The Response of the Stratosphere to the 11-year Solar Cycle, the Quasi-Biennial Oscillation, and the Pacific Decadal Oscillation

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Climate change prediction and “hiatus”

What is driving stall in rise of global temperatures since 2000?

Earth System Models of Intermediate Complexity

IPCC [2013; Figure 9.8]
Natural forcings of climate

- Quasi-biennial oscillation
- Pacific Decadal Oscillation
- The Sun

- SORCE and SOLSTICE
- Natural forcings of climate

- Earth's response to solar variability

- Wavelength dependent

- TSI 230 nm SSI

- HadISST

- 0.1% ~ 5%
Science questions and motivation

Motivation -> Investigate Sun’s impact on Earth system

• What is the role of varying solar spectral irradiance (SSI) in decadal climate variability?

• What is the role of the 11-year solar cycle and quasi-biennial oscillation (QBO) in influencing the northern polar stratosphere?

• Does the pacific decadal oscillation (PDO) influence the northern polar stratosphere and is it modulated by variable solar forcing?
Solar Irradiance: Largest Energy Source

Earth’s Energy Sources (Log scale)

- **Solar Irradiance**: 340.25 W m\(^{-2}\)
- **TSI 0.1%**: 0.34 W m\(^{-2}\)
- **All other sources**: 0.129 W m\(^{-2}\)

Top-down and bottom-up solar forcing

thermosphere

mesosphere

stratosphere

Bottom-up Mechanism

Troposphere

ENSO

Equator

Walker & Hadley Cell

PDO

oceans

AO, NAO

surface

SH

NH

TSI 0.1%

Top-down Mechanism

UV > 6%

O₃

QBO

ΔU

ΔU,T

ΔT

UV
Proposed Solar and QBO interaction on high latitudes

QBO → Modified wave propagation → Zonal wind anomaly in subtropical upper stratosphere

Solar Cycle → Modulation of upper stratospheric jet at midlatitudes → Zonal wind anomaly in subtropical upper stratosphere

Solar Cycle and QBO → Zonal wind Anomalies enhanced or diminished → Poleward – downward propagation

Weaker vortex in Smax/QBO west

[Kodera, 1991; Gray et al., 2004; Matthes et al., 2013]
Motivation

Compositing 30 hPa geopotential heights at North Pole as function of solar cycle and QBO phase

[Labitzke and Kunze, 2009]
### Whole Atmosphere Community Climate Model (WACCM)

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Case 1: 1850 – 2005 (WACCM4a)</th>
<th>Case 2: 1850 – 1943 (WACCM4b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical resolution</td>
<td>66 levels, surface to lower thermosphere (5.1 x 10^{-6} hPa)</td>
<td>Vertical resolution</td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>1.9° latitude by 2.5° longitude</td>
<td>Horizontal resolution</td>
</tr>
<tr>
<td>Atmospheric dynamics</td>
<td>Interactive ocean, sea ice, chemistry</td>
<td>Atmospheric dynamics</td>
</tr>
<tr>
<td>Volcanic activity</td>
<td>Specified</td>
<td>Volcanic activity</td>
</tr>
<tr>
<td>Greenhouse gas forcing</td>
<td>Transient 20\textsuperscript{th} century simulations</td>
<td>Greenhouse gas forcing</td>
</tr>
<tr>
<td>QBO</td>
<td>Internally generated, QBO at 30 hPa</td>
<td>QBO</td>
</tr>
</tbody>
</table>

Whole Atmosphere Community Climate Model (WACCM)
Reproducibility of observed QBO

Westerlies > 5 m/s  Easterlies < -10 m/s
Stratospheric response to solar cycle

Composite Solar Max – Solar Min

This study

[Austin et al., 2008]
Prior research suggests QBO modulation by solar cycle...

