Antarctic Stratospheric Sudden Warming and Split Ozone Hole of 2002

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OUTLINE

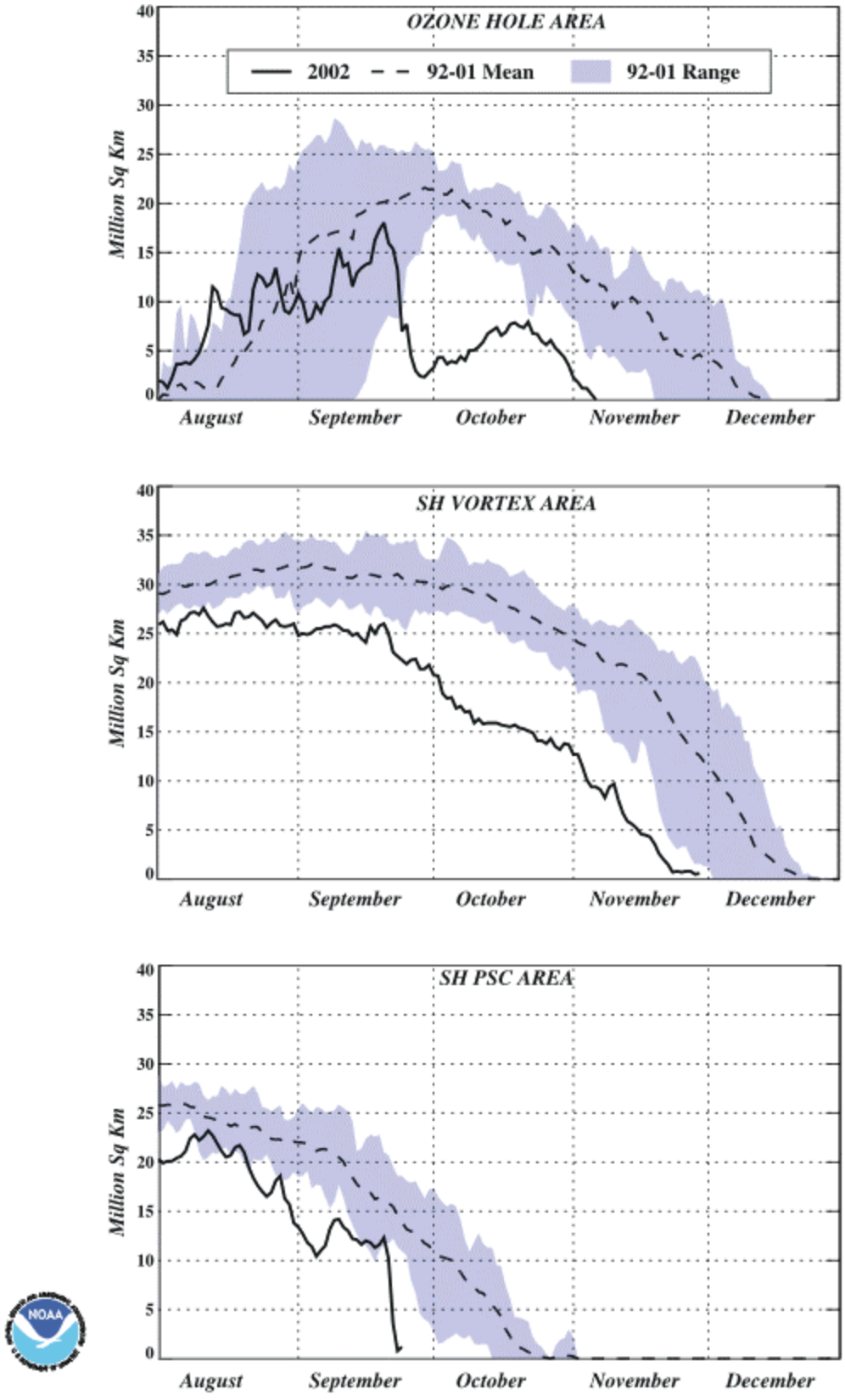
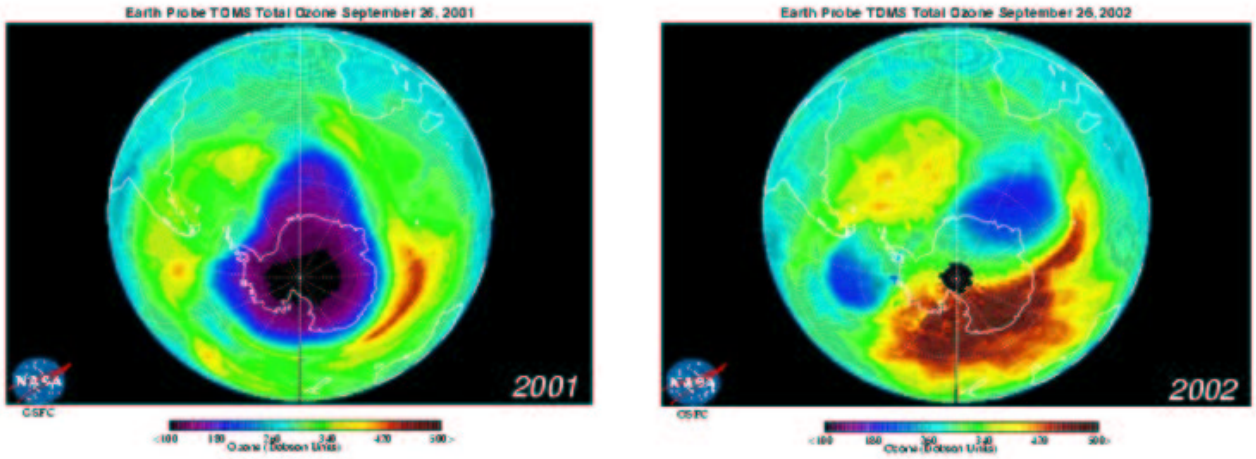


Figure 11. Time series of area of the ozone hole (total ozone < 220 DU), size of SH polar vortex (defined as 32 PVU contour enclosed area at 450K isentropic surface), and size of temperature < -78 C (also on the 450K isentropic surface). The shaded region illustrates the range of area sizes over the past ten years. The dashed line is the daily mean area for the past ten years.

What a Difference a Year Makes



Minimum = 99 Dobson Units *Minimum = 180 Dobson Units*

Courtesy of http://toms.gsfc.nasa.gov/

❖ **Antarctic ozone hole exhibited unprecedented features in 2002, (smaller size and split into two).**

Now our questions are:

1) **What caused this usual event?**
2) **Is the Stratosphere well understand?**
3) **Was it a signal of recovery of O_3 layer?**
4) **What are the implications for future ozone trend or climate trends?**
5) **Can SLIMCAT reproduce such event?**
6) **What can we infer from model output?**

