Introduction

Numerical weather prediction (NWP) has quickly evolved since its humble beginnings in the early 1950s, thanks to the rapid development of computing facilities throughout the last 70 years. The 30-ton computing powerhouse known as ENIAC provided Jule Charney and his team of pioneers with 357 arithmetic calculations per second (which was muscular for its day), but the Met Office’s new Cray XC40 aptly shows how far we’ve come since then – delivering over 14 000 trillion operations per second. Such advances have paved the way for smaller and smaller grid-spacings across the spectrum of weather models, from global ensembles to high-resolution limited-area domains; this has allowed the representation of complex flows over terrain, non-hydrostatic dynamics and a myriad of other benefits. The result, for the most part, has been clear: better accuracy comes with better resolution (Mass et al., 2002).

With resources like these at our fingertips, a bigger question is now beginning to emerge: is there an upper limit to resolution? A point where smaller and smaller grid-spacings do more harm than good? The answer, predictably enough, is familiar yet unremarkable: it depends. The interesting part, however, is what it depends on.

This article presents a brief introduction to some of the issues surrounding this new era of computational availability. With supercomputing centres for weather and climate on the rise worldwide, and with Moore’s law showing the early signs of crumbling, one thing seems clear – the coming years will be a very interesting time indeed for the world of NWP.

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The grey zone

Wyngaard (2004) coined the term ‘Terra Incognita’ as a way of describing a newly emerging numerical regime in which atmospheric motions on the model grid were becoming partially resolved, while the parameterisation scheme (the ‘sub-grid’ physics) would continue to handle what remained. Since the computing resources that exist today place us within the kilometric and sub-kilometric regimes for the highest-resolution models, it is convection and boundary-layer turbulence that come into focus. This is because the length scales of these features (somewhere around 100–1000m for turbulence and 1–10km for moist convection) can be similar to the grid spacing of the model itself. Scientists soon began referring to this regime as the ‘grey zone’, perhaps as a homage to our lack of understanding of what is really happening within.

Let us take, for example, the case of boundary-layer turbulence generated by sunny skies. The boundary layer is defined as that part of the atmosphere that is directly affected by the Earth’s surface, and so the effect of a sunny sky is to generate surface-driven thermal updraughts, which cause the boundary layer itself to swell and deepen throughout the day. Figure 1 shows the transition from a night-time stable boundary layer to a daytime convective boundary layer (CBL).

To model a boundary layer of this kind, there are two approaches. The first is to use a one-dimensional parameterisation known as a planetary boundary layer (PBL) scheme. Small motions within a grid box at low resolutions (Figure 1(a)) can safely be parameterised, with an average value for each grid box appearing in the output fields. During the daytime (Figure 1(b)), the low-resolution model continues to rely on the parameterisation to represent the boundary-layer processes. Thermally driven motions create eddies of rising and falling air, expanding the boundary layer. But because the grid boxes are large enough, several of these eddies will exist within each one; this allows the parameterisation to calculate the overall effects of this collection of eddies and pass along their contribution to the model’s overall evolution.

When the resolution is increased, the extra computing power usually benefits the accuracy of the model as a whole. The wind field at night, for instance, can now contain more detail, with finer-scale effects emerging in the output (Figure 1(c)). Flows over orography particularly benefit from higher resolution, not to mention nocturnal processes like low-level jets, katabatic winds, and fog formation (Boutle et al., 2016).

In Figure 1(d), we have the situation of a high-resolution model (say, one with a sub-kilometric grid spacing) simulating a progressively deepening daytime boundary layer. This time, the size of each grid box is large enough to contain, at most, one large thermal – often less than this. The model will nonetheless simulate the rising motions as best it can, but it cannot possibly represent all the finer detail of this one thermal. A cascade of energy exists within a thermal updraught, because the largest thermals diffuse their heat into smaller and smaller eddies, eventually coming to heat the air at the molecular level. One grid point per eddy is simply not enough to do this correctly.

