Representation of orographic effects in models

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Effects of orography on the flow

Wakes & von Karman vortices

Lee wave clouds

Winter mean longitudinal distribution of geopotential heights at 500hPa

Charney and Eliassen (1949)
Outline

• Resolved and subgrid orography
• Orographic drag schemes
• Uncertainties in the representation of orographic drag and impacts on the large-scale circulation
Why do we need to parametrize orographic effects?

Models cannot directly resolve detailed surface features, and more generally processes at subgrid scale.
Resolved & subgrid orography

Use $h$ to derive the mean (resolved) topographic height at each gridpoint

$$
\vec{\tau} = \vec{\tau}_{\text{res}} + \vec{\tau}_{\text{phy}}
$$

$$
\vec{\tau}_{\text{res}} = p_s \vec{\nabla} h = \text{resolved orographic stress}
$$

$$
\vec{\tau}_{\text{phy}} = \vec{\tau}_{\text{pbl}} + \vec{\tau}_{\text{sgo}} = \text{unresolved (subgrid) stress}
$$

$h$: topographic height above sea level (from global 1km data set)
Resolution sensitivity of resolved/subgrid fields

mean orography / land sea mask

standard deviation ($\mu$)
slope ($\sigma$)

Horizontal resolutions: ERA40~120km; T511~40km; T799~25km
Differences in resolved orography

Equivalent grid (km)

Orography variance

Total wavenumber

ERA-INTERIM 80 km
IFS 25 km
IFS 1.3 km
IFS OPER 9 km
UM 17 km
GDPS 25 km
ICON 13 km
Impact of resolved orography on forecast skill

CTL – IFS 25km

EXP1: 25 km with 80km resolved orography

EXP2: 25 km with 80km resolved and subgrid orography

Using a smoother resolved orography degrades significantly the forecast skill in terms of large-scale circulation, and near surface temperatures (during winter in the NH)
Consider stationary waves forced by sinusoidal orography with elevation $h(x)$: two regimes

$k > N/U$ (i.e. narrow-ridge case)  
(or equivalently $U\pi/L > N$, i.e. high frequency)  
Evanescent solution (i.e. fading away)  
Non-dimensional length $NL/U < \pi$

- waves decay exponentially with height  
- vertical phase lines  
- linear theory -> no drag. Steep small scales leading to form drag -> TOFD scheme

$$w = Ae^{-|m|z}\cos kx$$

$k < N/U$ (i.e. wider mountains)  
(or equivalently $U\pi/L < N$, i.e. low frequency)  
Wave solution  
Non-dimensional length $NL/U > \pi$

- energy/momentum transported upwards  
- waves propagate without loss of amplitude  
- phase lines tilt upstream as $z$ increases

$$w = A\cos(kx + mz)$$

For typical atmospheric wind and stability ($U=10$ m/s and $N=0.01$ s$^{-1}$): $L \approx 3$ km

$$N^2 = g \frac{d \ln \theta(z)}{dz}$$
Subgrid drag (stress) mechanisms in the ECMWF model

Scales smaller than 5 km

a) **Turbulent Drag - TURB** : Traditional MO transfer law with roughness for land use and vegetation.

b) **Turbulent Orographic Form Drag - TOFD** : drag from small scale orography (Beljaars et al. 2004); Other models use orographic enhancement of roughness.

Scales larger than 5 km

a) **Gravity Wave Drag - GWD** : gravity waves are excited by the “effective” sub-grid mountain height, i.e. height where the flow has enough momentum to go over the mountain.

b) **Orographic low level blocking - BLOCK** : strong drag at lower levels where the flow is forced around the mountain.

waves are evanescent and flow around steep orographic features will lead to form drag
Since 2006 ECMWF uses “Turbulent Orographic Form Drag (TOFD)” implemented as a tendency (or flux divergence) on model levels.

Orographic form drag (simplified Wood and Mason, 1993):

\[
\frac{\tau_{os}}{\rho} = 2 \alpha \beta C_m \theta^2 U^2(h_m)
\]

\(\alpha, \beta\) Shape parameters
\(C_m\) Drag coefficient
\(\theta\) Silhouette slope
\(U\) Wind speed
\(h_m\) Reference height

Vertical distribution (Wood et al, 2001):

\[
\tau_o = \tau_{os} e^{-z/h_m}
\]
Parameterization of TOFD flux divergence with a continuous orographic spectrum:

\[
\frac{\partial \tau_o}{\partial z} = -2 \rho \alpha \beta C_m \frac{\theta^2 U^2 (h_m)}{h_m} e^{-z/h_m}
\]

Assume: \(h_m \sim \min(2/k, 2/k_1)\) \(k_1 = 0.003 \text{ m}^{-1}\)

\[
\theta^2 = \int_{k_o}^{\infty} k^2 F(k) \, dk
\]

