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METEOROLOGY

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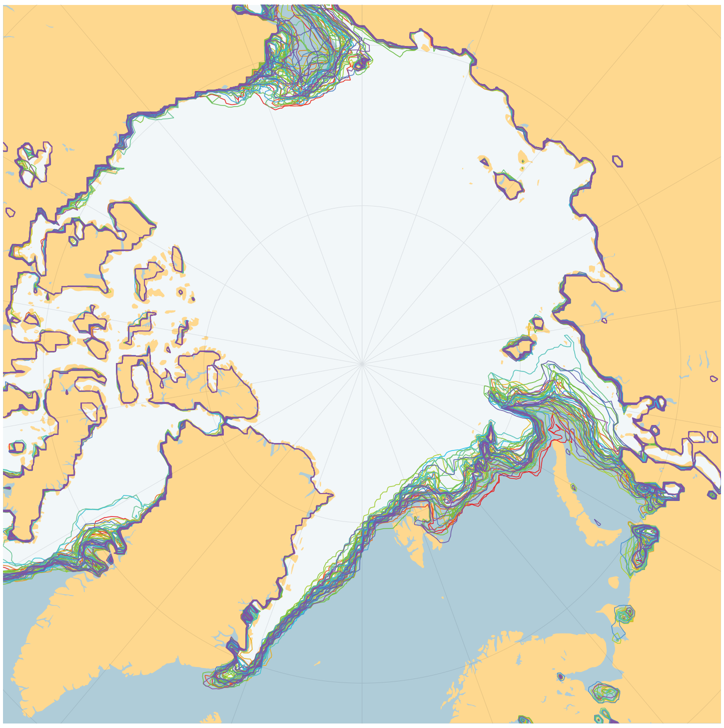

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Impact of orographic drag on forecast skill

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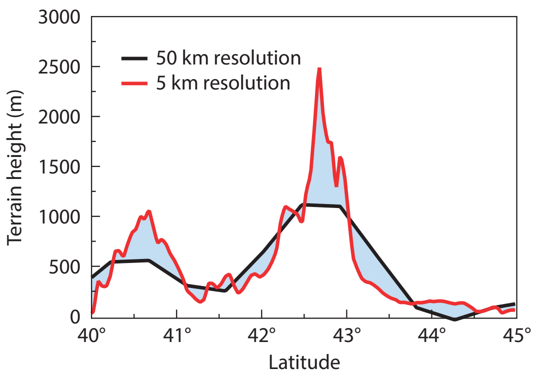
The flow of the atmosphere is strongly influenced by various features on the Earth's surface: vegetation, buildings, hills, mountains, ice ridges or ocean waves all slow down or deflect the airflow in a variety of ways. Close to the surface, the air is slowed by friction and deflected by larger obstacles, such as mountains. Atmospheric gravity waves triggered by mountains propagate upward and slow down the flow where they break, generally in the upper troposphere and in the stratosphere. All these processes contribute to the drag exerted by the Earth's surface on the atmosphere.

The drag exerted by topography (orographic drag) plays an important role for many aspects of the large-scale circulation, such as the northern hemisphere winter extratropical circulation, including the position of storm tracks in the North Atlantic. However, the representation of orographic drag processes in models is particularly challenging. First, the resolution of most global climate and numerical weather prediction (NWP) models is not fine enough to represent in the required detail surface features such as hills or mountains and the disturbances they introduce into the airflow. A model can only directly capture the effects of mountains that are several times larger than the model grid spacing (the mean or resolved orography, Box A). The effects of disturbances induced by smaller mountains (subgrid or unresolved orography) have to be parametrized (Box B). Furthermore, it is impossible to directly measure the amount and distribution of drag globally, or even regionally. In the absence of observational constraints, the parametrizations of these effects rely on heavily simplified assumptions mostly based on linear theory and idealized mountains. The extent to which they capture the non-linear effects exerted by complex topography remains unknown. As a result, the representation of orographic drag processes remains one of the major sources of uncertainty in NWP and climate models.

Mean and subgrid orography — A

The mean or resolved orography is the orography that is directly taken into account in the basic equations describing the flow. It is representative of mountains with scales equal to or larger than the model horizontal resolution (or grid spacing). To derive it, at ECMWF a global 1 km resolution surface elevation dataset based on satellite observations is used to compute the mean elevation for each model grid box. The subgrid or unresolved orography represents mountains with scales smaller than the model horizontal resolution. For each target resolution, the differences between a reference orography and the mean orography are used to derive the characteristics of the subgrid orography. The reference orography is obtained from the 1 km resolution dataset by filtering out scales below 5 km. The standard deviation, slope, orientation and anisotropy of the subgrid orography then feed into the subgrid orography parametrization (Box B), which represents the drag exerted by topographical features not resolved by the model. The derivation of the mean and subgrid orography at ECMWF is described in detail in Part IV, Chapter 11 of the IFS Documentation.