Ozone Hole observation

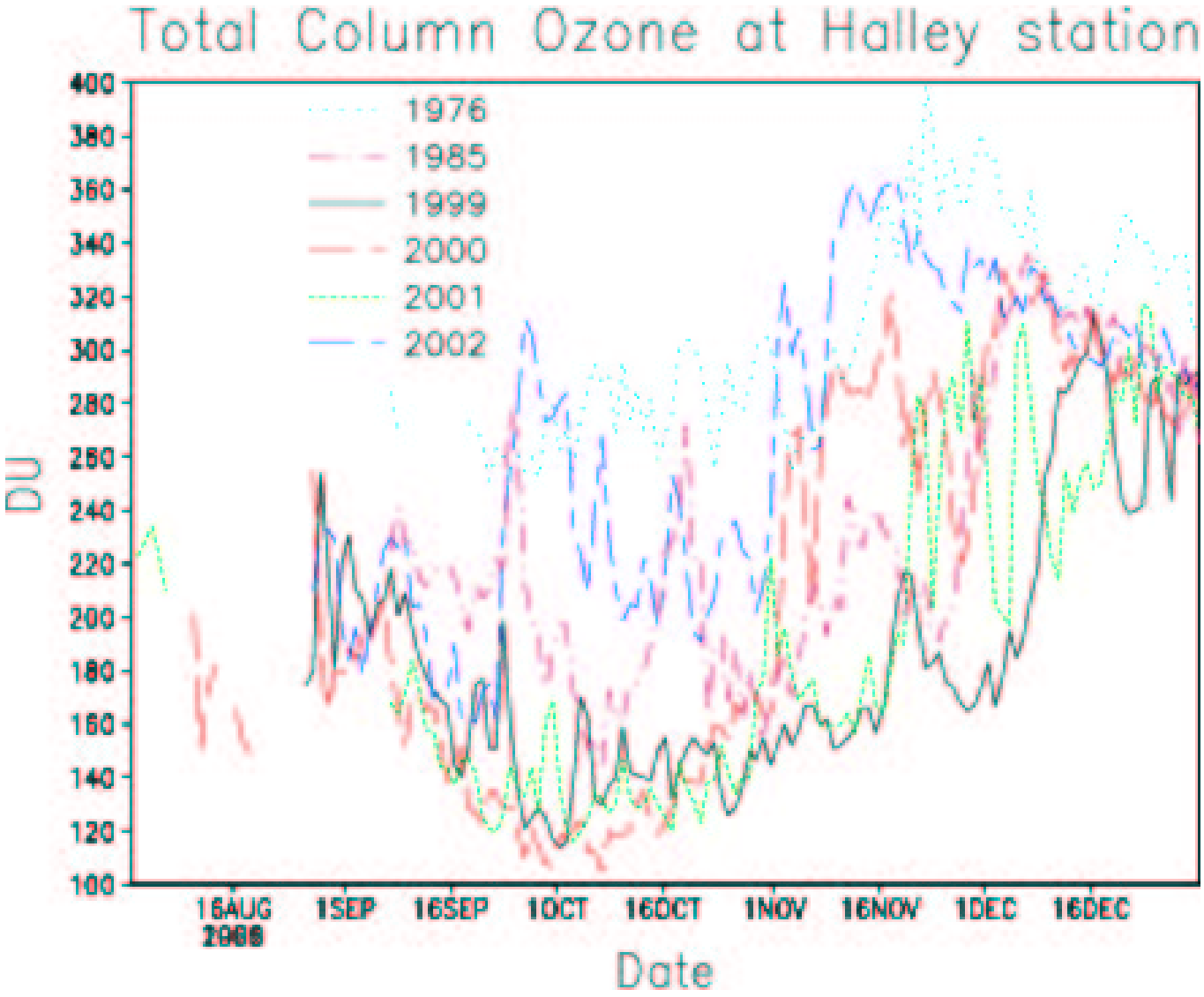


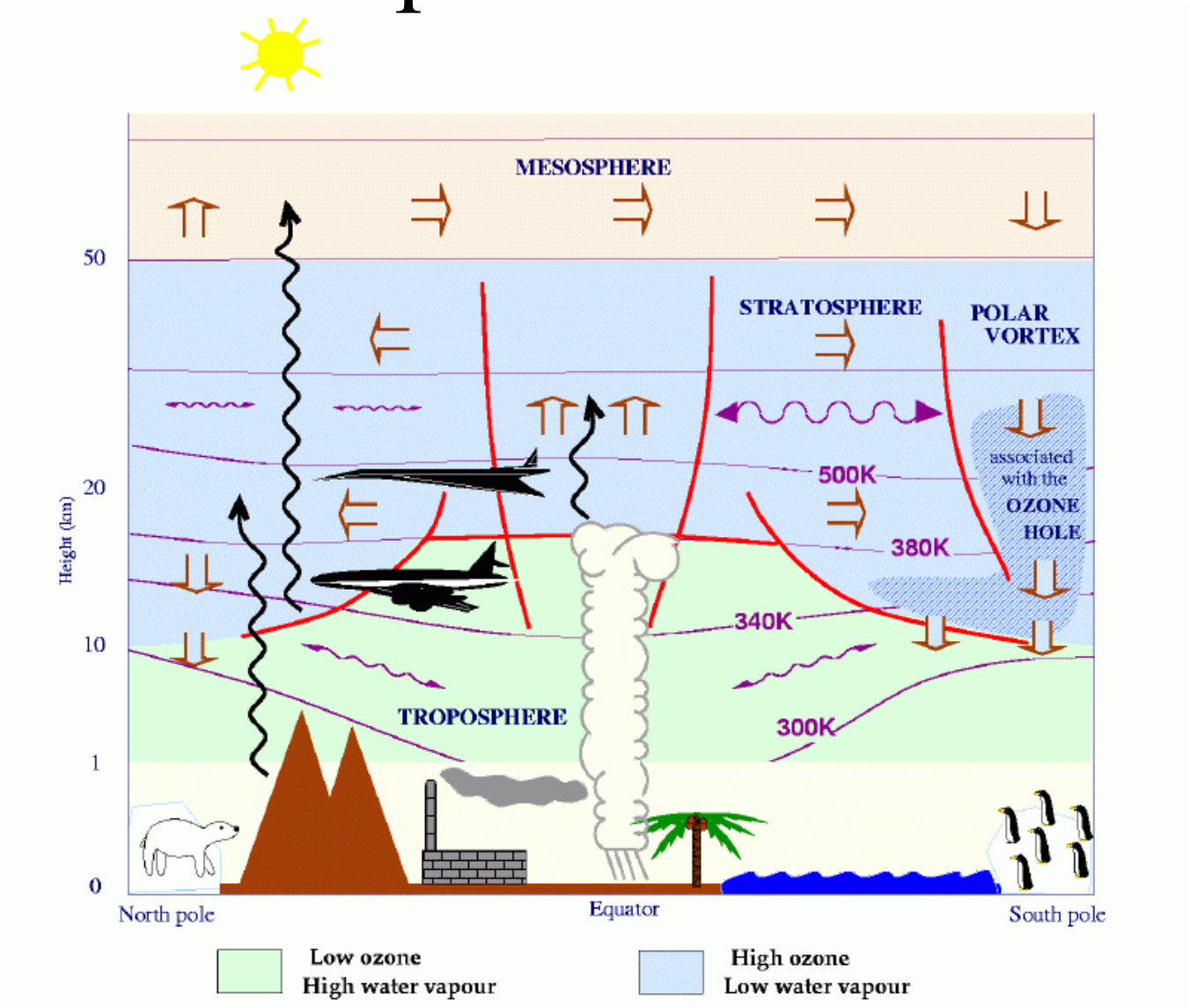
Fig. Total Column Ozone observed at Halley Station (~75S,26W) for selected years. Data Courtesy of BAS

Ozone Hole: area enclosed by 220DU contour

Firstly discovered by Farman et al (1985)

- **Begins to develop in Aug., broken up in Dec.**
- **2002 is very abnormal**

Transport in the UTLS

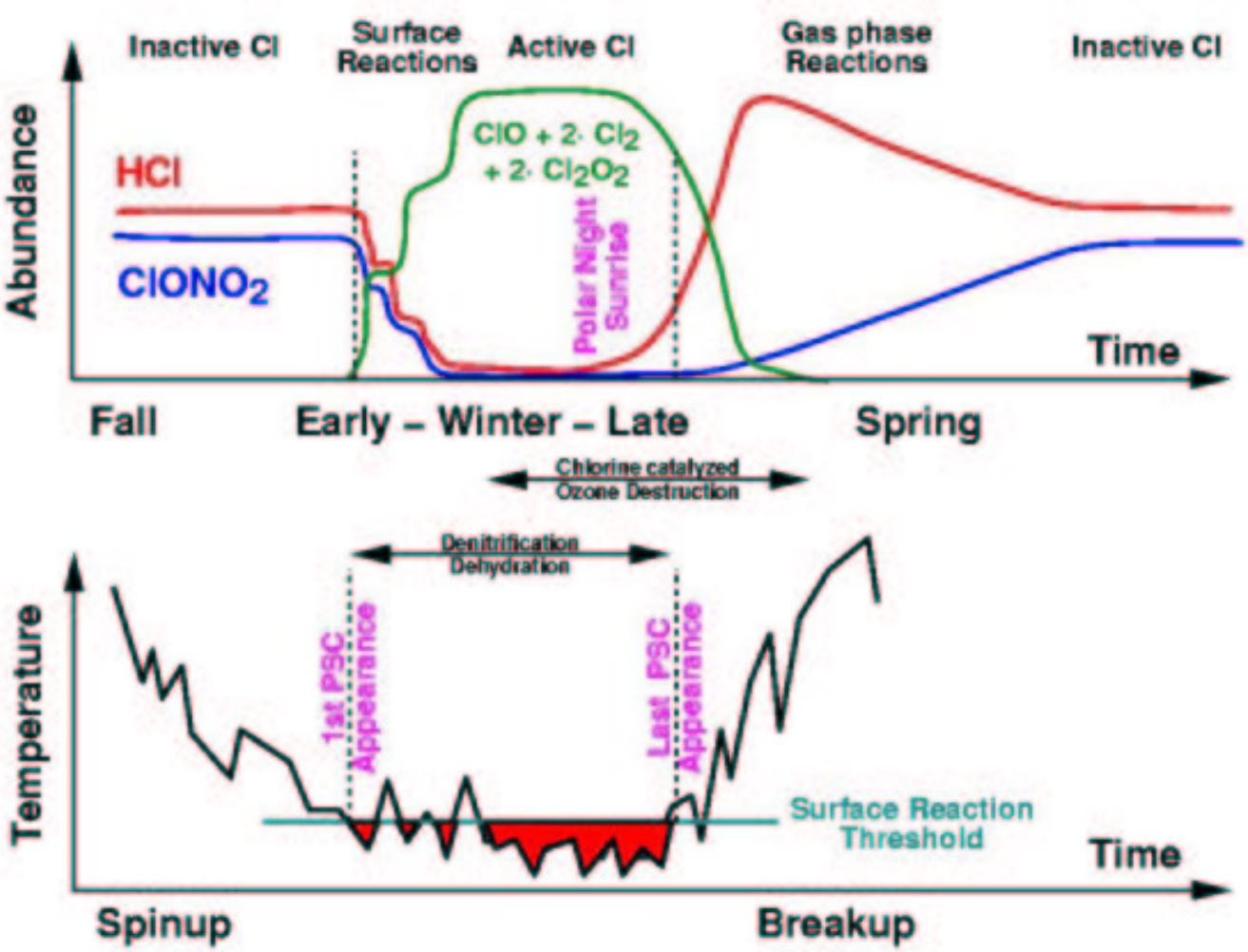


Schematic Diagram showing pattern of transport and mixing in the troposphere and stratosphere

Courtesy of Emily Shuckburgh in Uni. Of Cambridge

The purple lines represent isentropic surfaces. The arrows denote mixing. The red lines represent barriers to transport along isentropic surfaces. The approximate altitude at which passenger jets fly is shown . The green region (the troposphere) typically has low ozone and high water vapour mixing ratios. The blue region (the stratosphere) typically has high ozone and low water vapour mixing ratios.The blue shaded area represents the region in which ozone loss occurs in spring

Ozone depletion Chemistry

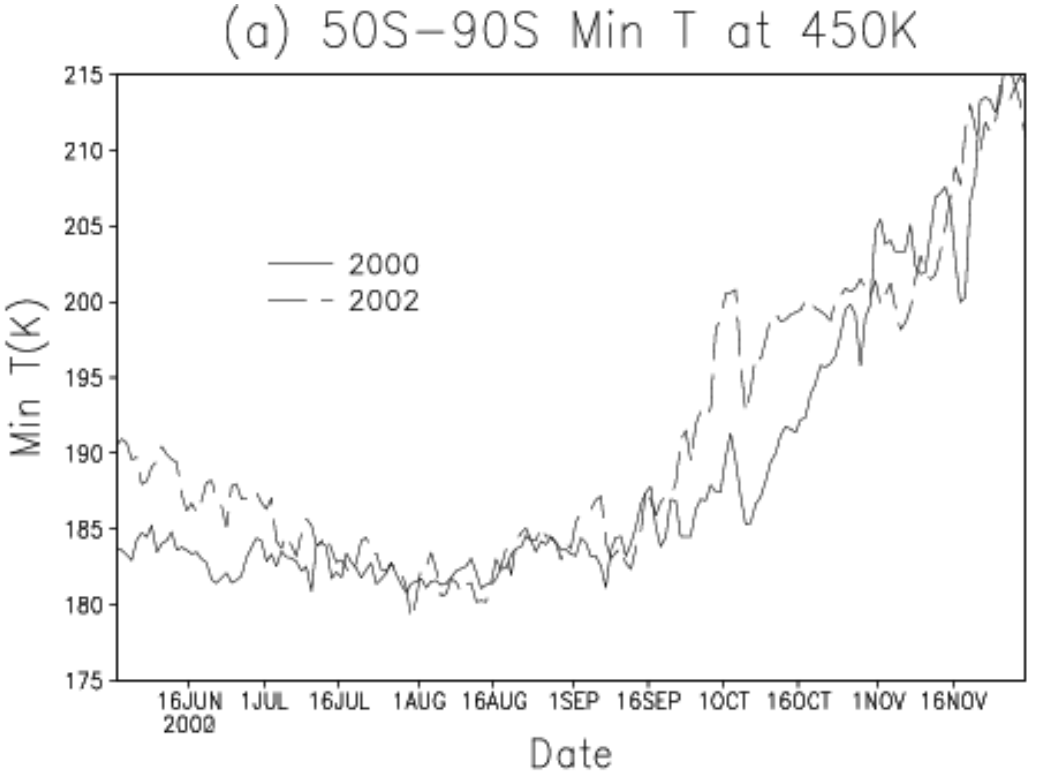


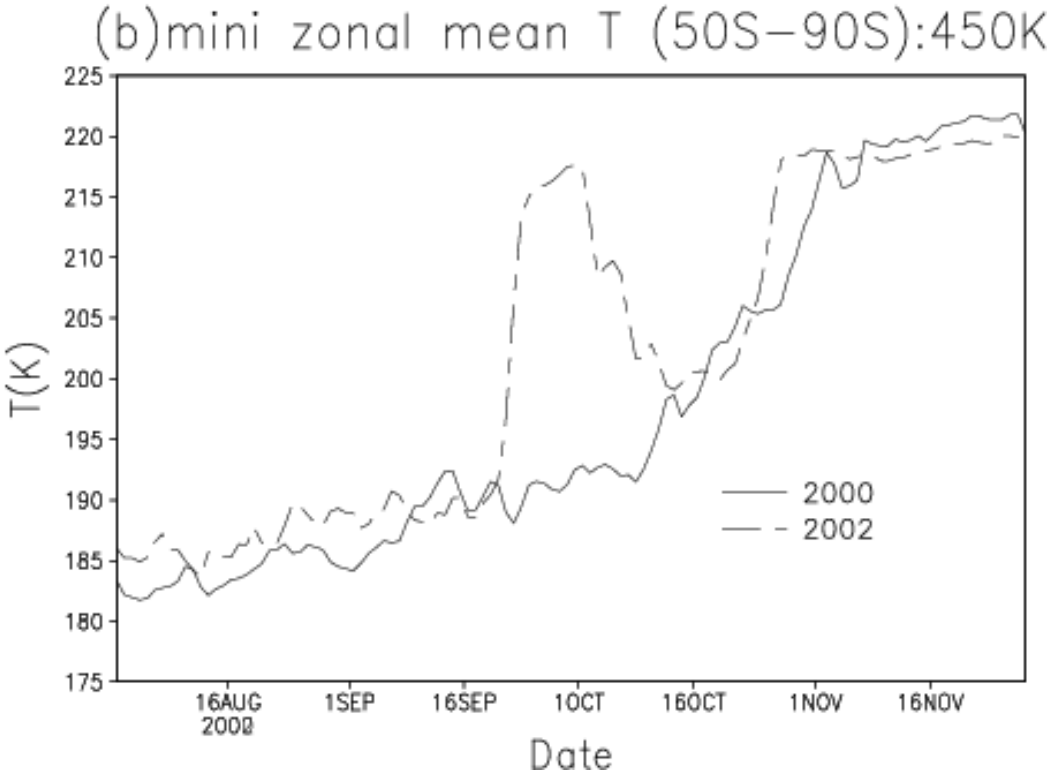
Heterogeneous Chlorine Chemistry Activation

