Interactive QBO simulations in a warming climate

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NCAR
Why is QBO important?

- Primary mode of variability in the Tropical stratosphere
- Influences mean meridional circulation, temperature & transport
- Affects the strength of the polar vortex
- Affects tropospheric climate (NAO)

Figures from Anstey & Shepherd (2014)
QBO Characteristics OBS:

From observations: 1952 - 2016

Westerly Amplitude

Easterly Amplitude

Period

Period ranges from 20 – 35 months
Mean: 28 months
QBOi: QBO Intercomparison Project

- **QBOi** is a SPARC activity to improve understanding of QBO
- Led by S. Osprey (Oxford), N. Butchart (MetOffice), & J. Anstey (CCCma)
- **First meeting:** March 2015; **2nd meeting:** September 2016
- Participating models: LMDz6 (France), HADGEM3 (UK), AGCM3-CMAM (Canada), MIROC (Japan), MRI-ESM2 (Japan), ECHAM5sh (Italy), ECMWF EC-EARTH, NRL NAVGEM, 60L-CAM and 110L-WACCM (NCAR)
QBOi Experiments:

<table>
<thead>
<tr>
<th>EXP</th>
<th>SSTs</th>
<th>CO₂</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXP1</td>
<td>Observed</td>
<td>Observed</td>
<td>1979-2010</td>
</tr>
<tr>
<td>EXP2</td>
<td>Climo 2002</td>
<td>2002</td>
<td>30</td>
</tr>
<tr>
<td>EXP3</td>
<td>Climo 2002 + 2K</td>
<td>2 x CO₂</td>
<td>30</td>
</tr>
<tr>
<td>EXP4</td>
<td>Climo 2002 + 4K</td>
<td>4 x CO₂</td>
<td>30</td>
</tr>
<tr>
<td>EXP5</td>
<td></td>
<td>Seasonal Hindcasts</td>
<td></td>
</tr>
</tbody>
</table>
110L CESM1 (WACCM): aka 110L-WACCM

- Based on Community Earth System Model, version 1 (CESM1)
- 0.9 x1.25° horizontal resolution
- CAM5.4 physics
- Zhang & McFarlane convection
- No CLUBB
- Top ~ 140 km
- 110 instead of 70 levels
- **500 m resolution** lower stratosphere
- Builds on 60-level CAM5
- Full chemistry or specified chemistry
- Additional GW parameterizations

Built by J. Richter & R. Garcia for QBOi (not default CMIP6 model)
1. Orographic GWs:
Uncertain: Efficiency

**Orographic GWs:**
- McFarlane (1987)
- 1 wave with $c = 0$
- Amplitude dependent on orography height and mean wind

2. Frontally generated GWs:
Uncertain: Efficiency, amplitude, phase speeds

- 40 waves with $-100 < c < 100$ m/s
- Gaussian distribution in phase speed centered at $U = 600$ mb
- Constant wave amplitude

3. Convectively generated GWs:
Uncertain: Efficiency, amplitude conversion

- 40 waves with $-100 < c < 100$ m/s
- Dominant $c$ related to $h$ (depth of heating)
- Wave Amplitude $= Q^2$
- Wave spectrum impacted by wind in heating

*Beres et al. 2004 (Beres = Richter)*
QBO: 70 vs 110L WACCM

QBO descends to 100 hPa as observed (tropical Kelvin and RG waves are well resolved in the 110L model)
QBO in EXP 1: 110L WACCM @ 20 hPa

**Westerly Amplitude**

- OBS
  - EXP1–CHEM

**Easterly Amplitude**

- OBS
  - EXP1–CHEM

**Period**

- mean: 28.0 months
  - OBS
  - EXP1–CHEM
- mean: 27.5 months
  - WACCM
QBO in Exp 1: Other models

QBOi EXP1: 1979 - 2009

OBS
WACCM
CMAM
ECHAM5sh
MRI
HadGEM-2
LMDz
MIROC-ESM
QBO in EXP 1: Other models

QBOi EXP1: 1979 - 2009
Previous Studies:

Predictions of QBO in future:

- Giorgetta & Doege (2005): shortened QBO period from 26 to 17 months (2 x CO₂)
- Kawatani et al (2011): lengthened period ~ 3 months (2 x CO₂)
- Watanabe & Kawatani (2012): lengthening ~ 3 months
- Schirber et al. (2015): Inconclusive