South–north cross section of terrain height across the Pyrenees at 0° longitude using a 50 km and a 5 km resolution orography. The difference is the subgrid orography that enters into the subgrid orography scheme (SGO).

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Boundary layer and subgrid orography schemes

B

Models often use more than one scheme to represent the drag associated with subgrid surface features. The reason is that different schemes account for different surface-induced drag processes. In the IFS, the boundary layer scheme (BL) represents stress associated with unresolved elements of the Earth's surface from horizontal scales of less than 5 km, while the subgrid orography scheme (SGO) represents stress associated with horizontal scales between 5 km and the model resolution. Each of these two schemes in turn accounts for several processes.

The boundary layer scheme uses a turbulence parametrization to represent turbulent drag associated with surface elements such as land use or vegetation. It also includes a turbulent orographic form drag parametrization (TOFD) to represent drag associated with subgrid orography elements at horizontal scales of less than 5 km, such as hills or individual mountains (*Beljaars et al.*, 2004). Other models (e.g. the Unified Model of the UK Met Office) do not have a special parametrization for turbulent orographic form drag but represent it by artificially enhancing the surface roughness length over orography, so that the orographic form drag is implicitly represented by the turbulence parametrization.

The SGO scheme (*Lott & Miller*, 1997) also represents different types of drag: (i) low-level blocking (BLOCK), which occurs when the air lacks the energy needed to go over a mountain and is partially blocked and partially goes around the mountain instead; and (ii) gravity wave drag associated with the breaking of gravity waves caused by air parcels that are forced to ascend while moving over topographic features. The magnitude of these effects crucially depends on the characteristics of the subgrid orography, particularly the standard deviation of its elevation.

Here we show that the representation of the mean orography differs even among models with similar resolution. We also illustrate how much models differ in terms of subgrid surface stress (or friction) and its partition among various processes. Finally, we use ECMWF's Integrated Forecasting System (IFS) to demonstrate that these issues significantly affect forecast skill.

Differences in orography

The mean orography used by global NWP models can be compared in terms of its variance at different scales (Figure 1). It appears that even models with a similar resolution differ significantly in terms of the orographic variance at the highest wavenumbers (smallest scales). For example, the Canadian Meteorological Centre's Global Deterministic Prediction System (GDPS) and the UK Met Office's Unified Model (UM) have much less variance at the smallest scales than IFS TL799, which is indicative of a smoother mean orography. The same is true when comparing the German National Meteorological Service's ICON model with IFS TCo1279. This may seem surprising as one would expect models with a similar resolution to have similar orographies.

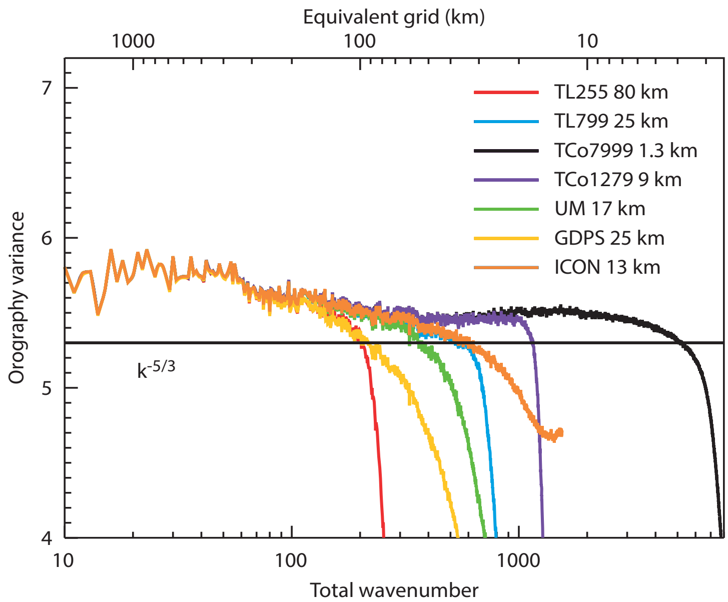

Figure 1 Variance of the mean orography scaled by the theoretical $k^{-5/3}$ law (horizontal line) as a function of the total wavenumber for different cubic and linear discretisations in the IFS (TL255 – corresponding to the ERA-INTERIM reanalysis; TL799; TCo7999; and TCo1279 – corresponding to the operational high-resolution configuration) and in other global NWP models (the UK Met Office's UM; the Canadian Meterorological Centre's GDPS; the DWD's ICON model).