Webster, C.R. et al., Science. 261:1130-1134. 1993

- **Formation of the ozone hole occurs during the polar night**
- **Temperature cold enough for formation of PSCs**
- **Heterogeneous chemistry on PSCs transforms inactive chlorine compounds into active forms**
- **Sunlight returns in spring and the Cl_2 is immediately photolyzed into free chlorine, Cl which destroys Ozone**

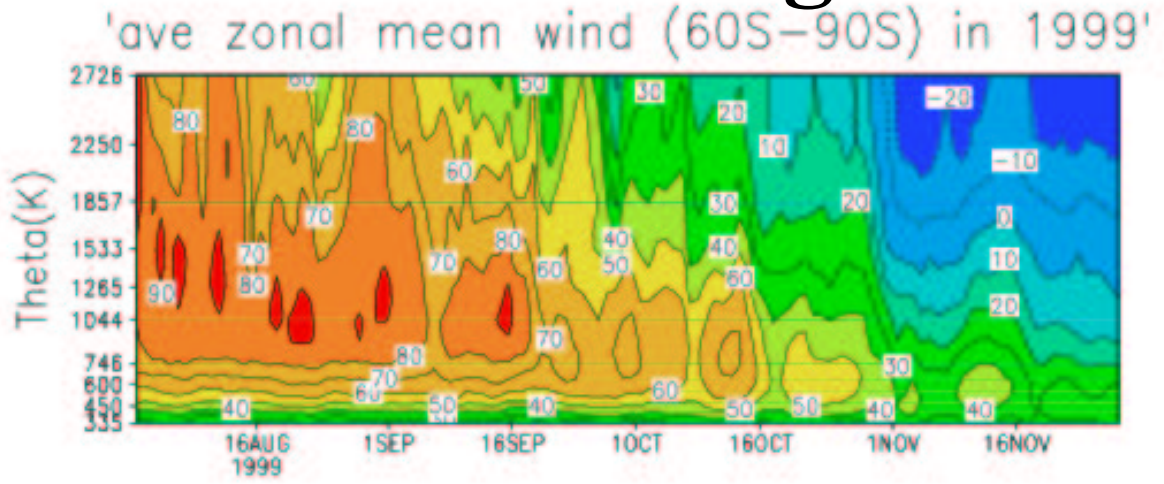
Sudden warming: Temperature

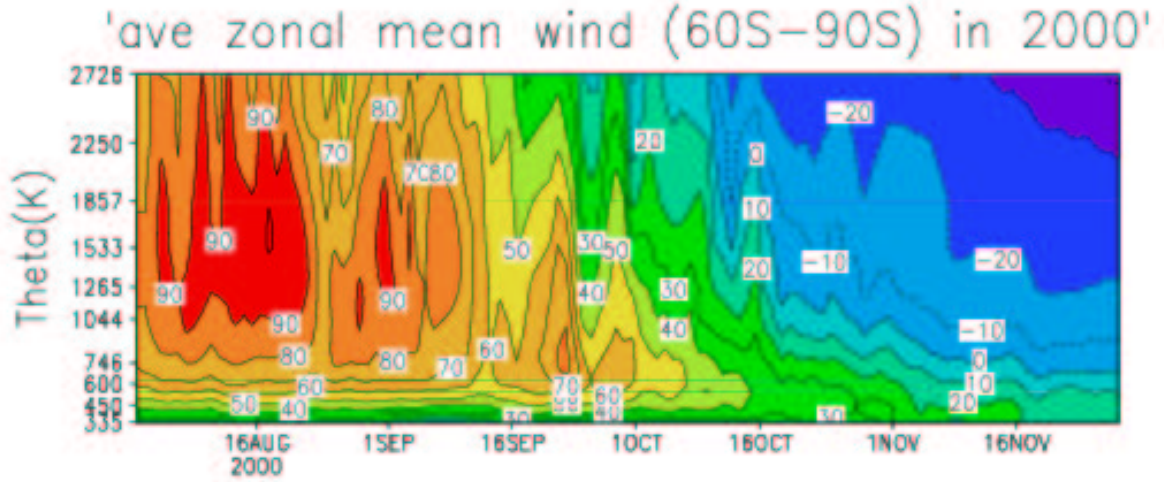


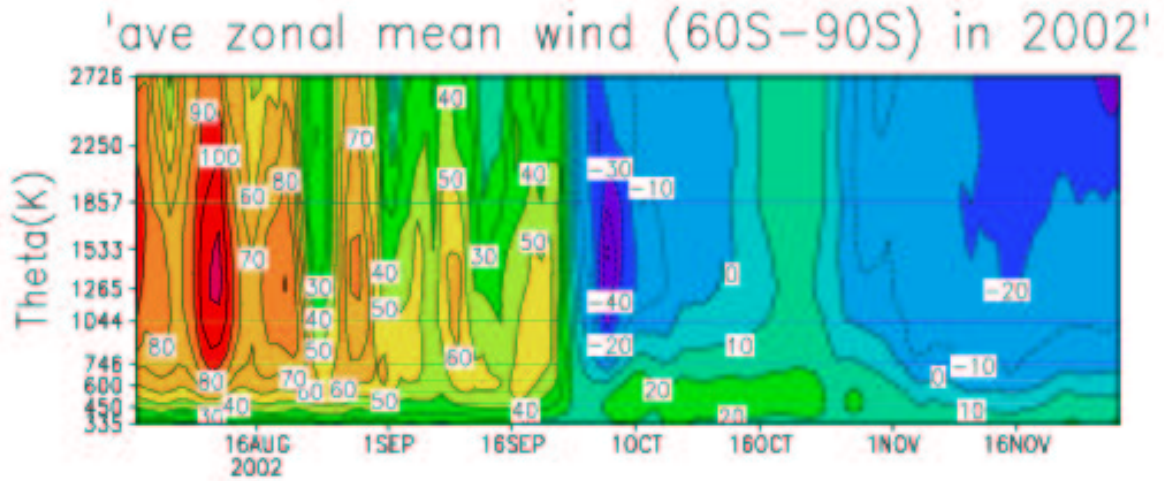


- Polar Temperature sudden warming late Sep

Sudden warming: Wind







- **Westerly Wind in 1999 and 2000, But**
- **2002 zonal mean wind turn easterly poleward of 60S in late September**

Stratospheric Sudden Warming(SSW)

Breakdown of polar vortex accompanied by warming of polar stratosphere

Temperature increase suddenly in a few days

Enhanced propagation of planetary waves

<u>Major Warming</u>: Zonal mean zonal wind reversal (polarward of 60S or 60N)

Occur on average every other Northern winter

Not observered Sourthern Hemisphere before 2002(SH polar vortex is stronger than in NH)

<u>Minor Warmings</u>:Circulation does not reverse

Occurs more frequently and on both hemisphere

Theory:Transformed Eulerian Mean (TEM) equations (Holton, 1992)

SLIMCAT 3D-CTM

- **3D Off-line Chemical Transport model**
- **Isentropic Vertical coordinate**
- **Tracer Transport**

Horizontal: Prather 2nd order moment scheme

Vertical: MIDRAD radiation Scheme

- **Detailed Chemical Scheme**

41 chemical species;

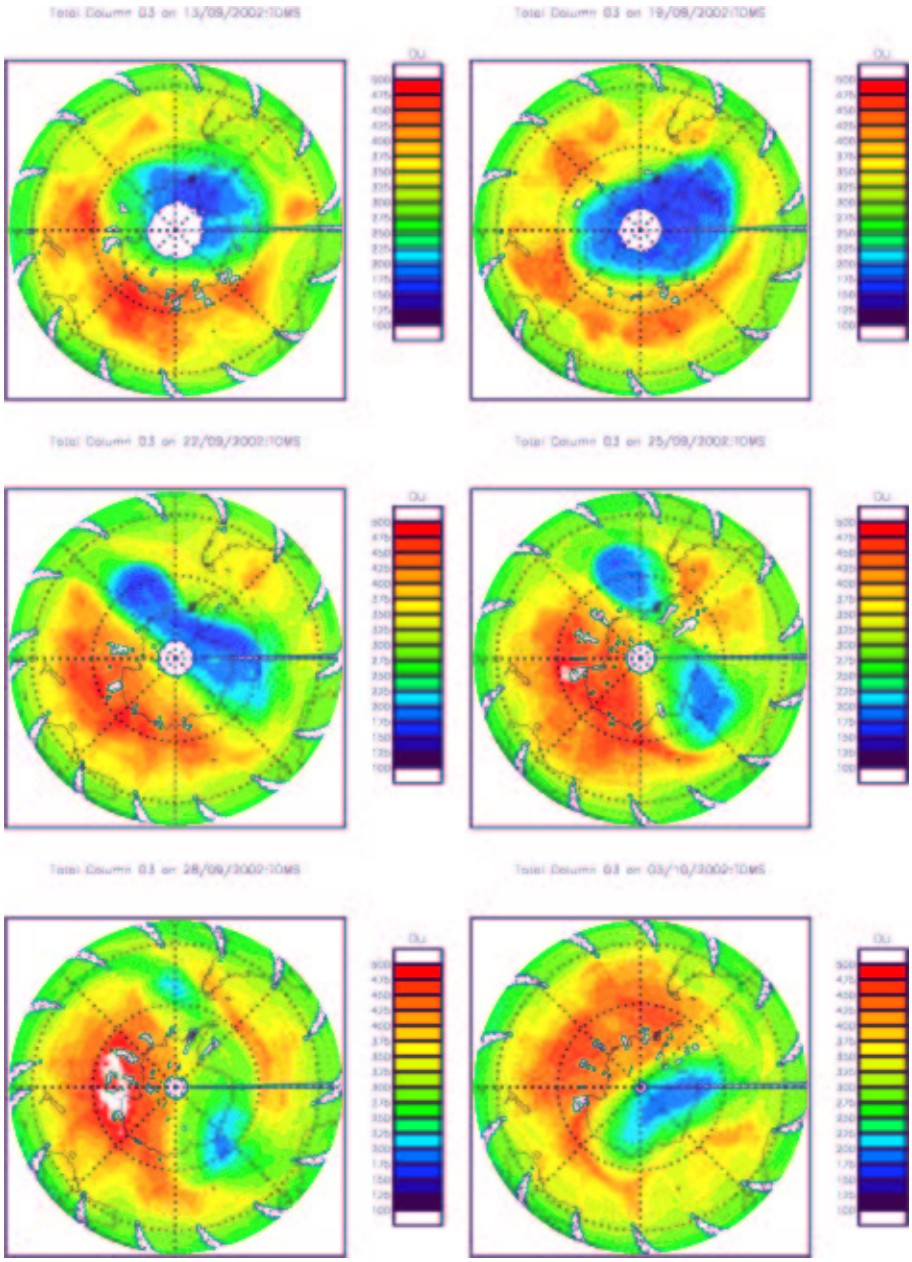
123 gas phase chemical reactions;

