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Non-hydrostatic modelling at ECMWF

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Hydrostatic equilibrium describes an atmospheric state in which the upward directed pressure gradient force (the decrease of pressure with height) is balanced by the (nearly) downward-directed gravitational pull of the Earth. This balance is fundamental to the maintenance of the Earth's atmosphere, and on average the Earth's atmosphere is always very close to hydrostatic equilibrium. This fact has been used to approximate the Euler equations underlying ECMWF's weather prediction model and these approximated 'hydrostatic equations' have been successfully applied at ECMWF for the past 30 years. However, non-hydrostatic effects become important when the horizontal and vertical scales of motion are similar. In atmospheric models this typically arises with horizontal scales of the order of 10 km resolved with grid intervals of order 2 km. For motions of larger scale that are resolved with grid intervals of order 10 km – as in the currently operational model – the hydrostatic approximation is well satisfied.

ECMWF plans to implement a horizontal resolution of 10 km by 2015 for its assimilation and deterministic forecast system, beyond which a non-hydrostatic dynamical core will be required. This article describes the work being carried out to investigate the implementation of a non-hydrostatic dynamical core in ECMWF's Integrated Forecasting System (IFS).

It can be concluded that the non-hydrostatic dynamical core is a possible choice for future, globally uniform high-resolution applications at ECMWF. However, there are issues, in particular with the computational efficiency, that still need to be addressed before it is fit to be used as the dynamical core of the operational model at all resolutions.

Non-hydrostatic formulations

Relaxing the hydrostatic approximation has unfortunately a number of consequences that need to be considered. For example, the unapproximated Euler equations support three classes of waves: acoustic waves, inertia-gravity waves and planetary (Rossby) waves. The hydrostatic approximation conveniently removes vertically propagating acoustic waves, with only insignificant influence on the other two wave types at those scales where the hydrostatic approximation is well satisfied. This leads to the derivation of a time discretisation of the equations that is efficient, stable and accurate even for long time-steps, typically 300 seconds to 1 hour for ECMWF's current NWP applications.

Using the unapproximated Euler equations requires a time discretisation procedure that, despite the presence of fast moving acoustic waves, is equally efficient, accurate and stable. However, a numerical discretisation of the IFS for the unapproximated Euler equations that satisfies all of the above properties for the hydrostatic as well as the non-hydrostatic regime is the subject of ongoing research. Arguably, acoustic waves may be considered irrelevant to numerical weather prediction, which suggests that they could be filtered out a priori (often referred to as anelastic approximation). There is renewed interest in such an approximation, as it may promise an alternative efficient and accurate solution procedure. However, a satisfactory (energy-invariant) form of the governing equations for global-scale applications that eliminates acoustic waves without compromising the other waveforms has yet to be found and is the subject of ongoing research.

Rather than developing a non-hydrostatic dynamical core for the Centre's model from scratch or investigate other existing formulations, it was decided to evaluate the non-hydrostatic formulation developed by the ALADIN group for regional NWP and made available by Météo-France in the global IFS/ARPEGE model framework (*Benard et al.*, 2010). The aim is to assess whether this formulation is able to fulfil the requirements of high accuracy, efficiency and robustness imposed by ECMWF's various global operational applications and has the potential to form the basis of ECMWF's future non-hydrostatic dynamical core. The governing equations of this non-hydrostatic model are the unapproximated Euler equations for the (optionally) deep or shallow atmosphere (i.e. further approximations may be made to the rotating spherical system).

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Testing framework

The tests performed ranged from seasonal climate runs at T159 (~125 km) to medium-range forecasts at T3999 (~5 km) to assess the performance of the non-hydrostatic model in the hydrostatic regime, all the way to idealised ultra-high resolution simulations in the non-hydrostatic regime (*Wedi et al.,* 2009). Experiments with the T2047 horizontal resolution indicate that the differences between the hydrostatic and the non-hydrostatic simulations are still not significant at this resolution.

