SC-WACCM and Problems with Specifying the Ozone Hole

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Motivation

To design a stratosphere-resolving model that can be used for studies of middle atmosphere dynamics without the expense of running interactive chemistry.
SC-WACCM Physics

- Based on CESM1(WACCM)
- Ozone and CO\(_2\) specified from prior fully-interactive WACCM simulations
- Excludes comprehensive chemistry - solves only for H\(_2\)O, CH\(_4\), N\(_2\)O, CFC-11 and CFC-12
- Radiative transfer:
  - CAM-RT below ~65 km
  - Short-wave heating rates prescribed above >65 km from same ‘fully-interactive’ simulations
  - Non-LTE cooling calculated from model temperature and prescribed CO\(_2\) >65km
- No auroral physics
- Parameterized non-orographic gravity waves as in WACCM
- TMS turned on
SC-WACCM Resolution

- 1.9° latitude x 2.5° longitude
- Same 66 levels as WACCM (fully-resolved stratosphere and mesosphere):
  - model top at 5.1x10^{-6} hPa (~140 km)
  - 18 pressure levels between the surface and 100 hPa are identical to CCSM4
  - Stratosphere: 17 levels in WACCM between 100 and 3 hPa (versus 8 in CCSM4)
  - 9 levels above 100 km
SC-WACCM Performance

<table>
<thead>
<tr>
<th>Model</th>
<th># cores</th>
<th>simulated years/day</th>
<th>core-hrs/simulated year</th>
</tr>
</thead>
<tbody>
<tr>
<td>WACCM</td>
<td>352</td>
<td>7.5</td>
<td>1130</td>
</tr>
<tr>
<td>SC-WACCM</td>
<td>352</td>
<td>14.8</td>
<td>573</td>
</tr>
<tr>
<td>CCSM4 2°</td>
<td>416</td>
<td>42.0</td>
<td>237</td>
</tr>
</tbody>
</table>

SC-WACCM is **half** the computational cost of WACCM
Pre-Industrial WACCM and SC-WACCM Simulations

- WACCM & SC-WACCM
  - 200 years, coupled 1850 pre-industrial control simulation
  - daily and monthly output (SC-WACCM available on glade and soon on the ESG)

- CCSM4
  - 500 years, coupled 1850 pre-industrial control simulation with monthly output
  - 54 years of daily output
Zonal Mean Differences in Wind and Temperature

Figure 6. Differences (WACCM minus SC-WACCM) in zonal mean temperature (a),(b) and zonal wind for (c),(d) for December-January-February (DJF) (a),(c) and June-July-August (JJA) (b),(d). Red (blue) contours are positive (negative) values. Contour intervals are 1 K and 1 m s$^{-1}$. 

$\Delta T$

$\Delta U$
Surface climate

Figure 13. Zonal mean surface air temperature (a), (b), sea-level pressure (c), (d) and precipitation (e), (f) for December-January-February (DJF) (a), (c), (e) and June-July-August (JJA) (b), (d), (f). Black, red and blue curves are WACCM, SC-WACCM and CCSM4.
Problems with Specifying an Ozone Hole


Sensitivity of Southern Hemisphere climate to zonal asymmetry in ozone

Julia A. Crook, 1 Nathan P. Gillett, 1 and Sarah P. E. Keeley 1, 2

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Sensitivity of climate to dynamically-consistent zonal asymmetries in ozone

N. P. Gillett, 1 J. F. Scinocca, 1 D. A. Plummer, 1 and M. C. Reader 1

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Effect of zonal asymmetries in stratospheric ozone on simulated Southern Hemisphere climate trends

D. W. Waugh, 1 L. Oman, 1 P. A. Newman, 2 R. S. Stolarski, 2 S. Pawson, 3 J. E. Nielsen, 3 and J. Perlwitz 4

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Effect of Specifying Monthly Mean Ozone

Monthly Mean

Daily Mean

Percent Difference

52hPa, 90S-70S Mean over 10yrs

Red minus Black
20^{th} Century Historical Simulations

- **WACCM**: 6 (3 New) members from 1955 to 2005 (started from differing atmospheric ICs)
- **SC-WACCM**: Uses **ensemble mean values** from prior WACCM runs for prescribed values

- 2 x 1955 to 2005 ensembles:
  1) **Zonal Mean, Monthly Mean O_3**
  2) **Zonal Mean, Daily Mean O_3**
Impact of a Monthly Mean Specified Ozone Hole

Ozone

WACCM minus SC; 90S-70S Mean; Dots Cover Insignificant Areas
Impact of a Monthly Mean Specified Ozone Hole

**Monthly**

**Ozone**

**Short Wave Heating**

WACCM minus SC; 90S-70S Mean; Dots Cover Insignificant Areas
Impact of a Monthly Mean Specified Ozone Hole

Monthly

Ozone

Short Wave Heating

Temperature

WACCM minus SC; 90S-70S Mean; Dots Cover Insignificant Areas
Impact of a Monthly Mean Specified Ozone Hole