32 photolysis reactions

Heterogeneous reactions (liquid, aerosols, NAT, ice)

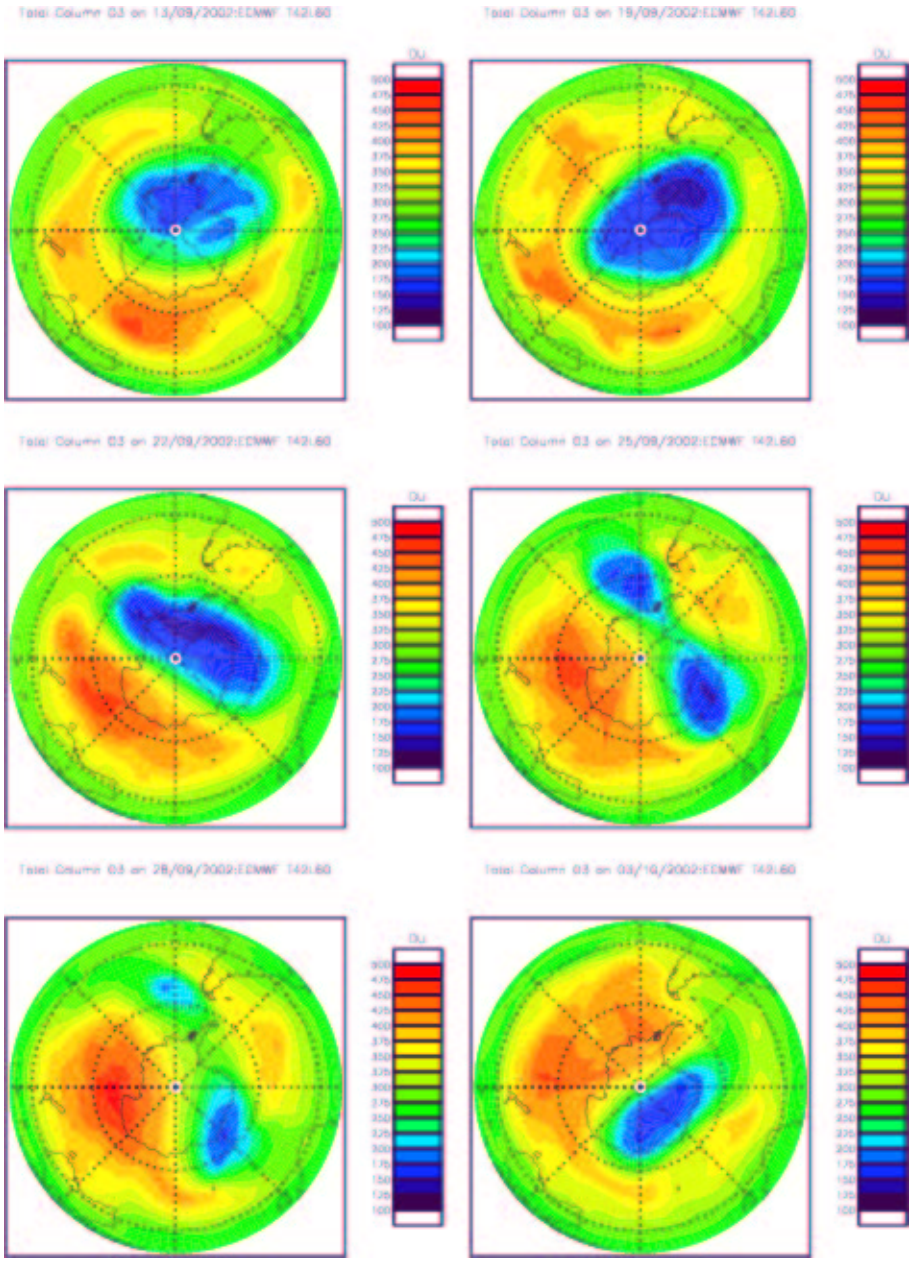
http://www.env.leeds.ac.uk/slimcat

TOMS Total Column Ozone



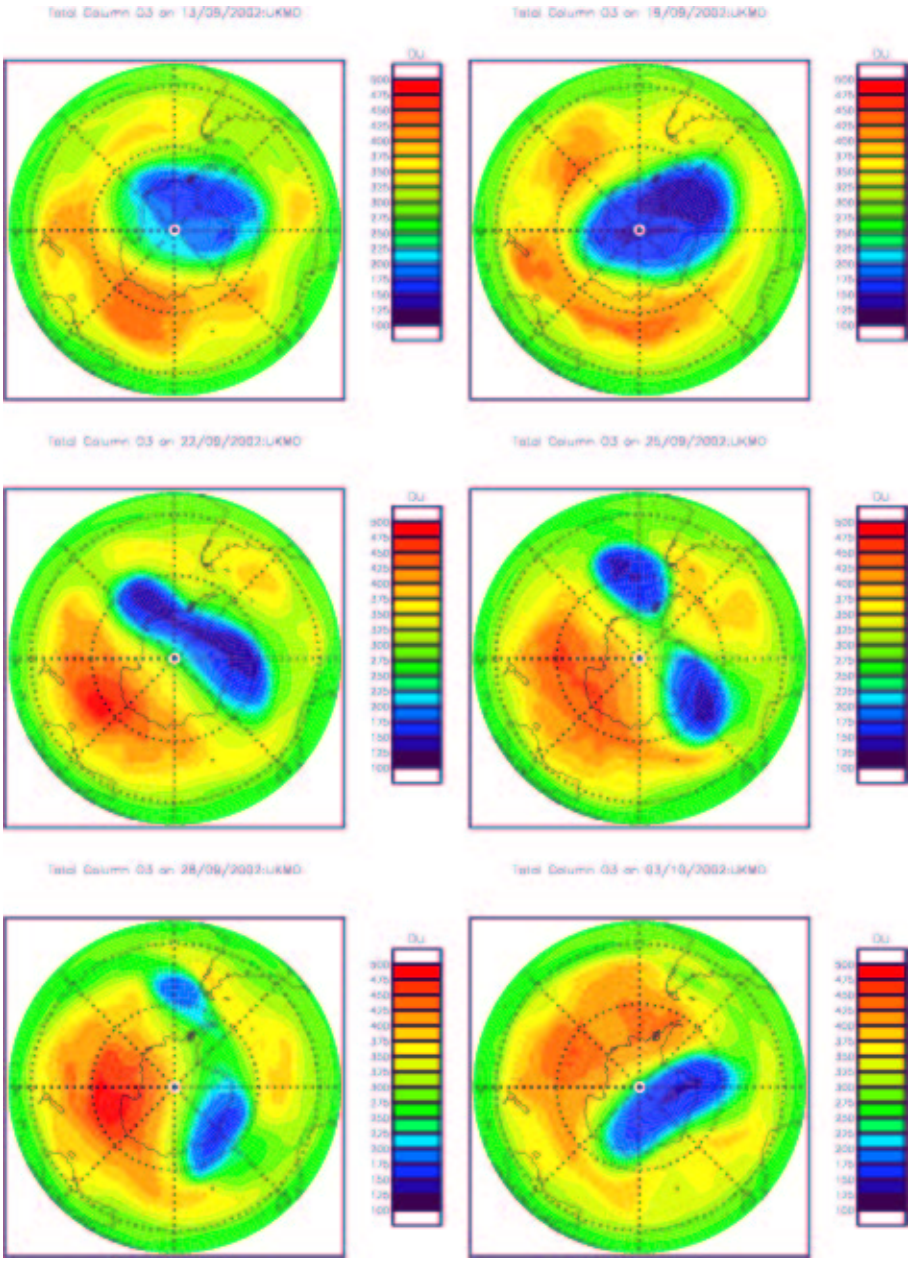
- ozone hole rotated eastward in mid September
- TOZ around Australia of ~450DU is larger
- Ozone hole split into two on 25 September

SLIMCAT TOZ with T42L60



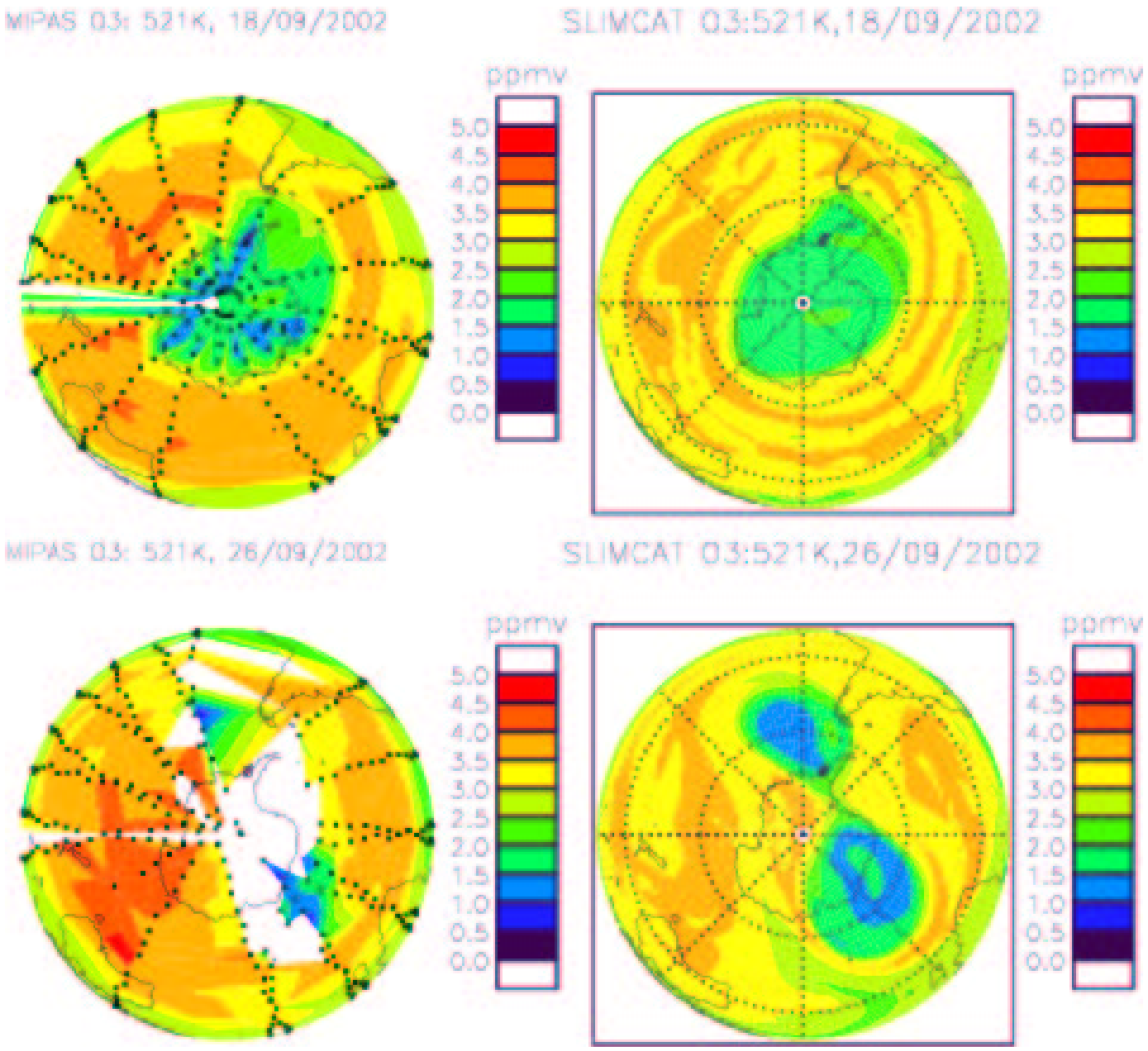
- **SLIMCAT with ECMWF analyses successfully simulate ozone split and evolution**

