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METEOROLOGY

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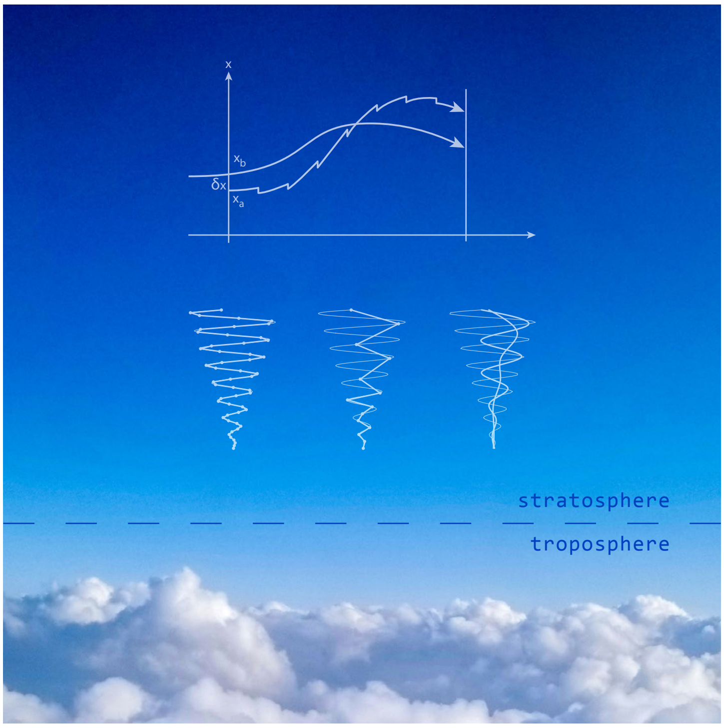

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Quintic vertical interpolation improves forecasts of the stratosphere

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ECMWF has over the years repeatedly increased the horizontal resolution of its forecasts to today's grid spacing of 9 km in high-resolution forecasts (HRES) and 18 km in ensemble forecasts (ENS). The resolution increases have greatly improved forecast quality in most parts of the atmosphere but have led to unphysical cooling in the lower to mid-stratosphere. This unphysical model behaviour arises from numerical errors accumulating due to insufficient vertical resolution in the stratosphere. In ECMWF's Integrated Forecasting System (IFS), fifth-order (quintic) vertical interpolation offers a cost-effective alternative to increasing the vertical resolution. Tests have shown that it leads to more physical model behaviour, reduced sensitivity to horizontal resolution, and better forecast skill in the lower to mid-stratosphere. It will therefore be implemented in the next upgrade of the forecasting system to IFS Cycle 47r1 planned for later this year.

Motivation

Accurately representing the stratosphere in a numerical weather prediction (NWP) model is important mainly for two reasons. The first is the need for successful data assimilation, i.e. the combination of observations with model information to obtain the best possible estimate of the state of the Earth system at the start of forecasts. In the stratosphere, high-quality model information in the data assimilation system is particularly important since here in-situ observations are relatively sparse and the weighting of satellite data is greatly influenced by model information. The second reason is that variability in the winter- and spring-time stratosphere can influence tropospheric weather patterns. This provides a potential for enhanced tropospheric predictability weeks and months after e.g. sudden stratospheric warming events and spring-time polar vortex breakdown events. Therefore, there has been a renewed impetus in recent years to understand and improve the performance of the IFS in the stratosphere.

The IFS suffers from a number of stratospheric temperature biases. In particular, the lower to mid-stratosphere is biased cold and the uppermost stratosphere is biased warm. These biases are found to be sensitive to horizontal resolution. At higher horizontal resolution, the cold bias in the lower to mid-stratosphere is exacerbated and the warm bias in the uppermost stratosphere is alleviated. This is because the whole stratosphere as modelled in the IFS experiences cooling when horizontal resolution is increased (Figure 1). Such sensitivity to horizontal resolution is highly undesirable for model development and especially for the 4D-Var data assimilation system, in which different calculations are performed at different horizontal resolutions.