Write flux divergence as:

\[
\frac{\partial \tau_o}{\partial z} = -2 \rho \alpha \beta C_m \int_{k_o}^{\infty} \frac{k^2}{h_m} F(k) U^2 (c_m / k) e^{-zk/c_m} \, dk
\]


training course: boundary layer; surface layer
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Low-level blocking and gravity wave drag scheme (Lott and Miller 1997)

• linear/flow-over regime (NH/U small)
• non-linear/blocked regime (NH/U large)

Blocking occurs if surface air has less kinetic energy than the potential energy barrier presented by the mountain.

\[
\begin{align*}
    h_{\text{eff}} &= H_c U / N \\
    z_{\text{blk}} &= H h_{\text{eff}}
\end{align*}
\]

Height \( h_{\text{eff}} \) is such that the Froude number \( Nh_{\text{eff}}/U \) reaches its critical value \( H_c \)

See Hunt and Snyder (1980)
The surface drag due to blocking and gravity wave generation

Drag at height \( z \) below blocking height applied on model levels:

\[
D_{blk}(z) = \rho C_d \max \left( 2 - \frac{1}{r}, 0 \right) \frac{\sigma}{2\mu} \left( \frac{z_{blk} - z}{z + \mu} \right)^{1/2} \left( B \cos^2 \psi + C \sin^2 \psi \right) \frac{U \left| U \right|}{2}
\]

with \( r = \frac{\cos^2 \psi + \gamma \sin^2 \psi}{y \cos^2 \psi + \sin^2 \psi} \)

Gravity wave stress above blocking height:

\[
\tau_{gwd} = \rho_H U_H N_H h_{eff}^2 \frac{\sigma}{4\mu} G(B \cos^2 \psi_H + C \sin^2 \psi_H, (B - C) \sin \psi_H \cos \psi_H)
\]

- \( B, C, G \) are constants
- \( \mu \) : Standard deviation
- \( \sigma \) : Slope
- \( \gamma \) : Anisotropy
- \( \theta \) : Orientation
- \( \psi \) is computed from \( \theta \) and wind direction
- Density of ellipses per grid box is characterized by \( \mu/\sigma \)

\( \mu \) : Standard deviation

\( \sigma \) : Slope

\( \gamma \) : Anisotropy

\( \theta \) : Orientation
Gravity wave dissipation

Strongest dissipation occurs in regions where the wave becomes unstable and breaks down into turbulence, referred to as wave breaking:

- Convective instability: where the amplitude of the wave becomes so large that it causes relatively cold air to rise over less dense, warm air

\[
N_{\text{min}}^2 = N^2 \left(1 + \frac{N \delta h}{U}\right)
\]

\(\delta h\) : amplitude of wave

\(N\) : mean Brunt-Vaisala frequency

- Kelvin-Helmholtz instability also important: associated with shear zones. Amplitude of wave is reduced such that \(Ri_{\text{min}}\) reaches critical value of 0.25 (saturation hypothesis; Lindzen 1981)

\[
Ri_{\text{min}} = \frac{N^2}{\eta^2} = Ri \left\{ \frac{1 - \alpha}{\left(1 + Ri^{1/2} \alpha^2\right)^2} \right\}
\]

\(\delta h\) : amplitude of wave

\(\alpha = N |\delta h| / U\)

\(\eta = \partial U / \partial z\)
Subgrid orography scheme used as input for the Lott and Miller scheme

- Elliptically shaped mountains are assumed with aspect ratio $a/b$, and orientation $\psi$ with respect to the wind
- Elliptic mountains are equally spaced
- Subgrid orography is characterized by:
  - Standard deviation $\mu$
  - Slope $\sigma$
  - Orientation $\theta$
  - Anisotropy $\gamma$ (1:circular; 0: ridge)

$$
\gamma^2 = \frac{K - (L^2 + M^2)^{1/2}}{K + (L^2 + M^2)^{1/2}}
$$

$$
\theta = 0.5 \tan^{-1}(M / L)
$$

$$
\sigma^2 = K + (L^2 + M^2)^{1/2}
$$

$$
\mu^2 = \overline{h^2} - \left(\overline{h}\right)^2
$$

$$
K = 0.5 \left( (\partial h / \partial x)^2 + (\partial h / \partial y)^2 \right)
$$

$$
L = 0.5 \left( (\partial h / \partial x)^2 - (\partial h / \partial y)^2 \right)
$$

$$
M = (\overline{\partial h / \partial x})(\overline{\partial h / \partial y})
$$
Preparation of the data sets to characterize the sub-grid orography

1. Global 1km resolution surface elevation data

2. Reduce to 5 km resolution by smoothing

3. Compute mean orography at model resolution

4. Subtract model orography (3) from 5km orography (2)

5. Compute standard deviation, slope, orientation and anisotropy for every grid box
Large inter-model spread in subgrid orography fields in NWP models

**Standard deviation**

![Standard deviation graph](image)

**Slope**

![Slope graph](image)

**Orientation**

![Orientation graph](image)