Wavelet analysis

QBO Period

QBO variation and UV spectral irradiance
### Solar and QBO interaction on high latitude winter

#### Composite and correlation analysis

<table>
<thead>
<tr>
<th>Model/Obs.</th>
<th>Period</th>
<th>QBO East</th>
<th>QBO West</th>
<th>n (East)</th>
<th>n (West)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WACCM4a</td>
<td>1850 - 1890</td>
<td>-0.04 [0.89]</td>
<td>0.22 [0.36]</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td>WACCM4b</td>
<td>1850 - 1890</td>
<td>-0.17 [0.58]</td>
<td>-0.13 [0.57]</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td>WACCM4a</td>
<td>1891 - 1931</td>
<td>0.06 [0.83]</td>
<td><strong>0.43 [0.08]</strong></td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>WACCM4b</td>
<td>1891 - 1931</td>
<td>-0.24 [0.34]</td>
<td>0.04 [0.87]</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>WACCM4a</td>
<td>1932 - 1972</td>
<td>-0.07 [0.77]</td>
<td>-0.04 [0.87]</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>WACCM4a</td>
<td>1973 - 2005</td>
<td>0.00 [0.98]</td>
<td><strong>-0.47 [0.09]</strong></td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>NCEP Reanalysis</td>
<td>1953 - 2005</td>
<td>-0.09 [0.73]</td>
<td><strong>0.61 [0.001]</strong></td>
<td>14</td>
<td>28</td>
</tr>
<tr>
<td>NCEP Reanalysis</td>
<td>1953 - 2012</td>
<td>-0.18 [0.47]</td>
<td><strong>0.36 [0.04]</strong></td>
<td>16</td>
<td>33</td>
</tr>
</tbody>
</table>
Solar and QBO interaction on high latitude winter

Monte Carlo sampling

Time-mean response of stratosphere to solar and QBO forcing

1. Winters (DJFM) randomly sampled from both WACCM cases (249 winters)
2. Each winter month, group years into QBO East and West
3. 16 East and 33 West randomly selected to match observational period 1953-2012
4. Compute correlation between 30 hPa heights at north pole and 255 nm irradiance.
5. Repeat a million times to get normalized $R$ correlation
Solar and QBO summary

- Examining Solar response in the stratosphere
  - WACCM simulations with internally generated QBO
  - Warming of ~ 0.5 K in tropical upper stratosphere
  - Solar modulation of QBO period or amplitude not found

- Solar-QBO relationship on high latitude winter
  - Correlation found over selected 40-yr periods of QBO west
  - Time-mean response not significant
  - Chance occurrence of solar-QBO correlation

### PDO Methodology

<table>
<thead>
<tr>
<th>WACCM Simulation</th>
<th>Hadley Centre SST dataset (HadISST)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1850 control simulation (200 years)</strong></td>
<td><strong>1900-2014 period</strong></td>
</tr>
<tr>
<td>Volcanic activity</td>
<td>Monthly SSTs</td>
</tr>
<tr>
<td>None</td>
<td>1° resolution</td>
</tr>
<tr>
<td>Greenhouse gas forcing</td>
<td></td>
</tr>
<tr>
<td>1850 pre-industrial levels</td>
<td></td>
</tr>
<tr>
<td>Solar forcing</td>
<td></td>
</tr>
<tr>
<td>Fixed SSI at solar avg</td>
<td></td>
</tr>
<tr>
<td>QBO</td>
<td></td>
</tr>
<tr>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>
DJF PDO spatial pattern
Principal Component Analysis

(b) HadISST PDO (25%)

(c) WACCM PDO (29%)

Temperature (C/sd)

-1.25 -1.00 -0.75 -0.50 -0.40 -0.30 -0.20 -0.10 0.00 0.10 0.20 0.30 0.40 0.50 0.75 1.00 1.25
Winter PDO signature in the stratosphere