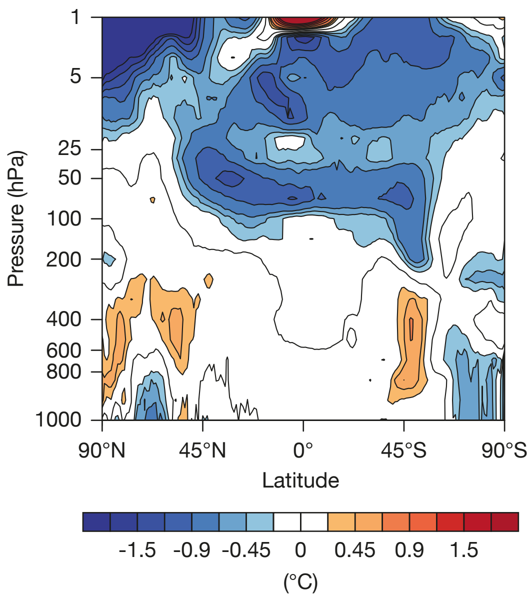

Figure 1 Difference in zonally (latitudinally) averaged temperature between forecasts at TCo1279 horizontal resolution (corresponding to a grid spacing of about 9 km) and TL255 horizontal resolution (corresponding to a grid spacing of about 79 km). Mean values over 31 forecasts starting in December 2017 and valid at day 10 are shown. Blue colours indicate that high horizontal resolution forecasts are colder.

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Identifying and solving the problem

The cooling that occurs when horizontal resolution is increased does not arise due to any misrepresentation of physical processes, such as gravity wave drag or mass transport circulation. Instead, it is due to numerical errors that accumulate in the dynamical core (the part of an NWP model in which differential equations that describe atmospheric dynamics are solved) when vertical resolution is not increased together with horizontal resolution. As the horizontal resolution increases, smaller-scale waves are resolved in the horizontal direction. Some of these waves have vertical wavelengths that cannot be resolved with the existing vertical resolution. Therefore, representing them in the vertical direction poses a challenge when vertical resolution is not appropriately increased as well (see e.g. Lindzen & Fox-Rabinovitz, 1989). The errors manifest themselves as unrealistic oscillations in the vertical direction in the temperature field at the scale of the vertical grid used in an NWP model. A schematic of how this happens is shown in Figure 2. As a result, at a fixed vertical resolution, high horizontal resolution forecasts in the stratosphere are less realistic than low horizontal resolution forecasts.

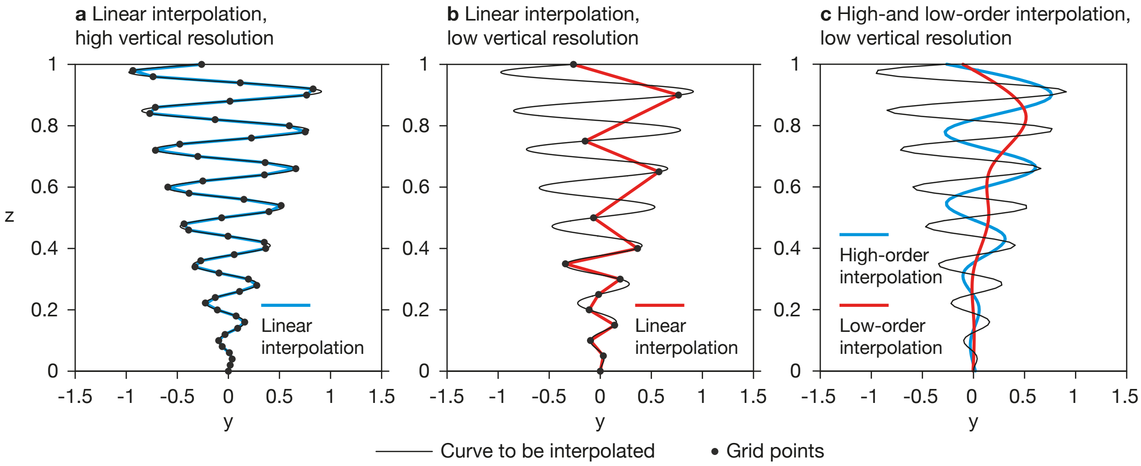

Figure 2 Schematic illustrating the effects of different vertical resolutions and higher- and lower-order vertical interpolation on representations of a wave given by $y = z \sin(50z)$, showing (a) highly accurate linear interpolation based on a large number of grid points in the vertical, (b) much less accurate linear interpolation based on a small number of grid points in the vertical and (c) relatively accurate higher-order interpolation and much less accurate lower-order interpolation based on a small number of grid points in the vertical. It can be seen that higher-order vertical interpolation better captures the wave structure than lower-order interpolation. The larger spacing of grid points in (b) with increasing altitude is similar to what is done in the IFS.