SLIMCAT TOZ with UKMO



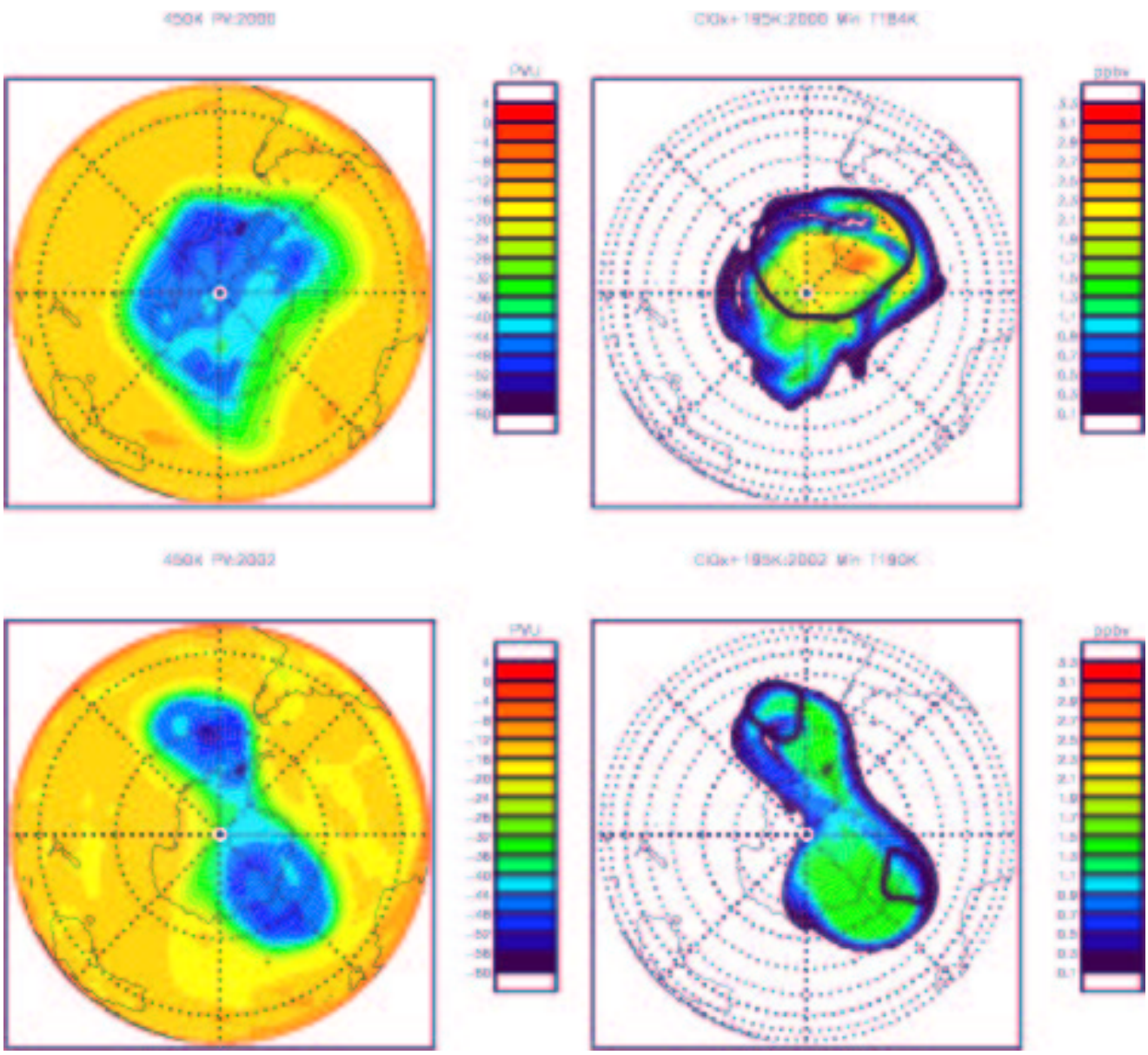
- **SLIMCAT forced by UKMO analyses also reproduce overall O_3 evolution, but underestimate the minimum O_3 column**

MIPAS VS SLIMCAT: O_3



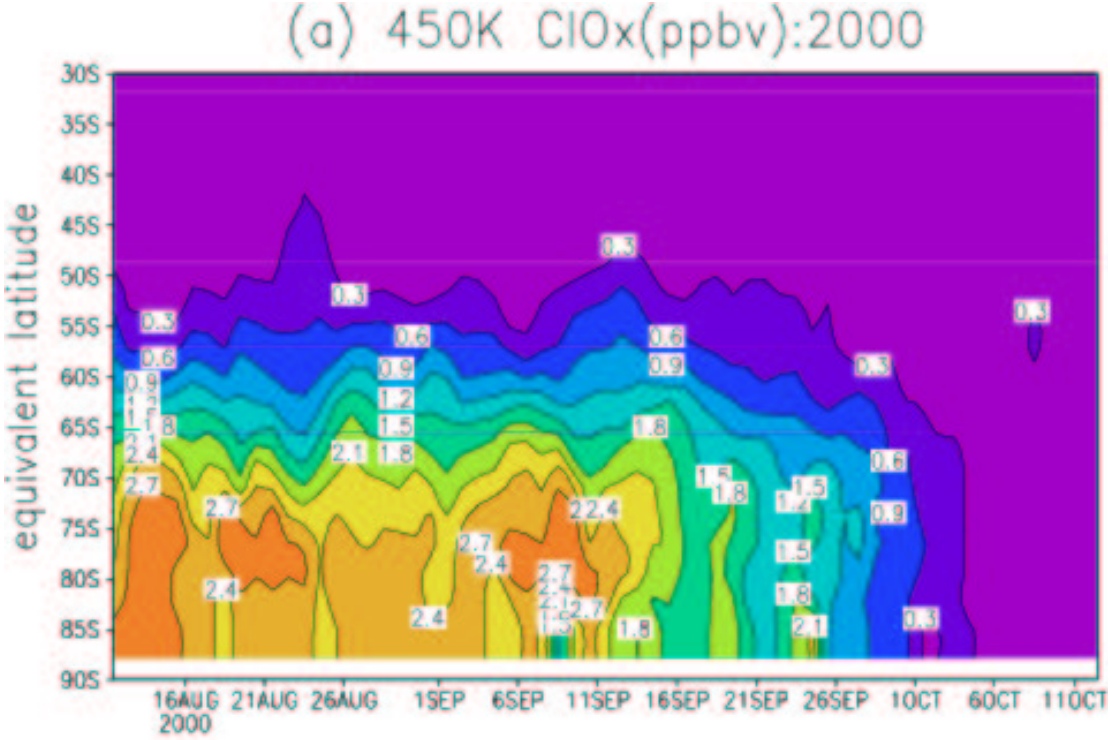
- **Observations and model match quite well**

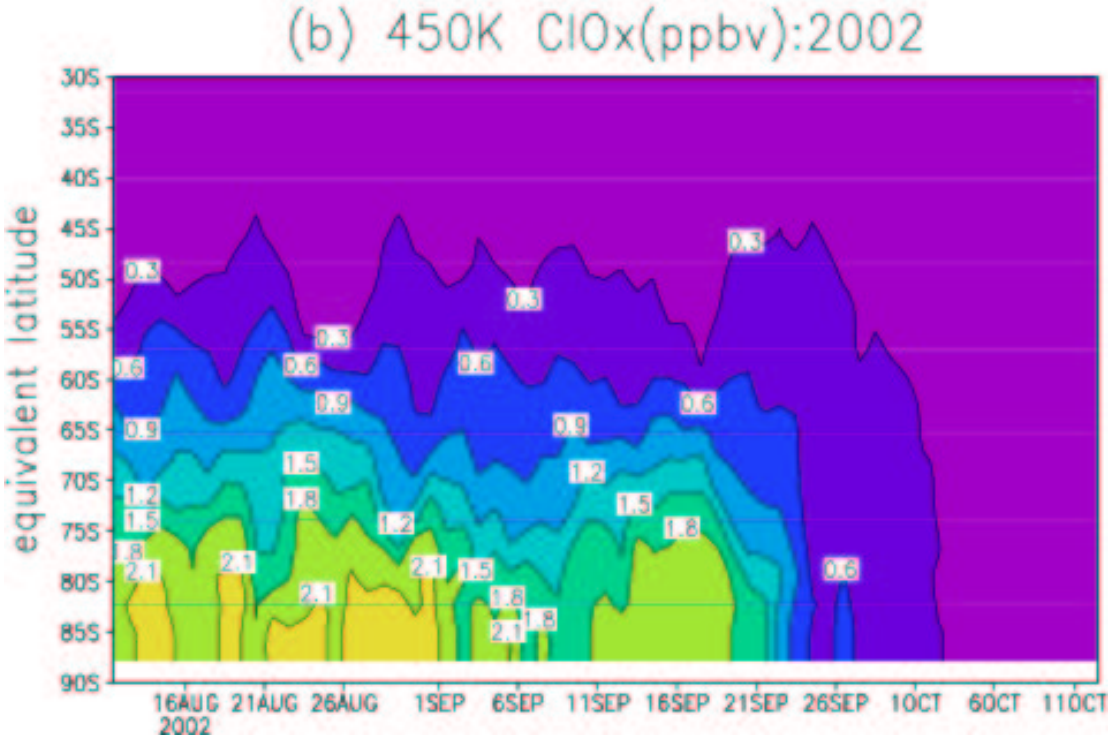
PV and ClOx



- Polar vortex is more stable in 2000
- dramatic polar vortex split of 2002
- ClO_x distribution is similar with polar vortex

