Stratospheric role for tropospheric circulation change

A high-top low-top comparison study with the GFDL climate model

Thomas Reichler (U. Utah)
Gang Chen (MIT), and Jian Lu (NCAR)
1. Introduction

In this modeling study, we explore the response of the atmospheric general circulation to anthropogenic climate change. We use the **uncoupled** GFDL AM2/3 climate model to understand how sensitive the response is to forcings such as ozone depletion, greenhouse gas increase, and warming SSTs.
2. Experimental Setup

We prescribe climatological mean SSTs from the coupled GFDL model. Each experiment is at least 40 years long and is conducted twice with the low- (L24) and high-top (L48) version of the model to understand the influence of stratospheric resolution for the simulation of climate. The following experiments are conducted:
## Simulations

<table>
<thead>
<tr>
<th>Name</th>
<th>Length</th>
<th>SSTs</th>
<th>GHGs</th>
<th>Ozone</th>
<th>Aerosols</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST\textsubscript{19}</td>
<td>500</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>O\textsubscript{3} SST\textsubscript{19}</td>
<td>200</td>
<td>P</td>
<td>P</td>
<td>I</td>
<td>V</td>
</tr>
<tr>
<td>\textfrac{1}{2}\text{CO}_2 \text{ SST}\textsubscript{19}</td>
<td>80</td>
<td>P</td>
<td>\textfrac{1}{2}</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>CO\textsubscript{2} SST\textsubscript{19}</td>
<td>“</td>
<td>P</td>
<td>I</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>2\text{CO}_2 SST\textsubscript{19}</td>
<td>200</td>
<td>P</td>
<td>x2</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>4\text{CO}_2 SST\textsubscript{19}</td>
<td>40</td>
<td>P</td>
<td>x4</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>CO\textsubscript{2} O\textsubscript{3} SST\textsubscript{19}</td>
<td>80</td>
<td>P</td>
<td>I</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>SST\textsubscript{20}</td>
<td>“</td>
<td>I</td>
<td>P</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>O\textsubscript{3} SST\textsubscript{20}</td>
<td>“</td>
<td>I</td>
<td>P</td>
<td>I</td>
<td>V</td>
</tr>
<tr>
<td>CO\textsubscript{2} SST\textsubscript{20}</td>
<td>“</td>
<td>I</td>
<td>I</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>CO\textsubscript{2} O\textsubscript{3} SST\textsubscript{20}</td>
<td>“</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>V</td>
</tr>
<tr>
<td>SST\textsubscript{21}</td>
<td>“</td>
<td>A1B</td>
<td>P</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>2\text{CO}_2 SST\textsubscript{21}</td>
<td>“</td>
<td>A1B</td>
<td>x2</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>SST\textsubscript{23}</td>
<td>“</td>
<td>A1B</td>
<td>P</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>2\text{CO}_2 SST\textsubscript{23}</td>
<td>“</td>
<td>A1B</td>
<td>x2</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>nV SST\textsubscript{19}</td>
<td>40</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>B</td>
</tr>
</tbody>
</table>

P: Pre-industrial  I: Industrial  V: Variable  B: Background

SSTs were derived from corresponding runs with the coupled version of the model (CM2.1).
3. Basic Response

T (DJF)

• Tropospheric warming - stratospheric cooling
• SSTs control tropospheric temperatures
• O₃ and CO₂ largely control stratospheric temperatures
• Strong O₃ related cooling (-5 K) over South Pole
u (DJF)

- In all cases intensified and poleward shifted polar vortex
- Clear tropospheric response (SAM+), even if only stratosphere is perturbed (downward influence)
Low frequency variability

- Considerable low-frequency variability in the stratosphere
- Frequency of stratospheric sudden warming events?
Phase Speed Spectra
DJFM

\begin{align*}
\text{O}_3 \text{ SST}_{19} & & \text{CO}_2 \text{ SST}_{19} & & \text{O}_3 \text{ CO}_2 \text{ SST}_{19} & & \text{SST}_{20} & & \text{O}_3 \text{ SST}_{20} & & \text{CO}_2 \text{ SST}_{20} & & \text{O}_3 \text{ CO}_2 \text{ SST}_{20}
\end{align*}
South Pole: T Seasonality

- Amplified $O_3$ cooling in L48
- Similar to observations reported by Thompson & Solomon (2002):
South Pole: Z Seasonality

- Amplified tropospheric SAM+ response in L48
- Again, very similar to Thompson & Solomon (2002):

![Graph showing 30-yr linear trends in Z with contours for SST, O3SST, CO2SST, and O3CO2SST anomalies.](image)
4. Widening of the General Circulation

Zonal mean circulation during JJA

Tropopause break
Jet core
Max. surface westerlies
Zero surface westerlies
Zero convergence
Maximum convergence
Zero crossing
SAM index
Annual Cycle Relationships

**HC • mmc**
- tropopause
- $u_{sfc} = 0$
- $-\text{div}(uv) = 0$

**STJ • $u_{250} = \text{max}$**
- HC equatorward during summer
- else joined
- EJ always poleward
- separated during SH winter
- else close (ca. 7°)

**EJ • $u_{sfc} = \text{max}$**
- $-\text{div}(uv) = \text{max}$
Widening: SH-DJF

Experiments:

- mmc
- tp
- $u_{sfc} = 0$
- $-\nabla (u'v') = 0$

Expansion degrees latitude

Experiment

- $u_{200}$
- $\text{baro}_{200}$
- SAM

- $u_{sfc} = \text{max}$
- $-\nabla (u'v') = \text{max}$
- etp
- ttp
Low/high-top differences
Total annual mean change

NAM/SAM

T_{sfc}

mmc

u_{s max}
Annual Mean Total Expansion

Expansion [degrees latitude]

Simulation type

Expansion indicators
5. Tropical Expansion

Averaged over 5 measures (jet, mmc, tp, u_{sfc}=0, d(uv)=0), the model simulates the following annual mean tropical expansion:

<table>
<thead>
<tr>
<th>Year</th>
<th>NH</th>
<th>SH</th>
<th>Total</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>0.6</td>
<td>0.8</td>
<td>1.4</td>
<td>1.1-1.6</td>
</tr>
<tr>
<td>2100 (A1B)</td>
<td>1.3</td>
<td>1.6</td>
<td>2.8</td>
<td>2.0-3.7</td>
</tr>
</tbody>
</table>
Factors for Tropical Expansion

Annual mean total tropical expansion average over five measures with respect to pre-industrial control in degrees latitude

<table>
<thead>
<tr>
<th></th>
<th>$\text{SST}_{19}$</th>
<th>$\text{SST}_{20}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{O}_3$</td>
<td>0.2</td>
<td>1.2</td>
</tr>
<tr>
<td>$\text{CO}_2$</td>
<td>0.1</td>
<td>1.1</td>
</tr>
<tr>
<td>$\text{O}_3 + \text{CO}_2$</td>
<td>0.5</td>
<td>1.4</td>
</tr>
</tbody>
</table>

• Note the individual effects are almost linearly additive
• SSTs are important, i.e., tropospheric control
• Some effect from stratosphere: $\text{O}_3$ and $\text{CO}_2$
Seasonality of Widening

mmc expansion by experiment and season

• As in observations, strongest expansion during summer and fall in each hemisphere (weak HC)
6. Conclusion

• Model simulated widening:
  – 1.4° by today
  – 2.8° by 2100

• Widening is not restricted to Tropics; many elements of the general circulation shift poleward

• Widening strongest during summer and over SH

• SSTs are most important contributor

• Tropospheric response of low-top model is very similar to that of high-top model