The response of parameterised gravity wave momentum fluxes in global models to secular changes in climate and ozone and the effects on the general circulation

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General Outline

- Climatology of parameterized momentum fluxes in the HadGEM
  - Filtering of non orographic waves (update of Warner et al. JAS 2001)
  - Orographic waves
- Trends in parameterized momentum fluxes in the HadGEM
  - Non-orographic waves
  - Orographic waves
- Climate impact of changes in parameterized momentum fluxes
  - Brewer-Dobson circulation / downward control / assumption of vertical propagation
  - Tropical upwelling
  - Impact on QBO period
  - South polar upper stratospheric downwelling
- Conclusions
Filtering eastward propagating momentum flux

Percentage of 300 hPa eastward momentum flux

January July

Waves launched with spatially constant eastward momentum flux at ~5km

Note the shadowing effect of the winter subtropical jets but not the summer jet

Zonal mean climatology from the Warner and McIntyre (1999)
NOGW parameterisation in the Hadley Centre climate model

cf. Warner et al. JAS 2005

Eastward propagating momentum flux preferentially filtered in the eastward polar night jets with more pronounced filtering in SH winter
Filtering westward propagating momentum flux

Percentage of 300 hPa westward momentum flux

Waves launched with spatially constant westward momentum flux at ~5km equal in magnitude to eastward flux

Zero net momentum flux at launch

Westward propagating momentum flux preferentially filtered in the westward summer jets

Zonal mean climatology from the Warner and McIntyre (1999) NOGW parameterisation in the Hadley Centre climate model

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Parameterised momentum fluxes for a latitude-independent source spectrum agree well with high (T213) resolution simulations.

Distribution of fluxes is relatively insensitive to details of the sources and is mainly determined by the filtering (for waves with non-orographic sources).

Modelled fluxes from Sato et al. GRL 2009
(horizontal wavelengths ≤ 1800 km)
Orographic/Nonorographic GW momentum fluxes

**Orographic Fluxes:**
- Almost entirely westward due to the predominance of surface westerlies.
- Of comparable, through slightly larger, magnitude than the non-orographic fluxes in the UTLS.
- Above the lower stratosphere are confined to a narrow latitude band and winter.

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**Nonorographic Fluxes:**

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Momentum flux trends for RCP8.5

Opposite trends 2006-2050 and 2050-2100 most likely related to ozone recovery.

Outside the tropics momentum flux trends determined by the trend in the zonal wind.

Contours: zonal wind trend (ms⁻¹ per decade)
Momentum flux trends for OGWs

Trends 2006 to 2050

January July

Contours: zonal wind trend (ms$^{-1}$ per decade)

Acceleration of subtropical jet increases the westward momentum flux reaching the lower stratosphere

Changes in high latitude fluxes extend upward from surface

Changes in surface winds (i.e. sources) more important than changes in upper level winds (i.e. filtering)?
Downward control influence of GWs on the zonal mean general circulation

TEM residual circulation
Brewer Dobson circulation

Contribution to the driving of the residual circulation from:

- resolved waves
- orographic gravity waves
- nonorographic gravity waves

Climatological annual mean mass stream function from the Hadley Centre climate model

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Downward control for parameterized gravity waves

“Downward control”

upwelling or downwelling  \( \overline{w^*} = -\frac{1}{\alpha \rho \cos \phi} \frac{\partial}{\partial \phi} \left( \int_{z}^{\infty} \frac{\rho F \cos \phi}{2\Omega \sin \phi} \, dz \right) \)  

(Haynes et al. 1991)

where  \( F \) is the zonal forcing from:

- Gravity wave drag
- EP-flux divergence
- Rayleigh friction

** Most gravity wave parameterizations assume vertical propagation **

\[
\therefore \int_{z}^{\infty} \rho F \, dz = (a \cos \phi)^{-1} \left[ F(z) |_{\infty} - F(z) |_{z} \right] \approx \rho \overline{u'w'} |_{z} 
\]