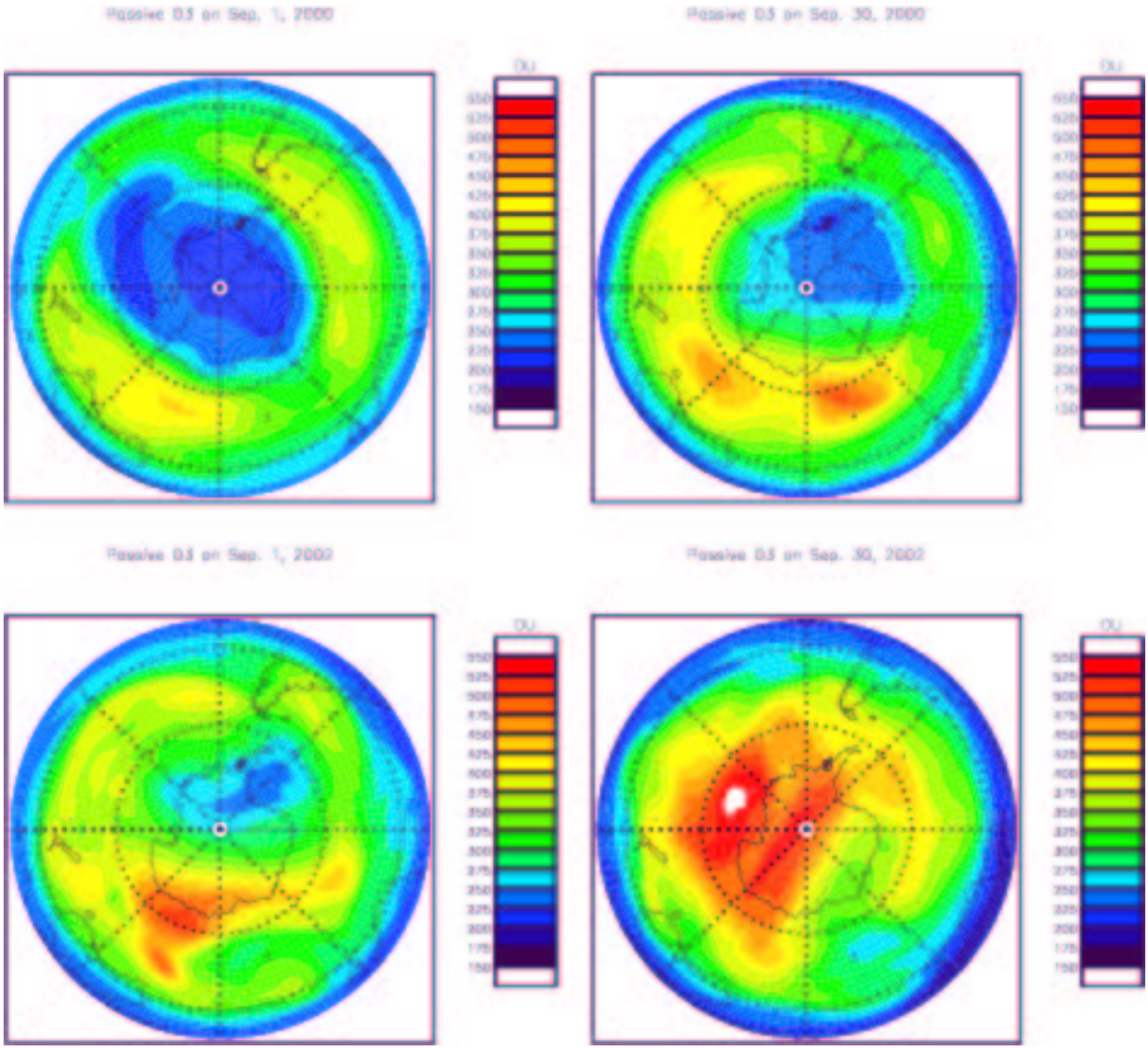
ClOx distrubution





- **Less chlorine activation in 2002**
- **More transport of activated air to midlatitude**

Passive Ozone



- **in 2000, due to the weak vertical transport associated with the strong, cold vortex**
- **in 2002, due to the vortex distortion and associated diabatic cooling cause strong decent**

Ozone Budget

$$\frac{\partial O_3}{\partial t} = P - L - \nabla \bullet \vec{V}_h O_3 - \frac{\partial \dot{\theta} O_3}{\partial \theta}$$

Where

P: Photochemical Production rate of O_3

-L: Chemical loss rate of O_3

$\vec{V}_h$ **: Horizontal Wind**

$\dot{\theta}$ **: Heating rate at the box centre**

$\frac{\partial O_3}{\partial t}$ **: O_3 change**

$-\nabla \bullet \vec{V}_h O_3$ **: Horizontal transport of O_3**

$-\frac{\partial \dot{\theta} O_3}{\partial \theta}$ **: Vertical transport of O_3**

Ozone budget

1) Overall Chemical Ozone Change

2) Horizontal and Vertical Transport of O_3

3) Chemical Loss Rates

Dominated by several key catalytic cycles, e.g.

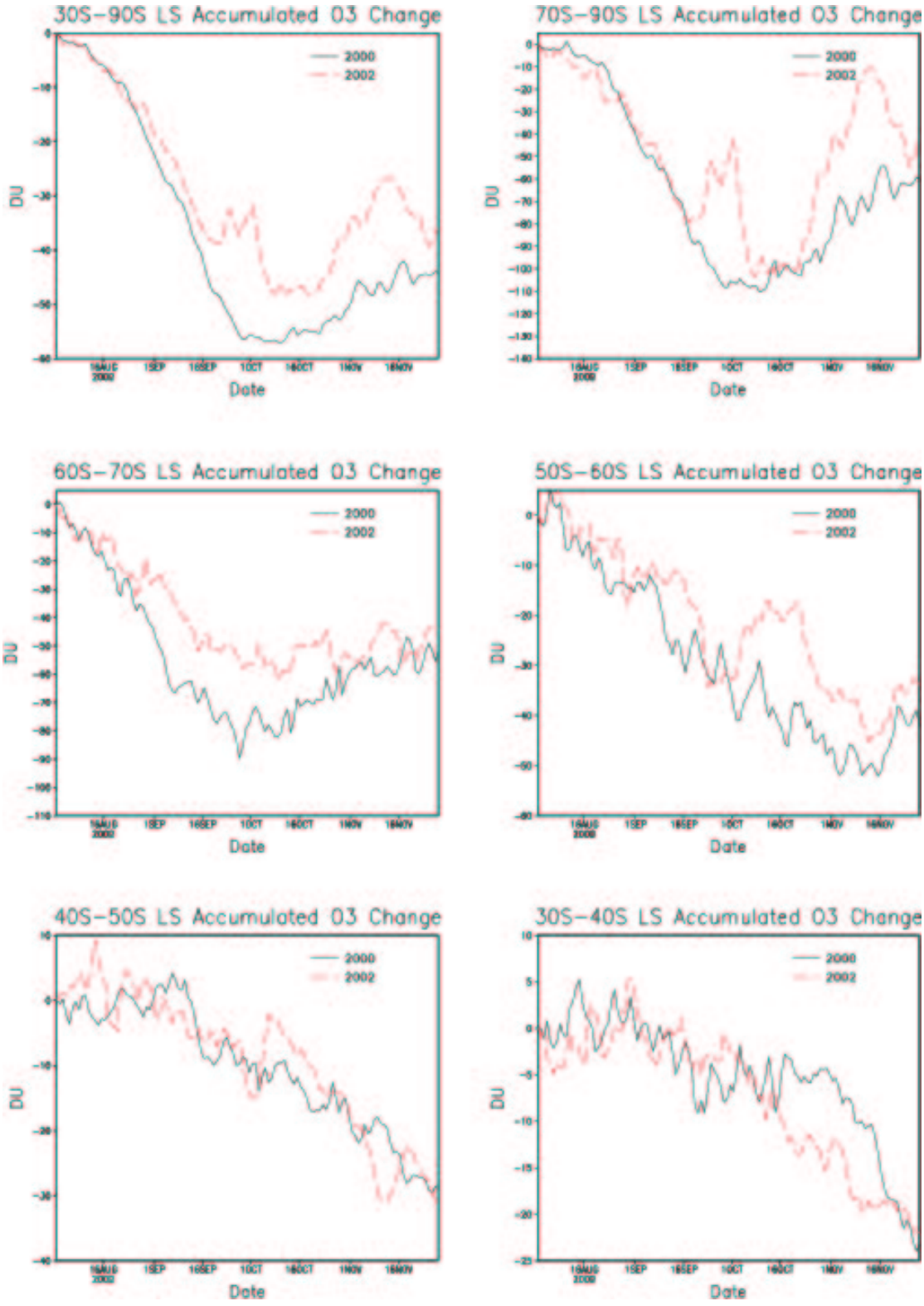
$$ClO + ClO + M \rightarrow Cl_2O_2 + M$$
$$Cl_2O_2 + h\gamma \xrightarrow{j_1} Cl + ClOO$$
$$ClOO + M \rightarrow Cl + O_2 + M$$
$$2 \times (Cl + O_3 \rightarrow ClO + O_2)$$
$$\text{---------------------}$$
$$net: 2O_3 \rightarrow 3O_2$$

$$BrO + ClO \xrightarrow{k_9} Br + ClOO$$
$$ClOO + M \rightarrow Cl + O_2 + M$$
$$or\,(BrO + ClO \xrightarrow{k_{10}} BrCl + O_2$$
$$BrCl + h\gamma + M \rightarrow Br + Cl + M)$$
$$Br + O_3 \rightarrow BrO + O_2$$
$$Cl + O_3 \rightarrow ClO + O_2$$
$$\text{---------------}$$
$$net: 2O_3 \rightarrow 3O_2$$

$$HO_2 + O_3 \xrightarrow{k_7} OH + 2O_2$$
$$OH + O_3 \rightarrow HO_2 + O_2$$
$$\text{---------------}$$
$$net: 2O_3 \rightarrow 3O_2$$

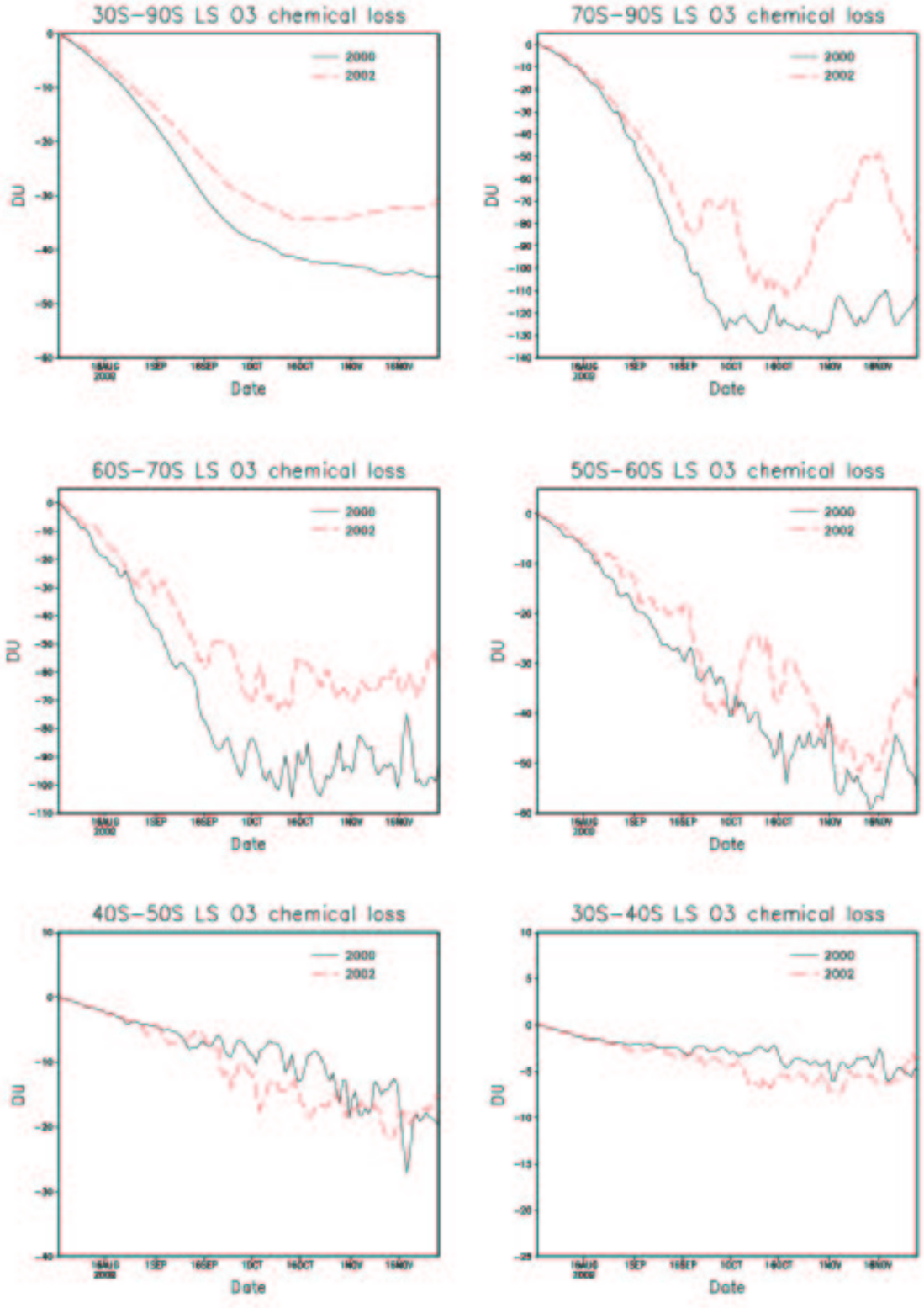
$$ClO + HO_2 \rightarrow HOCl + O_2$$
$$HOCl + h\gamma \xrightarrow{k_{13}} OH + Cl$$
$$Cl + O_3 \rightarrow ClO + O_2$$
$$OH + O_3 \rightarrow HO_2 + O_2$$
$$\text{---------------}$$
$$net: 2O_3 \rightarrow 3O_2$$