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However, in practice, especially at the smallest scales, the orographic variance crucially depends on any filtering of the original orography dataset used to derive the orography at the model resolution; the type of grid the model uses (linear, cubic, quadratic, icosahedral); and the degree of numerical diffusion applied. Moreover, in the past, dynamical cores were less performant than today and the orography has therefore often been smoothed in order to prevent model instability, unrealistic gravity waves and aliasing effects. The cubic octahedral grid used at present for high-resolution forecasts in the IFS (TCo1279) has only very little numerical diffusion and can stably support an orography with more variance in the small scales, thus providing a faithful representation of the original 1 km orography for almost all wavenumbers up to the truncation limit. It thus maintains much more orographic variance at the small scales than the other discretisations included in Figure 1.

Impact of orography

To what extent do differences in orography affect NWP skill? One way to answer this question is to examine how forecasts obtained with a certain NWP model change when the model is run with a different orography. We have used the IFS to perform several sets of ten-day forecasts using different orographies. The forecasts were run for a winter month when the circulation in the northern hemisphere is very sensitive to the representation of the orography. They were initialised every day at 00 UTC from the operational analysis for December 2015 and were run using a TL799 configuration that uses a linear grid and corresponds to a horizontal resolution of approximately 25 km at the equator.

The control set of forecasts was performed with the original TL799 mean and subgrid orographies (CTRL). In a first experiment (EXP1) the TL799 mean orography was replaced with a smoother mean orography, i.e. the orography corresponding to the TL255 configuration, which is used for the ERA-Interim reanalysis (corresponding to approximately 80 km at the equator). The use of a smoother mean orography has to be accompanied by the use of a subgrid orography which accounts for the scales which are truncated out of the mean orography (in this case scales between wavenumbers 255 and 799). Therefore, in a second experiment (EXP2) both the TL255 mean orography and the subgrid orography fields corresponding to this smoother mean orography (derived by subtracting the TL255 orography from the 5 km dataset, see Box A) were used instead of the TL799 ones. These experiments aim to assess the impact of differences

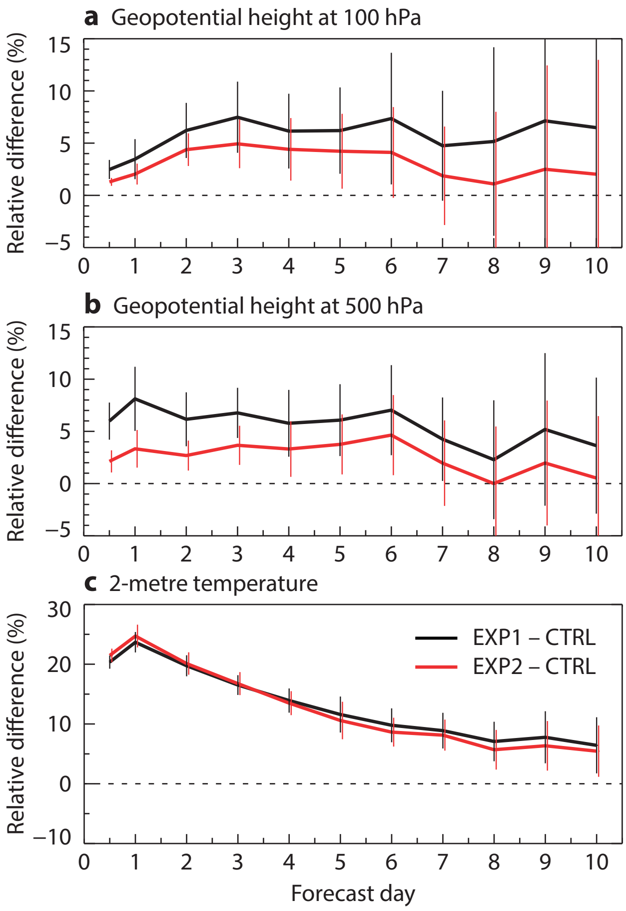

Figure 2 Relative difference in standard deviation (random error) between EXP1 and CTRL and between EXP2 and CTRL for forecasts of (a) geopotential height at 100 hPa, (b) geopotential height at 500 hPa, and (c) 2-metre temperature for the northern hemisphere extratropics (20°–90°N) in December 2015. A positive difference indicates a deterioration of the model performance in the experiment with respect to the CTRL. When error bars are entirely above/below the zero line, the performance of the respective experiment is significantly worse/better (95% confidence interval) than the CTRL. For all experiments the standard deviation was computed with respect to the corresponding analysis.