**Anisotropy**

![Anisotropy graph](image)
Numerics of fast processes

The time scales of flow blocking, TOFD and turbulent diffusion are short at the lowest model levels and raise stability issues. The tendency from these processes can be written as:

\[
\frac{dU}{dt} = D - C |U| U
\]

\[
\frac{dV}{dt} = D - C |U| V
\]

where \( C = C_{vdf} + C_{block} + C_{tofd} \)

To minimize time step dependencies, the three schemes are solved for together in one implicit computation:

\[
\frac{U^{n+1} - U^n}{\Delta t} = D^n - C^n |U^n| \{ \alpha U^{n+1} + (1 - \alpha)U^n \}
\]

\[
\frac{V^{n+1} - V^n}{\Delta t} = D^n - C^n |U^n| \{ \alpha V^{n+1} + (1 - \alpha)V^n \}
\]

\( \alpha = 1.5 \) to avoid (non-linear) instabilities in the vertical diffusion scheme.

Impact of the Lott and Miller scheme

Alleviation of systematic westerly bias in low resolution model (2.5°x3.75°) in 1985

Without GWD scheme

Icelandic/Aleutian lows are too deep
Siberian high too weak and too far south
Flow too zonal / westerly bias
Azores anticyclone too far east

Mean January sea level pressure (mb) for years 1984 to 1986

Analysis (best guess)

With GWD scheme

alleviation of westerly bias
better agreement

From Palmer et al. 1986
WGNE Drag project
– comparison of surface stress

PBL over land

SGO over land

PBL+SGO over land

ECMWF

UM
Inter-model differences in orographic drag (and its partition) impact circulation

Mean change in SP +6h

Mean change in SP +24h

Sandu et al. 2016, JAMES
Inter-model differences in orographic drag (and its partition) impact circulation

Fine balance between improving and degrading the forecast!
It matters how the drag is partitioned between the two schemes
Quasi-indentical response for H-TOFD at 16km
The trouble won’t go away with high resolution anytime soon!

Changes in surface stress also affect longer timescales (seasonal to climate)
How much do the subgrid orography fields contribute to inter-model spread in surface stress?

IFS experiments where SSO fields are substituted with MetUM SSO fields

Inter-model variability in SSO fields can be of first-order importance to the variability in surface stress seen across models

Zadra (2013)
How much do the subgrid orography fields contribute to inter-model spread in surface stress?

IFS experiments where SSO fields are substituted with MetUM SSO fields

Combined effect of height & slope required to explain response in surface pressure (t+24h)

IFS
MetUM
Relative diff.

Jan, 2012

Dec, 2016

IFS
IFS with MetUM
SSO fields
Relative diff.

Inter-model variability in SSO fields can be of first-order importance to the variability in surface stress seen across models

Elvidge, et al 2019
In summary:

Models don’t agree:
• in the resolved orography, nor in the subgrid orography
• in total subgrid drag, nor in its partition between different processes and the diurnal cycle, particularly over orography
• The differences in subgrid drag and in its partition are partly the result of repeated tuning exercises designed to improve model skill (NWP or climate), also strongly related to the derivation of the subgrid orography fields

Subgrid orographic drag processes:
• have a large impact on the large-scale circulation, at all timescales
• are responsible for known systematic circulation biases
• the orographic drag parametrizations are fairly simplistic and especially poorly constrained, and don’t necessarily behave well with resolution (van Niekerk, 2016, Vosper, 2016)

The way forward: constraining drag processes

Use observations, inverse modelling and high resolution simulations to better understand these processes, identify caveats of existing parameterizations, and improve upon them, and thereby reduce the associated systematic errors

Sandu et al., perspective, NPJ Climate and atmospheric science, 2019
Understanding the effects of resolved and parametrized orographic drag through the COORDE-nation of different modeling groups.

**Aims:**

- Expose differences in orographic drag parametrization formulation between models
- Understand impacts of differences in orographic drag parametrizations for modelled circulation
- Use high resolution simulations to quantify drag from small-scale orography, typically unresolved in models used for climate/seasonal projections, in order to evaluate orographic drag parametrizations
- Understand differences in resolved and parametrized orographic drag across models

**Protocol:** [https://osf.io/37bsy/](https://osf.io/37bsy/)

Participants currently include: Environment Canada, DWD, CMA, JMA, NOAA/NCEP, KIAPS, Meteo-France, Met Office and ECMWF.
Plots show the impact of small-scale resolved orography (left) and parametrized orographic drag (right) on zonal winds in two models.

**Method:**

1) High resolution experiments (4km / 9km) with high resolution and low resolution orography are used to determine impact of resolved orography on circulation.

2) Low resolution experiments (150km / 125km) with and without parametrized orographic drag used to determine impact of parametrized orographic drag on circulation.
van Niekerk et al. (2018), JAMES
Errors in the circulation response induced by orographic drag at low/intermediate resolution are due to both the parametrizations and their coupling with the dynamics.

van Niekerk et al. (2018), JAMES