Sensitivity of resolved and parameterized surface drag to changes in resolution and parameterization

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With thanks to: Simon Vosper, Stuart Webster, Andy Elvidge, Irina Sandu and Sylvie Malardel
Large spread in model climatology

Multi-model mean bias

Inter-model bias spread

300hPa Zonal wind $\text{CI} = 1 \text{ ms}^{-1}$

Delcambre et al 2013
Large spread in model response
Multi-model mean bias      Inter-model bias spread

300hPa Zonal wind  CI = 1 ms$^{-1}$

a. Ensemble Mean Bias

b. Model Standard Deviation of Bias

Delcambre et al 2013

Multi-model mean response
Inter-model response spread

e) CMIP5 slp (hPa)
f) CMIP5 slp std (hPa)

Manzini et al 2013
Large spread in model response

Models do not agree on the sign of the shift in the mid-latitude surface jets, let alone the magnitude

Barnes and Polvani (2013)
How can we reduce model uncertainty?

- Better understanding of processes governing the range seen in climatological circulation of models

WGNE Drag Project, Report No.1, A. Zadra (2013)
Momentum budget as a tool for understanding circulation sensitivity to drag

Vertically integrated zonal mean angular momentum budget:

\[
\frac{\partial}{\partial t} \left[ \int_{z_0}^{\infty} m \rho dz \right] = -\frac{1}{r \cos \phi} \frac{\partial}{\partial \phi} \left( \left[ \int_{z_0}^{\infty} m v \rho dz \right] \cos \phi \right) \\
+ \left[ \int_{z_0}^{\infty} f v r \cos \phi \rho dz \right] - \left[ p_0 \frac{\partial z_0}{\partial \lambda} \right] - [F_0 r \cos \phi]
\]

\[
m = u r \cos \phi
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Angular momentum flux convergence (AMFC)

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\]

\[m = ur \cos \phi\]

 Boundary layer (BL)  Sub-grid scale orographic (SSO)

\[F_0 = F_{BL} + F_{GWD} + F_{Blocking}\]
Sources of uncertainty in surface drag:

1) Model Resolution:
   - Models with different horizontal resolutions will have different resolved surface drag
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Aim: Understand the contributions to model uncertainty from parameterized and resolved orographic drag
Momentum budget as a tool for understanding circulation sensitivity

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F_0 = F_{BL} + F_{GWD} + F_{Blocking}
\]
Earth’s angular momentum budget – constrained through initial conditions

A. Brown (2004), QJRMS
Nudge towards ERA-interim in free atmosphere

\[ \frac{\Delta X}{\Delta t} = F(X) + \frac{(X_A - X_M)}{\tau} \]

\[ X = (u, v, T) \]

Hartmann 2007
Model Setup

• **Model:** UK Met Office Unified Model (ENDGame)
  Non-hydrostatic, semi-Lagrangian, regular lat/lon grid
  85 hybrid-height vertical levels extending to 85km
• **AMIP-style:** Prescribed SSTs and sea ice
• **Months for analysis:** January 1998 and January 2010 (1 month spin up with nudging) & short range forecasts
• **3 resolutions:** 130km (climate resolution N96), 60km (‘new’ climate resolution N216), 25km (seasonal forecasting N512)
Sensitivity of resolved and parametrized surface drag to changes in resolution and parametrization

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The relative contributions of resolved and parametrized surface drag towards balancing the atmospheric angular momentum flux convergence (AMFC) and their sensitivity to horizontal resolution and parametrization are investigated in an atmospheric model. This sensitivity can be difficult to elucidate in free-running climate models, in which the AMFC varies with changing climatologies and, as a result, the relative contributions of surface terms balancing the AMFC also vary. While the sensitivity question has previously been addressed using short-range forecasts, we demonstrate that a nudging framework is an effective method for constraining the AMFC. The Met Office Unified Model is integrated at three horizontal resolutions ranging from 130 (N96) to 25 km (N512), while relaxing the model’s wind and temperature fields towards the ERA-Interim reanalysis within the altitude regions of maximum AMFC. This method is validated against short-range forecasts and good agreement is found. These experiments are then used to assess the fidelity of the exchange between parametrized and resolved orographic torques with changes in horizontal resolution. Although the parametrized orographic torque reduces substantially with increasing horizontal resolution, there is little change in resolved orographic torque over 20–50°N. The tendencies produced by the nudging routine indicate that the additional drag at lower horizontal resolution is excessive. When parametrized orographic blocking is removed at the coarsest of these resolutions, there is a lack of compensation, and even compensation of the opposite sense, by the boundary layer and resolved torques, which is particularly pronounced over 20–50°N. This study demonstrates that there is strong sensitivity in the behaviour of the resolved and parametrized surface drag over this region.
Sources of uncertainty in surface drag:

1) Model Resolution:
   - Models with different horizontal resolutions will have different resolved surface drag

2) Parameterization:
   - Orographic drag parameterization formulation varies between models
AMFC is well constrained at three resolutions.
Shading indicates range over model resolutions

BL does not change much with resolution

\[- \frac{1}{r \cos \phi} \frac{\partial}{\partial \phi} \left( \left[ \int_{z_0}^{\infty} m v \rho dz \right] \cos \phi \right) \]

\[- F_{BL} \]
Shading indicates range over model resolutions.