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in orography similar to those found between the TL799 configuration and the GDPS model, which are run at the same horizontal resolution (Figure 1). Like the orography of the GDPS model, the TL255 orography contains much less variance at small scales than the TL799 orography.

EXP1 and EXP2 lead to a considerable deterioration in the representation of both near-surface variables and upper-air atmospheric variables throughout the forecast range compared to CTRL, as indicated by the increase in standard deviation (random error) in forecasts of 2 m temperature and geopotential height at 500 and 100 hPa in the northern hemisphere (Figure 2). The deterioration in 2 m temperature forecasts amounts to approximately 10% in the medium range and it is nearly entirely due to the use of a smoother mean orography (EXP1). There is also an increase in the absolute mean bias ranging from 0.5 to 3 K (after 24 hours) in all mountainous regions (not shown).

Computing the subgrid orography fields in a consistent way with the mean orography in EXP2 reduces the degradation in forecast skill seen in EXP1 in the upper troposphere, but it has virtually no effect near the surface (Figure 2c). A significant albeit smaller deterioration in forecast skill is also found for the southern hemisphere throughout the atmosphere. This is again related primarily to the change in mean orography (not shown). Similar results were obtained in experiments performed with the GDPS at a nominal resolution of 25 km, where the removal (or reduction) of the smoothing in the mean orography was shown to reduce the root mean square error (against radiosonde observations) of geopotential height at 500 hPa by approximately 2% in medium-range forecasts over the northern extratropics in winter (not shown).

The representation of the mean orography thus appears to play an important role for the prediction of both near-surface temperatures and large-scale circulation. This is not surprising since the low-level atmospheric spectra closely follow the mean orography spectra (not shown). The degradation in forecast skill resulting from using a smoother mean orography can only partially be alleviated by using more variability in the subgrid orography. This suggests that the parametrized drag does not affect the flow in exactly the same way as the resolved drag.

Differences in parametrized surface stress

The Working Group for Numerical Experimentation (WGNE) of the World Meteorological Organization (WMO) recently compared the parametrizations associated with surface drag, i.e. the schemes currently employed by NWP and climate models to compute subgrid surface stresses (*Zadra*, 2013). This represented a first step towards a broader goal, namely to draw the attention of the scientific community to the importance of, and the challenges in correctly representing, momentum transfer in global models.

First results of this project suggest that while the inter-model spread is relatively small over the oceans, the total subgrid or parametrized surface stress is highly model-dependent over land (Figure 3). As the subgrid stress characterises the unresolved part of the flow, the inter-model spread found over land is in part due to differences in horizontal resolution. Nevertheless, the zonally averaged magnitude of the total subgrid stress can still differ by as much as 20% over land even for models of comparable resolution, such as the IFS and the UM (16 and 25 km at the time of the inter-comparison, respectively). These differences in the zonal average stress are mostly related to differences in stress over orography (not shown). Moreover, the partitioning of the total stress between the boundary layer and subgrid orography schemes is also model dependent (Figure 3). The UM for example has almost twice as much subgrid orography stress and up to 50% less boundary layer stress than the IFS over land in the northern hemisphere. Finally, the diurnal cycle of the total stress is quite different among the models. Figure 4 shows that over the Himalayan region the UM has more stress than the IFS between 12 and 18 UTC but generally less stress between 00 and 06 UTC.

These differences have multiple reasons: the underlying subgrid orography fields are different; models use different schemes; the schemes are implemented in different ways; they represent the dependency of stress on wind speed and stability in different ways; and there are a number of poorly constrained parameters entering the schemes that are often tuned to maximise NWP skill.