Interpolation in semi-Lagrangian advection

A

To determine the state of a field at a given point in time as air parcels are transported around (advected), the semi-Lagrangian technique finds departure and arrival points of air parcels and interpolates the values of the transported field based on grid points near the departure and arrival points. In the current operational IFS dynamical core, in the vertical and horizontal direction a quasi-cubic interpolation is used, which means that a Lagrange polynomial of degree 3 interpolates a field using 4 neighbouring points. With quintic vertical interpolation, a Lagrange polynomial of degree 5 interpolates a field using 6 neighbouring points. A schematic illustrating higher-order interpolation is shown in Figure 2c. Higher-order interpolation ensures that waves are better represented. Therefore, increasing the order of vertical interpolation can serve as a substitute for increasing the number of vertical levels.

A possible solution to the cooling problem is to increase vertical resolution when increasing horizontal resolution. The need for an increase in vertical resolution is particularly great in the stratosphere. Here, vertical resolution in the IFS is much coarser than in the troposphere. However, increasing vertical resolution is computationally expensive, and therefore cheaper alternatives have been explored to alleviate cooling in the stratosphere at high horizontal resolution (see Polichtchouk et al., 2019, for a detailed discussion). It was found that increasing the order of accuracy of vertical interpolation of the temperature field in the semi-Lagrangian advection (see Box A) alleviates the cooling problem. In particular, moving from third-order (cubic) to fifth-order (quintic) vertical interpolation reduces unphysical cooling at high horizontal resolution in the stratosphere with little impact at low horizontal resolution (Figure 3). As a result of this finding, quintic vertical interpolation of the temperature field and of the closely thermodynamically related specific humidity field will be implemented in the next IFS cycle. A historical perspective on unrealistic temperature oscillations in the stratosphere in the IFS and how they were addressed can be found in Box B.

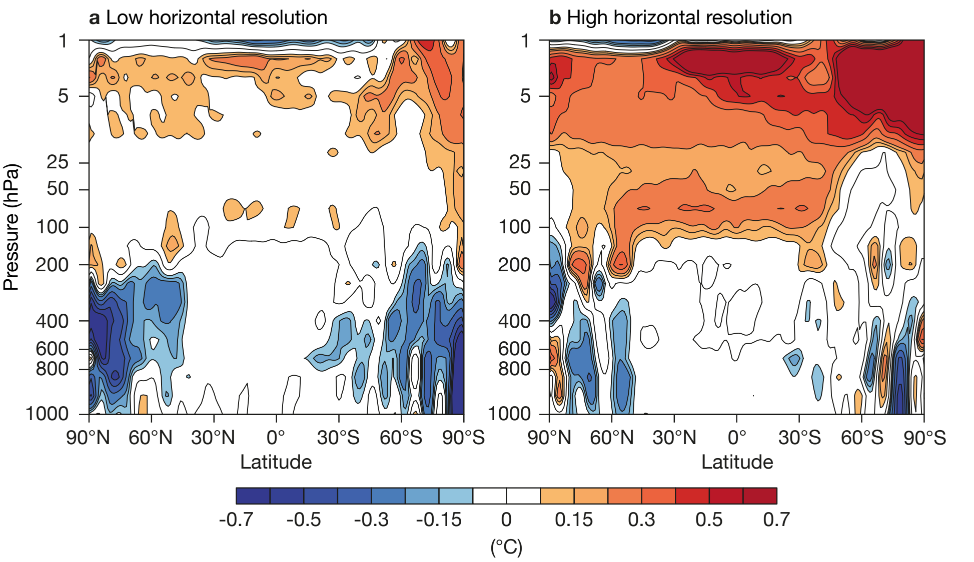

Figure 3 Differences in zonally (latitudinally) averaged temperature between quintic and cubic vertical interpolation forecasts for (a) TL255 horizontal resolution (corresponding to a grid spacing of about 79 km) and (b) TCo1279 horizontal resolution (corresponding to a grid spacing of about 9 km). Mean values over 31 forecasts starting in July 2017 and valid at day 10 are shown. The plots show that quintic vertical interpolation warms the stratosphere more at high horizontal resolution. Closer investigations have shown that the cooling seen in these plots in the troposphere at high latitudes has no significant effect on forecast performance (see also Figures 4 and 5).