Increased Wave Momentum Flux → Shorter QBO period

Increased \( w^* \) → Longer QBO period
WACCM: EXP 2, 3, 4

**EXP2**: annually-repeating SSTs, 1 X CO$_2$

**EXP3**: annually-repeating SSTs + 2K, 2 X CO$_2$

**EXP4**: annually-repeating SSTs + 4K, 4 X CO$_2$
WACCM: Exp 2, 3, 4

Exp 2
Climo SST, 1 X CO\(_2\)

Exp 3
Climo SST+2K, 2 X CO\(_2\)

Exp 4
QBO Interruption
Climo SST+4K, 4 X CO\(_2\)

Changes due primarily to SSTs. No significant changes due to CO\(_2\).
QBO amplitude and period @ 20 hPa: EXP2, 3, 4

In WACCM, QBO period decreases systematically as SSTs increase in EXP3, EXP4.
QBO Forcing: EXP2, EXP4

Decrease of QBO period in EXP4 due to increased GW source momentum flux & increased Kelvin wave activity
### QBO Periods in EXP 2, 3, 4: Other Models

<table>
<thead>
<tr>
<th>Model</th>
<th>EXP 2</th>
<th>EXP 3</th>
<th>EXP 4</th>
<th>GW Source</th>
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</thead>
<tbody>
<tr>
<td>WACCM</td>
<td>28.8</td>
<td>21</td>
<td>15</td>
<td>Interactive</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Beres et al. 2004</td>
</tr>
<tr>
<td>CMAM</td>
<td>29</td>
<td>40</td>
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<td>Fixed (McFarlane)</td>
</tr>
<tr>
<td>MRI</td>
<td>24</td>
<td>24+</td>
<td>24+</td>
<td>Fixed (Hines)</td>
</tr>
<tr>
<td>LMDz</td>
<td>28</td>
<td>30</td>
<td>100</td>
<td>Interactive</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lott and Guez (2013)</td>
</tr>
<tr>
<td>ECHAM5sh</td>
<td>27</td>
<td>27</td>
<td>N/A</td>
<td>Fixed (Hines)</td>
</tr>
<tr>
<td>MIROC-ESM</td>
<td>24</td>
<td>26</td>
<td>33</td>
<td>Fixed (Hines)</td>
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<tr>
<td>MIROC-AGCM</td>
<td>19.5</td>
<td>20.5</td>
<td>23</td>
<td>None</td>
</tr>
</tbody>
</table>

**Preliminary results from QBOi Paper 2 (in preparation):**
Robustness of QBO’s response to climate forcing: EXP2, EXP3, EXP4

**Co-leads:** Yaga Richter, Neal Butchart
LMDz Convective GW flux:

- Stochastic parameterization: frequency & wave numbers chosen randomly
- Wave amplitude is related to precipitation, which is converted into heating rate
- Distribute latent heat in Gaussian similarly to Beres et al. 2004 (chose ‘dz’)

Negligible changes in GW source momentum flux because changes in precipitation are very small

Precip EXP2 ~ Precip EXP4
GW Flux EXP2 ~ GW Flux EXP4

Total Precipitation 2039 (kg/m²/day)
QBO in warming climate: Uncertainties

There are large uncertainties as to how the QBO will change in the future climate

- How accurate are convective parameterizations in future climates?
- Will relationships between convective heating and GWs hold in future climate?
- How will the resolved waves change?
- How will the residual circulation change?
Thank you!

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QBO interruption in EXP4

February 2016

WACCM: March 1981, EXP4

• QBO morphology similar in EXP4 (3/1981) and observations (2/2016)

• Easterly EP Flux Divergence plays a role in both

from Osprey et al. (Science, 2016)
TEM momentum budget at 40 hPa

- Overall behavior and magnitudes similar in WACCM and observations

- in WACCM:
  - horizontal mean advection is not negligible
  - GW drag and div(F) have comparable magnitude

- Otherwise, U, vertical advection and div(F) have comparable magnitudes in WACCM and observations

Osprey et al. (*Science*, 2016)

\[ U, \quad \frac{\partial (F_y)}{\partial y}, \quad \frac{\partial (F_z)}{\partial z}, \quad \text{w}^* U_z, \quad \text{div}(F) \]