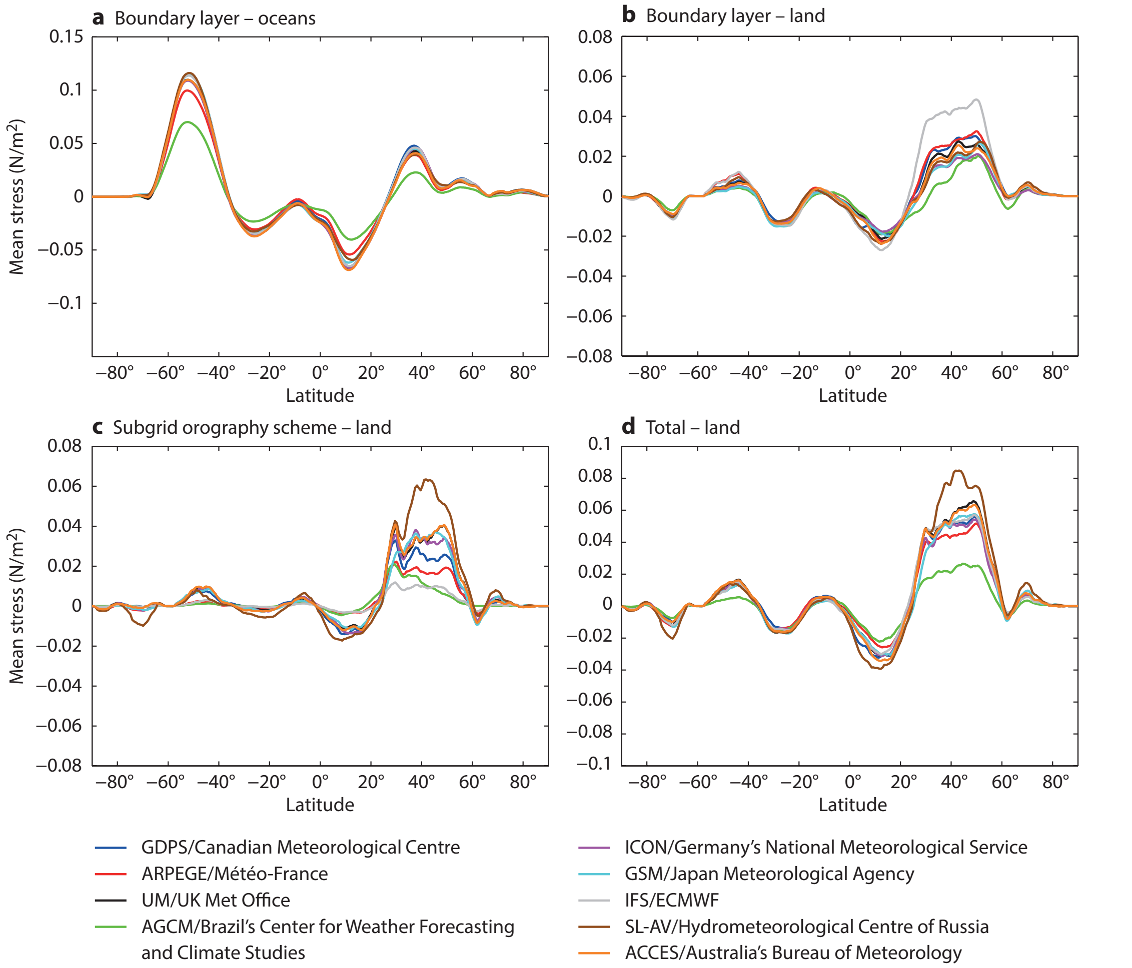

Figure 3 Zonal averages of subgrid surface stress, using the 00–24 UTC average from the results submitted by the different groups to the WGNE Drag Project for short-range forecasts for January 2012, showing (a) the boundary layer contribution over oceans, (b) the boundary layer contribution over land, (c) the subgrid orography scheme contribution over land, and (d) the total subgrid surface stress over land.