December Composite PDO (+) – PDO (-)
# Potential PDO modulation by solar cycle

<table>
<thead>
<tr>
<th>Peak Solar Year</th>
<th>DJF PDO</th>
<th>JF PDO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1907</td>
<td>-0.32</td>
<td>-0.43</td>
</tr>
<tr>
<td>1917</td>
<td>-1.07</td>
<td>-1.01</td>
</tr>
<tr>
<td>1928</td>
<td>0.34</td>
<td>0.70</td>
</tr>
<tr>
<td>1937</td>
<td>0.33</td>
<td>-0.22</td>
</tr>
<tr>
<td>1947</td>
<td>-0.55</td>
<td>-0.38</td>
</tr>
<tr>
<td>1957</td>
<td>-1.04</td>
<td>-1.19</td>
</tr>
<tr>
<td>1968</td>
<td>-0.55</td>
<td>-0.42</td>
</tr>
<tr>
<td>1979</td>
<td>-0.50</td>
<td>-0.54</td>
</tr>
<tr>
<td>1989</td>
<td>-0.93</td>
<td>-1.3</td>
</tr>
<tr>
<td>2000</td>
<td>-1.32</td>
<td>-1.24</td>
</tr>
<tr>
<td>2013</td>
<td>-0.92</td>
<td>-0.79</td>
</tr>
</tbody>
</table>
PDO summary and future work

• **PDO stratospheric signal**
  • WACCM PDO can reproduce observed PDO
  • Hemispheric and zonal mean warming over polar region in PDO (+)
  • Contamination between PDO and ENSO
  • Future study beneficial to examine interplay between PDO and ENSO

• **Solar forcing of PDO and “hiatus”**
  • Future study needed to investigate PDO modulation by solar cycle
  • Decadal climate prediction can be aided by understanding PDO

1. Targeting winter storms affecting Alaska and U.S.
2. Regions sensitive to added dropsonde data
3. Real-time support for Global Hawk – improve forecasts
Thank you
All other sources of energy
Solar and non-Solar
Originally presented in *Sellers* [1965]

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Flux Density [W m(^{-2})]</th>
<th>Relative to Total Solar Irradiance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Irradiance</td>
<td>340.25</td>
<td>1.000</td>
</tr>
<tr>
<td>Secondary Sources of Solar Origin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anthropogenic Heat Flux</td>
<td>0.028</td>
<td>8.2E-05</td>
</tr>
<tr>
<td>Infrared Radiation from Full Moon</td>
<td>0.012</td>
<td>3.5E-05</td>
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<tr>
<td>Reflected Radiation from Full Moon</td>
<td>0.0038</td>
<td>1.1E-05</td>
</tr>
<tr>
<td>Airglow Emission</td>
<td>0.00349</td>
<td>1.03E-05</td>
</tr>
<tr>
<td>Auroral Emission</td>
<td>0.00252</td>
<td>7.4E-06</td>
</tr>
<tr>
<td>Solar Atmospheric Tides</td>
<td>0.00165</td>
<td>4.8E-06</td>
</tr>
<tr>
<td>Magnetic Storm Dissipation</td>
<td>0.001</td>
<td>2.9E-06</td>
</tr>
<tr>
<td>Zodiacal Irradiance</td>
<td>5.65E-05</td>
<td>1.66E-07</td>
</tr>
<tr>
<td>Lightning Discharge Energy</td>
<td>8.6E-06 to 8.6E-05</td>
<td>1.4E-07</td>
</tr>
<tr>
<td>Earthshine</td>
<td>3.08E-07</td>
<td>9.1E-10</td>
</tr>
<tr>
<td>Total</td>
<td>0.053</td>
<td>1.6E-04</td>
</tr>
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<tr>
<td>Secondary Sources of non-Solar Origin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earth’s Interior Heat Flux</td>
<td>0.06 to 0.092</td>
<td>2.2E-04</td>
</tr>
<tr>
<td>Cosmic Radiation</td>
<td>3.51 to 7.42E-05</td>
<td>1.6E-07</td>
</tr>
<tr>
<td>Lunar Tides</td>
<td>1.89E-05</td>
<td>5.6E-08</td>
</tr>
<tr>
<td>Dissipation of Energy of Micrometeorites</td>
<td>3.8E-07</td>
<td>1.1E-09</td>
</tr>
<tr>
<td>Extragalactic Light</td>
<td>1.26E-08</td>
<td>3.7E-11</td>
</tr>
<tr>
<td>Total</td>
<td>0.076</td>
<td>2.2E-04</td>
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</table>