Projections of stratospheric changes and their role in climate

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Introduction

Key questions:

- How will stratospheric ozone evolve (recover) in the 21st century (21C), and what will be the impact of climate change?
- What will be the impact of stratospheric ozone recovery on tropospheric climate and weather?

Examine above using stratospheric-resolving chemistry-climate models (CCMs).

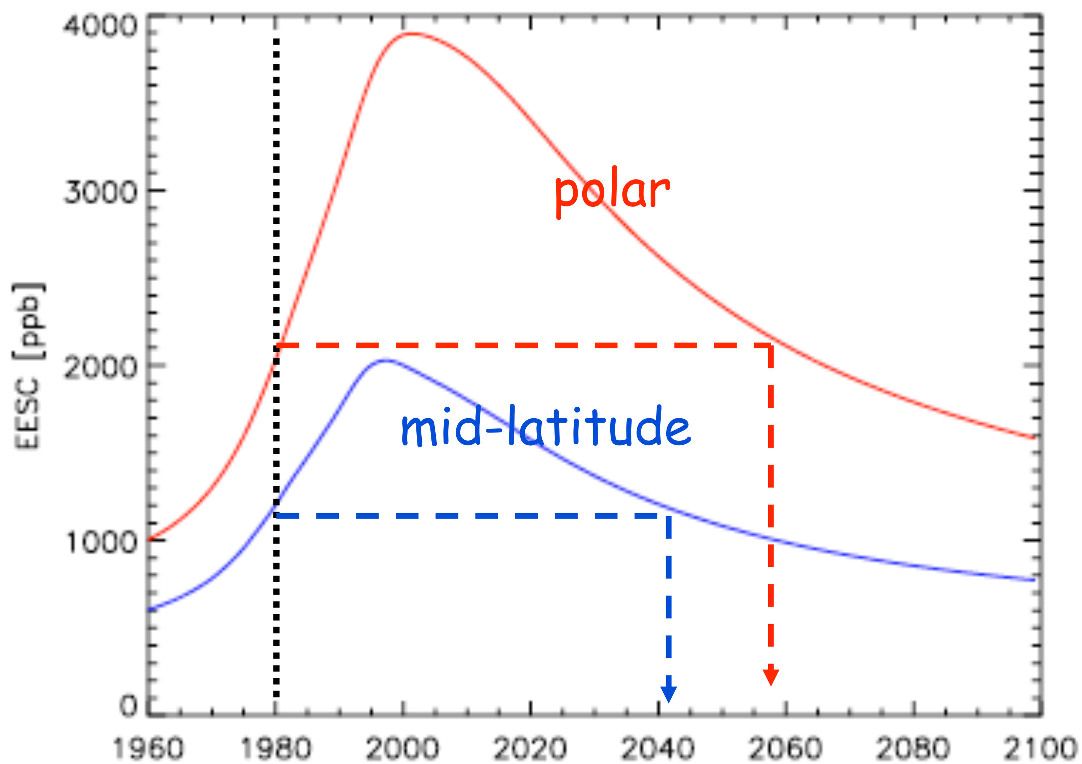
Outline

1. Multi-model projections of stratospheric ozone (+inorganic chlorine, temperature, and circulation) in the 21C (CCMVal-1).
2. Quantification of relative role of different mechanisms (GEOSCCM).
3. Sensitivity to GHG scenario (GEOSCCM).
4. Impact of ozone recovery on tropospheric climate (CCMVal-1, IPCC AR4 models).

Mechanisms influencing O_3 in the 21C

As the concentration of halogen containing ozone depleting substances (ODSs) decrease back to pre-1980 values O_3 is expected to "recover".

EESC = Cly +50Bry



However, ...

Mechanisms influencing O_3 in the 21C (cont.)

Stratospheric O_3 also influenced by changes in greenhouse gases (GHGs) which change, for example, the

- temperature (reaction rates, PSCs),
- circulation, and
- nitrogen- and hydrogen-containing radicals.

Need to include chemical, dynamical, and radiative processes and couplings

=> Three-dimensional chemistry-climate models

Stratospheric CCMs

Examine stratospheric projections from 11 stratospheric-resolving chemistry-climate models (CCMs)*. [WMO 2006, Eyring et al., JGR, 2007]

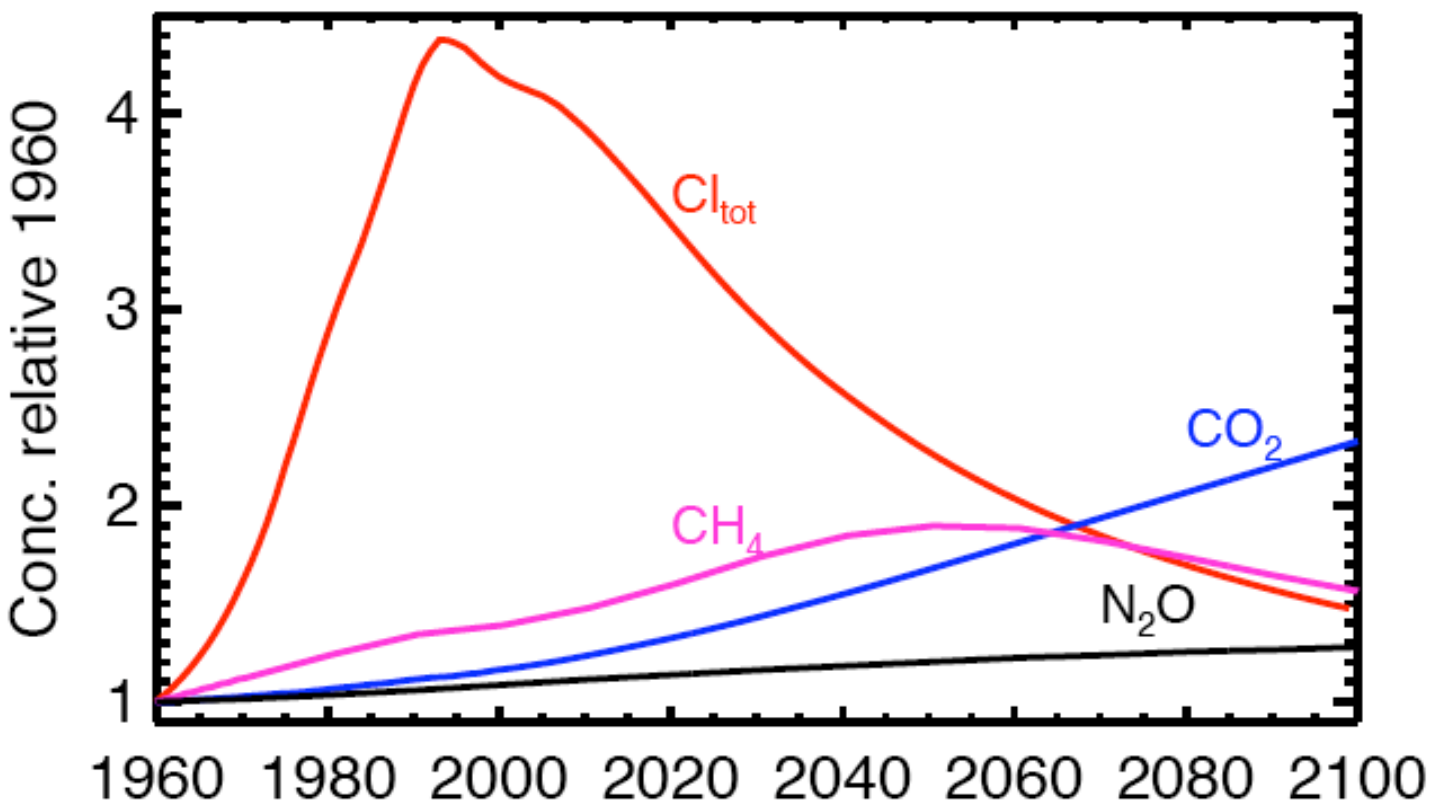
Name	Reference
AMTRAC	Austin et al. (2006)
CCSRNIES	Akiyoshi et al. (2004)
CMAM	Fomichev et al. (2007)
E39C	Dameris et al. (2005)
GEOSCCM	Pawson et al. (2008)
MAECHAM4CHEM	Steil et al. (2003)
MRI	Shibata and Deushi (2005)
SOCOL	Egorova et al. (2005)
ULAQ	Pitari et al. (2002)
UMSLIMCAT	Tian and Chipperfield (2005)
WACCM	Garcia et al. (2007)

* Prescribed SSTs, no trop. chemistry

Surface Concentrations

CCMs simulations use the same surface concentrations of

- halogens (scenario Ab, WMO 2002), and
- GHGs (CO_2, N_2O, CH_4) (scenario A1B, IPCC 2001).



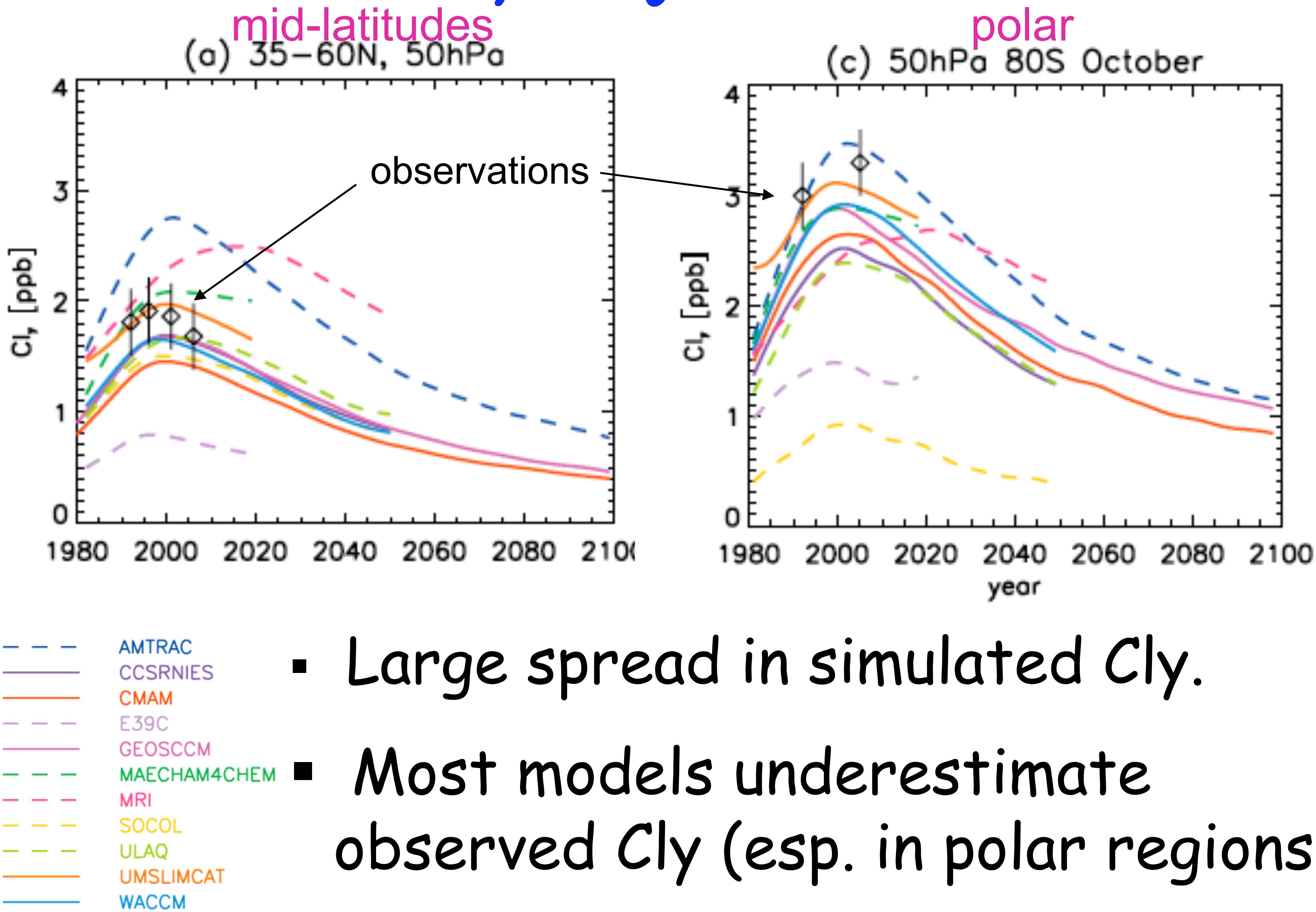
Projections of quantities that influence O_3

Before examining projections of stratospheric O_3 we consider projections of quantities that have a strong influence on O_3:

- Inorganic chlorine (Cl_y)
- Temperature
- Circulation

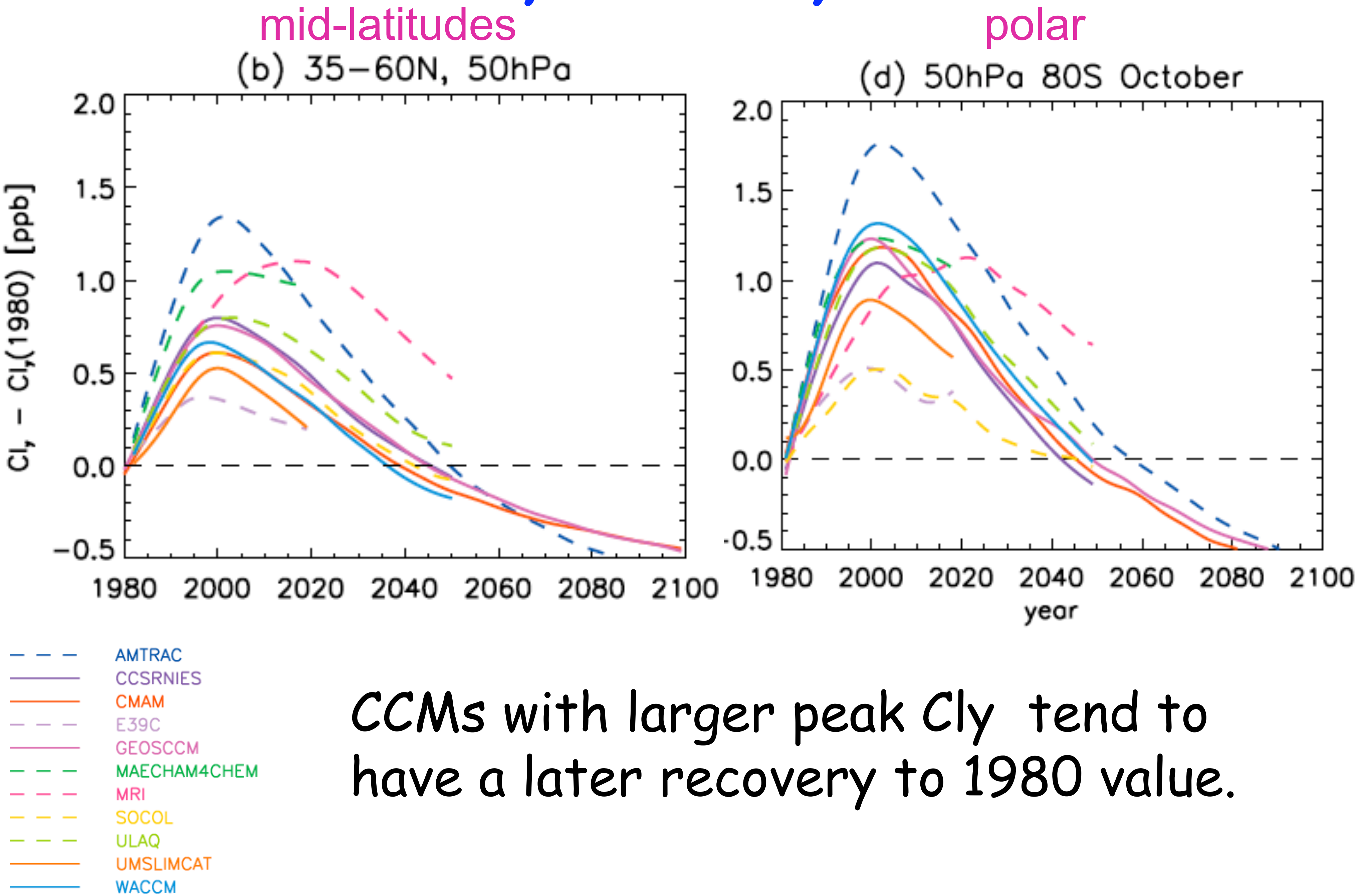
Changes in H_2O and NO_y are small.