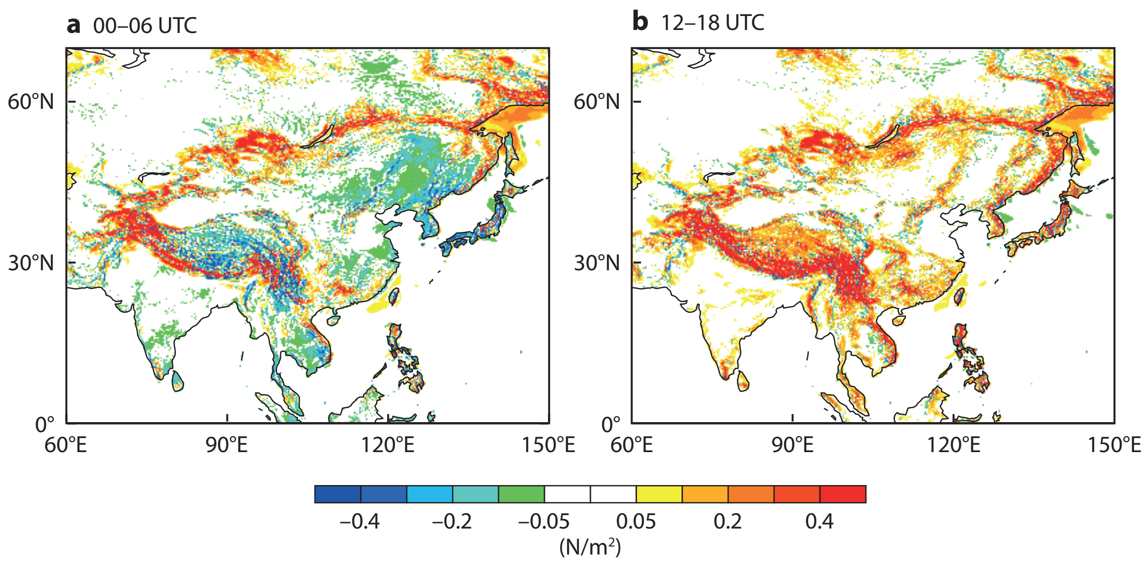

Figure 4 Difference in total surface subgrid stress between the UK Met Office's Unified Model (UM) and the IFS for (a) 00–06 UTC and (b) 12–18 UTC, from the results submitted to the WGNE Drag Project for January 2012.

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Impact of subgrid orography

The WGNE Drag Project emphasised the importance of further constraining the representation of subgrid stress in models, especially in regions with orography. It also highlighted the need to better understand to what extent the inter-model differences in subgrid stress affect the quality of forecasts or climate predictions. Here we illustrate how such inter-model differences in subgrid stress in regions with orography impact short- to medium-range forecasts.

Following the approach adopted by *Sandu et al*. (2016), differences in the total zonally averaged subgrid surface stress (over land areas) that resemble those found in the WGNE Drag Project were mimicked in the IFS by making changes that lead to an increase of the total subgrid surface stress over orography. One way to increase the subgrid surface stress over orography is to change the orographic drag parametrizations themselves, another is to change the underlying subgrid orography fields.

Several sets of ten-day forecasts were run for December 2015, with a TCo399 configuration (25 km at the equator, a possible future configuration for monthly and seasonal forecasts at ECMWF) with the following changes that all lead to an increased subgrid surface stress over orography: (a) a change in the BLOCK parametrization that leads to increased blocking from large mountains (BLOCK), (b) a change in the TOFD parametrization that leads to an increased form drag from hills (TOFD), (c) a change in the way the subgrid orography is computed (two sets of runs hereafter referred to as 4dx and 8dx) . All runs lead to an increase of 5–15% in the zonally averaged subgrid surface stress over land in the NH with respect to a control (CTRL) run performed with the default model configuration.

The last set of runs were motivated by a recent study by *Vosper et al.* (2016), which suggested that the subgrid orography should not represent scales smaller than the grid box (or the headline resolution), but scales smaller than the effective resolution of the model. Indeed, due to the nature of numerical solutions and parametrizations, the effective resolution of a model is not equal to its headline resolution or grid box size but corresponds to a few grid spacings (4 to 8 dx depending on the model, where dx denotes the headline resolution). One can argue that the resolved orographic drag accounts only for scales larger than this effective resolution, and therefore the subgrid or unresolved part should account for scales smaller than the effective resolution rather than the headline resolution.

To evaluate the impact of this hypothesis on forecast skill, the subgrid orography fields were recomputed for the 4dx and 8dx runs by taking the difference between the 5 km dataset (BOX A) and a mean orography smoothed by applying a 4dx and an 8dx filter respectively, instead of the dx filter used in the control run (CTRL). This approach generally leads to an increased standard deviation of the subgrid orography, and hence to an increased contribution to the total surface stress from the subgrid orography parametrization. In the 8dx experiment, for example, the standard deviation of the subgrid orography increases by a factor of two with respect to the CTRL run in the global average, but this factor exhibits strong local variations. The choice of these filters is motivated by the fact that the effective resolution for the cubic octahedral discretisation is about 4dx.