Accumulated modelled O_3 change



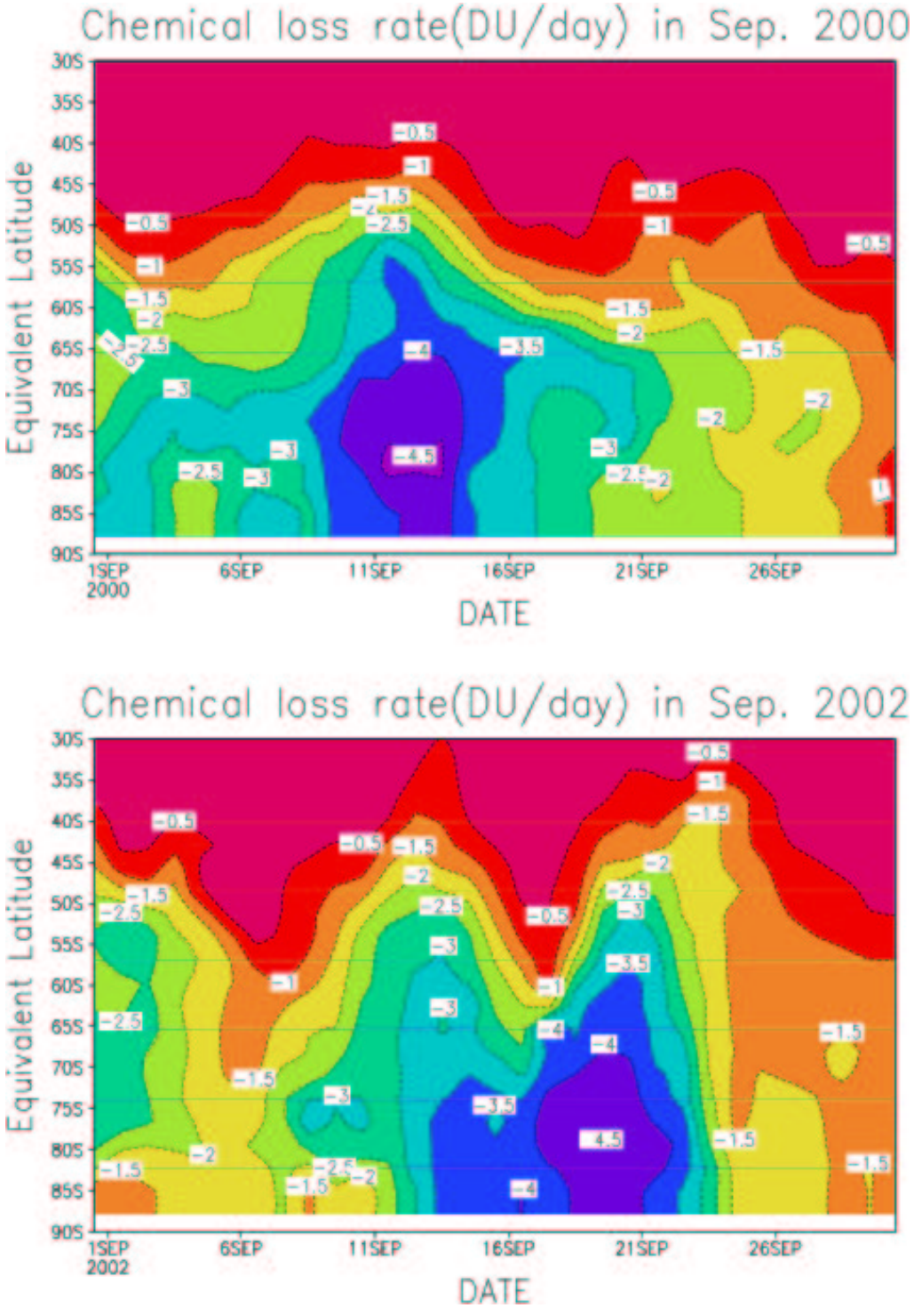
- 2002 modelled O_3 change smaller ~50DU
- O_3 change differs in different region

Chemical Ozone loss



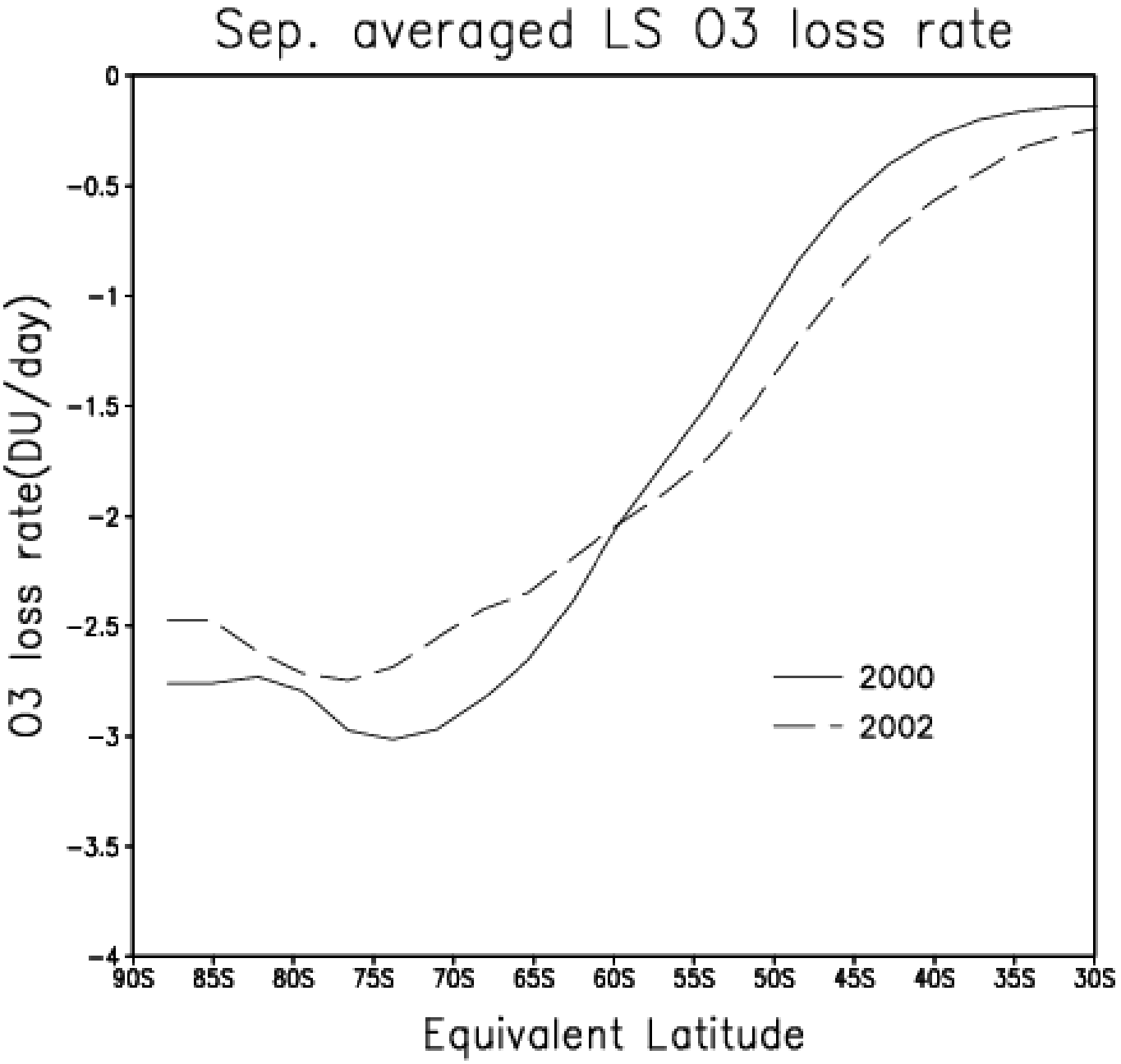
- Similar results about chemical loss compared with O_3 change in 70-90S, 60S-70S

Chemical Loss Rate



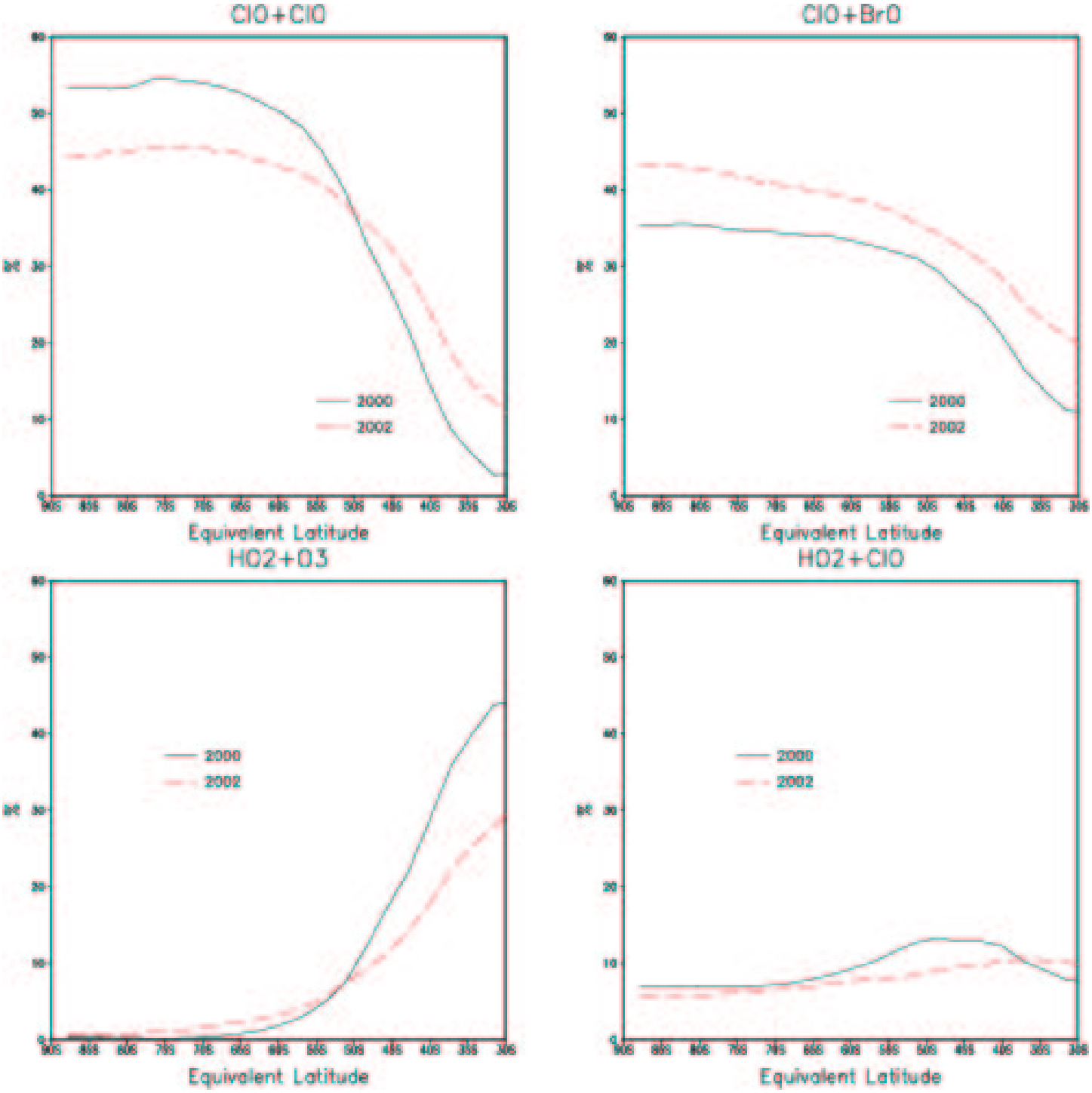
- **Maximum loss in the polar region ~-4.5DU/day**
- **loss rate in early September in 2002 is less than 2000 and extends more equator-ward**