Cly Projections

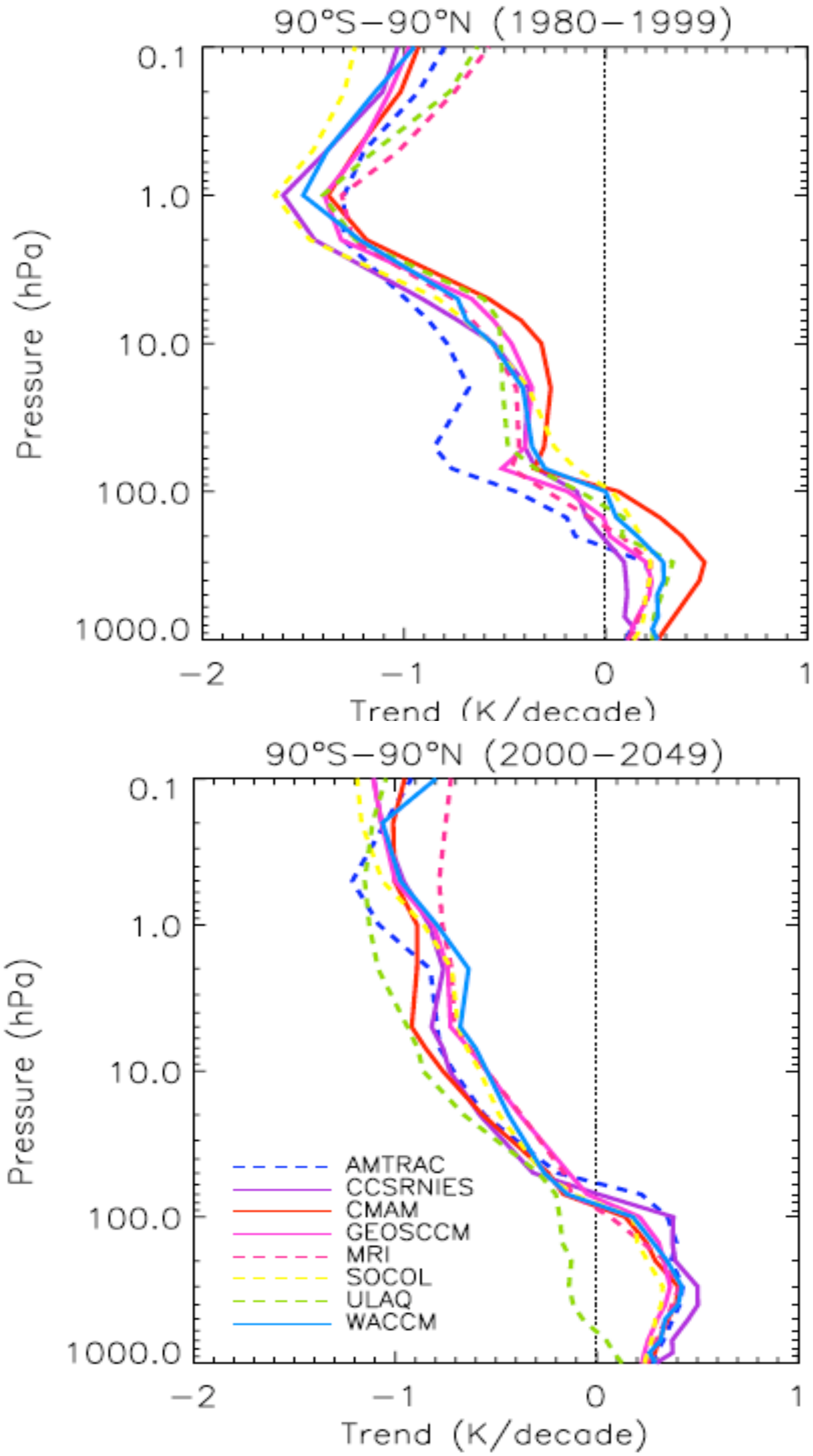


- Large spread in simulated Cly.
- Most models underestimate observed Cly (esp. in polar regions).

Cly Recovery



CCMs with larger peak Cly tend to have a later recovery to 1980 value.



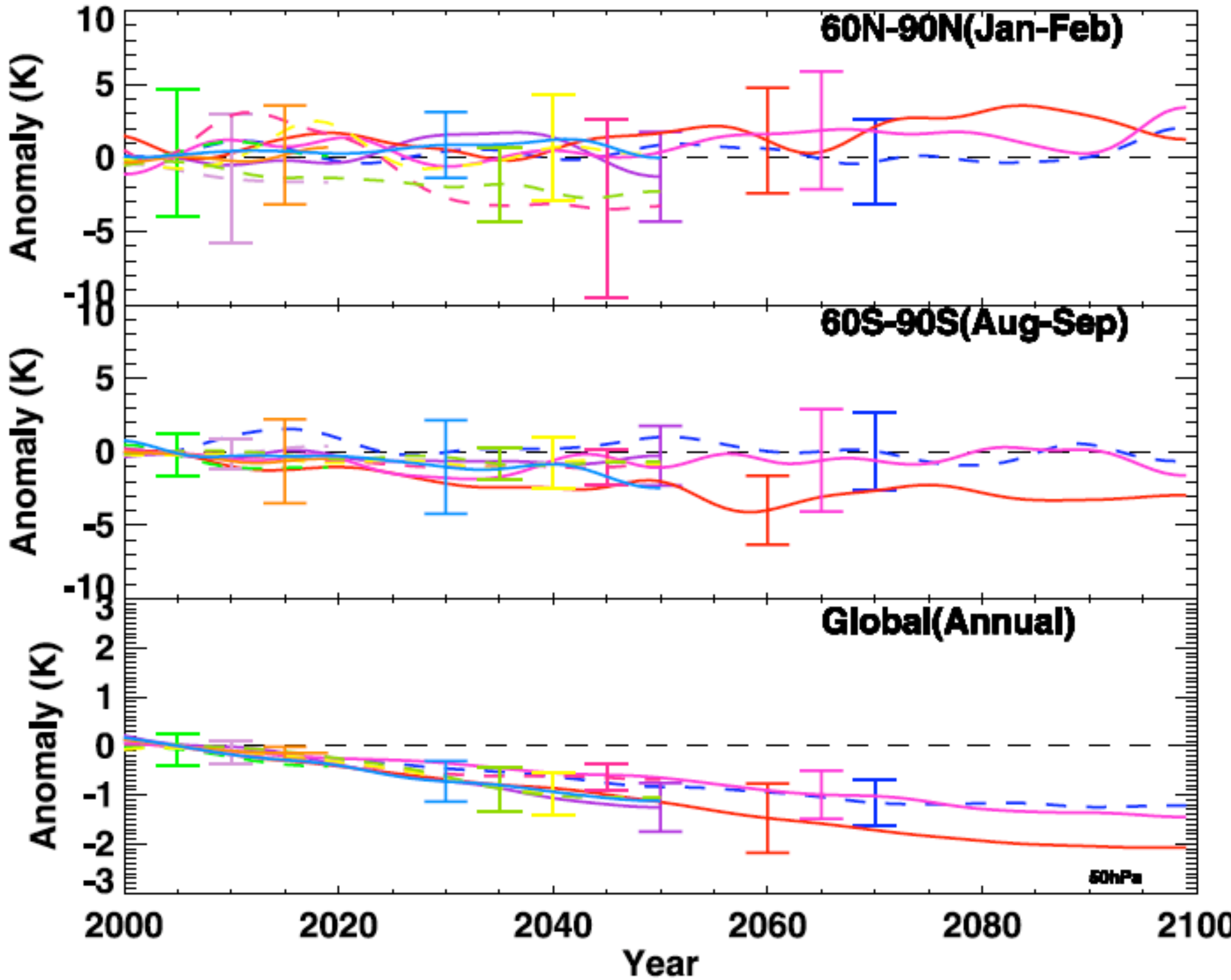
Temperature Trends

All CCMs show large cooling in middle-upper stratosphere.

This cooling slows rate of gas-phase reactions that destroy O_3.

[Eyring et al., JGR, 2007]

Polar Temperatures

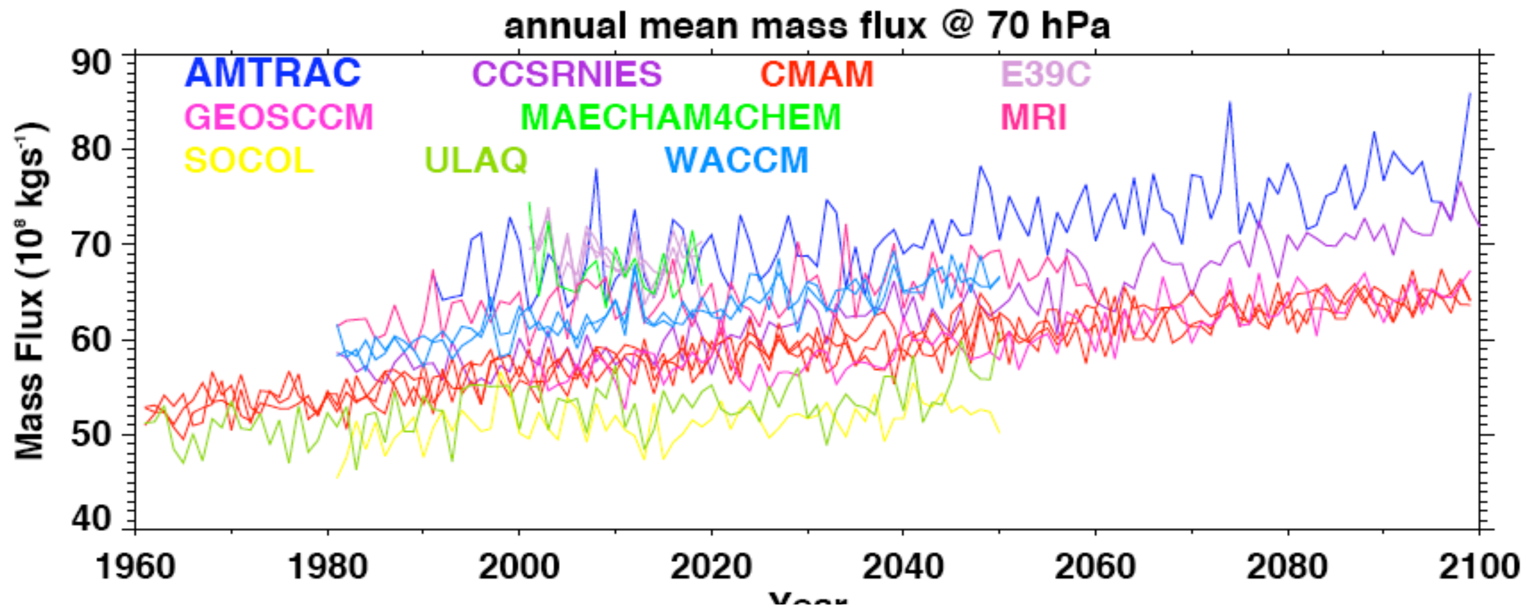


50 hPa temperatures

[Eyring et al. 2007]

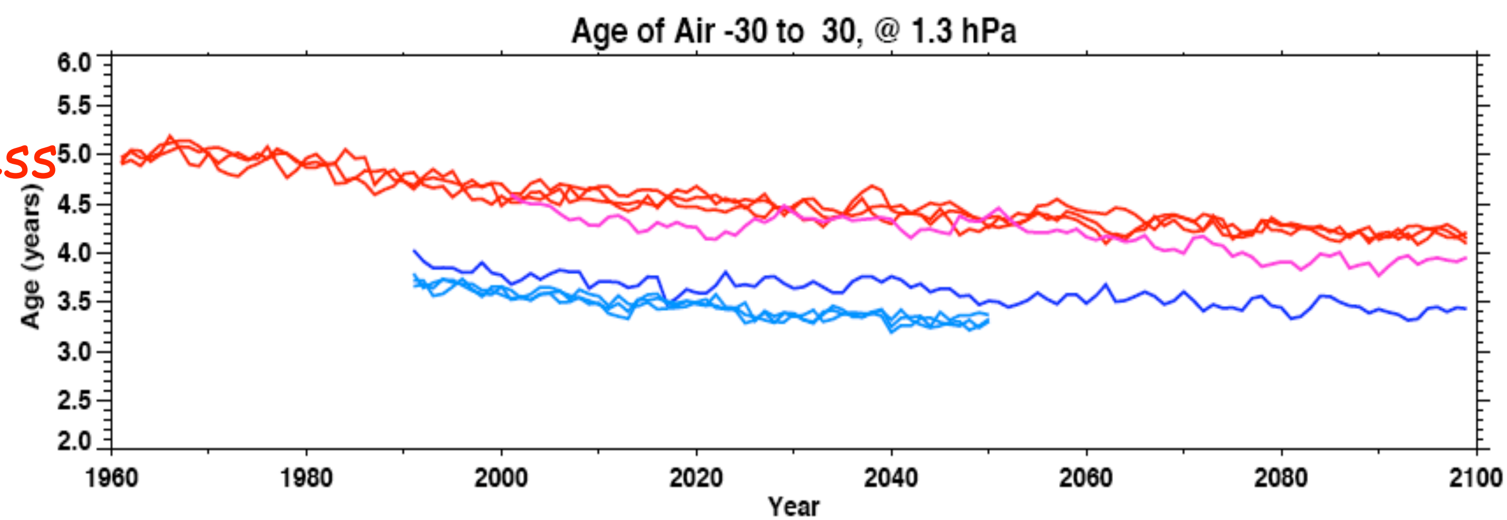
Projected trends in polar lower stratosphere are very small, with no consistent sign.

Circulation



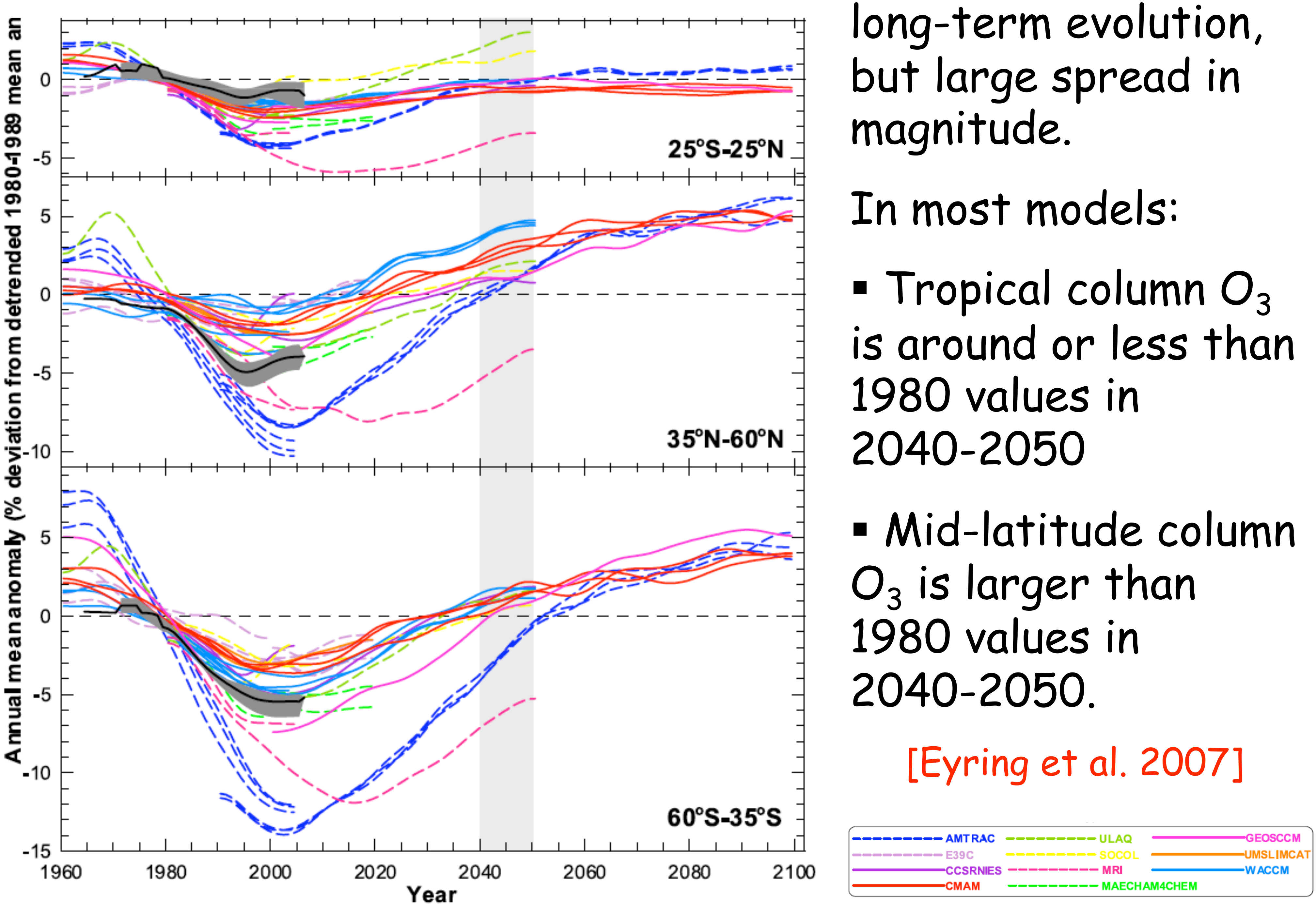
Butchart
POSTER

Garcia,
McLandress
TALKS



All CCMs predict increasing tropical upwelling and decreasing mean age from 1960 to 2100.

Extra-Polar Column O_3



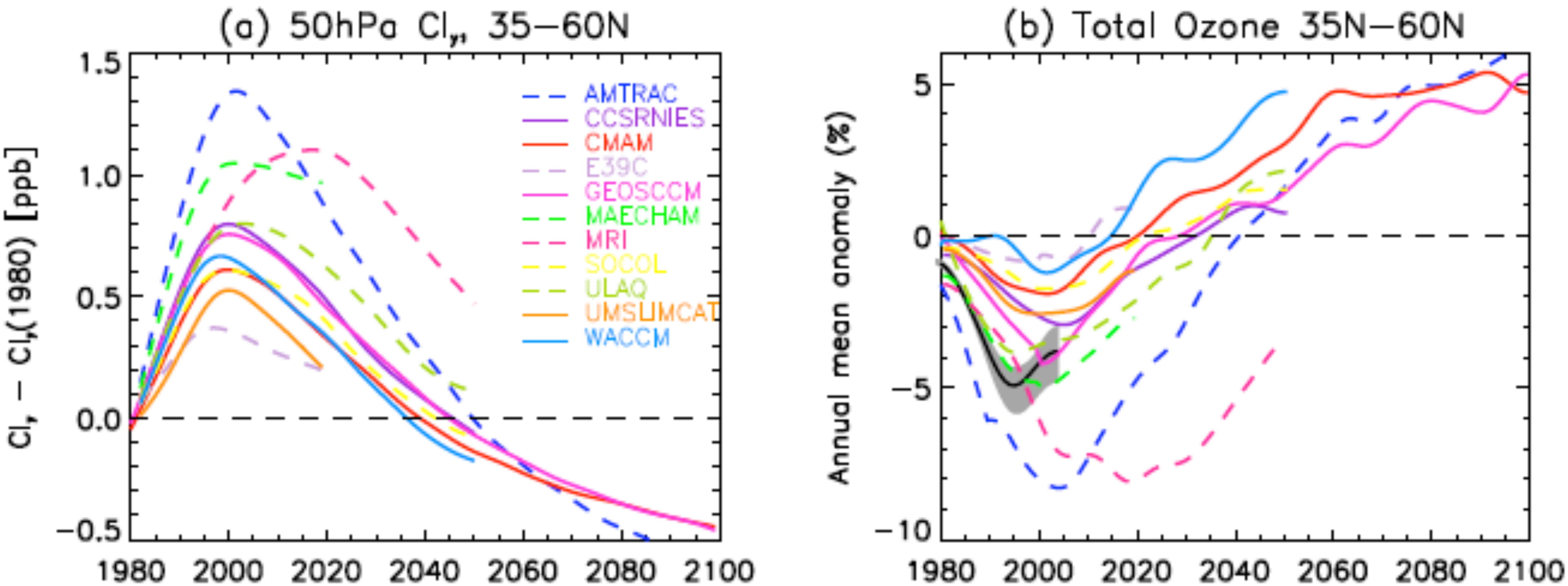
CCMs project similar long-term evolution, but large spread in magnitude.