Large change in parameterized orographic torque with resolution.

\[- \frac{1}{r \cos \phi} \frac{\partial}{\partial \phi} \left( \int_{z_0}^{\infty} m v \rho dz \right) \cos \phi \]

\[- F_{BL} - F_{GWD} - F_{Blocking} \]
Little change in resolved orographic torque with resolution over 30N to 60N

\[- \frac{1}{r \cos \phi} \frac{\partial}{\partial \phi} \left( \int_{z_0}^{\infty} m v \rho dz \right) \cos \phi \]

\[\left[ p_0 \frac{\partial z_0}{\partial \lambda} \right] \]

Shading indicates range over model resolutions
Good agreement with short-range forecasts

Shading indicates range over model resolutions
Hemispheric Contributions

Resolution sensitivity predominantly over Eastern Hemisphere

(a) SSO - Jan 2010

(b) Resolved - Jan 2010

Shading indicates range over model resolutions
Nudging Tendencies

Nudging tendencies indicate too much drag at lower resolutions

\[-\frac{1}{r \cos \phi} \partial \left( \left[ \int_{z_0}^{\infty} m \nu \rho dz \right] \cos \phi \right)\]

\[-F_{BL} - F_{GWD} - F_{Blocking} - \left[ p_0 \frac{\partial z_0}{\partial \lambda} \right]\]

Nudging tendencies (reflects model error)
Drift in short range forecasts also indicate too much drag at lower resolutions.
Nudging Tendencies

Jan 1998
- Total Orographic Torque
- Nudging

Jan 2010
- Total Orographic Torque
- Nudging

Jan 2010 - Forecast
- Total Orographic Torque
- 4 x Forecast Drift

Jan Climatology (1981 - 2012)
- Total Orographic Torque
- Nudging

Lowest (climate) resolution
Nudgment Tendencies

Jan 1998

Budget Term (10^{18} Nm)

Jan 2010

Budget Term (10^{18} Nm)

Climatological Nudging (Jan 1981-2012)

Jan Climatology (1981 - 2012)

(c)

Total Orographic Torque

Nudging

N96 resolution
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Model Comparison

TL1279 vs TL159

N768 vs N96

Dec 2015 - ECMWF

Dec 2015 - Met Office

(Thanks to Andy Elvidge, Irina Sandu and Sylvie Malardel)
Model Comparison

TL1279 vs TL159

N768 vs N96

$\Delta = \text{High Resolution} - \text{Low Resolution}$

Similar orographic drag resolution sensitivity in ECMWF IFS & Met Office UM
Variability

Short range forecasts

Little variability in the sign of the parameterized drag
Sensitivity to parameterization

Unexpected decrease in resolved orographic torque when blocking is switched off

Solid line is CNTRL and shading indicates range over CNTRL and no blocking experiment
No blocking minus control (Nudged runs)

Increased surface pressure on lee-ward side of Himalayas when blocking is switched off – consistent with reduction in resolved drag

High blocking minus control (24 hour lead time)

Δ Surface pressure (850hPa wind vectors)

Sandu et al. 2016
Sensitivity to parameterization

No blocking minus control

Change in nudging indicates change in total surface drag
Sensitivity to parameterization

Partial compensation from BL

Partial compensation from resolved torque

Little change in nudging
Sensitivity to parameterization

- Decrease in nudging
- Weak compensation from BL
  - SSO (Jan 2010)
  - BL (Jan 2010)

- Weak compensation from resolved torque
  - Advection (Jan 2010)

- Decrease in nudging
  - Nudging (Jan 2010)
Sensitivity to parameterization

Weak compensation from BL

SSO (Jan 2010)

BL (Jan 2010)

Weak compensation from resolved torque

Advection (Jan 2010)

Increase in nudging

Nudging (Jan 2010)
Sensitivity to parameterization

Little/No compensation from BL

Compensation from resolved torque

Little change in nudging
Sensitivity to parameterization

Weak compensation from BL

Reduction in resolved torque

Decrease/change of sign in nudging
Summary

- Nudging framework for constraining AMFC can be useful for resolution and parameter sensitivity studies (and model inter-comparison)
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• Total orographic drag is dependent on resolution: circulation is non-robust to changes in resolution – particularly over NH mid-latitudes
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• Nudging framework for constraining AMFC can be useful for resolution and parameter sensitivity studies (and model inter-comparison)

• Total orographic drag is dependent on resolution: circulation is non-robust to changes in resolution – particularly over NH mid-latitudes

• Regional dependence of parameterization formulation: retuning of schemes for subjectively desirable features of circulation is not globally consistent – can lead to model discrepancies