Effect on mid-latitude



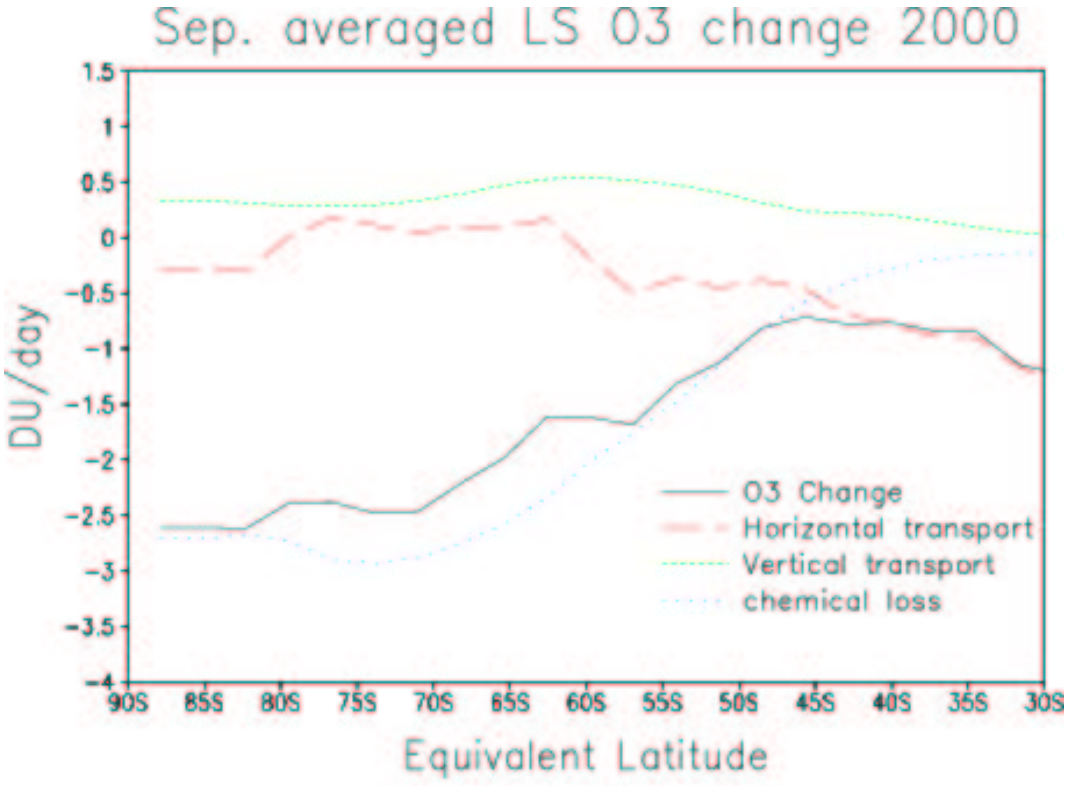
- **Loss rate increases with latitude, maximum loss near the vortex edge.**
- **a large depletion in 2002 equator-ward of 60S**
- **disturbed vortex of 2002 resulted in a large impact of polar processing on middle latitude**

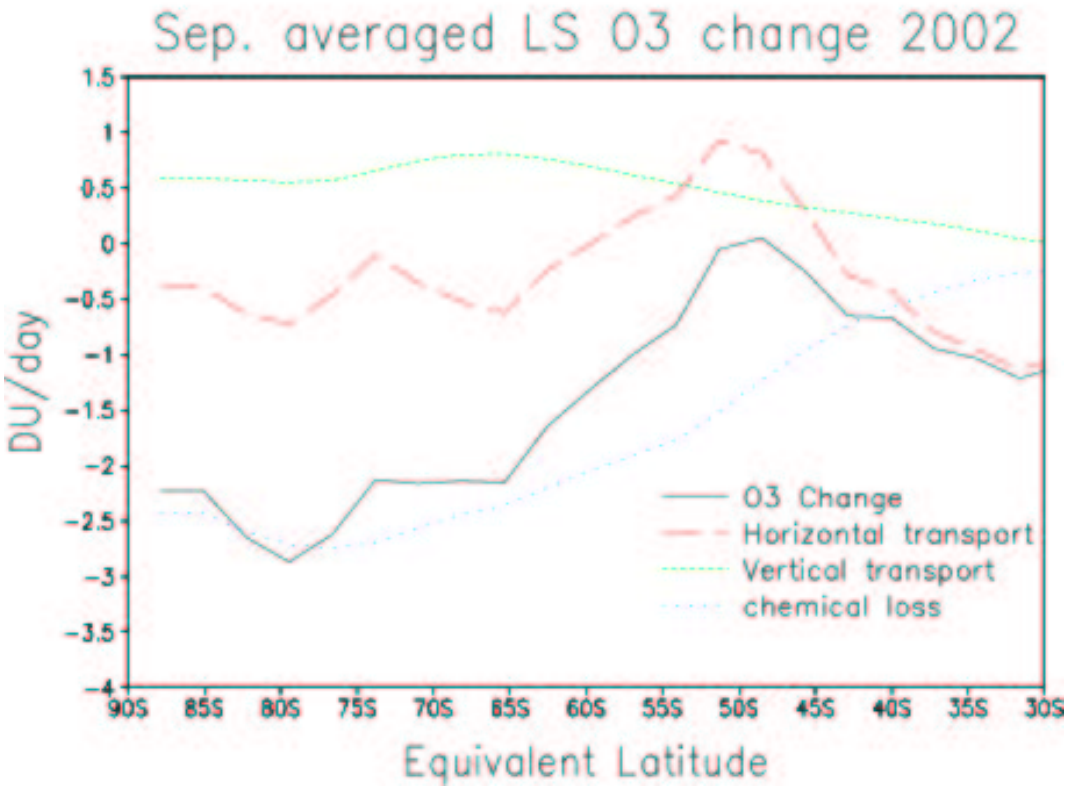
catalytic cycles contribution



- **high latitude loss occurs principally by ClO+ClO and ClO+BrO cycles, ~90%**
- **HO_2+O_3 , HO_2+ClO important in mid-latitude**

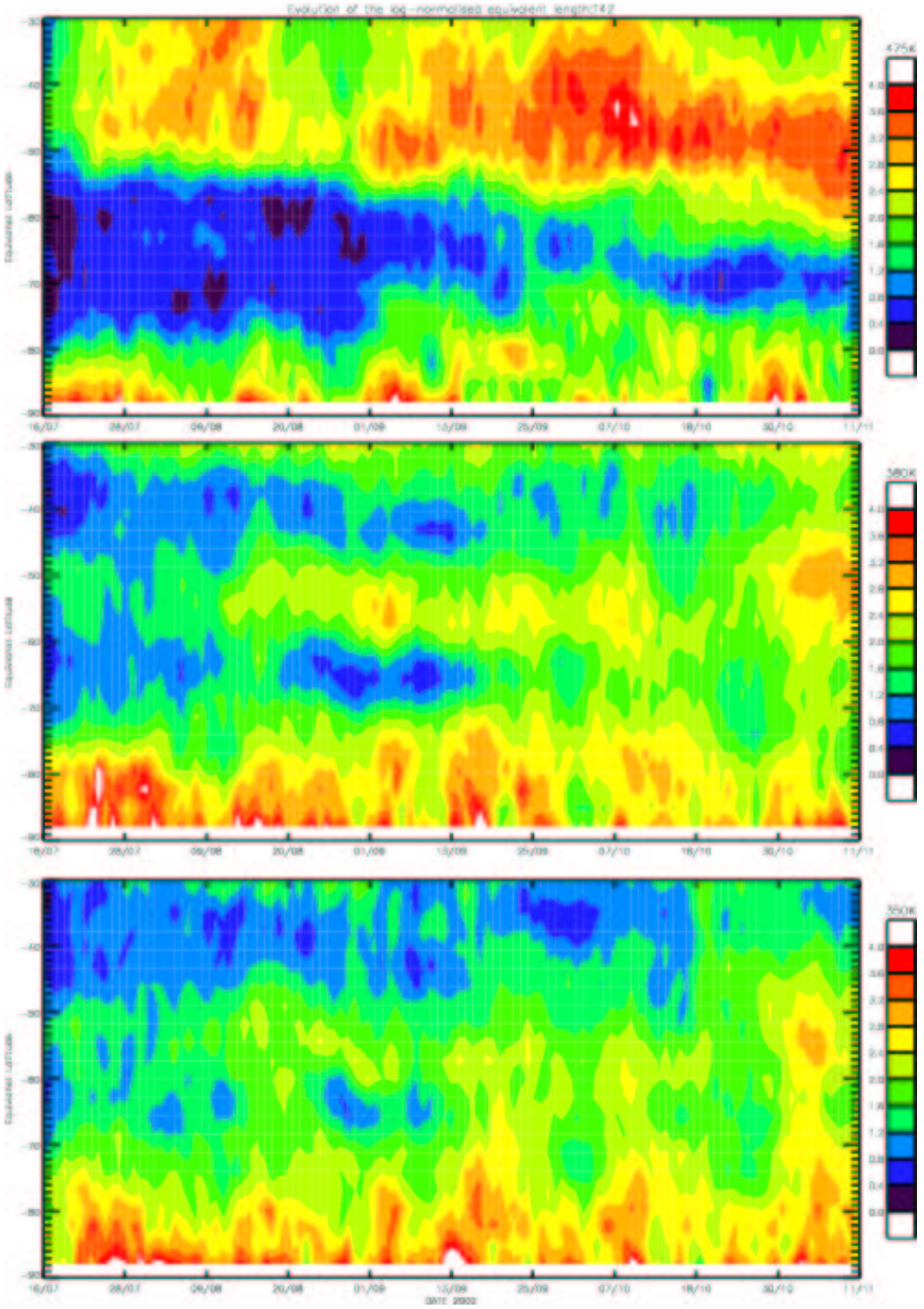
Contribution to Ozone Change





- **polar region O_3 change dominate by chem. Loss**
- **negative contribution from horizontal transport**

Diagnostic of transport /mixing



- Broad region of weak mixing and narrow with time
- Strong mixing in the mid-latitude

Conclusion

- **Unusual 2002 Antarctic Ozone Hole due to Stratospheric Sudden Warming**

- **SLIMCAT produce good simulation of evolution of the vortex, its break up**

- **Ozone chemical loss rates is less than 2000 due to smaller average ClOx**

- **Disturbed vortex of 2002 cause a larger influence of polar processing on SH middle latitude**

Future Work

- **Sensitivity experiment Simulation**
- **Compare other tracers of MIPAS with SLIMCAT**
- **To study 2002/03 Winter Arctic Ozone mini-hole**
- **data assimilation…..**