In most models:

- Tropical column O_3 is around or less than 1980 values in 2040-2050
- Mid-latitude column O_3 is larger than 1980 values in 2040-2050.

[Eyring et al. 2007]

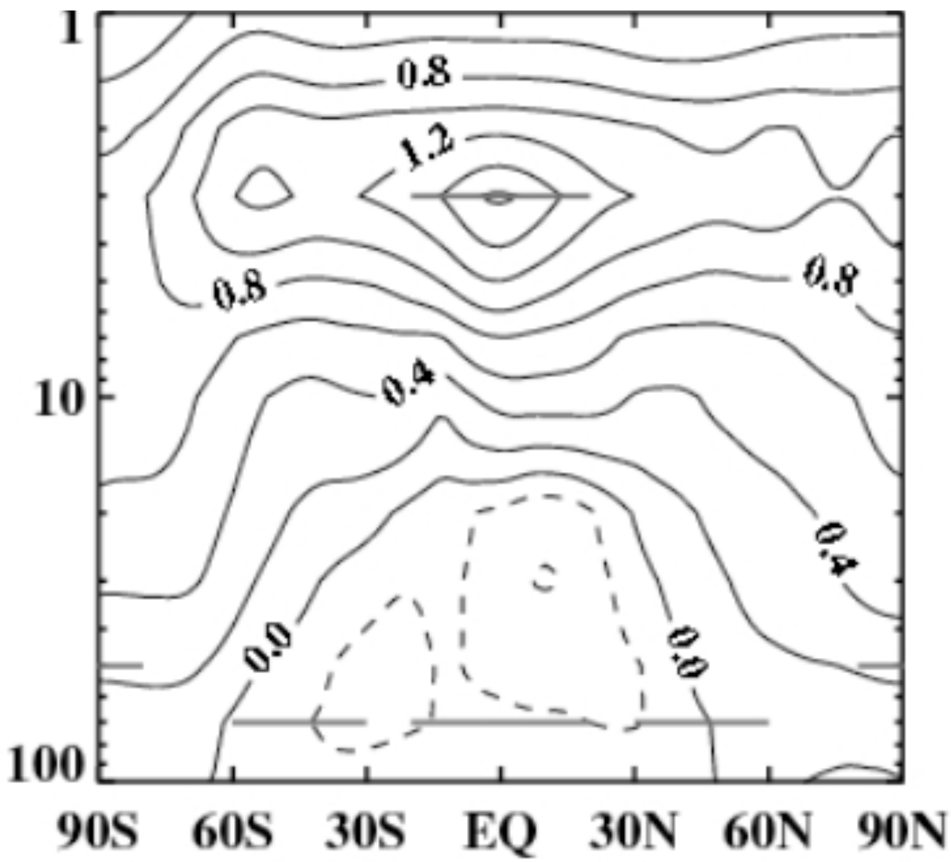
Cl_y and O_3



Differences in the simulated Cl_y can explain a lot of the differences in the O_3 simulations.

Extra-Polar O_3: Vertical Variations

2100 - 1960 O_3 (GEOSCCM)

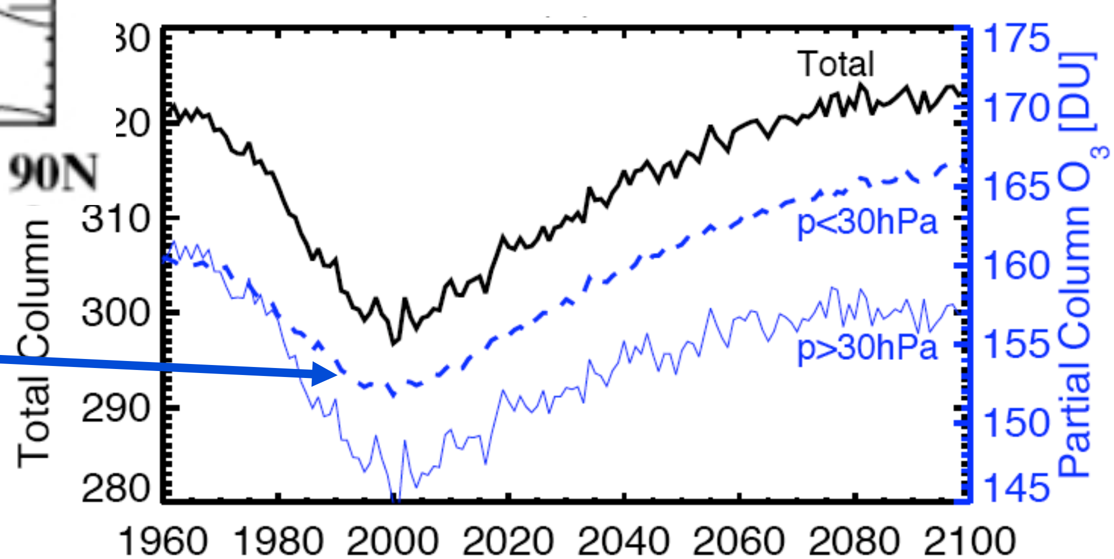


Extra-polar O_3 in 2100 is

> 1960 values in upper stratosphere, but

< 1960 values in the lower stratosphere.

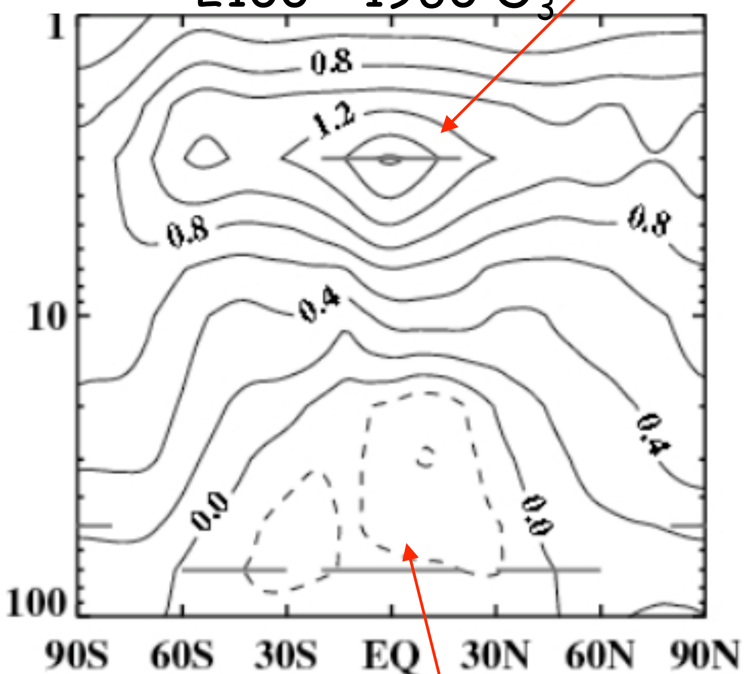
60S-60N Partial column O_3

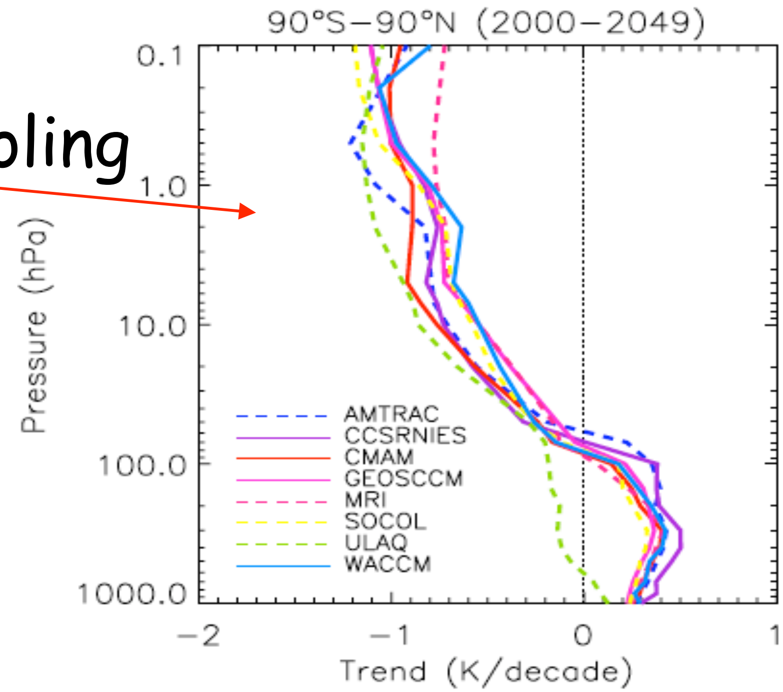


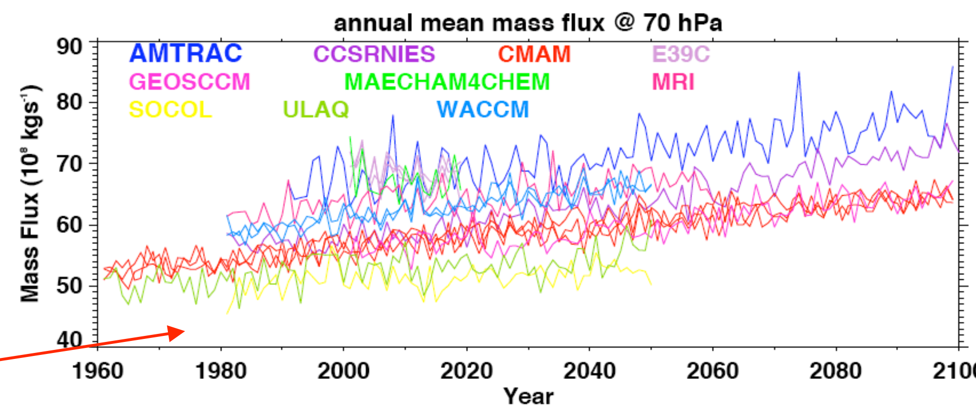
Temperature and Upwelling

Increase in upper stratospheric O_3 consistent with cooling

2100 - 1960 O_3

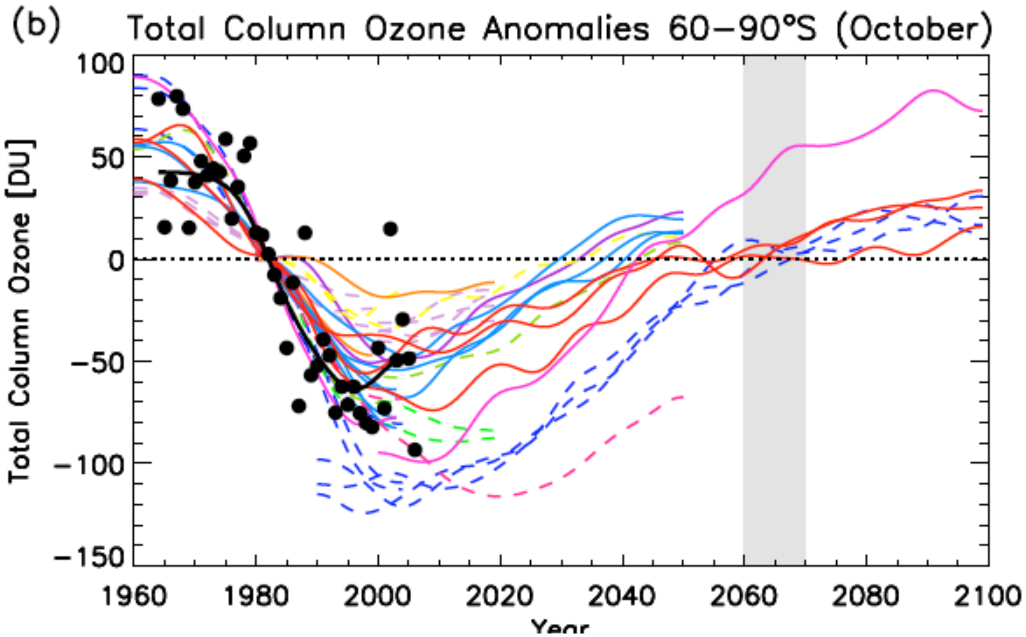




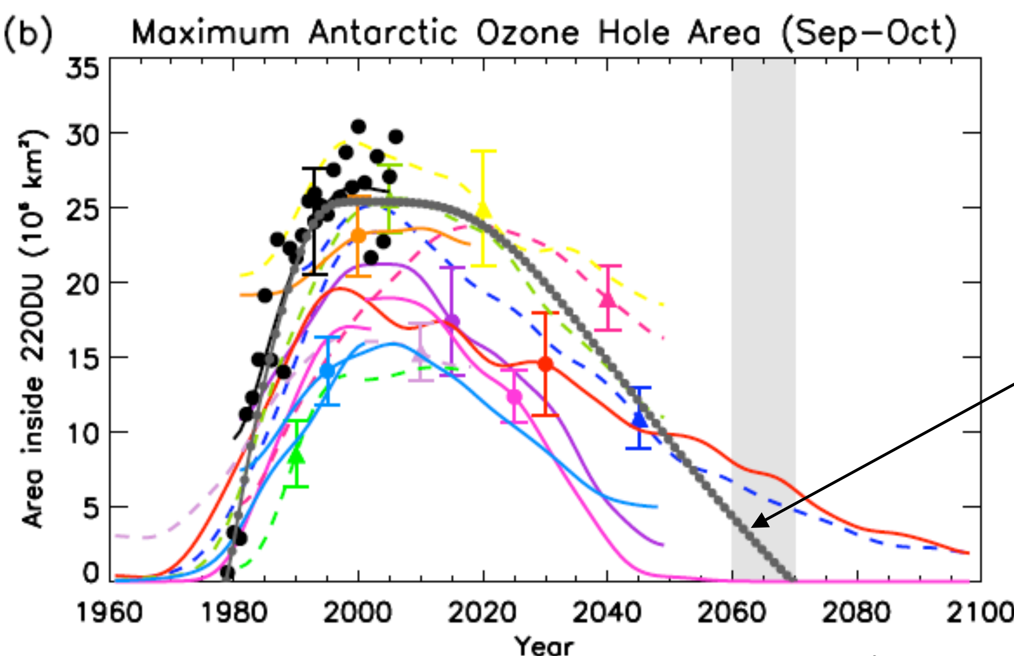


Decrease in lower stratosphere O_3 consistent with increased upwelling

Antarctic O_3



Again, CCMs project similar long-term evolution, but large spread in magnitude of anomalies and date of disappearance of ozone hole.



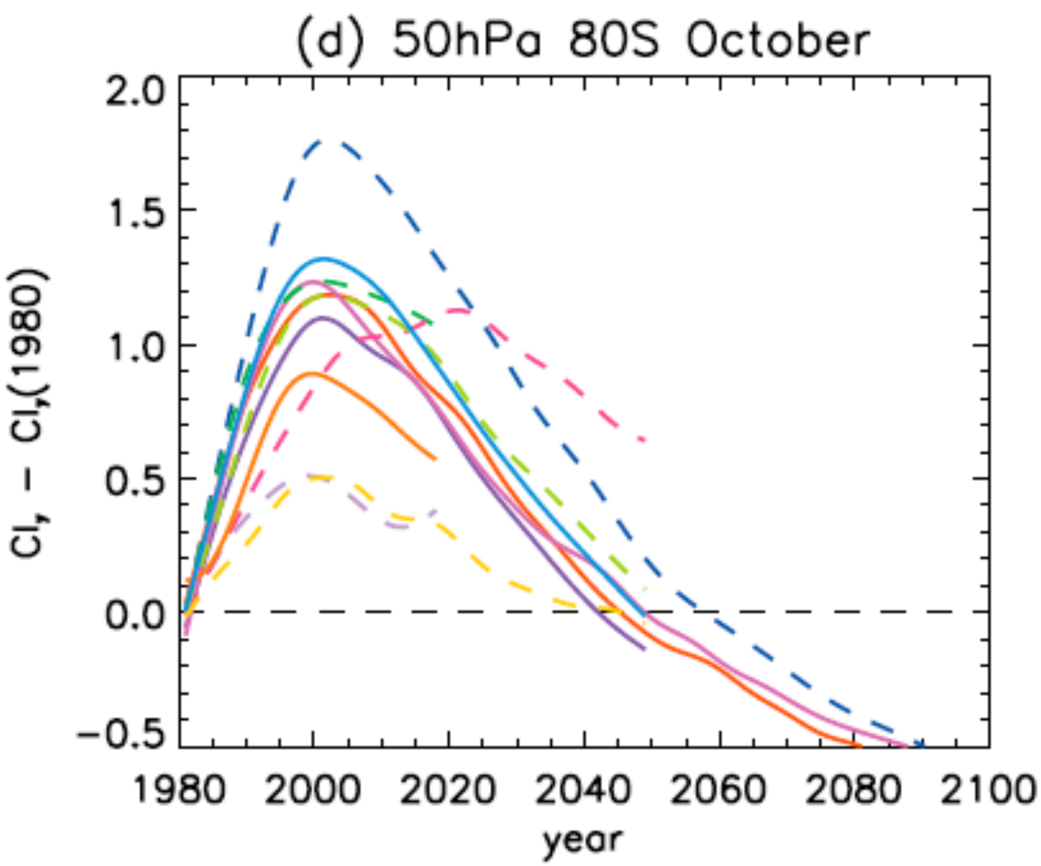
Projection based on empirical relationship with EESC [Newman et al. 2006].