Monthly

Ozone

Short Wave Heating

Temperature

WACCM minus SC; 90S-70S Mean; Dots Cover Insignificant Areas
Impact of a Monthly Mean Specified Ozone Hole

Ozone

Short Wave Heating

Temperature

WACCM minus SC; 90S-70S Mean; Dots Cover Insignificant Areas

**WACCM**  Peak = 13 m/s

**SC-Monthly**  Peak = 10 m/s

**SC-Daily**  Peak = 12 m/s

WACCM  
Peak = 13 m/s

SC-Monthly  
Peak = 10 m/s

SC-Daily  
Peak = 12 m/s
Impact on Surface Climate Trends

DJF Zonal Mean Wind at 867hPa

DJF Zonal Mean Precipitation
Summary

• SC-WACCM’s climatology in the troposphere and stratosphere are indistinguishable from WACCM.

• 1/2 Cost Of WACCM (with Chemistry)

• Temporal smoothing of the specified ozone forcing file leads to significant changes in southern hemispheric trends from 1955 to 2005.
Back Up Slides and Extra Info
Figure 3. Climatological monthly and zonal mean WACCM pre-industrial total column ozone in Dobson Units (DU).
Figure 4. Annual and zonal mean (a) total short-wave heating rate (QRS) for WACCM in K day$^{-1}$, (b) QRS$_{TOT}$ (WACCM minus SC-WACCM) in K day$^{-1}$ and (c) QRS in %. Red (blue) contours are positive (negative) values. Contour interval is 2$^{-2}$, 2$^{-1}$, 2, 2$^2$, ..., K day$^{-1}$ in (a), 0.25 K day$^{-1}$ in (b) and ...,-25, -15, -5, 5, 15, 25,... in (c). Gray shading indicates regions that are significantly different at the 95% level.
Annual Short-Wave Heating Rate Differences

(a) WACCM QRS (ANN)

(b) ΔQRS (K day⁻¹; ANN)

(c) QRS (%; ANN)

Red (blue) contours are positive (negative) values. Contour interval is 2, 2, 1, 2, 2, ..., K day⁻¹ in (a), 0.25 K day⁻¹ in (b) and ...,-15, -5, 5, 15, 25,... in (c). Gray shading indicates regions that are significantly different at the 95% level.
Ozone has a diurnal cycle in WACCM but not SC-WACCM

Instantaneous zonal profile of ozone (ppmv) for a day in January at the equator, at 60km, and at 12 midnight 0E. Solid in WACCM ozone and dashed is SC-WACCM ozone (Sassi and Garcia, 2005).
Figure 4. Annual and zonal mean (a) total short-wave heating rate (QRS) for WACCM in K day$^{-1}$, (b) $\Delta$QRS (K day$^{-1}$; ANN) and (c) $\Delta$QRS in %. Red (blue) contours are positive (negative) values. Contour interval is 2, 2, 1, 1, 2, ..., K day$^{-1}$ in (a), 0.25 K day$^{-1}$ in (b) and ..., −25, −15, −5, 5, 15, 25, ... in (c). Gray shading indicates regions that are significantly different at the 95% level.
Interpolation of monthly QRS onto model time-step causes seasonal biases

Figure 5. As in Figure 2 but for December-January-February (DJF).
Figure 13. Zonal mean surface air temperature (a), (b), sea-level pressure (c), (d) and precipitation (e), (f) for December-January-February (DJF) (a), (c), (e) and June-July-August (JJA) (b), (d), (f). Black, red and blue curves are WACCM, SC-WACCM and CCSM4.
Surface Climate

Figure 12. Surface air temperature (SAT) in WACCM, SC-WACCM and CCSM4 as a function of month. (a) Global mean, (b) Northern Hemisphere (NH) polar cap average and (c) Southern Hemisphere polar cap average. Months when CCSM4 is not significantly different from WACCM at the 95% level are highlighted with gray shading. (d), (e) and (f) as (a), (b) and (c) but for the standard deviation of SAT.
Table 1. WACCM, SC-WACCM and CCSM4 annual mean surface air temperature ($SAT$), precipitation ($P$), sea-level pressure ($SLP$), and sea ice extent ($SIE$) for preindustrial conditions. Climatological means are calculated over 200 years for WACCM, 195 years for SC-WACCM and 501 years for CCSM4. The 2$\sigma$ uncertainties in the means are listed in parentheses.

