Changes in stratospheric dynamics and circulation diagnosed from the CCMVal reference simulations

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Introduction

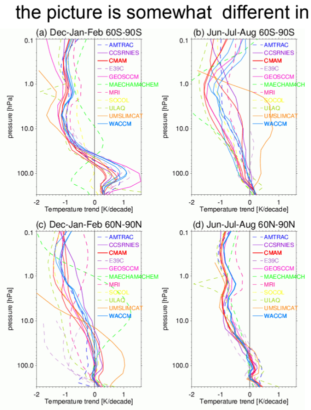
In support of the 2006 WMO/UNEP Scientific Assessment of Ozone Depletion the Chemistry-Climate Model Validation Activity for SPARC (CCMVal) organised a multi-model ensemble of simulations using near identical forcings:

- 11 CCMs were run for 1980-2100 (see Table).
- Surface concentrations of greenhouse gases (GHGs) followed the IPCC A1b scenario.
- Sea surface temperatures and sea ice amounts were taken from ocean-atmosphere simulations using the same GHG scenario.
- Surface halogens were prescribed according the A1b scenario of WMO(2003).

Model	Group	Horizontal resolution	Vertical layers/ Upper Boundary	Runs
AMTRAC	GFDL, USA	2°x 2.5°	48L/ 0.0017hPa	3x1990-2099
CCSRNIES	NIES, Japan	2.8°x 2.8°	34L / 0.01 hPa	1980-2100
CMAM	University of Toronto, Canada	3.75°x 3.75°	71L / 0.0006 hPa	3x1960-2099
E39C	DLR, Germany	3.75°x 3.75°	39L / 10 hPa	3x1980-2019
GEOSCCM	NASA/GCFC, USA	2°x 2.5°	55L / 0.01 hPa	1x2000-2100
MAECHAM4CHEM	MPI Mainz/Hamburg, Germany	3.75°x 3.75°	39L / 0.01 hPa	1x2000-2019
MRI	MRI, Japan	2.8°x 2.8°	68L / 0.01hPa	1x1980-2099
SOCOL	PMOD/WRC & ETHZ, Switzerland	3.75°x 3.75°	39 L / 0.01hPa	1980-2050
ULAQ	University of L'Aquila, Italy	10°x 22.5°	26 L / 0.04 hPa	1980-2049
UMSLIMCAT	University of Leeds, UK	2.5°x 3.75°	64 L/ 0.01hPa	1980-2019
WACCM	NCAR, USA	4°x 5°	66 L / 10^{-6} hPa	1980-2049

Temperatures

The increasing GHG concentrations produced a global warming/cooling of the troposphere/stratosphere. However because of adiabatic warming and/or ozone recovery the picture is somewhat different in the high latitudes – see figure.



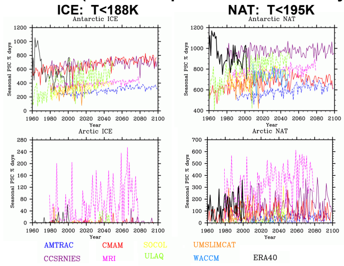
- In the Austral summer all but two of the models indicate a warming of the upper troposphere/lower stratosphere due to ozone recovery.
- The spread between the models is largely due to different rates of ozone recovery predicted by the CCMs.

- In the Boreal winter 5 of the 8 models with simulations that extended at least to 2050 were in good agreement with near zero cooling in the lower stratosphere.
- This suggests that increased adiabatic warming in the Arctic winter is maybe a robust feature of climate change and balances the increased radiative cooling from GHGs.

Polar stratospheric clouds

PSC area (% of hemisphere x duration in days)

ICE: T<188K **NAT: T<195K**



Antarctic

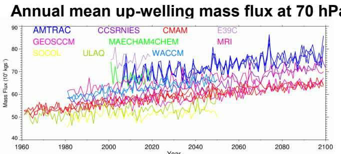
- The models, on average, under predict the area and/or duration of PSCs compared to ERA40.
- Most models indicate an increase in the area and/or duration of ICE and NAT due to climate change.

Arctic

- The presence of ICE and NAT varies widely between models.
- Compared to the Antarctic inter-annual variability is large.
- There is better agreement with ERA40.

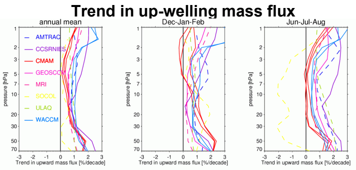
Tropical up-welling

Annual mean up-welling mass flux at 70 hPa



All the simulations show an increase in the upward mass flux entering the stratosphere above the tropical tropopause, i.e. an acceleration of the Brewer-Dobson circulation.