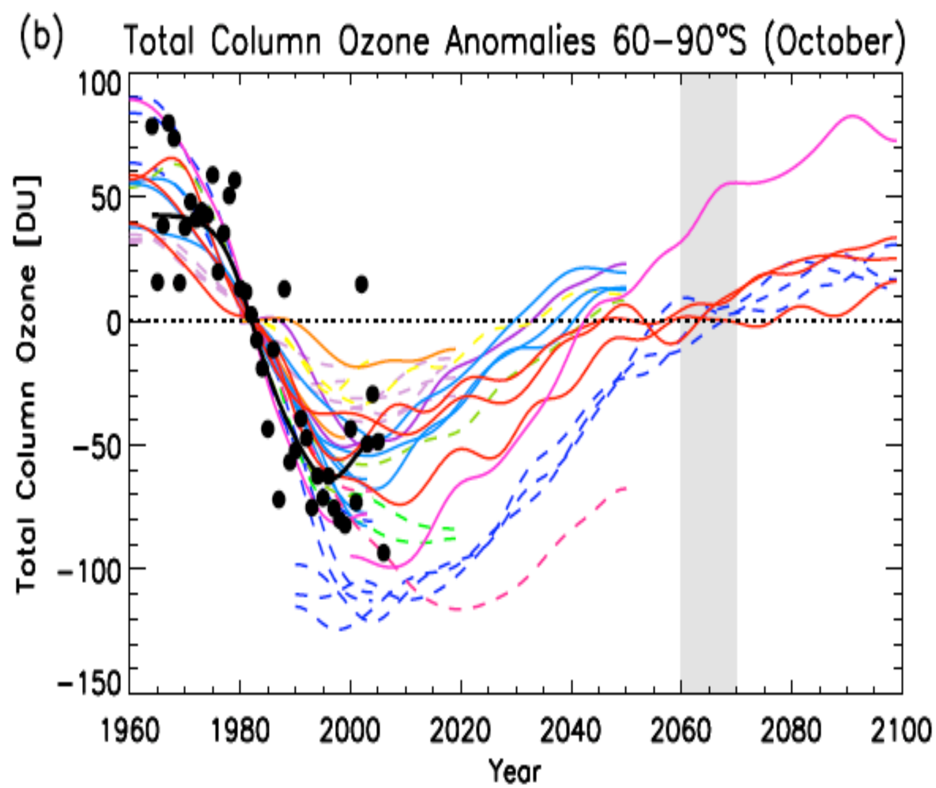
[Eyring et al. 2007]

Spread primarily due to Cly differences.

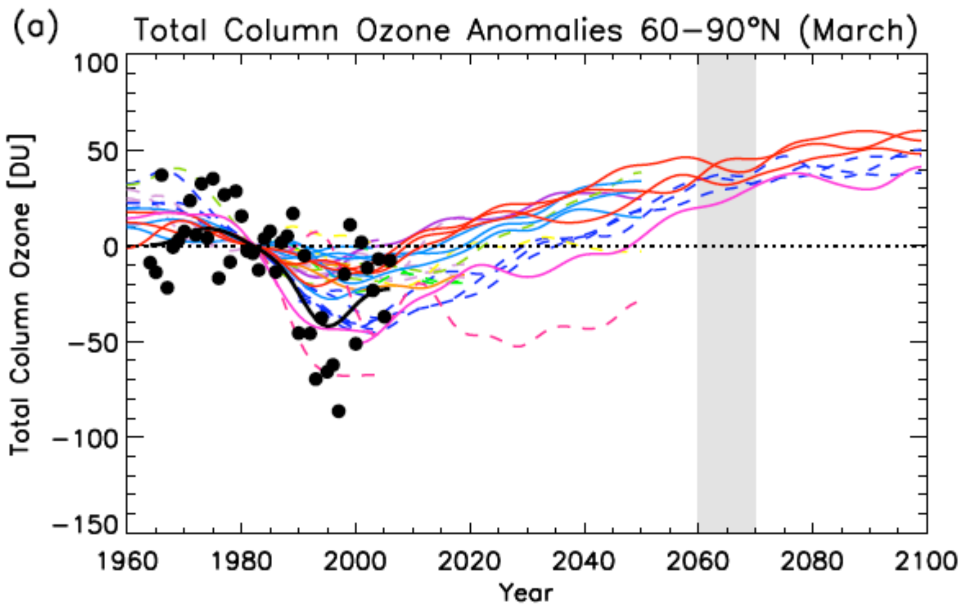
Polar Cly and O_3

Spread in projected Antarctic O_3 recovery primarily due to differences in model Cl_y. "Earlier" recovery due to bias in Cly simulations not changing B-D circulation.

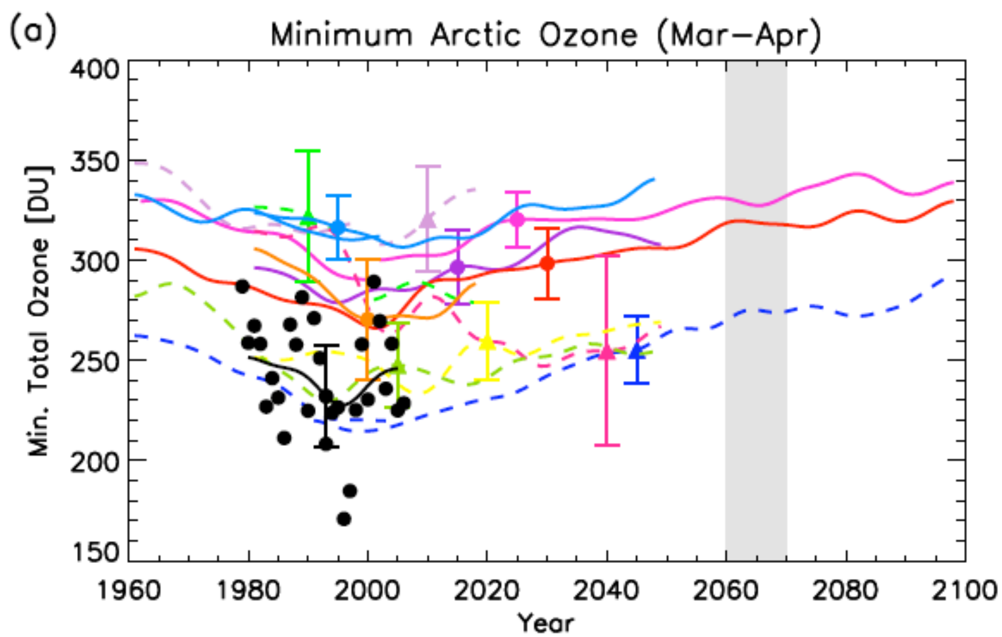




Arctic O_3



CCMs show small trends in Arctic O_3, with large year-to-year variability.



No indication of large decreases of Arctic O_3 in the future in any model.

[Eyring et al. 2007]

Summary of multi-model projections

- In general, the projected column O_3 evolution is mainly determined by decreases in ODSs and continued cooling due to increases in GHGs.

- Extra-polar O_3 is projected to increase to 1980 values before ODSs return to 1980 values, because cooling in upper stratosphere.
Antarctic O_3 is projected to follow decrease in ODSs.

- Differences in Cly among CCMs are key to diagnosing intermodels differences in O_3 recovery.

[from Eyring et al. 2007]

Quantification of relative role of different mechanisms

Eyring et al. (2007) did not quantify the contribution of different mechanisms to changes in ozone.

Such quantification is performed using GEOSCCM simulations:

(1) Comparison of simulations with time-varying and fixed ODS, and

(2) Multi-Linear Regression analysis of "standard" projections .

Impact of Increasing GHGs on O_3 Recovery

The impact of increasing GHGs on recovery of O_3 is examined by comparing two simulations:

(1) "Reference": time-varying GHGs and ODSs.

(2) "Fixed-ODS": time-varying GHGs but ODSs fixed at 1960 values.

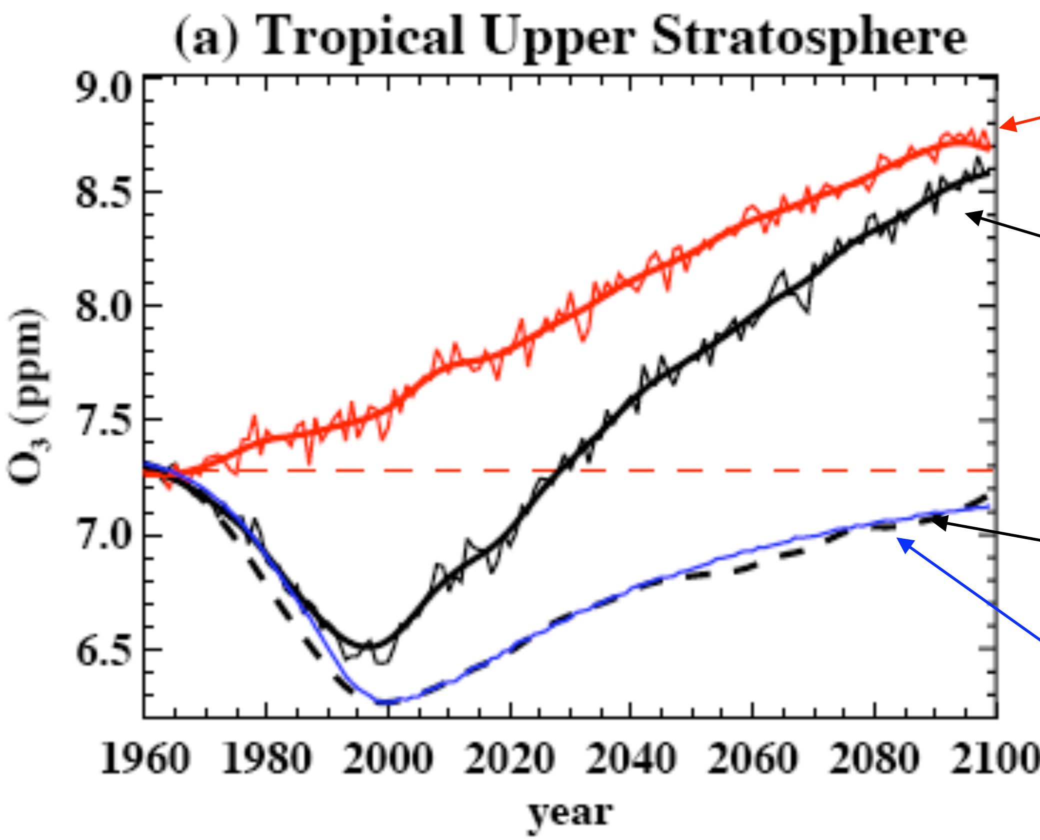
(2) => changes in O_3 due to increasing GHGs,

(1) - (2) => changes in O_3 due to changing ODSs [direct + indirect].

GEOSCCM model, 1960 to 2100.

[Waugh et al. 2008]

Impact of GHGs: Upper Stratosphere



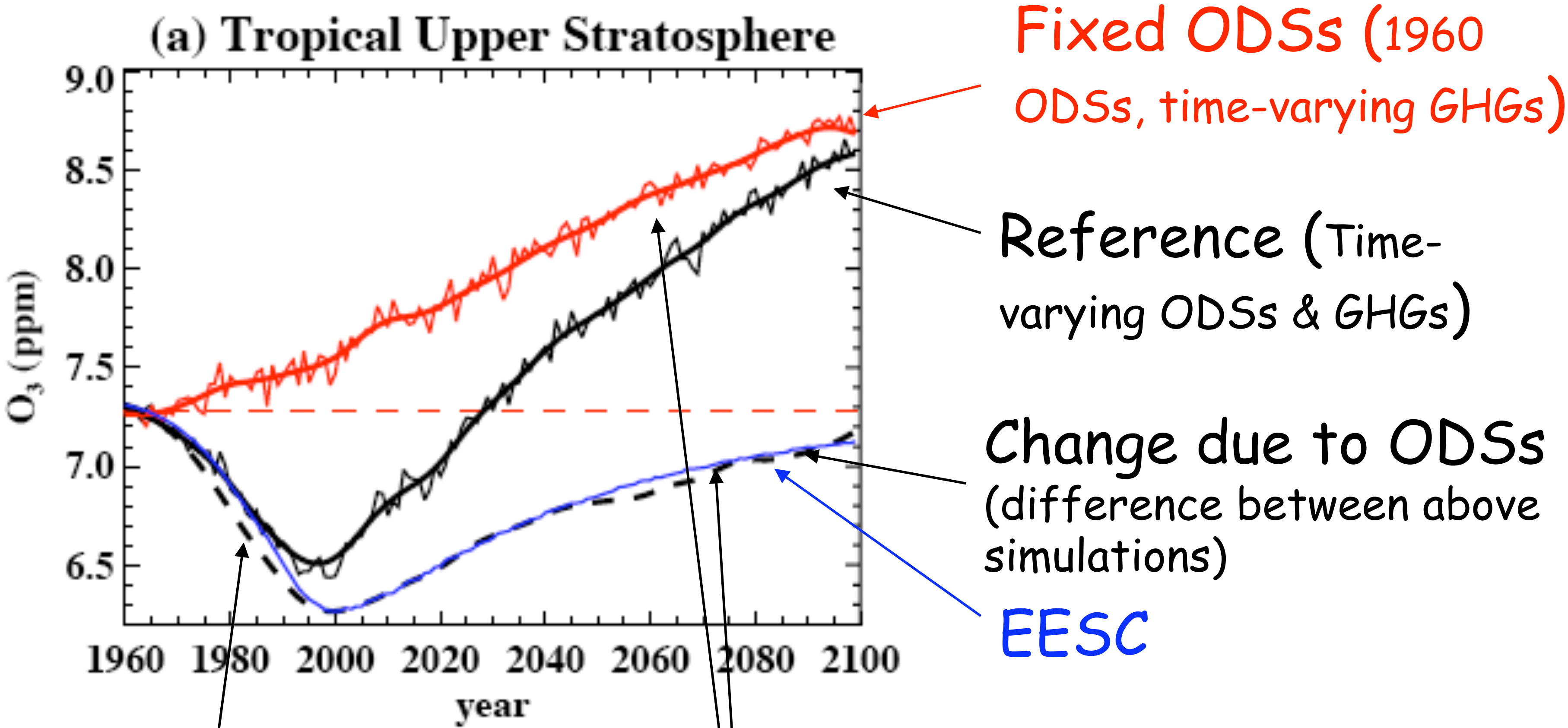
Fixed ODSs (1960 ODSs, time-varying GHGs)

Reference (Time-varying ODSs & GHGs)

Change due to ODSs (difference between above simulations)

EESC

Impact of GHGs: Upper Stratosphere



- O_3 decreases during last part of 20th century due primarily to increasing ODSs.
- O_3 increases during 21st century due to rough equal contribution from decreasing ODSs and increasing GHGs.