Even the finest horizontal resolution at which the IFS can be run to date (T3999) is still too coarse to fully resolve non-hydrostatic phenomena. Consequently a test bed has been developed that enables testing of the global non-hydrostatic dynamical core at non-hydrostatic scales at an affordable computational cost. Rather than create a two-dimensional vertical slice model of the three-dimensional global model or develop a limited area version of the IFS, a testing framework more suited for the global code was considered.

The testing framework is based on the idea of shrinking the radius of the planet such that, with an affordable number of grid-points covering the globe, the desired resolution resolving non-hydrostatic phenomena is achieved, but without incurring the prohibitive cost associated with such a fine resolution on the full-sized planet (*Wedi & Smolarkiewicz*, 2009). The size of the computational domain is reduced without changing the depth or the vertical structure of the atmosphere. The underlying assumption is that the essential flow characteristics remain unchanged when the ratio of horizontal to vertical scales is reduced. Consequently, the planetary radius is suitably reduced to capture non-hydrostatic phenomena without incurring the computational cost of actual simulations of weather and climate at non-hydrostatic resolution.

It is desirable to directly compare, both quantitatively and qualitatively, non-hydrostatic simulations with analytic solutions and with large-eddy simulation (LES) benchmarks of limited-area models published in the literature. The following sections describe a selection of examples using small-planet simulations that illustrate the difference between hydrostatic and non-hydrostatic simulations while assessing the efficacy of the non-hydrostatic IFS model in more detail.

Orographically-forced gravity waves

An example that illustrates the difference between hydrostatic and non-hydrostatic models is the propagation of orographically-forced gravity waves in the presence of vertical wind shear. In this case consider the flow over a mountain with a height of 100 m in a vertically stratified atmosphere with constant Brunt-Väisälä frequency and with the wind linearly increasing from 10 ms^{-1} at the surface to 35 ms^{-1} at the tropopause and then constant aloft. The reference solution (Figure 1a) is provided by the state-of-the-art model EULAG (*Prusa et al.*, 2008). This shows trapped, horizontally-propagating gravity waves.

Figures 1b and 1c show the non-hydrostatic and the hydrostatic solutions from the IFS. While the hydrostatic model produces vertically-propagating mountain gravity waves, the non-hydrostatic version correctly generates the trapped, horizontally-propagating gravity waves. The image in Figure 2 shows an example of such wave motions – likely to be misrepresented in a hydrostatic model – off Amsterdam Island in the southern Indian Ocean. The ship-wave like banded cloud structures are stretching far leeward of the island. The corresponding observed vertical wind shear that is necessary to guide the gravity waves in the horizontal direction is shown in Figure 3, as analysed by ERA-Interim.

Other examples that test the veracity of the IFS model using the unapproximated Euler equations range from horizontally- and vertically-propagating spherical acoustic waves, through ‘local-scale’ orographically forced gravity waves in the presence of shear and critical levels, to ‘global-scale’ planetary Rossby waves in idealised global-scale simulations. The interested reader can find further information in *Wedi et al.* (2009) and references therein.