Trend in up-welling mass flux

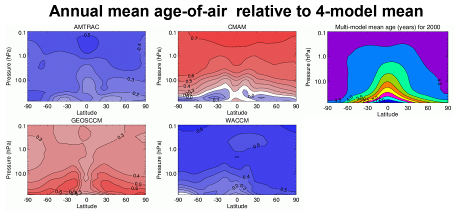


The positive trend in the upward mass flux in the tropics occurs in all seasons and throughout the depth of the stratosphere in nearly all the models.

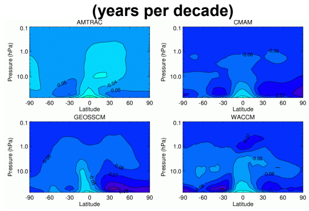
Age-of-air

- Models with the stronger tropical up-welling (AMTRAC and WACCM – see above) have younger air (blue shading).
- This relation breaks down in the extra-tropical lower stratosphere probably due to differences in mixing.

Annual mean age-of-air relative to 4-model mean



Trend in annual mean age-of-air (years per decade)

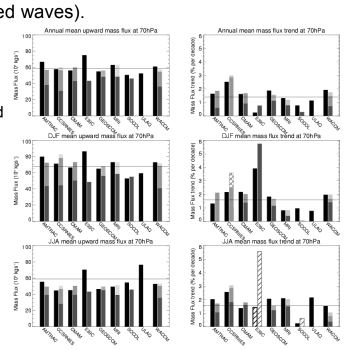


- Due to the acceleration of the Brewer-Dobson circulation climate change reduces the mean age-of-air throughout the stratosphere.
- The age trends are fairly uniform outside the tropical lower stratosphere.

Downward control

The Brewer-Dobson circulation is a wave driven circulation. For steady conditions the downward control principle allows the tropical up-welling at a particular level to be derived from the zonal mean wave forces above that level. These forces are given by the Eliassen-Palm flux divergence (for resolved waves) and the parameterized orographic and non-orographic gravity wave drag (for unresolved waves).

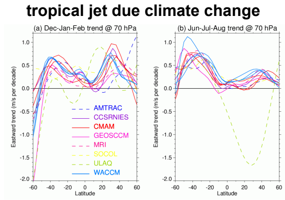
- Generally there is reasonably good agreement between actual up-welling mass fluxes and trends at 70 hPa (black bars) with those derived from downward control (grey bars – dark grey: contribution from EP-flux divergence, lighter shadings: contributions from orographic and non-orographic (lightest shade) gravity waves (GWs)).
- In most models the **orographic** GWs are of similar importance to the resolved waves both in determining the up-welling and its trend at 70 hPa.



Gravity waves

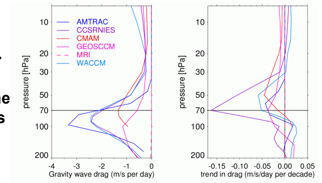
Orographic GW parameterizations typically deposit momentum on the upper side of the subtropical jets, especially in the northern hemisphere. Due to climate change there is an eastward acceleration of the jets causing the OGWs to break higher, reducing the drag below 70 hPa and increasing it above.

Eastward acceleration of sub-tropical jet due climate change



Breaking level for the orographic gravity waves in the sub-tropics moves upward

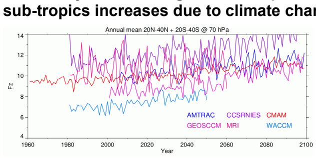
NH OGWD used in the downward control calculation of the tropical up-welling



Resolved waves

Resolved waves propagate both horizontally and vertically and can be refracted. Nonetheless climate change in the models produces an increase in the upward flux of wave activity at 70 hPa in the sub-tropics consistent with the increased wave driving of the tropical up-welling.

Wave activity flux entering the stratosphere in the sub-tropics increases due to climate change



Conclusions

- Recovery of the ozone hole causes a warming of the upper troposphere/lower stratosphere.
- In the Arctic lower stratosphere increased adiabatic warming balances radiative cooling.
- Climate change increases the area and/or duration of PSCs in the Antarctic.
- Increasing tropical up-welling is a robust feature of climate change in the simulations.
- Increases in up-welling occur in all seasons and throughout the depth of the stratosphere.
- Models with stronger (weaker) than average up-welling have younger (older) air.
- The acceleration of the Brewer-Dobson circulation reduces the age-of-air everywhere.
- Downward control explains the up-welling and its trends, with orographic GWD of similar importance to the resolved waves.
- The trend in the up-welling results from (a) the eastward acceleration of the sub-tropical jets causing the OGWs to break higher and (b) increasing upward EP-flux in the sub-tropics.

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