Ozone Recovery Milestones

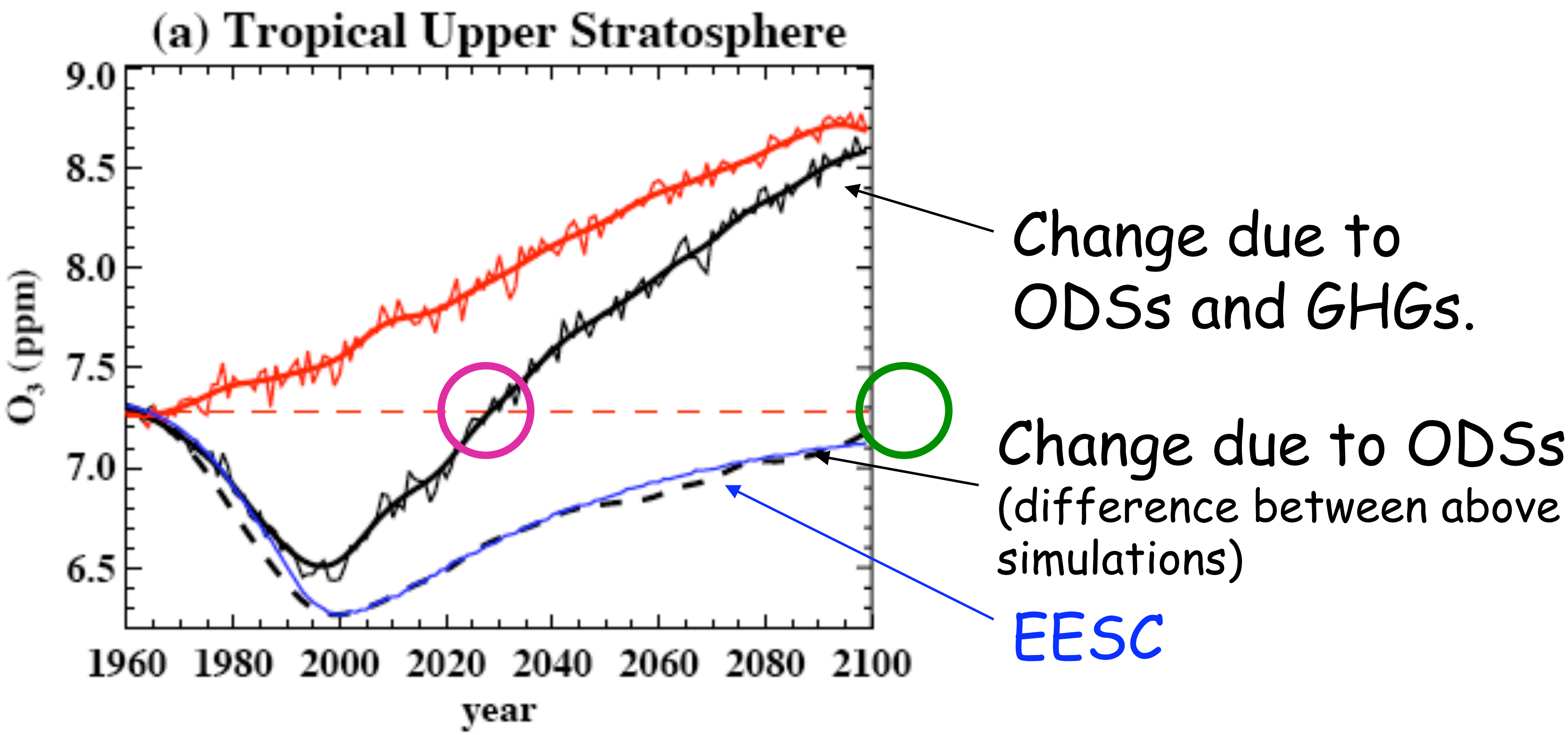
Climate changes due to increasing GHGs can also impact the date O_3 recovery milestones are reached. Two established milestones of full recovery are:

1. The date when O_3 returns to specified historical value (e.g., 1980).

2. The date when O_3 is no longer significantly affected by ODSs ["full ozone recovery from ODSs", WMO 2007].

Milestone (2) involves attribution but not (1).

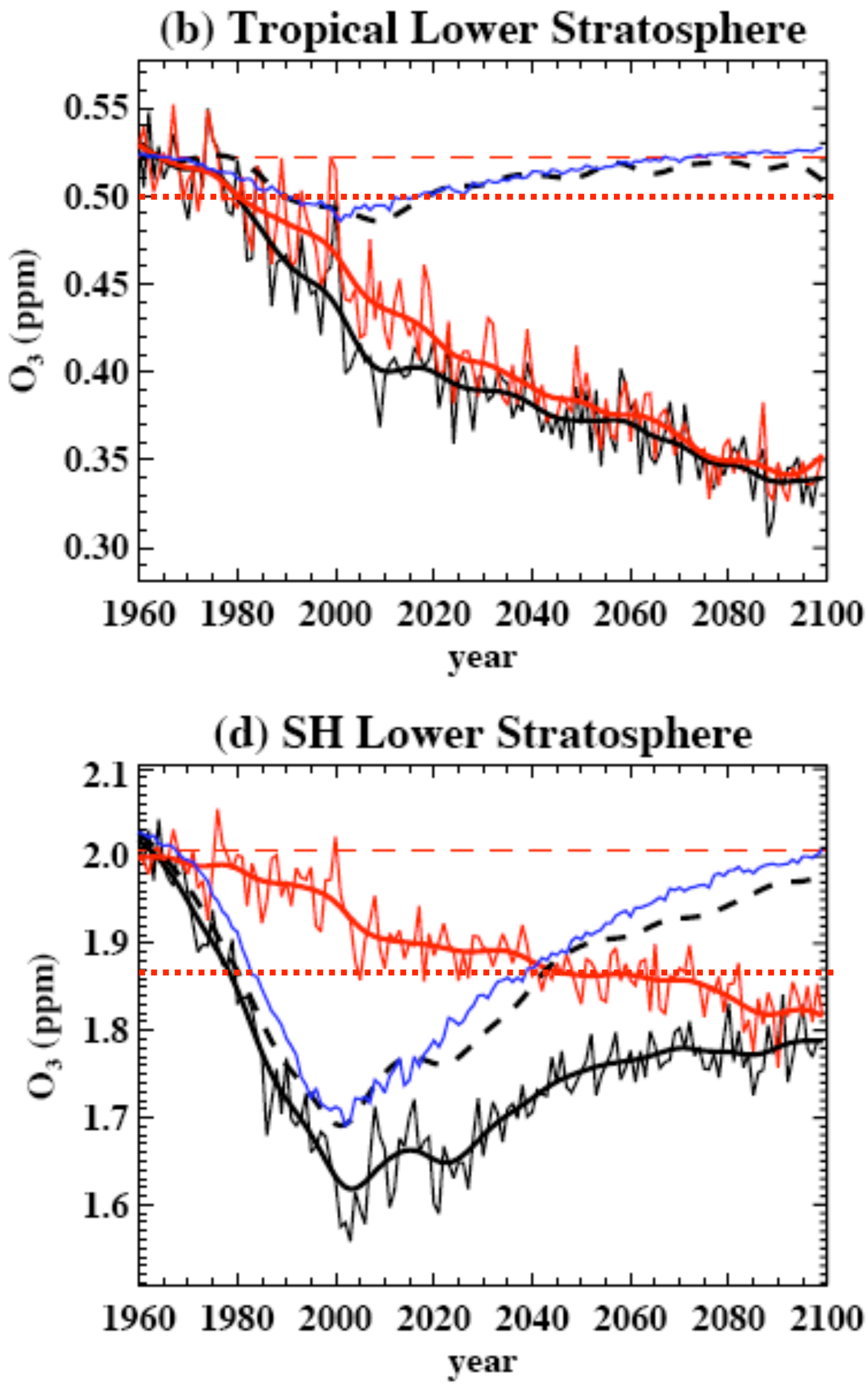
Recovery of Upper Stratosphere



O_3 returns to 1960s values around 2030

Full recovery from ODSs not until 22nd century.

Regional Variations



The recovery process differs between regions:

In some regions, O_3 may never return to 1980 or 1960 values even when anthropogenic ODSs are all removed from the atmosphere.

[Waugh et al. 2008]

Multi-Linear Regression (MLR)

Above analysis does not isolate the contribution of different mechanisms to the changes in ozone.

To do this multiple linear regression is performed, i.e.,

$$\Delta O_3(t) = \sum_j m_{X_j} \Delta X_j(t) + \epsilon(t).$$

where X_j are the different factors that could influence ozone (e.g., T, EESC) and the coefficients m_X are the sensitivity of ozone to the factor *X*, e.g,

$$m_T = \partial O_3 / \partial T$$

is the sensitivity to temperature changes.

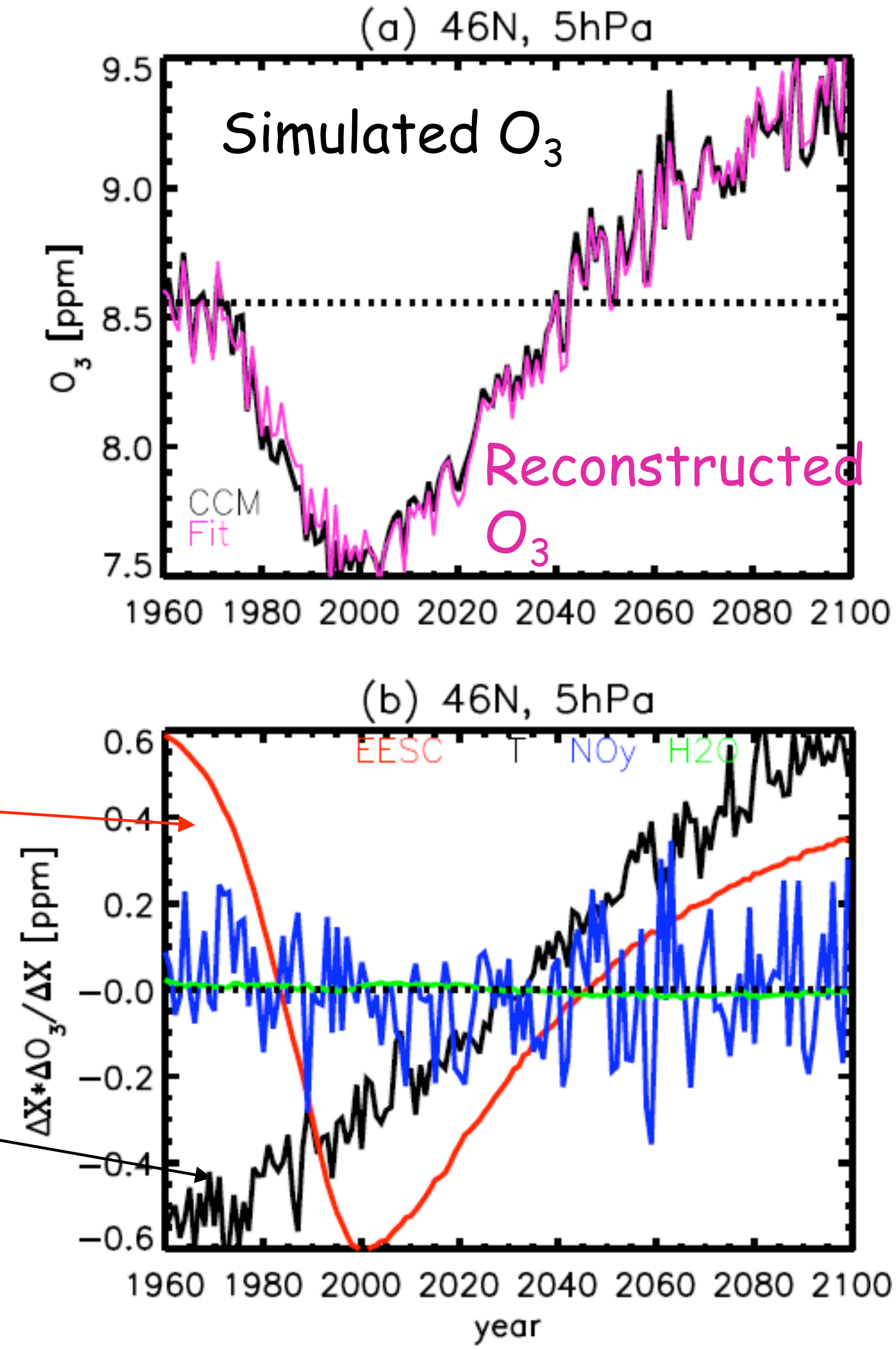
MLR method has been applied to GEOSCCM simulations.

X=EESC, T, NOy, HOx.

MLR: Upper Stratosphere

MLR reconstruction reproduces ozone variations

Long-term changes in O_3 are dominated by changes in **EESC** and **T**, with cooling the cause of long-term ozone increase.

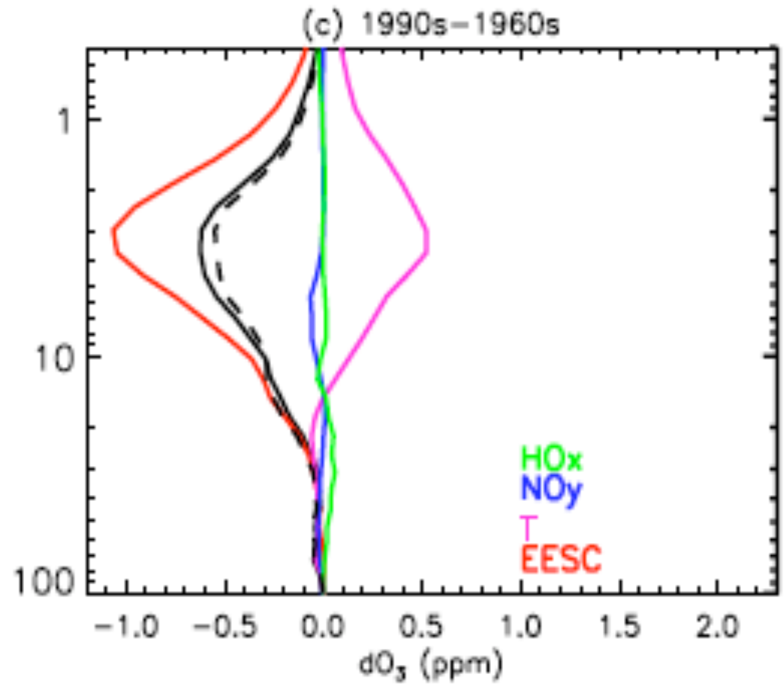


Contribution due to changes in **EESC**

Contribution due to changes in **T**

[Oman et al., in prep]

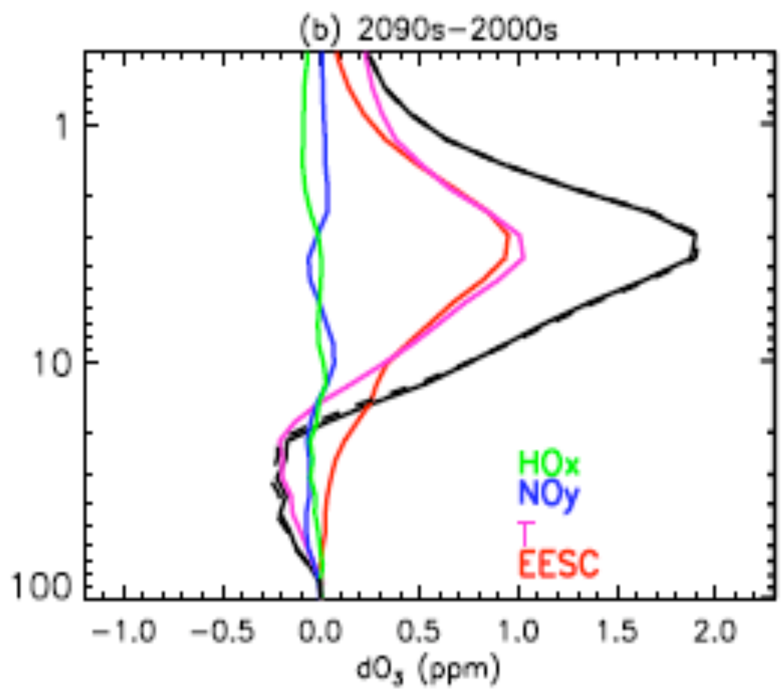
MLR: Vertical Variation



<u>Upper Stratosphere</u>: O_3 change is due to changes in EESC and T.

1960-2000 O_3 decrease due to increasing EESC ~ twice as large as increase due to cooling.

2000-2100 similar O_3 increase due EESC and T changes.



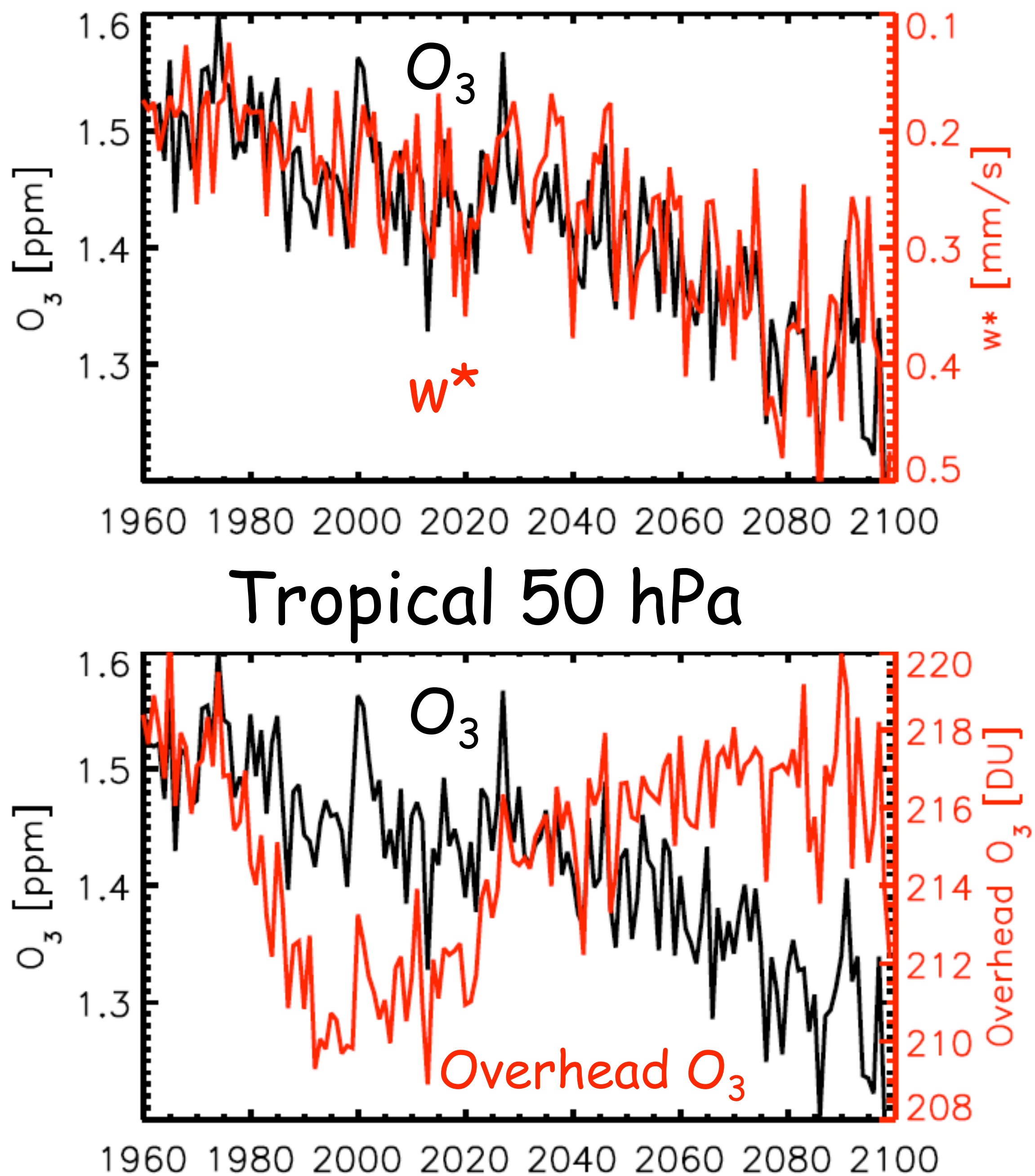
<u>Mid-Stratosphere (20 hPa)</u>: Limited O_3 changes.