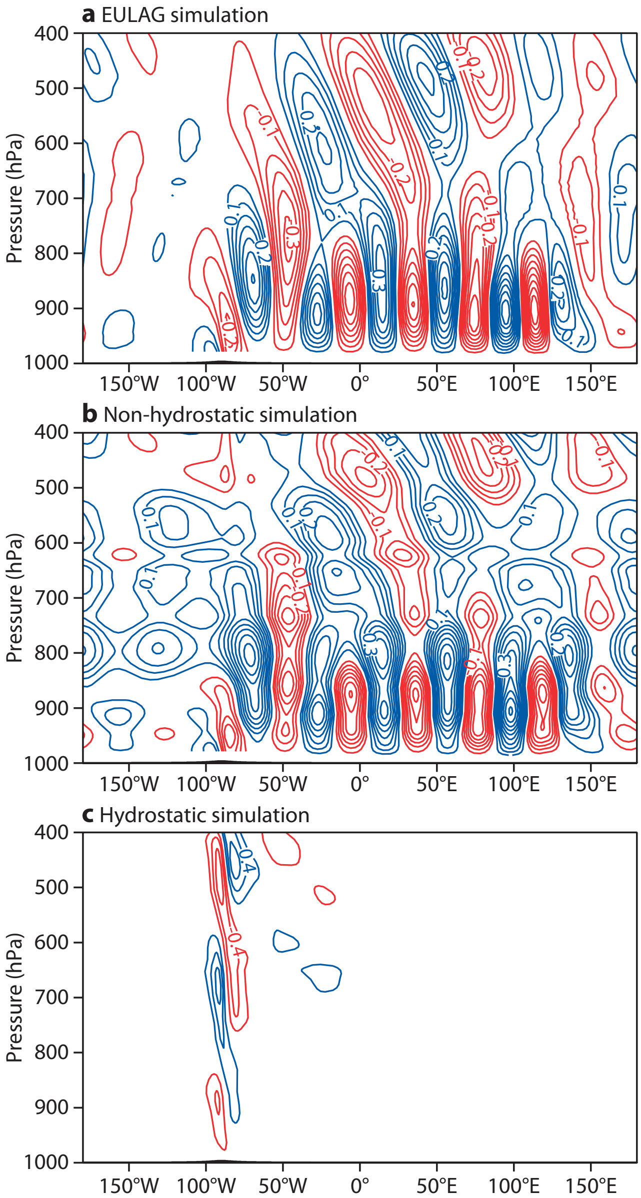

Figure 1 Vertical cross-section at the equator of vertical velocity comparing (a) the non-hydrostatic EULAG simulation with (b) non-hydrostatic and (c) hydrostatic IFS simulations for a linearly-sheared flow past a quasi-two-dimensional 'witch of Agnesi' obstacle at the equator on the reduced-size sphere. The atmosphere is vertically-stratified (Brunt-Väisälä frequency N = 0.01 s^{-1}) and there is a zonal flow of 10 ms^{-1} impinging on the mountain near the surface, increasing linearly to 35 ms^{-1} at 10.5 km (or approximately 687 hPa) and constant above. Contour interval is 0.05 ms^{-1}; blue/red lines denote positive/negative contours.

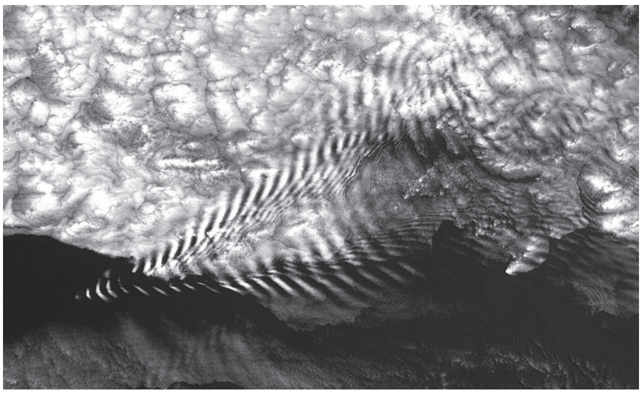

Figure 2 NASA satellite image (MODIS imager on board the Terra satellite) of a trapped lee wave forming off Amsterdam Island. Image taken on 19 December 2005.

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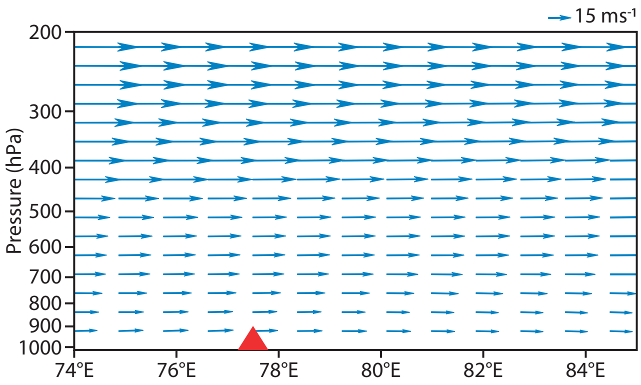

Figure 3 Vertical cross-section at 37.8°S of analysed ERA-Interim winds on 19 December 2005. The location of Amsterdam Island is indicated by the red marker.

