World-avoided simulations using a fully-coupled chemistry-climate model

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Outline

• Motivation
• Model and simulations
• Results
• Conclusions
CFC are both ozone depleting substances (ODS) and greenhouse gases (GHG)

• Velders et al. (PNAS, 2007) pointed out that control of ODS by the Montreal Protocol produced a significant reduction in radiative forcing (the “World avoided”)
Consequences of continued growth of ODS into the 21st century

- Newman et al. (ACPD, 2009) demonstrated a rapid collapse of the Ozone layer after midcentury, with corresponding very large increases in UV index.

- but Newman et al. used a model with specified SST, so they could not assess climate change due to greenhouse effects of ODP.

Fig. 2. Annually-averaged global ozone for the WORLD AVOIDED (solid black), reference future (red), fixed chlorine (green), and reference past (blue) simulations. The curves are smoothed with a Gaussian filter with a half-amplitude response of 20 years, except for the WORLD AVOIDED, which is unsmoothed. The dashed line shows the 2-D coupled model simulation of the "world avoided". The grey-shaded inset shows the WORLD AVOIDED total ozone plotted against global annually-averaged EESC at 4.5hPa from Fig. 1.

Fig. 14. UV index versus year for the WORLD AVOIDED (black), reference future (red), and fixed chlorine (green) simulations. As with Fig. 13, the UV index is calculated using the July 30°–50°N zonal-mean ozone, and assuming a time of local noon on 2 July. The standard UV index "risk" scale is also superimposed on the bottom left. The horizontal grey line shows the 1975–1985 average of the UV index from the fixed chlorine simulation.
A fully coupled model is the right tool for looking at tropospheric climate change

Whole Atmosphere Community Climate Model

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<th>Model Framework</th>
<th>Dynamics</th>
<th>Tracer Advection</th>
<th>Resolution</th>
<th>Chemistry</th>
<th>Other Processes</th>
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<td>Based upon NCAR Community Atmosphere Model, CAM4</td>
<td>Finite Volume Dynamical Core (Lin, 2004)</td>
<td>Flux-form Finite Volume (Lin, 2004)</td>
<td>Horizontal: 1.9° x 2.5° or 4.0° x 5.0° (lat x lon)</td>
<td>Middle Atmosphere Mechanism</td>
<td>Gravity-wave parametrization (for unresolved, mesoscale gravity waves)</td>
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<td>Part of the NCAR Community Earth System Model, v.1</td>
<td>Fully-interactive, i.e., consistent with model-derived, radiatively active gases: O₃, CO₂, CH₄, N₂O, H₂O, CFC11, CFC12, O₂, NO</td>
<td>Vertical: 66 levels 0-140km &lt; 1.0km in UTLS 1-2 km in stratosphere 3 km in MLT</td>
<td>Vertical: 66 levels 0-140km &lt; 1.0km in UTLS 1-2 km in stratosphere 3 km in MLT</td>
<td>Middle Atmosphere Mechanism 57 Species including Ox, HOx, NOx, BrOx, and ClOx</td>
<td>Molecular diffusion (Banks and Kockarts, 1973)</td>
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<td></td>
<td>QBO may be specified from observations</td>
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<td>No NMHCs</td>
<td>Auroral processes, including ion drag, and Joule heating</td>
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<td>Coupled to full ocean model (NCAR POP)</td>
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<td>E-region Ion Chemistry</td>
<td>Longwave, shortwave, and chemical potential heating</td>
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Simulations

Control: 1985-2070; IPCC CMIP-5 scenario RCP4.5 beyond 2005

World-Avoided: same as Control, but Cl and Br from anthropogenic sources increase at 3.5% from 1987

RCP4.5 is a “moderate” scenario, with GHG stabilization towards the end of the 21st century

EECL: Equivalent effective chlorine. Follows Montreal protocol in the Control run

In the World avoided simulation, EECL continues to grow at 3.5% per year throughout 21st century
Results

• stratospheric composition and dynamics
• global climate change
• look at behavior in 21st century (through 2070)
Stratospheric Ozone in 2070

World avoided compared to Control, in 2070:

• ozone maximum is reduced by more than half in the middle stratosphere

• the ozone maximum moves to lower altitude (self-healing)

• ozone loss in the lower and upper stratosphere is even greater than in the middle stratosphere
Zonal-mean temperature changes

- much larger changes in World avoided than in the Control case: 2X in the troposphere, and up to 10X in the stratosphere (which cools due to both enhanced IR emission and reduced ozone heating)

- tropical tropopause altitude increases to ~20-22 km in World avoided case
Ozone column evolution: 2005-2070

- plot shows ozone columns smoothed with 12-month running mean to emphasize the long-term trend

- the ozone column decreases through the 21st century in the World avoided run (cf. ozone recovery in the Control run)

- decrease is gradual at high latitudes; at lower latitudes, the ozone column collapses rapidly after ~2045. This is driven by the evolution of ozone in the lower stratosphere
O$_3$ in the tropical lower stratosphere

CLO$_X$-O$_3$-T positive feedback leads to collapse of tropical ozone (cf. Newman et al., 2009)

CLO$_X$: “active chlorine”

(CI + 2 Cl$_2$ + ClO + OClO + 2 Cl$_2$O$_2$ + HOCl + BrCl)
Global Climate Indicators

RESTOM: global residual flux at “top of model”
TS: global surface temperature
TS LAND: global land temperature
SST: global sea-surface temperature

- the World avoided global radiation budget is increasingly out of balance as CFC concentrations increase over the period studied
- over 2005-2070, TS increases ~2.5 K in the World avoided simulation (vs. ~ 1 K in the Control case)
Surface temperature changes

- Surface T changes in the Control case are in line with expectations for a “moderate” scenario of GHG (CO₂, N₂O, CH₄) growth.

- The World avoided case produces substantially larger surface T changes, approaching 8 K in the Arctic, and 2-4 K over all land areas.
Annual-mean Humidity Changes

- Changes in relative humidity are small (except where the tropopause moves up).
- Changes in specific humidity are large, especially in the World avoided case.
Annual Precipitation rate changes

- Drying in the subtropics intensifies in the World avoided simulation compared to Control.
- The climate is overall much wetter in World avoided and the changes are highly significant.
Changes in the Ocean: ENSO

- Increase in tropical ocean T is seen in both simulations; stronger in World avoided
- There is a significant decrease in ENSO power after about 2030; more marked in World Avoided
Conclusions

• Fully coupled simulations allow study of both composition and climate changes due to continued CFC growth into the 21st century

• Composition and temperature change radically by 2070: In the World avoided run, temperature decreases by up to 20 K in the lower stratosphere and increases by over 4 K in the tropical troposphere. The stratospheric ozone column collapses worldwide after ~2045

• The Brewer-Dobson circulation in the lower stratosphere accelerates strongly in the World avoided simulation as a result of changes in the propagation and dissipation of Rossby waves in the subtropical lower stratosphere

• Surface temperature increases (and precipitation decreases) by 2070 are substantially larger in the World avoided simulation than in the Control case

• There is substantial ocean warming in World avoided and significant changes in ENSO