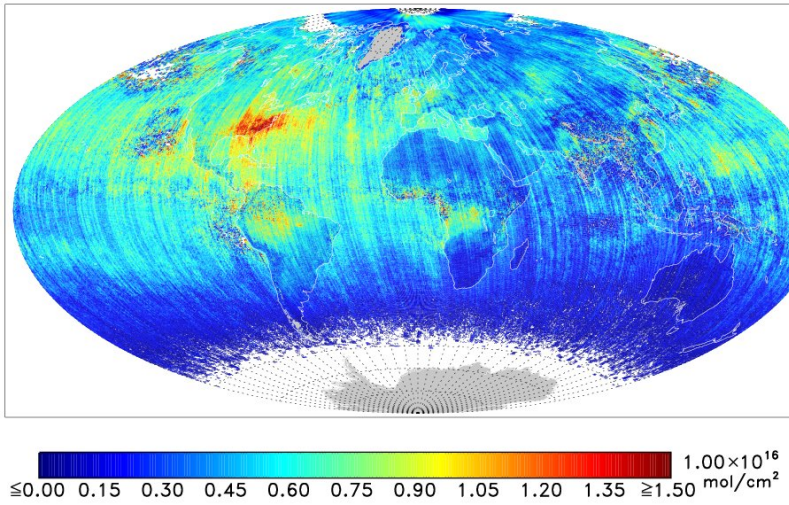




Satellite data for some important constituents of troposphere

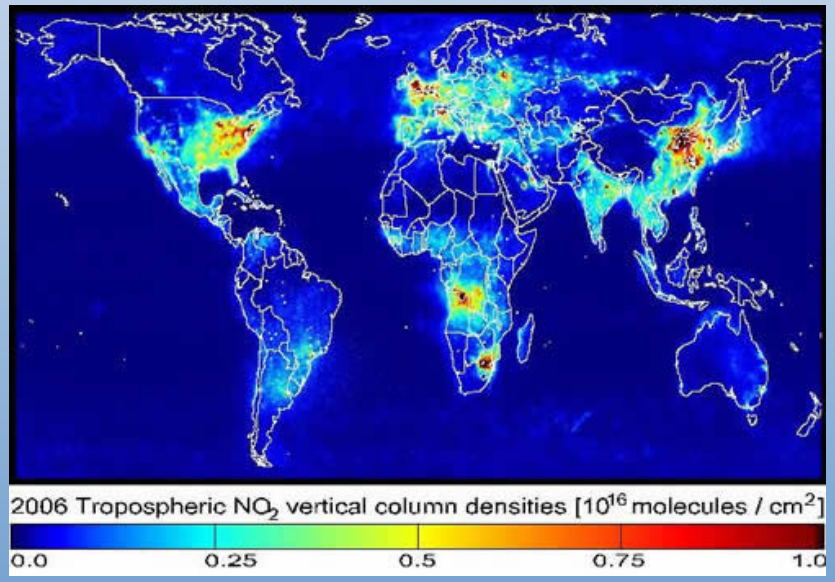
Measurements from OMI on Aura

Formaldehyde (representative of VOCs)



Average OMI HCHO geometric vertical columns for the month of July 2005. Only ground pixels with a cloud cover of 20% or less has been included. Note that this image is not corrected for the stripes. Level-2 products are effected by residual errors in the dark current correction of the level-1b radiance and irradiance products, which is manifested as along-track stripes.

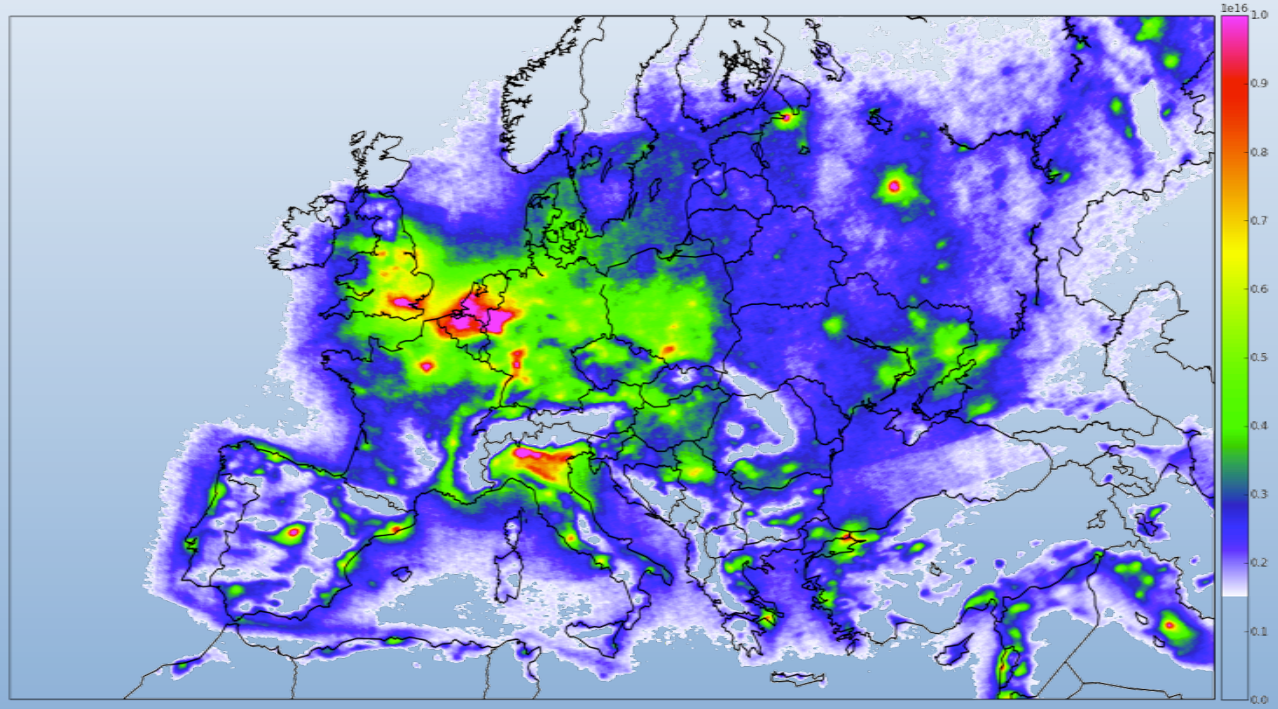
NO_2 (representative of NO_x)



NOx + VOCs → Ozone

NO2 over Europe (Annual Average)

Measurements from OMI on Aura



Satellite measurements of important tropospheric gases can bring an added perspective to our knowledge gained from in-situ measurements and models

Summary

- GEOS CCM effort at Goddard is working towards Earth System model
- Simultaneous consideration of ODS and GHG changes gives fingerprint for expected ozone recovery
- Nitrous oxide effects on future ozone complicated by GHG change
- Satellite data brings added perspective to tropospheric ozone/chemistry change