<u>Lower Stratosphere</u>: O_3 decrease correlated with changes in T.

Changes in O_3 and T both due to increased upwelling.

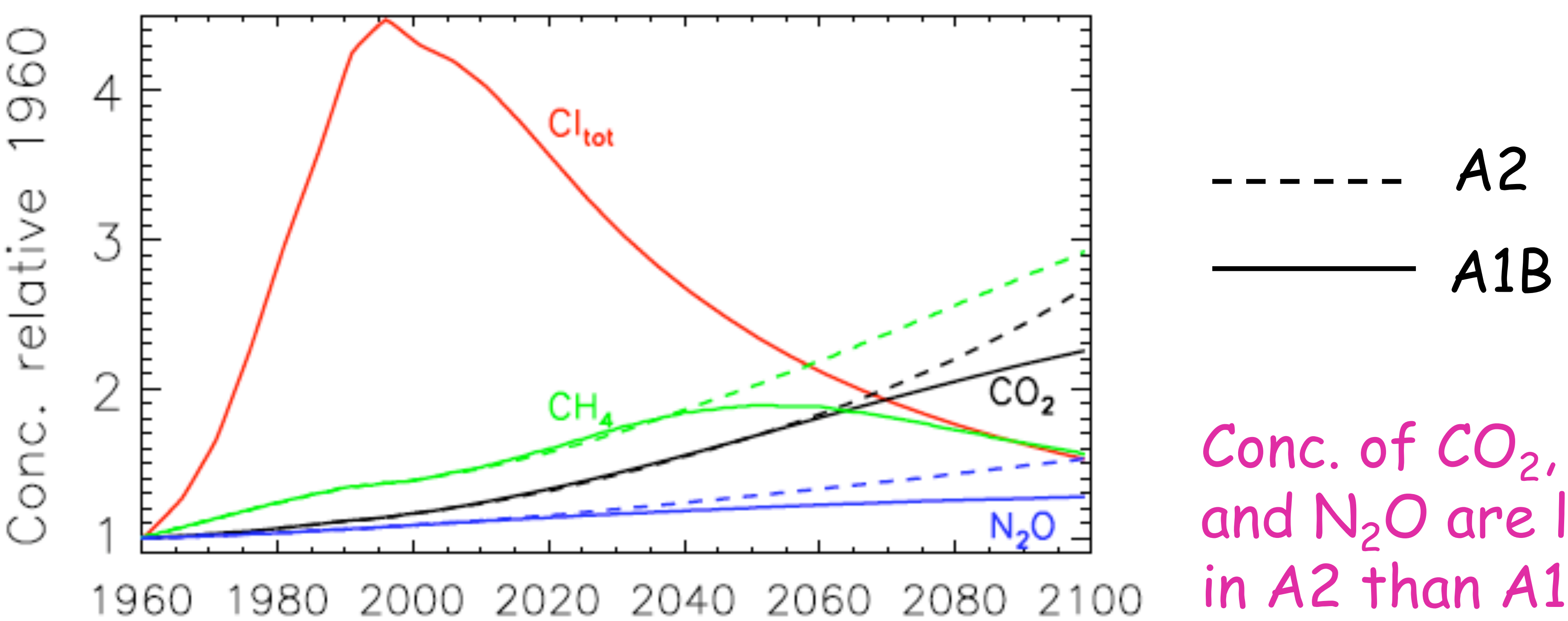
MLR: Tropical Lower Stratosphere

Decrease in tropical lower stratospheric is due to increased upwelling (and not changes in overhead O_3).



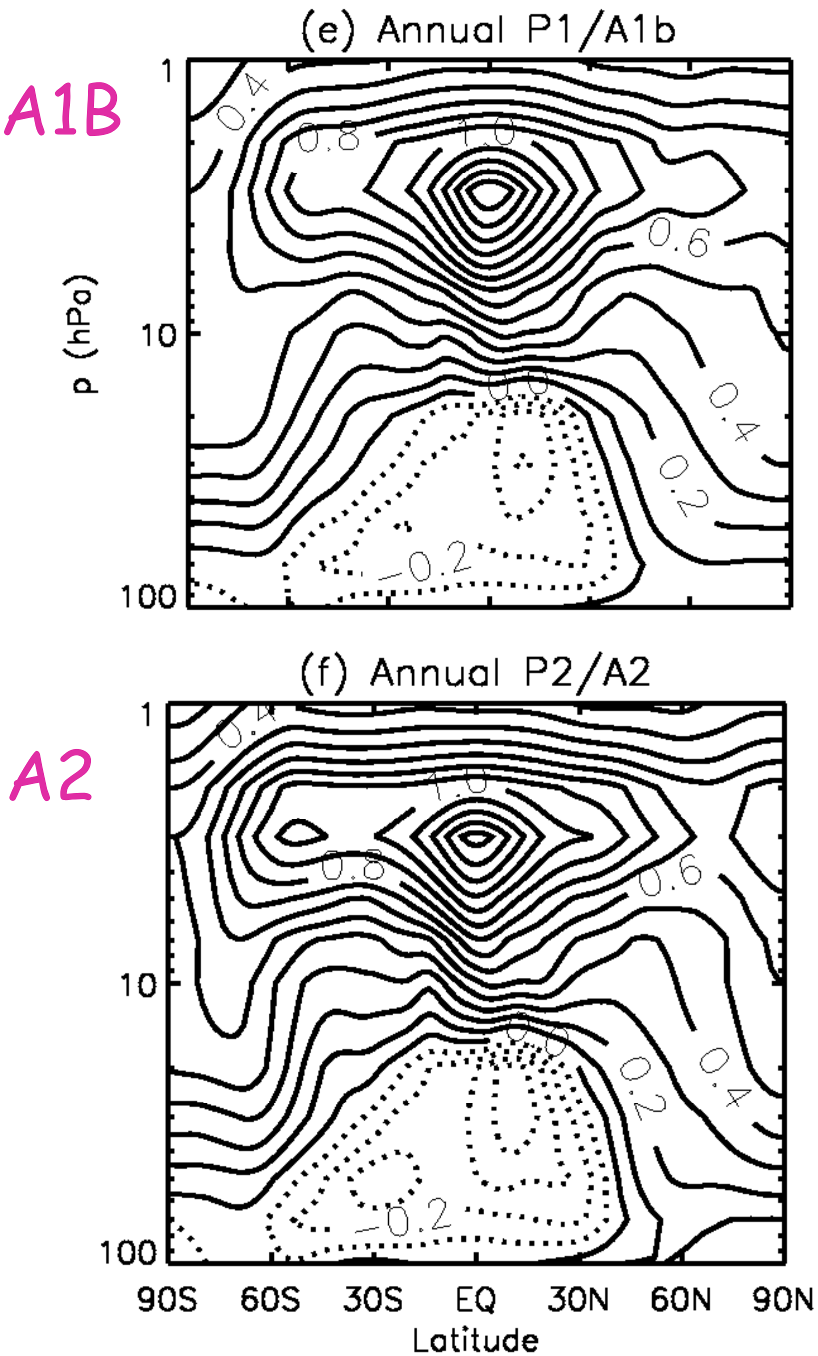
Sensitivity to GHG scenario

Above simulations all used a single GHG scenario. To examine sensitivity to GHG we compare GEOSCCM simulations using A1B and A2 scenarios (IPCC 2001). [Oman et al.; in prep]

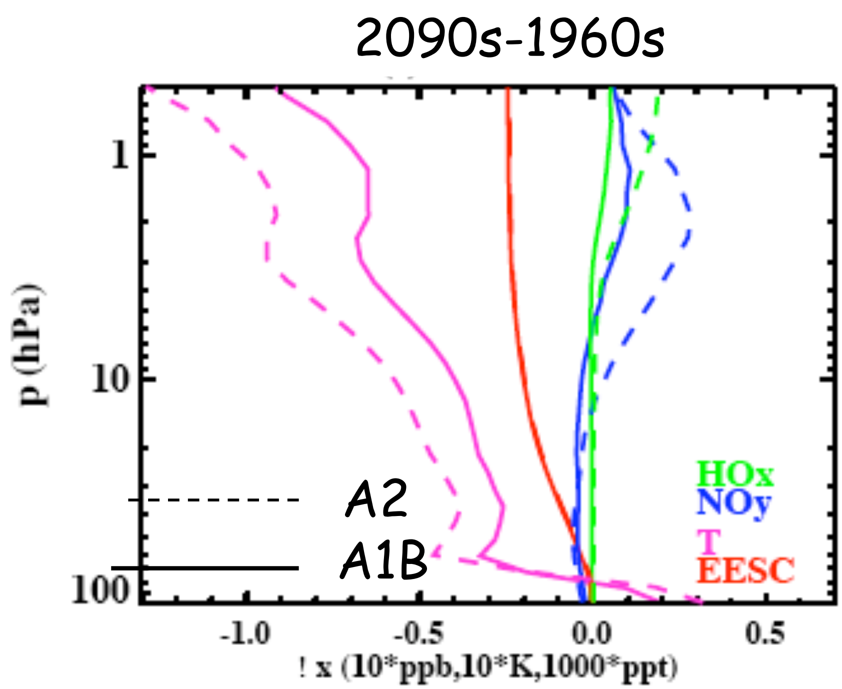


Conc. of CO_2, CH_4, and N_2O are larger in A2 than A1B

Sensitivity to GHG scenario: Change in O_3

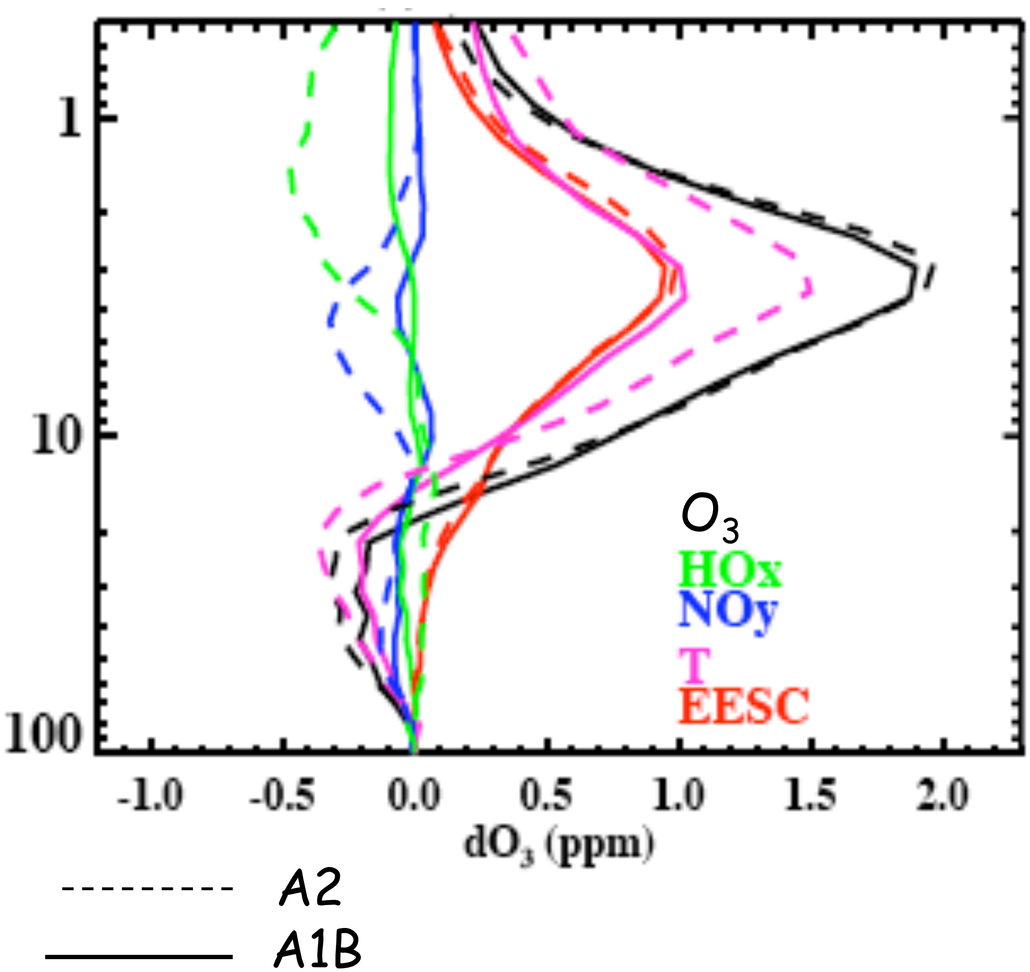


The change in O_3 between 1960 and 2100 is similar in the 2 simulations, even though the changes in T, NOy, and HOx are larger in A2 (consistent with larger CO_2, CH_4, and N_2O).



Sensitivity to GHG: Relative Contributions

Contributions to 1960s to 2090s
O_3 changes



The change in O_3 is similar in the 2 simulations as

the larger increase in O_3 in A2 due to the increased **cooling** is balanced by larger O_3 decreases due to increased **NOy** and **HOx**.

=> Increase in upper stratospheric O_3 in 21C will depend on relative increases of CO_2, CH_4, and N_2O [e.g. Chipperfield & Feng 2003].

IMPACT ON TROPOSPHERE

What will be the impact of stratospheric ozone recovery on tropospheric climate and weather?

Examine changes in

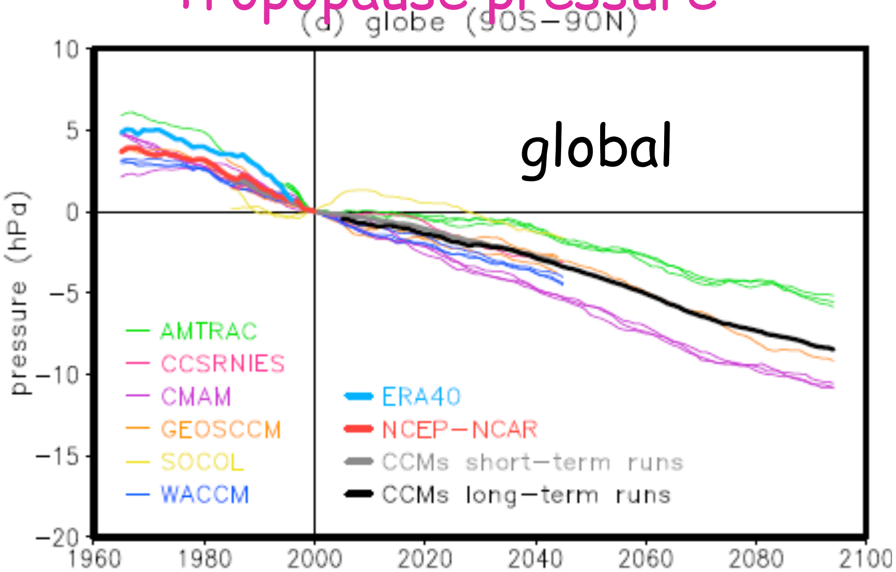
- Tropopause [Son et al., 2008a]
- Jet Location [Son et al. 2008b, Perlwitz et al. 2008]
- Hadley Cell [Son et al., in prep.]

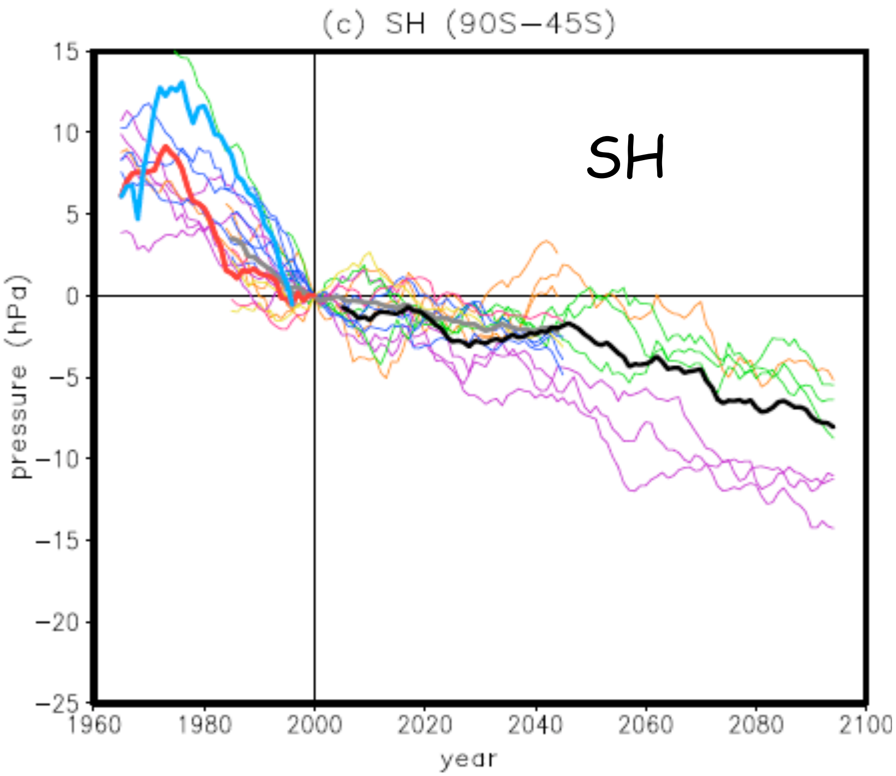
in CCMs (and IPCC AR4 models).