Historical perspective

B

To give a historical perspective, stratospheric cooling due to grid-scale oscillations in the vertical direction was a larger problem in the IFS decades ago, when the finite difference method with Lorenz staggering was used to discretise the model in the vertical direction. It is well known that this configuration results in grid-scale noise in the vertical (Arakawa & Moorthi, 1988), leading to cooling in the IFS. This grid-scale noise, and therefore stratospheric cooling, was greatly reduced by the introduction of a vertical finite element scheme in the hydrostatic IFS in 2003 (Untch & Hortal, 2004).

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Impact on forecast skill scores

Since quintic vertical interpolation warms the stratosphere, forecast scores improve in the lower to mid-stratosphere, where the model is biased cold, and they deteriorate slightly in the uppermost stratosphere, where the model is biased warm. This slight degradation is acceptable compared to the overall benefits that quintic vertical interpolation brings (i.e. increased physical realism of the model and reduced horizontal resolution sensitivity). The impact of quintic vertical interpolation on HRES medium-range forecast scores is shown in Figures 4 and 5 for root-mean-square error of temperature and geopotential height verified against the operational analysis. The figures show that medium-range forecast scores in the lower to mid-stratosphere improve as a result of quintic vertical interpolation, with error reductions in geopotential height of up to about 45%. Moreover, Figures 4c,d and 5c,d show that this improvement can also be seen in the 47r1 test suite. In addition to quintic vertical interpolation, the future IFS Cycle 47r1 incorporates other model changes, such as weak-constraint 4D-Var, which has a positive impact on the analysis in the stratosphere (see separate article in this Newsletter). There is thus a positive impact on medium-range forecast scores in the stratosphere as a result of quintic vertical interpolation even when other model changes are incorporated. There is also some indication that the forecast skill scores of total column water vapour improve as a result of quintic vertical interpolation on the specific humidity field (not shown). As quintic vertical interpolation mainly affects high horizontal resolution forecasts, the skill improvement is most pronounced at high horizontal resolution.