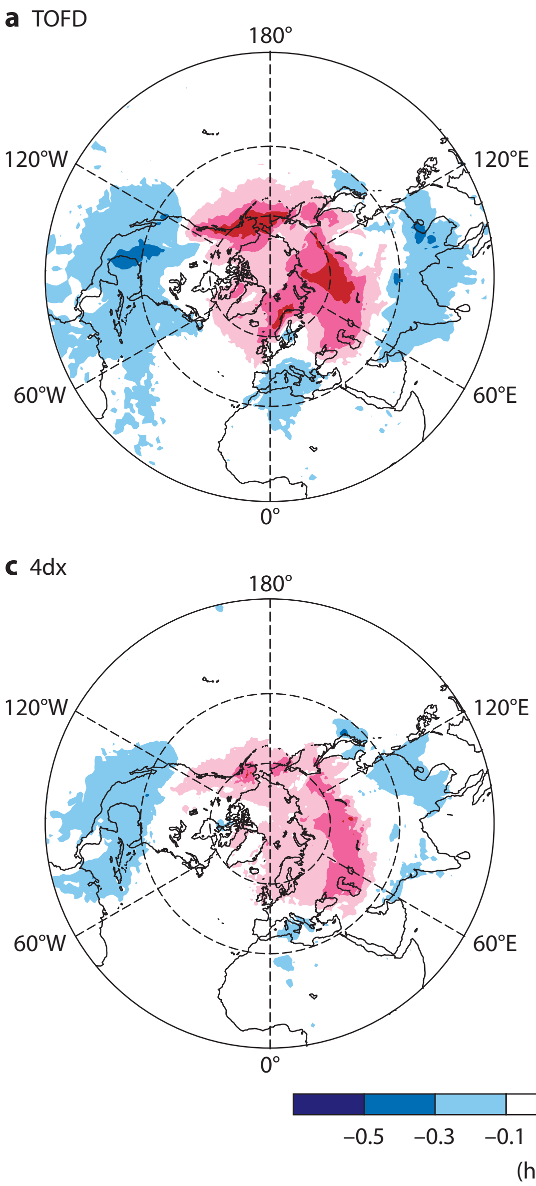

Figure 5 Mean change in surface pressure with respect to the CTRL run in the experiments in which (a) the TOFD stress is enhanced, (b) the BLOCK stress is enhanced, (c) the subgrid orography fields are computed using a 4dx filter, and (d) the subgrid orography fields are computed using an 8dx filter. The monthly means are based on 24-hour forecasts initialised at 00 UTC every day in December 2015.

The enhancement in total subgrid surface stress simulated by increasing either the TOFD or the BLOCK stress, or by changing the underlying subgrid orography, leads to changes in the predicted mean surface pressure in a matter of hours (Figure 5). Thus, pressure gradient changes across the regions with the largest mountain chains (the Himalayas and the Rocky Mountains), as well as an increase in surface pressure over Europe, can already be observed within the first six hours of the forecasts (not shown). During the first 24 hours, these changes amplify and extend to larger spatial scales in all cases, although they have different strengths for the various experiments (Figure 5). As suggested by *Zadra et al*. (2003) and discussed in *Sandu et al*. (2016), the local response in surface pressure over the largest mountain chains can be understood in terms of geostrophic balance. The enhanced stress over orography slows down mid-latitude surface westerlies, which results in a meridional pressure gradient across the Rockies, the Alps and the Himalayas.

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Although they are similar in terms of zonally averaged surface stress (within 10% over land), the different experiments have different impacts on forecast skill in the northern hemisphere (Figure 6). The changes to the TOFD stress considerably degrade the ability of the model to reproduce the hemispheric circulation in the entire troposphere up to forecast day 4, while those made to the BLOCK stress lead to a slight improvement of forecast skill at 500 hPa. The experiments with changed subgrid orographies also affect the large-scale circulation in different ways. The 4dx experiment seems fairly neutral on average over the hemisphere but has positive effects locally (over North America and Asia, not shown), while the 8dx experiment significantly degrades the representation of the circulation up to forecast day 4.

These results illustrate that poorly constrained parametrizations and uncertainties in how best to construct the subgrid orography can translate into significant impacts on forecast skill.