<table>
<thead>
<tr>
<th>Model</th>
<th>$SAT$(K)</th>
<th>$P$(mm day$^{-1}$)</th>
<th>$SLP$(hPa)</th>
<th>$SIE$(10$^6$km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WACCM</td>
<td>286.8 (0.2)</td>
<td>2.83 (0.03)</td>
<td>1011.3 (0.05)</td>
<td>–</td>
</tr>
<tr>
<td>SC-WACCM</td>
<td>286.7 (0.2)</td>
<td>2.83 (0.03)</td>
<td>1011.4 (0.05)</td>
<td>–</td>
</tr>
<tr>
<td>CCSM4</td>
<td>286.5 (0.2)</td>
<td>2.93 (0.02)</td>
<td>1011.2 (0.04)</td>
<td>–</td>
</tr>
<tr>
<td>21°-90°N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WACCM</td>
<td>281.1 (0.3)</td>
<td>2.00 (0.04)</td>
<td>1016.9 (0.4)</td>
<td>14.0 (0.6)</td>
</tr>
<tr>
<td>SC-WACCM</td>
<td>281.0 (0.3)</td>
<td>1.99 (0.05)</td>
<td>1016.9 (0.4)</td>
<td>14.0 (0.5)</td>
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<tr>
<td>CCSM4</td>
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<td>2.13 (0.04)</td>
<td>1014.9 (0.5)</td>
<td>13.3 (0.5)</td>
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<td>21°S-21°N</td>
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<tr>
<td>WACCM</td>
<td>298.2 (0.4)</td>
<td>4.10 (0.08)</td>
<td>1010.6 (0.4)</td>
<td>–</td>
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<tr>
<td>SC-WACCM</td>
<td>298.2 (0.5)</td>
<td>4.10 (0.08)</td>
<td>1010.7 (0.4)</td>
<td>–</td>
</tr>
<tr>
<td>CCSM4</td>
<td>298.2 (0.4)</td>
<td>4.20 (0.07)</td>
<td>1011.9 (0.3)</td>
<td>–</td>
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<tr>
<td>21°-90°S</td>
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<tr>
<td>WACCM</td>
<td>279.9 (0.2)</td>
<td>2.25 (0.04)</td>
<td>1006.6 (0.4)</td>
<td>16.4 (0.9)</td>
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<td>SC-WACCM</td>
<td>279.8 (0.2)</td>
<td>2.25 (0.04)</td>
<td>1006.5 (0.4)</td>
<td>16.5 (0.7)</td>
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<tr>
<td>CCSM4</td>
<td>279.0 (0.2)</td>
<td>2.33 (0.04)</td>
<td>1006.7 (0.4)</td>
<td>20.4 (1.1)</td>
</tr>
</tbody>
</table>
Figure 7. Zonal mean temperature for (a),(c),(e) December-January-February (DJF) and (b),(d),(f) June-July-August (JJA). Panels (a) and (b) are for WACCM, (c) and (d) are for SC-WACCM and (e) and (f) are for CCSM4. Shading interval is 10 K.
Figure 8. Zonal mean zonal wind for (a), (c), (e) December-January-February (DJF) and (b), (d), (f) June-July-August (JJA). Panels (a) and (b) are for WACCM, (c) and (d) are for SC-WACCM and (e) and (f) are for CCSM4. Shading interval is 10 m s$^{-1}$. 
The residual circulation is also well represented in SC-WACCM.
The residual circulation is well represented in SC-WACCM.
The tropical water vapor tape recorder

Plots show the deviation in water vapor mixing ratio (ppmv) from the time-mean average profile averaged over 10°N-10°S.
Sudden stratospheric warming (SSW) frequency
Sudden stratospheric warming (SSW) frequency

Winter Frequencies:
- WACCM: 0.5 SSWs yr\(^{-1}\)
- SC-WACCM: 0.4 SSWs yr\(^{-1}\)
- CCSM4: 0.08 SSWs yr\(^{-1}\)
Polar vortices

U at 60N, 10hPa

RMSE of U at 60N, 10hPa

U at 60S, 10hPa

RMSE of U at 60S, 10hPa

NH

SH
Figure 14. Probability density distributions of 10 hPa December-January-February-March (DJFM) total (a) and anomalous (c) zonal mean eddy heat flux averaged from 45-to-75° N, total (b) and anomalous (d) polar cap averaged temperature. Black, red and blue curves are WACCM, SC-WACCM and CCSM4. Probability density distributions are computed using a kernel density estimator, which performs a non-parametric, smoothed fit to the data.
Figure 16. Probability density distributions of the North Atlantic Oscillation (NAO) index. Black, red and blue curves are WACCM, SC-WACCM and CCSM4. The NAO index is the time series of the leading EOF of monthly sea-level pressure anomalies for the North Atlantic region, 20°N and 90°W-30°E. Probability density distributions are computed using a kernel density estimator, which performs a non-parametric, smoothed fit to the data.
Figure 17. (a) Power spectrum and (b) probability density distributions of the NINO 3.4 index for WACCM (black), SC-WACCM (red) and CCSM4 (blue). Thin gray, pink and blue lines in (a) show 50-year spectra for WACCM, SC-WACCM and CCSM4, respectively. The NINO 3.4 index is the time series of sea surface temperature anomaly averaged over the tropical Pacific region, \(5^\circ S-5^\circ N\) and \(170^\circ W-120^\circ W\).
Changes in the Zonal Mean Winds 

Change from 
WACCM Difference
Jet Changes and Temperature

**a) DJF Zonal Wind: WACCM**

**b) DJF Zonal Wind: SC-WACCM (monthly)**

**c) DJF Zonal Wind: SC-WACCM (daily)**

**d) DJF Temperature: WACCM minus SC-WACCM (monthly)**

**f) DJF Temperature: WACCM minus SC-WACCM (daily)**