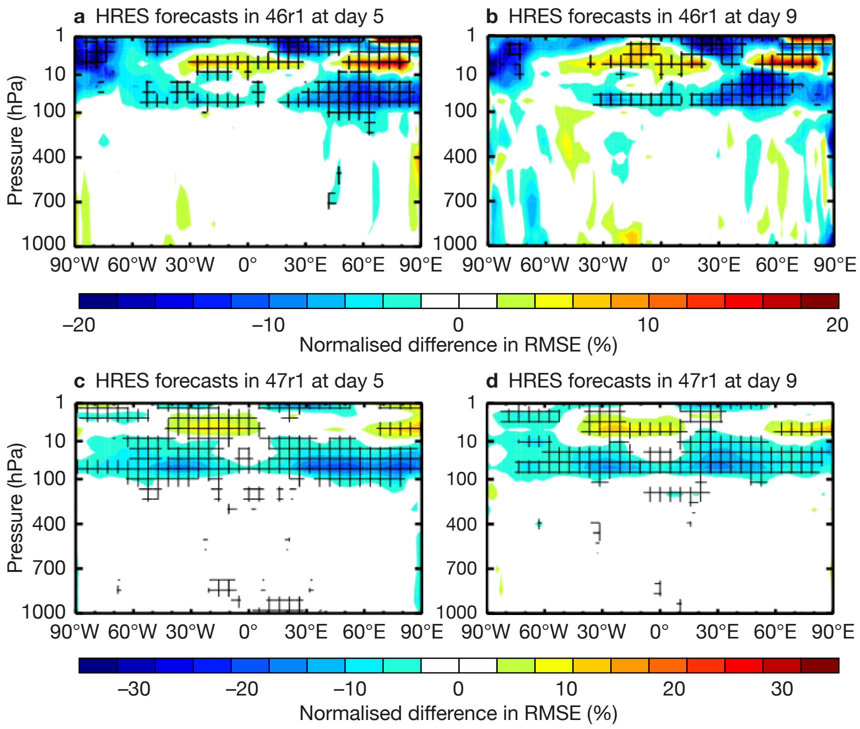

Figure 4 Change in root-mean-square error (RMSE) of temperature forecasts when moving from cubic to quintic vertical interpolation for (a) HRES forecasts in July 2017 at day 5, (b) HRES forecasts in July 2017 at day 9, (c) HRES forecasts in the IFS Cycle 47r1 test suite at day 5, i.e. with weak-constraint 4D-Var, for 20 July to 19 December 2019, and (d) HRES forecasts in the IFS Cycle 47r1 test suite at day 9, i.e. with weak-constraint 4D-Var, for 20 July to 19 December 2019. The operational analysis in IFS Cycle 46r1, i.e. without weak-constraint 4D-Var, was used for verification in all cases. In (c) and (d), the results are similar when the 47r1 test suite analysis is used, i.e. with weak-constraint 4D-Var. Blue colours indicate that errors are smaller when quintic vertical interpolation is used. Hatched areas indicate statistical significance at an estimated 90% confidence level.

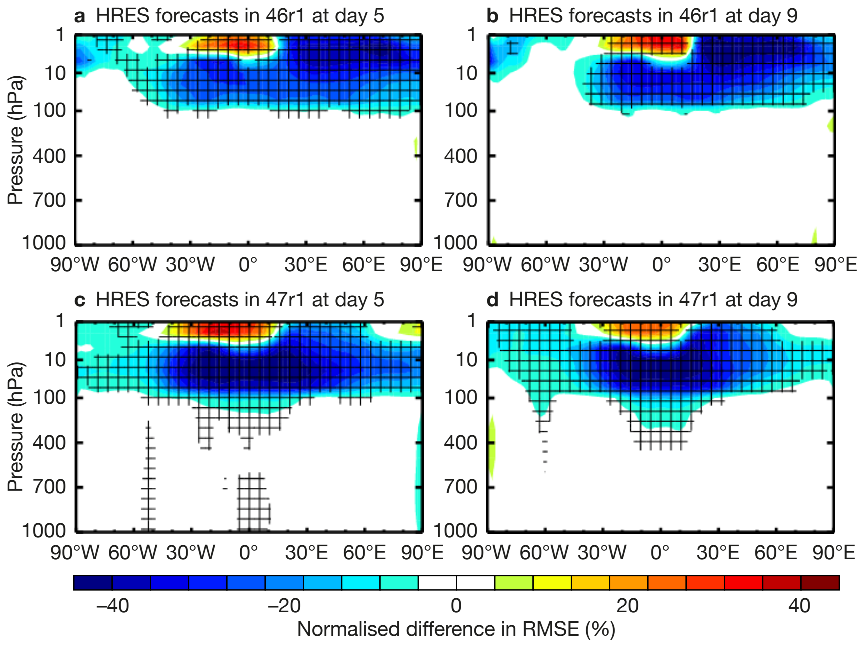

Figure 5 Change in root-mean-square error (RMSE) of geopotential height forecasts when moving from cubic to quintic vertical interpolation. The panels (a) to (d) show the same experiments as detailed for Figure 4. Blue colours indicate that errors are smaller when quintic vertical interpolation is used. Hatched areas indicate statistical significance at an estimated 90% confidence level.

Outlook

While quintic vertical interpolation alleviates unphysical cooling in the stratosphere at high horizontal resolution, it does not completely eliminate it. A filter that damps the grid scale noise in the vertical direction is under investigation to further reduce horizontal resolution sensitivity of temperature. As near grid-scale temperature oscillations are not believed to be important meteorologically, filtering them out altogether should not adversely impact the performance of the model. The warming in the stratosphere resulting from quintic vertical interpolation and/or a vertical filter does have a negative impact on forecast skill in the uppermost stratosphere. But once the physical realism of the model is improved, this can be tackled via changes to e.g. the UV spectrum in the radiation scheme, which is uncertain at these altitudes. Finally, it is worth emphasising that the planned vertical resolution upgrade of ensemble forecasts from 91 to 137 vertical levels once the new ECMWF data centre in Bologna, Italy, is operational will also substantially improve the representation of the stratosphere in ENS forecasts.

Further reading

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