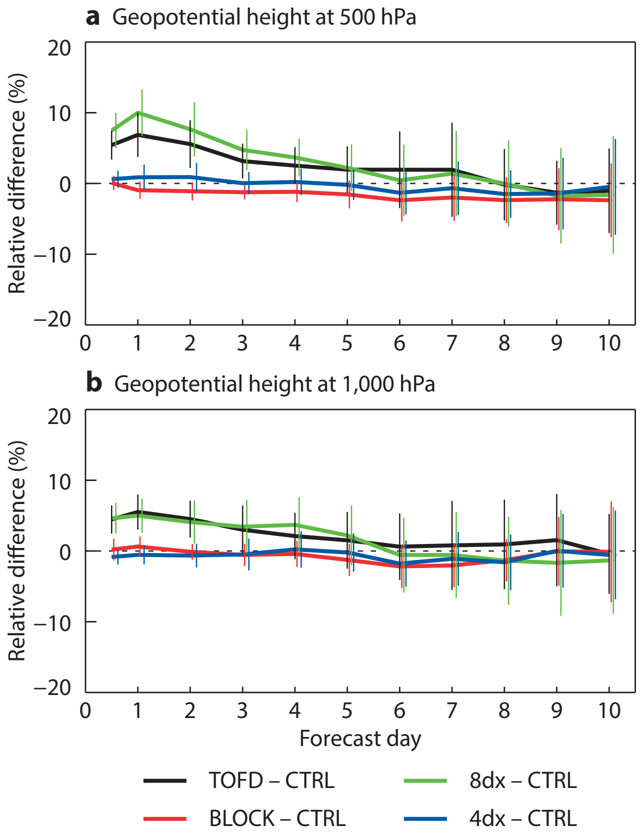

Figure 6 Relative difference in standard deviation (random error) between each of the experiments (TOFD, BLOCK, 4dx and 8dx) and CTRL for forecasts of (a) geopotential height at 500 hPa and (b) geopotential height at 1,000 hPa for the northern hemisphere extratropics (20°–90°N) in December 2015. A positive difference indicates a deterioration of the model performance in the experiment with respect to the CTRL. When error bars are entirely above/below the zero line the performance of the respective experiment is significantly worse/better (95% confidence interval) than the CTRL. For all experiments the standard deviation was computed with respect to the corresponding analysis.

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Way forward

A lot of questions regarding orographic drag processes, their effects on the large-scale circulation and their representation in models remain open. For example, we need to better understand how orographic drag depends on thermal stability and wind speed and how surface orographic drag affects the flow on different timescales. On the modelling side, we do not know how orographic drag should be partitioned between various schemes; what scales the subgrid orography should represent; and even how different modelling centres construct their mean and subgrid orography fields.

A recent workshop that brought together experts from major NWP centres and academia at ECMWF concluded that progress needs to be made in three fields in particular: (i) a better theoretical understanding of drag processes and their impacts on the circulation; (ii) a better understanding of inter-model differences; and (iii) using high-resolution simulations and observations as well as new techniques to understand model errors and to constrain and improve the representation of orographic drag in models. For more details on the workshop, see *Sandu & Zadra* (2016).

The next activities of the WGNE Drag Project will aim to achieve a better understanding of inter-model differences in surface stress and to find ways to improve the representation of orographic drag in models. They include a survey regarding the way the mean and subgrid orography are derived in NWP and climate models; numerical experiments which aim to better define the appropriate sub-grid scales for orographic fields as a function of the model's (effective) resolution; and a comparison of the tendencies given by the various parametrizations in regions of maximum uncertainty.

Further reading

Beljaars, **A.**, **A. Brown**, & **N. Wood**, 2004: A new parameterization of turbulent orographic form drag, *Q. J. R. Meteorol. Soc.*, **130**, 1327–1347.

Lott, **F.**, & **M. Miller**, 1997: A new subgrid orographic drag parameterization: Its formulation and testing, *Q. J. R. Meteorol. Soc.*, **123**, 101–127.

Sandu, **I.**, **P. Bechtold**, **A. Beljaars**, **A. Bozzo**, **F. Pithan**, **T.G. Shepherd** & **A. Zadra**, 2016: Impacts of parameterized orographic drag on the Northern Hemisphere winter circulation, *J. Adv. Model. Earth Syst.*, **8**, 196–211, doi:10.1002/2015MS000564.

Sandu, **I.** & **A. Zadra**, 2016: Experts discuss role of drag processes in NWP and climate models, *ECMWF Newsletter* **No. 149**, 8–9.

Vosper, **S.B.**, **A.R. Brown** & **S. Webster**, 2016: Orographic drag on islands in the NWP mountain grey zone, *Q.J.R. Meteorol. Soc.*, doi:10.1002/qj.2894.

Zadra, **A.**, 2013: *WGNE Drag Project – An inter-model comparison of surface stresses*. Report No. 1.

Zadra, **A.**, **M. Roch**, **S. Laroche** & **M. Charron**, 2003: The subgrid-scale orographic blocking parametrization of the GEM model, *Atmos. Ocean*, **41**, 155–170.

 doi:10.21957/icghjblyn7