The parameterisation scheme tries to compensate, but because there are not enough eddies to take a proper sample of the average behaviour of a whole field of different eddies, it too fails in its task. The resulting output tends to differ depending on the grid used (it is ‘grid-dependent’), the onset of the resolved motion tends to become delayed (with the delay also depending on the grid size), and these problems have knock-on effects for the rest of the system (such as failure of the eddies to initiate moist convection above the boundary layer).

Clearly, the grey zone is an unwanted obstacle.

Simulating the large eddies

One solution to the problem of the grey zone is quite simple – add more resolution and merely jump over it. With a small enough grid spacing, most of the turbulent energy spectrum can be explicitly simulated, not just the largest updraughts. Resolving each individual eddy in this way is known...
as large-eddy simulation (LES), a technique that has existed for many decades. This way, a PBL scheme is no longer needed, instead the parameterisation scheme (which in an LES parameterisation is generally three-dimensional) is needed only for the purposes of diffusing away energy at the very smallest scales.

The problem, of course, is that we do not have the computing power to use large-eddy simulation techniques for anything beyond a research environment, where domain sizes can be small and there are fewer constraints on runtime. Sure, a global LES model would be great, but unfortunately this concept is little more than fiction in the current computing age. Indeed, such a model may never be feasible, so for now at least, the grey zone will persist.

**Perturb, blend, and adjust**

A popular concept in the grey-zone literature is this: if the grey zone lies somewhere between the realm of 1D PBL schemes and 3D LES formulations, then could a possible solution emerge from some combination of these two approaches?

Honnert et al. (2011) derived similarity relationships\(^3\) that quantified the behaviour of the Météo-France Meso-NH model between the mesoscale and LES limits. Using these similarity relationships, Boutle et al. (2014) were then able to develop a method of blending PBL parameterisations with LES techniques in the Met Office Unified Model (UM). The method relies on a blending function, a parameter that applies greater weight to LES methods near the LES limit, and similarly so for the mesoscale limit. This allows for a smoother transition through the grey zone, rather than using an arbitrary grid-spacing for the model to simply ‘decide’ when to abruptly switch from a PBL scheme to a LES scheme. From a pragmatic viewpoint, blending is very effective. However, there are several other grey zone issues that blending does not yet address.

One problem that the blending scheme does not solve is the delay in model ‘spin-up’. Spin-up is a commonly used term in meteorology, but its exact meaning can vary between different contexts. In climate simulations, for example, researchers may begin a simulation a few days earlier than the time period of interest, to allow the model to spin-up, before collecting results. The reason for this is to establish some

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\(^3\)Similarity relationships are derived from patterns and empirical evidence, allowing the formation and grouping of dimensionless variables. These variables and groups are very useful when certain quantities cannot be derived from first principles.

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Figure 1. Visualisation of model grids over a homogeneous land surface, showing (a) a low-resolution grid at night and (b) on a sunny day; (c) a high-resolution grid at night and (d) on a sunny day. Red arrows represent thermal updrafts, while other motions are shown by blue arrows. (b) and (d) show the scale of the grid spacing (Δx) relative to the length of the dominant boundary-layer eddies (L). Vertical model levels are not shown.

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Figure 2. Turbulence kinetic energy time series for the CBL during day 33 of the Wangara experiment at 400m resolution. (Adapted from Kealy et al., 2019.)
resolved motion and natural variability at the grid scale. This is not possible when studying the CBL, since the window of interest is so much shorter (less than one diurnal cycle). In the grey zone, natural variability at the grid scale tends to disappear each night when the boundary layer becomes shallow and the PBL scheme becomes dominant (as shown in Figure 1). The following morning, transitioning from the shallow, fully parameterised stable boundary layer to the larger and partially parameterised CBL is impeded. The delay in making this transition increases as a function of resolution. In this context, spin-up is not something we can just wait for; instead, we must actively seek to encourage the initiation of resolved motions on the grid scale.

Figure 2 presents an example of the spin-up issue that the grey zone creates. Adapted from our work in Kealy et al. (2019), the figure shows a timeseries of turbulence kinetic energy (TKE) for the evolving CBL during day 33 of the Wangara experiment, a well-studied Australian boundary-layer field campaign. TKE is a quantity derived from the variability in the momentum fields. Here, it can be thought of as the amount of energy present in the turbulent structures that the model develops at the grid scale.