See Son et al., POSTER P91

Tropopause

Tropopause pressure

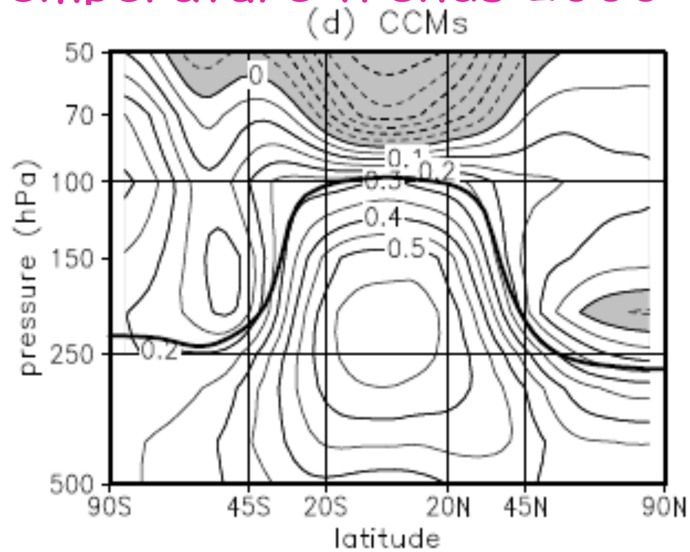




CCMs indicate tropopause pressure will continue to decrease, but future trends weaker than in the past.

Weakening due to ozone recovery.

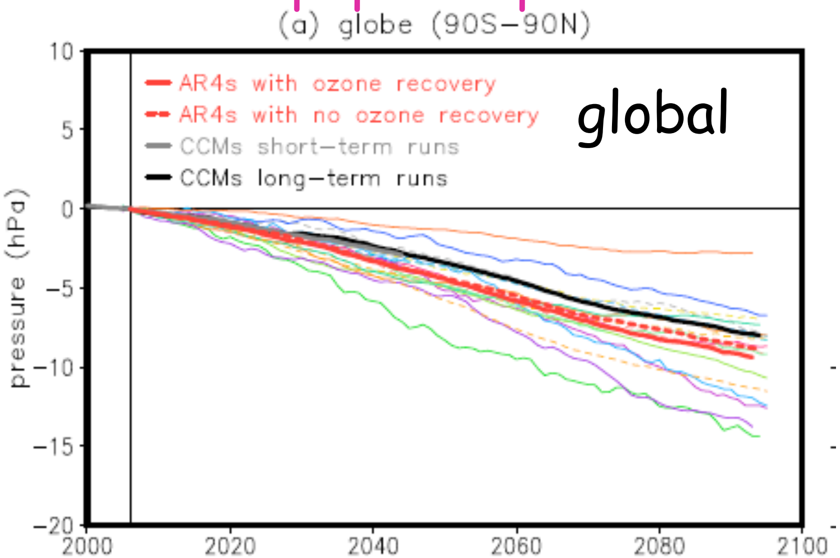
Temperature trends 2000-2099

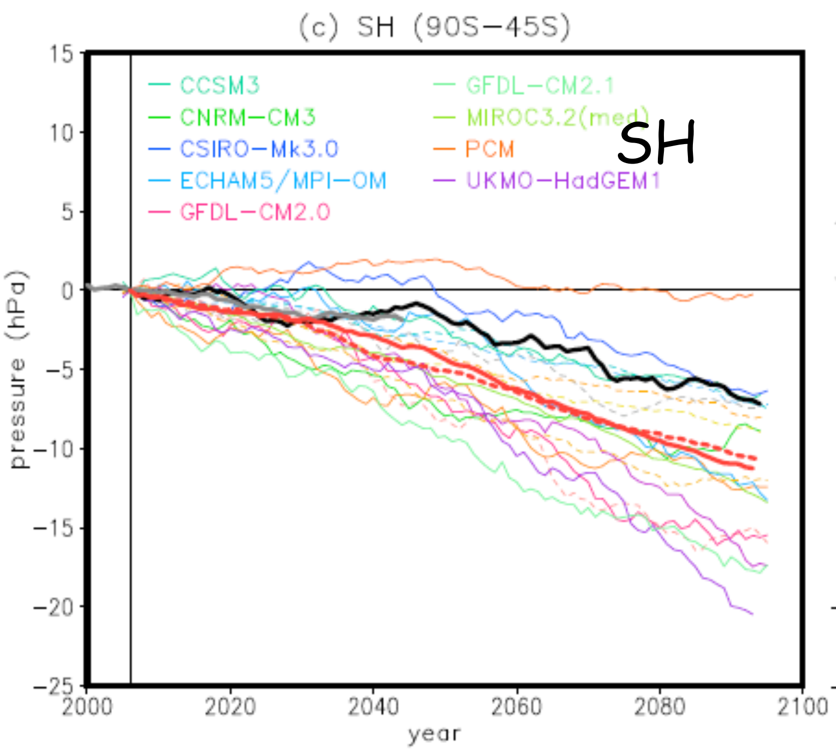


[Son et al., 2008a]

Tropopause II

Tropopause pressure

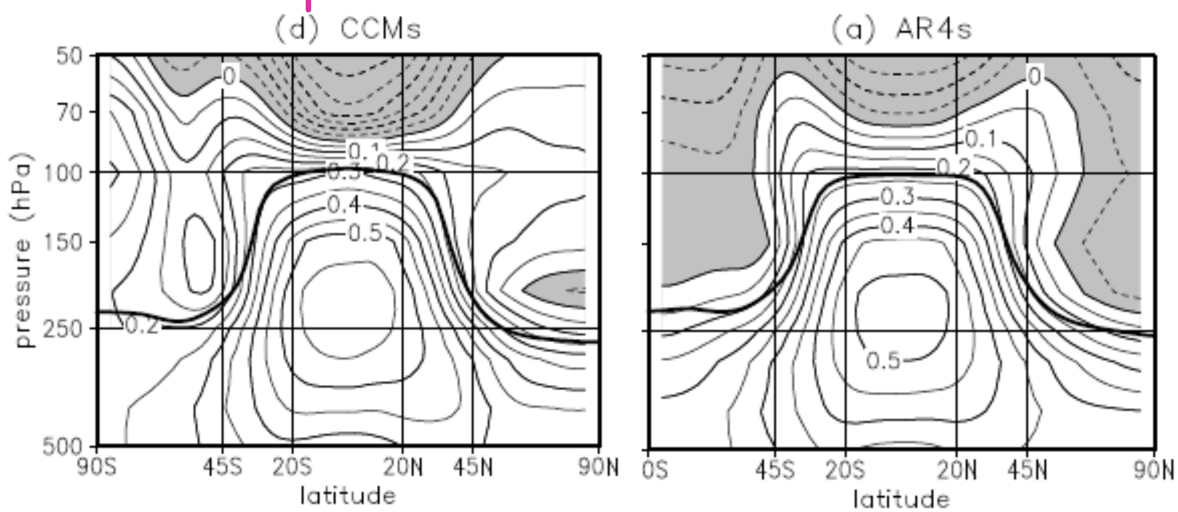




Future tropopause trend in CCMs are weaker than in IPCC models.

Consistent with differences in stratospheric temperature trends.

Temperature trends 2000-2099



[Son et al., 2008a]

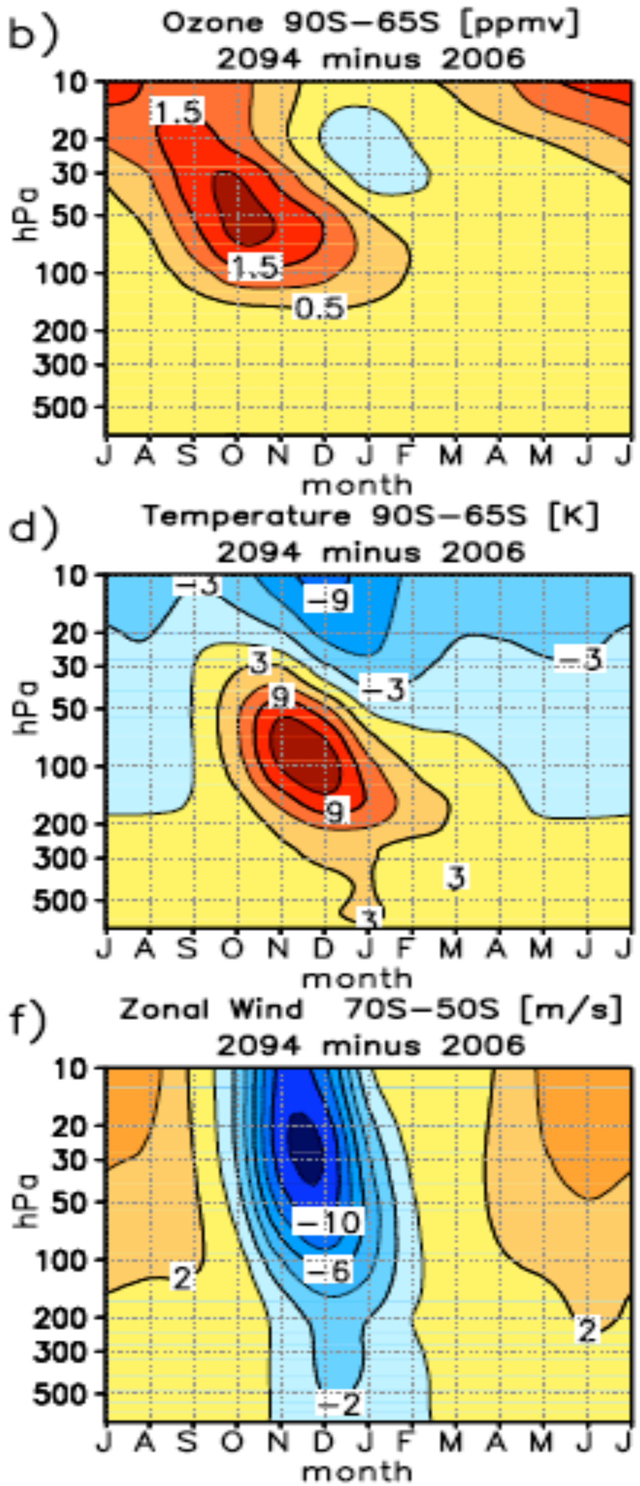
SH Tropospheric Jet

Analysis of GEOSCCM simulations Perlwitz et al [2008] shows that Recovery of ozone hole in 21C

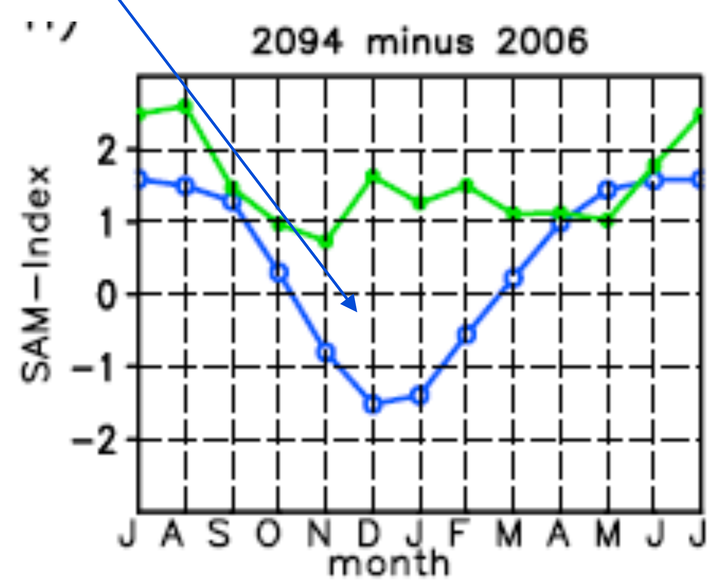
-> warming of polar UT/LS

-> weakening of mid-latitude (50-70S) zonal winds (in DJF)

-> decrease in SAM.

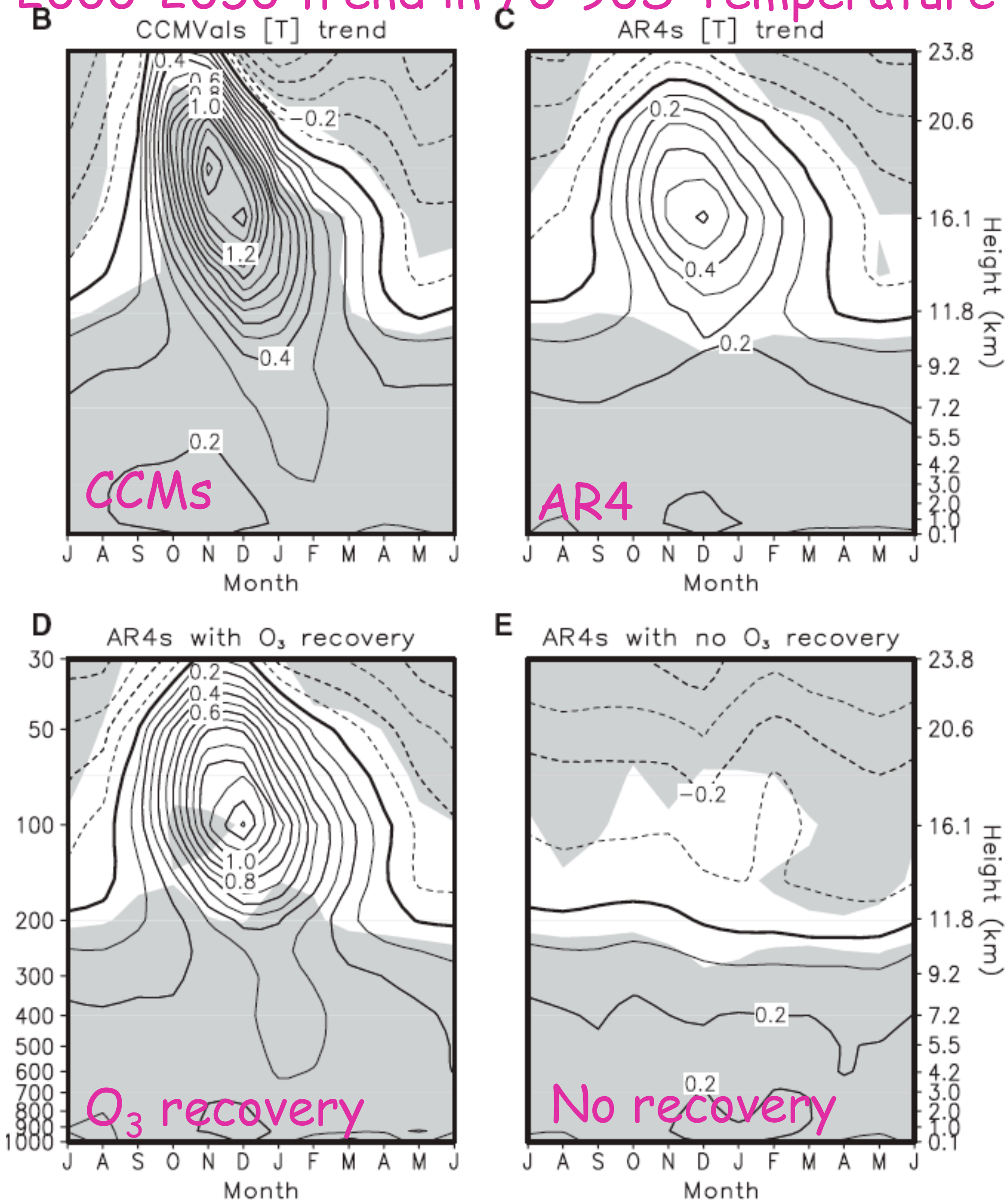


[Reverse of 1970 to 2000 changes]



Tropospheric Jet: Comparison with AR4

2000-2050 trend in 70-90S Temperature

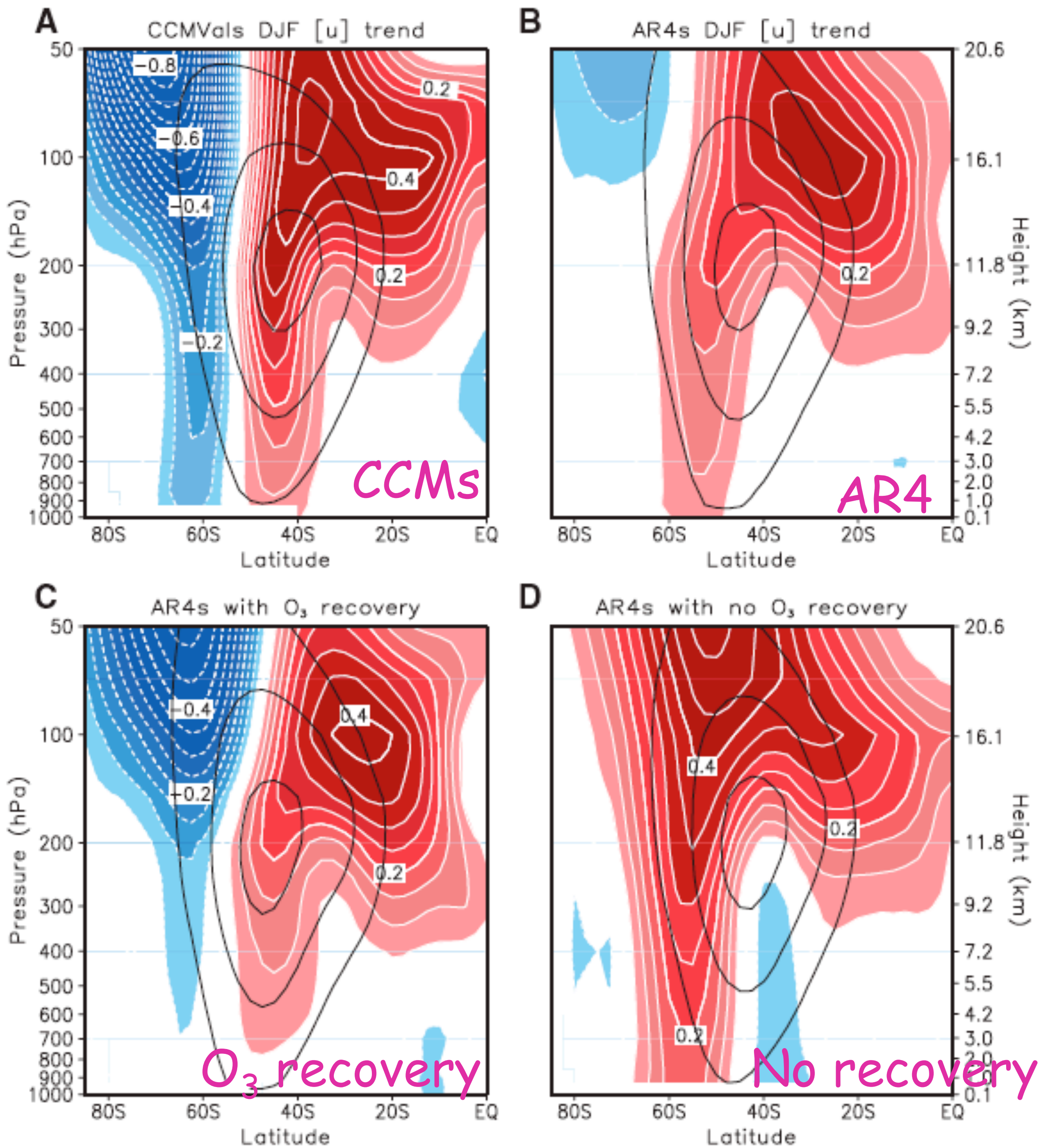


- Similar T change for multi-CCM mean.
- Much weaker change in IPCC AR4 simulations.
- Importance of ozone can be seen by comparing AR4 models with and without ozone recovery.