Explicit deep convection

The previous example has been run using only the dynamical core of the IFS model. In IFS the physical parametrizations ('physics') are computed separately from the dynamical core ('dynamics') of the model (apart from the change of air density due to moist quantities and their advection by the wind). Therefore, this section focuses on cloud simulations on the reduce-size planet, with an emphasis on sensitivities regarding hydrostatic versus non-hydrostatic dynamics.

Theoretical considerations

The prognostic evolution of the vertical velocity in the non-hydrostatic system of equations (as opposed to the diagnostic determination of vertical velocity in the hydrostatic equations) is required to adequately describe the vertical accelerations in deep convective clouds and buoyancy-driven gravity waves triggered by convection. To resolve deep convective clouds (Cumulonimbus, Nimbostratus) a resolution at least of order 2 km is needed.

The development of a deep convective cloud is due to a positive feedback between the vertical motion, determined by the non-hydrostatic momentum equation, and the (micro-physical) parametrization of condensation in the physics. With a grid interval of order 10 km and using a hydrostatic model such processes are entirely sub-grid scale and a deep convection parametrization is required instead.

It is worth noting that there is a common perception that a hydrostatic model cannot reproduce the high vertical velocities found in a deep convective cloud. To the contrary, the vertical velocity in convective updrafts, diagnosed from a hydrostatic model used with a grid interval of order 2 km, is usually stronger than the vertical velocity predicted by the non-hydrostatic model. The classical explanation is that the non-hydrostatic model accurately describes the transient stage during which the ascending air has to 'push' the air above and is slowed down in the process. In contrast, in a hydrostatic model the air is supposed to reach a hydrostatic equilibrium instantaneously thus neglecting the effect of deceleration. Based on these considerations, it should now be apparent that, despite some success of hydrostatic models in modelling motions at increasingly finer grid intervals, the hydrostatic equations are an approximation that is no longer justified for resolved atmospheric scales of order 10 km or less.

Simulation of explicit deep convection

One of the first tests used to validate a model for explicit deep convection is to simulate the ascent of warm and/or moist bubbles. The air in the grid boxes included in the bubble is positively buoyant compared to the air in the grid boxes outside the bubble. If the bubble reaches its level of neutral buoyancy before being saturated, the bubble decelerates and the ensuing oscillation around its level of neutral buoyancy excites gravity waves. But if the level of condensation is reached, the vertical motion of the bubble may continue up to the tropopause due to the warming associated with latent heat release of cloud formation.

With the small planet configuration, a T159 resolution on a planet with a radius of 64 km has a horizontal resolution of about 1.25 km. Dry and moist bubbles triggered by a low-level warming near the equator of the small planet in an initial no-wind environment are rising to their level of neutral buoyancy. When the condensation scheme of the current ECMWF physics is activated, the updraft reaches the tropopause and a large cloud develops (Figure 4). Even with these relatively simple microphysics of clouds and precipitation (no airborne rain or snow), the model reproduces the feedback between the vertical acceleration and the warming due to condensation, both in the hydrostatic and the non-hydrostatic simulation.

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The cloud in the hydrostatic simulation appears after 25 min (Figure 4a). Yet after a further 10 min of cloud development, the hydrostatic model produces unrealistic vertical velocities of more than 60 ms^{-1} in the centre of the updraft. The cloud in the non-hydrostatic simulation appears later (after 35 minutes), and vertical velocities do not reach more than 30 ms^{-1} (Figure 4b). These results show that the hydrostatic model develops a faster, more intense cloud and also spreads the cloud more horizontally than in the non-hydrostatic simulation.

