Decadal Trends in the Width of the Tropical Belt

A modeling 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 characteristics of the poleward shift of the atmospheric general circulation under anthropogenic climate change. We use the uncoupled GFDL AM2/3 climate model to understand how sensitive this shift 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 strato-spheric 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&lt;sub&gt;19&lt;/sub&gt;</td>
<td>120</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>V</td>
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<tr>
<td>O&lt;sub&gt;3&lt;/sub&gt; SST&lt;sub&gt;19&lt;/sub&gt;</td>
<td>100</td>
<td>P</td>
<td>P</td>
<td>I</td>
<td>V</td>
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<tr>
<td>½CO&lt;sub&gt;2&lt;/sub&gt; SST&lt;sub&gt;19&lt;/sub&gt;</td>
<td>40</td>
<td>P</td>
<td>½</td>
<td>P</td>
<td>V</td>
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<tr>
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<td>&quot;</td>
<td>P</td>
<td>I</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>2xCO&lt;sub&gt;2&lt;/sub&gt; SST&lt;sub&gt;19&lt;/sub&gt;</td>
<td>&quot;</td>
<td>P</td>
<td>x2</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
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<td>P</td>
<td>x4</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt; O&lt;sub&gt;3&lt;/sub&gt; SST&lt;sub&gt;19&lt;/sub&gt;</td>
<td>&quot;</td>
<td>P</td>
<td>I</td>
<td>P</td>
<td>V</td>
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<td>I</td>
<td>P</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>O&lt;sub&gt;3&lt;/sub&gt; SST&lt;sub&gt;20&lt;/sub&gt;</td>
<td>&quot;</td>
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<td>P</td>
<td>I</td>
<td>V</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt; SST&lt;sub&gt;20&lt;/sub&gt;</td>
<td>&quot;</td>
<td>I</td>
<td>I</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt; O&lt;sub&gt;3&lt;/sub&gt; SST&lt;sub&gt;20&lt;/sub&gt;</td>
<td>&quot;</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>V</td>
</tr>
<tr>
<td>SST&lt;sub&gt;21&lt;/sub&gt;</td>
<td>&quot;</td>
<td>A1B</td>
<td>P</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>2xCO&lt;sub&gt;2&lt;/sub&gt; SST&lt;sub&gt;21&lt;/sub&gt;</td>
<td>&quot;</td>
<td>A1B</td>
<td>x2</td>
<td>P</td>
<td>V</td>
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<tr>
<td>SST&lt;sub&gt;23&lt;/sub&gt;</td>
<td>&quot;</td>
<td>A1B</td>
<td>P</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>2xCO&lt;sub&gt;2&lt;/sub&gt; SST&lt;sub&gt;23&lt;/sub&gt;</td>
<td>&quot;</td>
<td>A1B</td>
<td>x2</td>
<td>P</td>
<td>V</td>
</tr>
<tr>
<td>nV SST&lt;sub&gt;19&lt;/sub&gt;</td>
<td>&quot;</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
- $O_3$ and $CO_2$ largely control stratospheric temperatures
- Strong $O_3$ related cooling (-5 K) over South $O_3$ $CO_2$ Pole
In all cases intensified and poleward shifted polar vortex

Clear tropospheric response (SAM+), even if only stratosphere is perturbed (downward influence)
Low frequency variability $u$ (DJF)

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

DJFM
South Pole: T Seasonality

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

Polar cap (65-90S) temperature anom.

$SST_{20}$

$O_3SST_{20}$

$CO_2SST_{20}$

$O_3\ CO_2SST_{20}$

$7 \text{ K}$

$6.5 \text{ K}$

$8.5 \text{ K}$

(month)
South Pole: Z Seasonality

- Amplified tropospheric SAM+ response in L48
- Again, very similar to Thompson & Solomon (2002):
4. Widening of the General Circulation

Zonal mean circulation during JJA
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:

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

Expansion degrees latitude

STJ

- \( u_{200} \)
- \( \text{baro}_{200} \)

EJ

- \( u_{sfc} = \text{max} \)
- \( -\nabla (u'v') = \text{max} \)

HC

- Experiment

SAM

- etp
- ttp
Low/high-top differences
Total annual mean change

NAM/SAM

T_{sfc}

mmc

u_{s, max}
Annual Mean Total Expansion

Simulation type:
- mmc
- tp
- jet
- uszero
- duvzero
- usmax

Expansion indicators:
- 2xCO2_SSTA1B
- CO2_SSTA1B
- SSTg20k
- 4xCO2_SSTg19k
- 2xCO2_SSTg19k
- CO2_SSTg19k
- 05CO2_SSTg19k
- CO2_O3_SSTg19k
- O3_SSTg20k
- CO2_O3_SSTg20k
- O3_SSTg19k
- nV_SSTg19k

Expansion [degrees latitude]
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:

Annual mean expansion with respect to pre-industrial control in degrees latitude

<table>
<thead>
<tr>
<th></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><strong>1.4</strong></td>
<td>1.1-1.6</td>
</tr>
<tr>
<td>2100 (A1B)</td>
<td><strong>1.3</strong></td>
<td>1.6</td>
<td><strong>2.8</strong></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>SST(_{19})</th>
<th>SST(_{20})</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>1.0</td>
</tr>
<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; entire general circulation seems to shift

• Widening strongest during summer and over SH

• SSTs are most important contributor

• Low-top model is very similar to high-top (exception: O₃ sensitivity)