(Shepherd and Shaw 2004)

Contribution from gravity waves to the streamfunction  \( \psi \) at level  \( z \) depends only on the parameterized momentum flux at level  \( z \)  
(minus the flux escaping to outer space)

streamfunction  \( \psi_{gw}(\phi, z) \sim -\frac{\cos \phi}{2\Omega \sin \phi} \rho \overline{u'(\phi, z)w'(\phi, z)} \)  

where  \( \overline{w^*} = \frac{1}{\alpha \rho \cos \phi} \frac{\partial \psi}{\partial \phi} \)
Orographic GWD / tropical upwelling
(from CCMVal phase 1)

Annual mean tropical upwelling mass flux at 70 hPa
Mean flux for 2000

Projected trend in 21st century

From residual vertical velocities
From downward control
- Orographic gravity wave drag
- Nonorographic gravity wave drag
- EP-flux divergence

On average 59% (77% in DJF) of the increase in upwelling is due to an increase in orographic gravity wave drag

From Butchart et al. J. Climate 2010

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Sub-tropical jets

Projected 21st century trend in eastward wind at 70 hPa for CCMVal-1 models

Westward acceleration due to ozone recovery

From Butchart et al. J. Climate 2010
OGWD at the NH turnaround latitudes contributing to the downward control integral.

Acceleration of the subtropical jets raises the breaking level for the OGWs increasing the drag above 70 hPa.

Increased zonal forcing in the downward control integral hence increased the tropical upwelling.

NB: Increasing the source of waves already breaking below 70 hPa cannot increase the flux at 70 hPa.

From Butchart et al. *J. Climate* 2010
Local tropical response to momentum flux filtering

From RCP8.5 simulation of the Hadley Centre Climate model

Eastward acceleration of the zonal wind at the tropical tropopause

Filters out more eastward but allows more westward flux with an increase in the gross flux

Change from 2005-2015 to 2090-2099

Sensitivity of QBO period to momentum flux
From Scaife et al. GRL 2000

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QBO period declines from ~26 to ~21 months due to climate change (RCP 8.5) despite increased tropical upwelling. Effects of increases in momentum fluxes in the tropics outweigh those of increased upwelling.

? Resolved wave contribution?

See talk by Andrew Bushell.

cf. Kawatani et al. JAS early online releases => increased period for 2 x CO₂
Extra-tropical mesospheric drag (from CCMVal phase 2)

Westward acceleration of the PNJ in spring is a robust feature of 5 (of 6) CCMVal-2 models.

Decrease in the westward drag in the upper stratosphere and mesosphere could lead to:

- Fractional (percentage) change in drag very similar despite large spread in actual drag.
South polar downwelling
(from CCMVal phase 2)

GWD is a significant contributor to SH polar downwelling in spring in the upper stratosphere.

Weaker PNJ in spring filters more westward momentum flux lower down reducing westward drag in the upper stratosphere.

Reduction in the polar downwelling

Increased downwelling

Polar downwelling south of 60° S
Conclusions

- Distribution of parameterised momentum fluxes largely determined by filtering for nonorographic waves
- Parameterised momentum fluxes agree well with high resolution model fluxes
- Trends in the momentum flux follow those in the polar night and subtropical jets
- Eastward acceleration of the sub-tropical jets raises the breaking level of parameterized OGWs and thereby accelerates the tropical upwelling under climate change in a multi-model ensemble
- QBO period decreases in the HadGEM under climate change (-> Increases in the BDC outweighed by increased wave forcing)
- A weakening of the SH PNJ in spring filters more westward momentum flux lower down reducing upper stratospheric drag and hence polar downwelling
- ? How much of the multi-model robustness of the climate feedback involving the filtering of parameterised GWs is the result of the similarities in the schemes and the inherent assumptions (e.g. vertical propagation, wave saturation assumptions.........)?