The cooling resulting from the evaporation of the precipitation underneath the cloud creates resolved downdrafts which spread out into density currents near the surface. In this low-wind environment, the density currents isolate the convective ascent from its low-level moist inflow and the main cloud starts to dissolve after about 15 minutes of development in both simulations. The density currents trigger new ascents on the sides and smaller clouds develop as the main cloud decays – see the bottom panels in Figure 4.

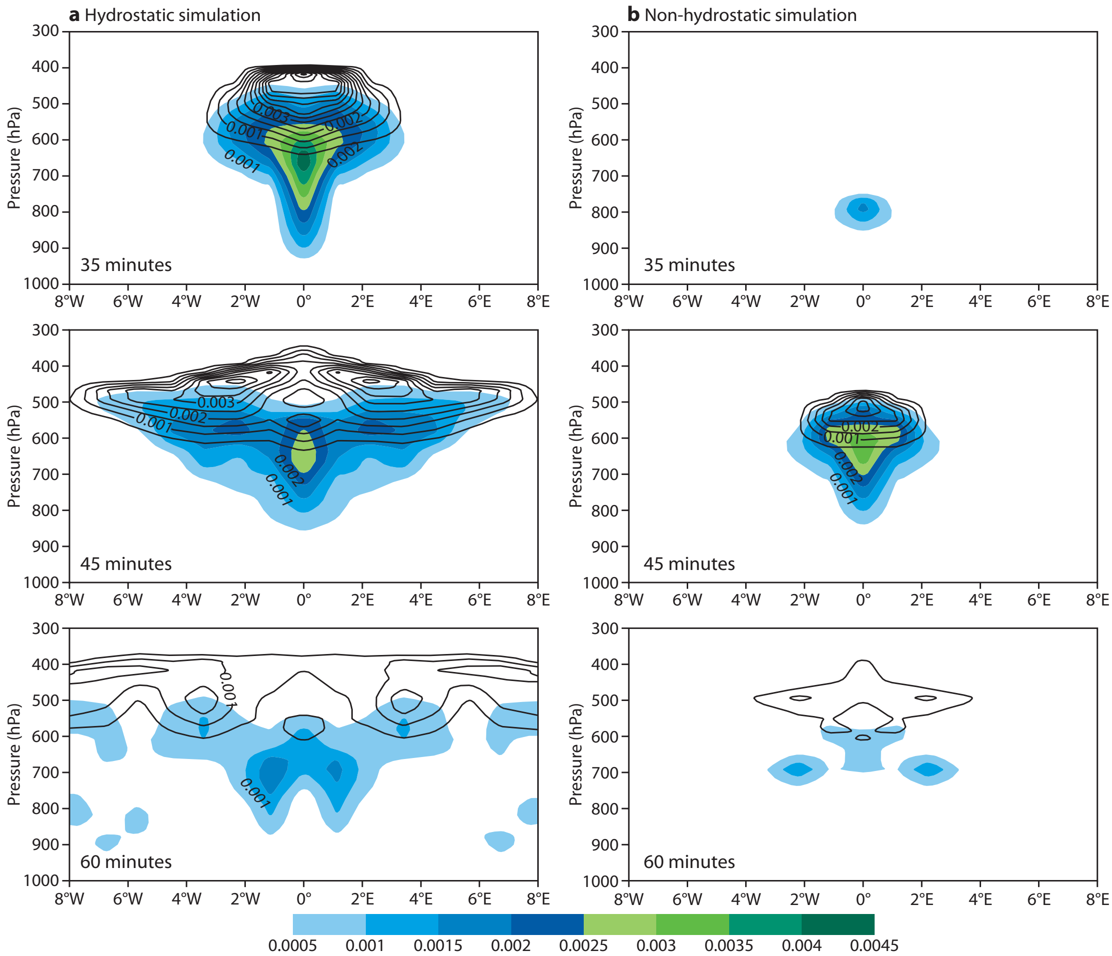

Figure 4 Vertical cross-sections along the equator showing the evolution of the cloud liquid water content (shading, kg/kg) and the cloud ice water content (black contours, kg/kg) in (a) hydrostatic and (b) non-hydrostatic simulation after 35, 45 and 60 minutes.