A control simulation using a grid spacing of 400m (designated CNTL400 in Figure 2) was run using the Met Office NERC Cloud-resolving (MONC) model, based on a commonly used LES configuration. Because a grid spacing of 400m lies firmly within the grey zone of turbulence, the results showed a large delay in spin-up, with resolved motions appearing quite suddenly around the middle of the day. ‘Course-grained’ fields are also shown in the figure; these are derived from a 50-m LES simulation (LE50), and they act as our best approximation to a ‘desirable’ result (one in which spin-up occurs in tandem with the earliest appearance of the newly forming CBL eddies).

The most striking aspect of the MONC model’s simulation of Wangara in the grey zone was its response to changing the initial perturbations of potential temperature. LES simulations are always initialised with pseudo-random numbers, which are injected into the potential temperature fields at the beginning of the run – this is to instigate heterogeneity and acts as a catalyst for the model’s evolution. When we removed the perturbations entirely in our grey zone runs, resolved motion did not occur at all (blue line, Figure 2). We also altered the seed upon which the random numbers were based, and though this does affect the deterministic evolution of the model, the spin-up time remained the same.

The factor that seems to cause delayed spin-up appears to be energy diffusion. When the CBL is just developing and still very shallow, using a LES technique in the grey zone causes the model to diffuse the energy away too quickly, effectively removing the heterogeneity that the random numbers introduce.

Dynamic formulations of LES techniques are one approach to combat this issue. Recently, Efthathiou et al. (2018) – based on earlier work by authors like Germano et al. (1991) – developed a method of creating a scale-awareness in the model, such that the diffusivity in the parameterisation scheme could evolve alongside the growing CBL. Spin-up was greatly enhanced, and the model evolution was able to follow the LES much more closely, while using resolutions far lower than those required of a true LES model. But the technique is computationally demanding and is therefore not quite ready for operational applications just yet.

Using a simplified dynamic formulation that assigns a dependence on CBL depth to the model diffusivity, and injecting structured perturbations at discrete intervals (that also depend on the CBL depth), we were able to enhance spin-up at various resolutions. Figure 3 shows the new method in use at a grid spacing of 400m. Moving forward from this idealised platform, the question now is whether the techniques developed in this environment can be applied in a meaningful way to a full NWP model running real cases.

**What about moist convection?**

The grey zone of deep convection is entirely different from that of boundary-layer turbulence. Although sub-kilometric grid-spacings are not yet common in operational NWP grid spacings in the range 1–10km are very much in use operationally across the world, and the problem of grid-dependant rainfall is now a pressing one for limited-area models.

The Met Office run a limited-area model, known as the UKV, as an operationally maintained UM suite. The UKV operates at 1.5km across most of its domain, a resolution that should theoretically be able to resolve the dominant motions in thunderstorms and large showers, while the boundary-layer remains fully parameterised beneath.

However, moist convection depends on the boundary-layer as a trigger, so once again, things become complicated. Not only that, but the motions within the convective structures may not be fully resolved either, so contributions from the convection and shallow cumulus parameterisation schemes can also play a role in certain situations.

As a boundary-layer scientist, I won’t presume to say more about the in-cloud processes. However, the perturbations imposed upon the potential temperature in the boundary layer may have another story to tell. When it comes to full NWP suites running real cases, rather than the idealised environment of the MONC model, the fundamental processes at play can inevitably become obscured.

In Kealy et al. (2019), we found that the manner of imposing the potential temperature perturbations makes a large impact on the CBL evolution in the grey zone. Wondering if a similar effect would appear in a real case, we ran the UM at both 1.5km (the vicinity of the turbulence mesoscale limit) and 400m (deep in the turbulence grey zone), both with the perturbations applied and without them. Interestingly, the 1.5km simulation (Figure 4)
Concluding remarks

This article presents a brief introduction to some of the issues to be faced as we transition to higher and higher NWP model resolutions. Techniques to pragmatically improve the accuracy of models in the grey zone are very welcome, but sometimes these come at a cost. It seems that, by its very nature, the accuracy of models in the grey zone are some of the key factors at play in this exciting new regime of sub-kilometric NWP.

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