[Son et al., 2008]

Trop. Jet: Comparison with AR4 (cont.)

2000-2050 trend in Zonal Wind



- Deceleration poleward side of jet (decrease in SAM) also found in for multi-CCM mean.
- Opposite response in mean of IPCC AR4 simulations.
- Importance of ozone can be seen by comparing AR4 models with and without ozone recovery.
- Weaker response in AR4 models with O_3 recovery.

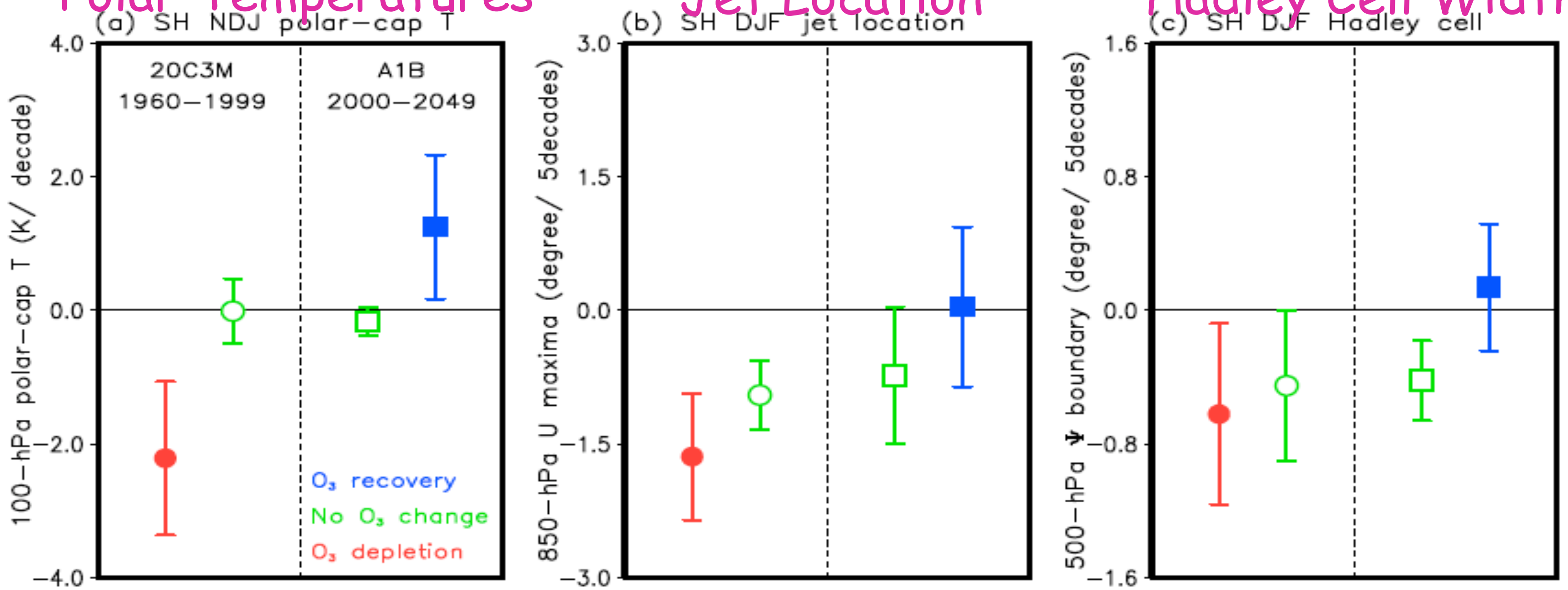
[Son et al., 2008]

Hadley Cell

Changes in polar ozone may also affect the width of the Hadley Cell (and hence location of subtropical dry regions).

Compare multi-model mean trends in IPCC models, with and without O_3 trends:

Polar Temperatures / Jet Location / Hadley Cell Width



Increase in polar O_3 -> polar warming
-> equatorward shift of subtropical jet and
contraction of Hadley Cell.

[Son POSTER P91]

What causes the differences between CCMs and AR4 models with recovery?

Possible causes of differences include

1. Poorly resolved stratosphere in AR4 models,

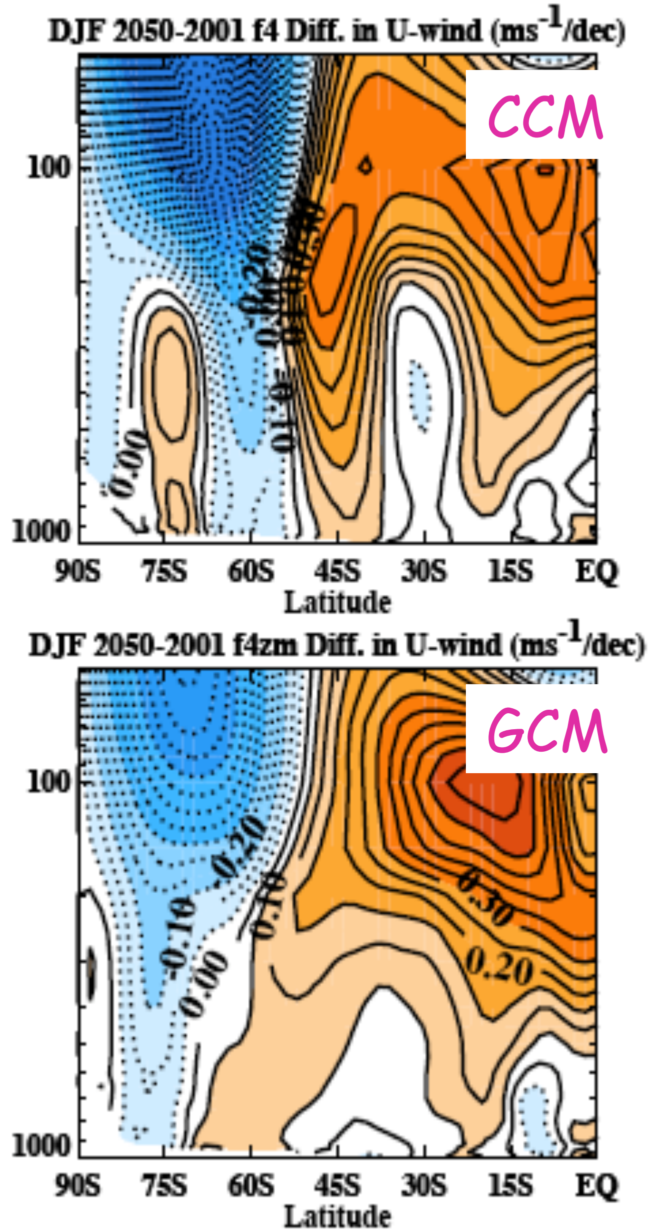
2. Lack of dynamical ocean in CCMs,

3. Lack of interactive chemistry in AR4 models.

Test (3) with GCM run using monthly-mean zonal-mean O_3 from CCM, and everything else the same in GCM and CCM. [See also Sassi et al. 2005, Crook et al. 2007]

Testing impact of interactive chemistry.

2000-2050 trend in Zonal Wind



1. CCM "REF2" run.

2. GCM run with monthly-mean zonal-mean O_3 from CCM "REF2" run.

Response in GCM is weaker than CCM, with difference similar to CCM vrs AR4 with recovery.

[Luke Oman]

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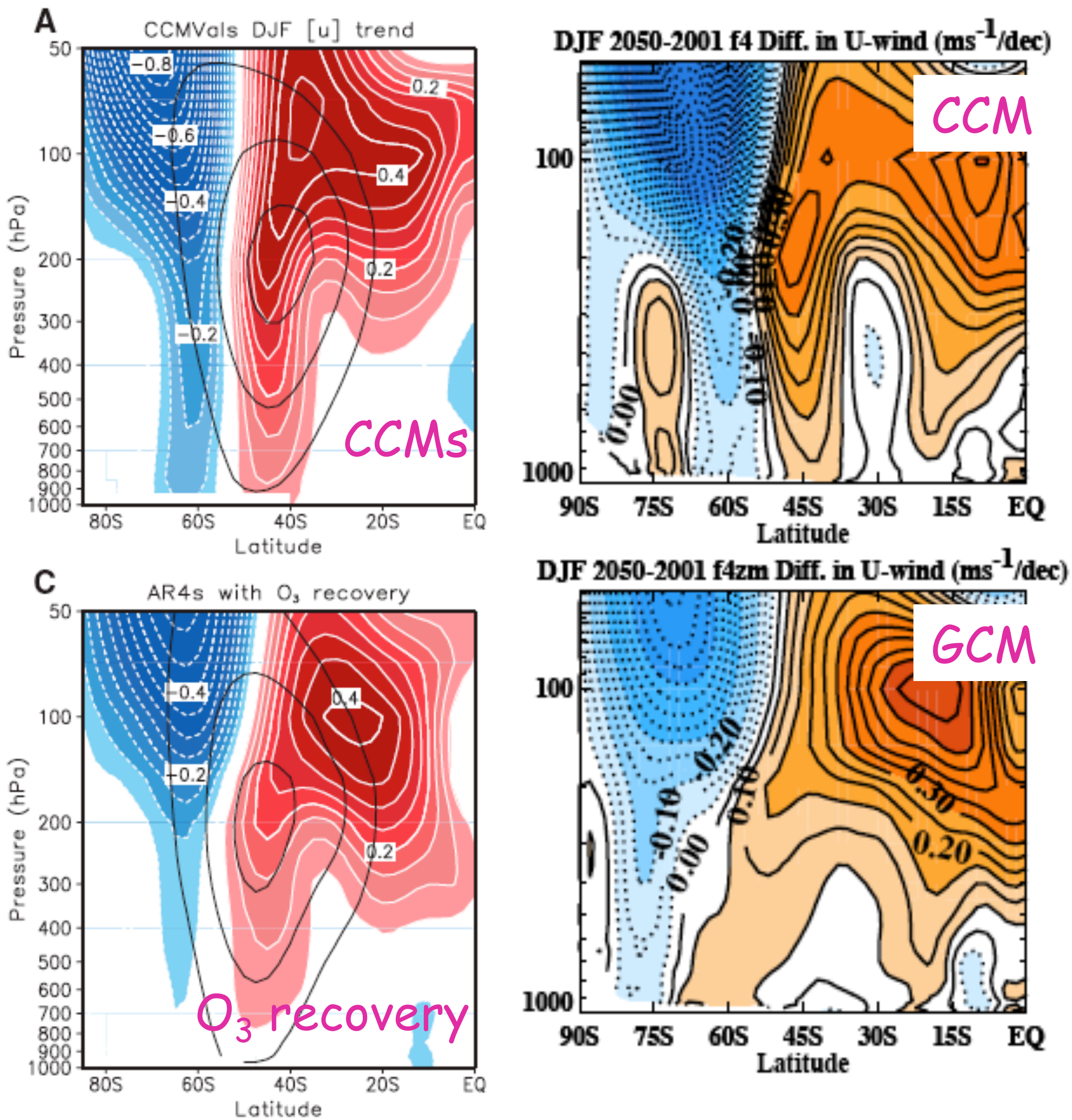

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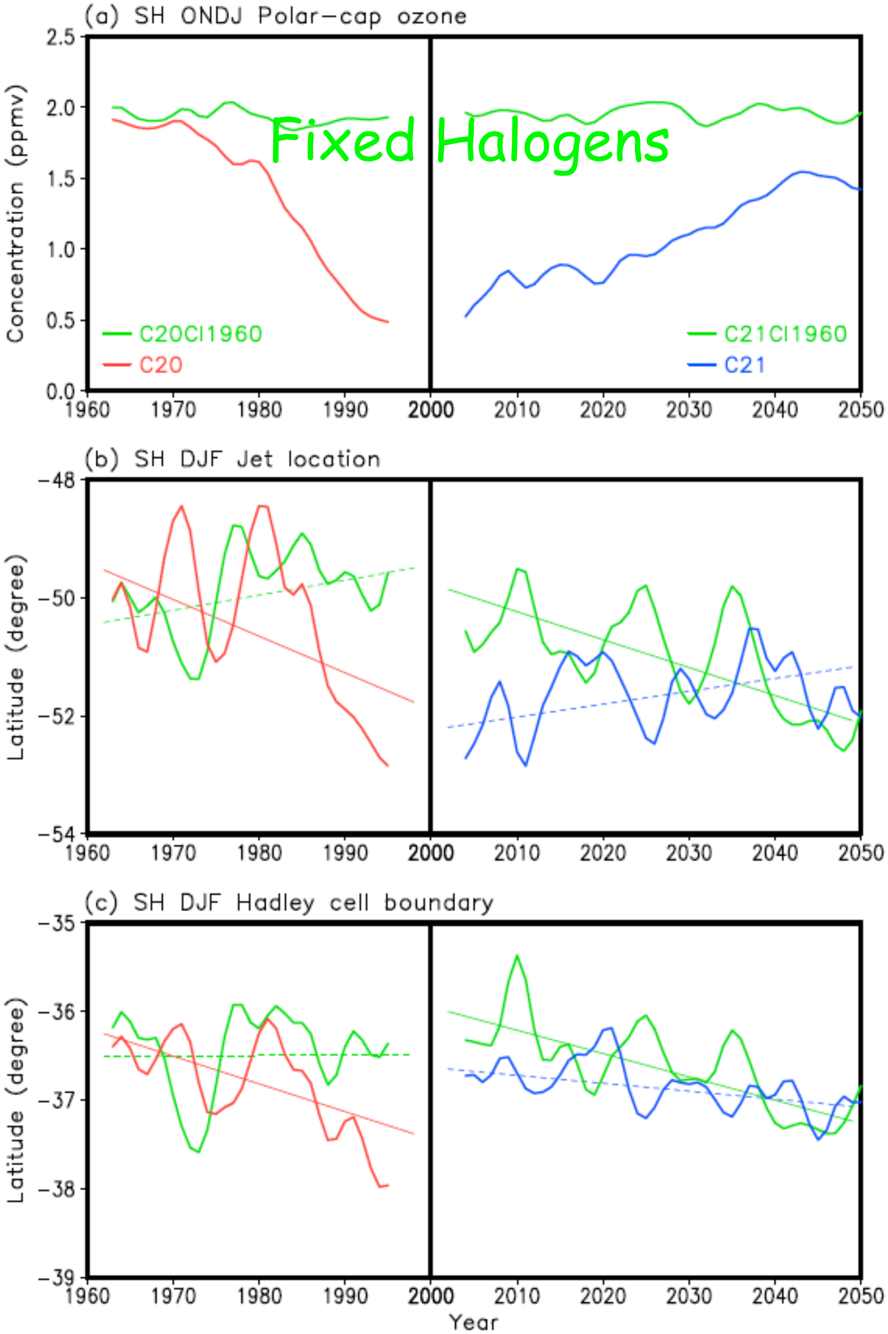
[Luke Oman]

SUMMARY

- Climate change due to increased GHGs will impact O_3 recovery, primarily through cooling and changes in circulations (details depend on GHG scenario).
- CCMs project similar long-term O_3 evolution, but large spread in magnitude of anomalies and "recovery dates".
- Differences in Cly among CCMs are key in diagnosing intermodel differences in O_3 recovery.
- The timing of established milestones varies between milestones and regions.
- Ozone recovery is likely to have a profound affect on SH tropospheric climate (e.g, jet location, Hadley Cell extent).

THE END

Hadley Cell II



GEOSCCM simulations also indicate that an decrease (increase) in polar O_3 leads to an poleward (equatorward) shift of subtropical jet and expansion (contraction) of Hadley Cell.

However, SSTs also important and ensemble runs needed.

[Son et al., in prep]

Impact of GHGs: Polar Stratosphere