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Other implications for the IFS model

When the IFS is used at resolutions permitting the mechanisms for explicit deep convection, this type of – albeit very idealised – simulations is useful to validate the numerical algorithms (e.g. semi-Lagrangian advection, semi-implicit time stepping or the impact of the spectral transforms), investigate the coupling between the physics and the dynamics, and evaluate the effect of additional prognostic quantities such as rain or snow.

As water vapour is the 'main fuel' of deep convection, the local conservation of hydrometeors is very important for a correct simulation of explicit deep convection. However, as the IFS semi-Lagrangian advection scheme is neither conservative nor strictly preserves monotonicity, especially near regions of sharp gradients like the tropopause or near the surface, spurious sources of water or potentially warm or cold air may appear and dramatically change the buoyancy of the bubbles. Therefore, modifications to the semi-Lagrangian advection are investigated to remedy this shortcoming.

The recent advances in the development of prognostic microphysics (available in the IFS from cycle 36r4) will allow more sophisticated test cases of idealised squall lines and tropical cyclones in the future. These simulations will be run on the small planet and complemented with selected simulations at ultra-high resolution (in the non-hydrostatic regime) to study also the interaction of deep convective updrafts with tropical waves and their mesoscale convective organisation.

Ultra-high resolution global weather forecasts

The limits of the existing software and hardware capabilities have been explored by conducting the first T3999 global 24-hour forecasts with the IFS in its operational configuration. Figure 5 shows a comparison of the cloud cover distribution over the Scandinavian Peninsula for the non-hydrostatic (Figure 5a) and the hydrostatic (Figure 5b) T3999 simulations. Differences are starting to appear, in particular leeward of mountains due to the aforementioned influence of orographically-forced gravity waves, although the overall patterns are still very similar with a substantial accumulation of clouds in the blocked flow region upwind of the Scandinavian Peninsula ('Staubewölkung'). At this resolution (5 km grid interval) each prognostic variable has approximately 21 million points per vertical level. It takes approximately 50 minutes using 128 nodes (i.e. half of one of the IBM clusters installed at ECMWF) to produce a 24-hour forecast. The results are very reasonable with substantially more topographic detail compared to the current operational T1279 (~16 km) resolution.

While challenging ECMWF's infrastructure in many ways (e.g. post-processing, archiving and plotting – many thanks to Manuel Fuentes, Sylvie Lamy-Thépaut and Fernando Ii), most importantly this feasibility study emphasises the importance of efficient spectral transforms (see Box A for more details) and the associated efficacy of the non-hydrostatic code framework. The latter arises because of the likely need to change from the hydrostatic to the non-hydrostatic IFS at 5 km resolution. Doubling the resolution from approximately 10 to 5 km comes therefore with a substantial change in the way each part of the model contributes to the cost of a single time-step and with an increase of the total cost. The current version of the non-hydrostatic IFS model takes approximately three times longer at T3999 resolution (2.5 hours for a 24-hour forecast) due to the increased number of spectral transforms required for a numerically stable model integration.

The spectral transform method

A

The spectral transform method has been successfully applied at ECMWF for approximately thirty years. It involves discrete spherical harmonics transformations between physical (grid point) space, where the semi-Lagrangian advection and the physical parametrizations are computed, and spectral (spherical harmonics) space, where the Helmholtz equation – arising from the semi-implicit scheme – can be solved easily and horizontal gradients are computed accurately.
A spherical harmonics transformation is a Fourier transformation in longitude and a Legendre transformation in latitude.

The Fourier transform is computed numerically very efficiently by using the Fast Fourier Transform (FFT). However, due to the relative cost increase of the Legendre transforms compared to the grid point computations, very high-resolution spectral models may become prohibitively expensive.
For the hydrostatic model at a horizontal resolution of T2047 (10 km) the computational cost of the spectral transforms in terms of total floating point operations per time-step is about 50% of the total. Yet, due to the very high level of optimisation achieved for the spectral computations, the transforms only contribute less than 20% to the elapsed time at T2047 resolution.

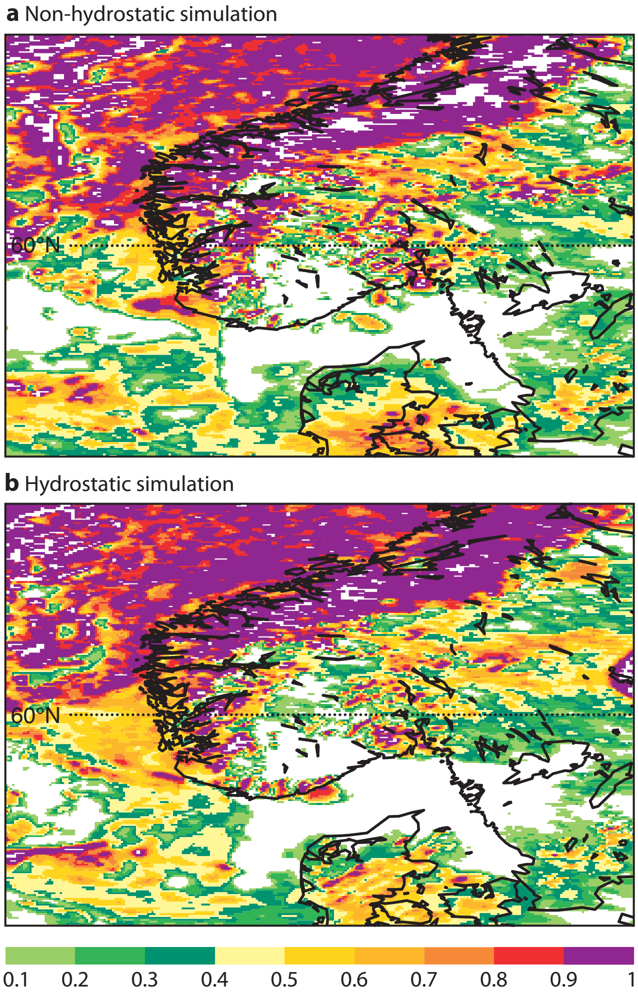

Figure 5 Comparison of the cloud cover for (a) non-hydrostatic and (b) hydrostatic IFS forecasts for 17 March 1998 at T3999 (~5 km) resolution, with a north-westerly flow impinging on the Scandinavian Peninsula. The differences in the cloud cover between the two simulations may be attributed to the different representation of the flow over the mountainous regions in the presence of wind shear.

Future developments

Current research at ECMWF focuses on:

- Exploring recent developments of ‘Fast Legendre Transforms’ aimed at reducing the number of calculations required in the spectral transforms.
- Reducing the number of transforms required by exploring *a priori* filtering of acoustic waves (i.e. sound-proofing of the governing equations).

Also further developments are planned with a focus on the dynamics-physics coupling and the accuracy of the semi-Lagrangian advection scheme to prepare for the transition from parametrized to cloud-resolving simulations.

A workshop held at ECMWF (8–10 November 2010) brought together leading experts in the field of non-hydrostatic modelling to discuss recent developments in this area and to provide further recommendations on how to prepare the IFS for global atmospheric modelling at future high to ultra-high resolutions.

Finally, given the increased sensitivity to topographic detail at the targeted resolutions where non-hydrostatic effects matter, a separate project is under way with a view to replacing the topographic maps underlying ECMWF’s current operational weather forecasts with the latest available satellite-derived products.

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Further reading

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