Extension of the Met Office Unified Model into the Thermosphere

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Introduction

The Met Office UM aims to extend its Unified Model (UM) for weather and climate into a whole-atmosphere model to simulate the atmosphere from the surface to the thermosphere above altitudes of 100km. This poster covers a range of activities taking place in developing and assessing the capabilities of this Extended UM.

This work is an important part of the EU Horizon 2020 project: SWAMI (Space Weather Atmosphere Model and Indices).

Diagnosing Instabilities

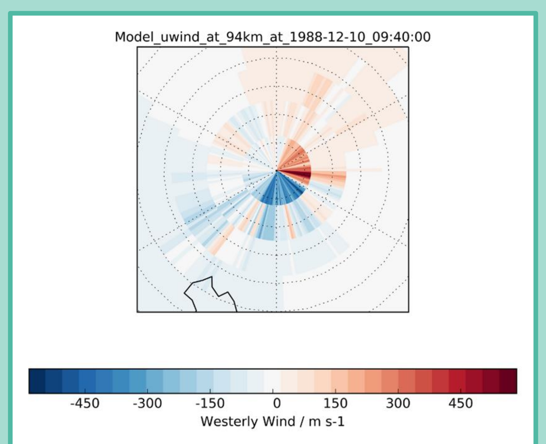


Figure 1: Stereographic plot of westerly wind in a 100km altitude simulation at the top model level at the south pole.

Running the UM with existing parametrisations and a raised lid lead to unstable and inaccurate solutions. These were due to huge, unphysical changes in wind speed velocities at adjacent grid points at the South Pole. (Figure 1).

These high altitude polar wind speeds are primarily driven by:
• Shortwave radiative heating
• Chemical heating
Radiation and chemistry schemes for the UM are still in development.

Nudging to Climatology

In the meantime, these instabilities are addressed by nudging the mesosphere and thermosphere (above 70km) to a climatological temperature profile. This is a Newtonian relaxation to a globally uniform temperature profile (Figure 2) with a timescale of 24 hours.

It is based on the US Standard Atmosphere temperature profile between 70 and 86km, and the COSPAR International Reference Atmosphere between 86 and 119.7km. Above this, the temperature asymptotes to a selected exobase temperature. This allows us to represent different parts of the solar cycle.

This gives a reasonably accurate and robust representation of the mean state of the mesosphere and thermosphere.

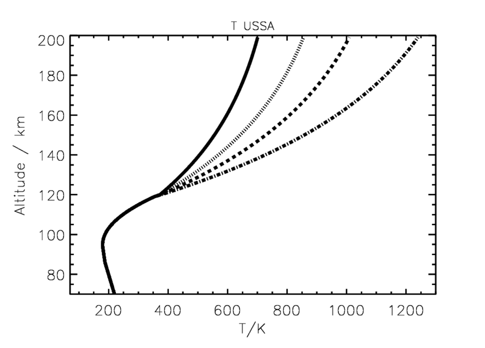


Figure 2: Global mean temperature profile used for the nudging scheme. Exobase temperatures of 800K (solid), 1000K (dotted), 1200K (dashed) and 1500K (dot-dashed) are shown.

Extended UM Assessment

The UM now includes:

- Nudging to climatology from either 70km altitude, or from 90km altitude with a 10km linear function from 80km to introduce the nudging gradually.
- Updated NLTE (non-local-thermodynamic-equilibrium) radiation scheme (see David Jackson's poster 11 for more details).

Here, we assess the UM's current capabilities as it is extended upwards above 100km, varying the range of altitudes, and horizontal and vertical resolutions. The results of some stability tests are shown in Table 1. It can be seen that with higher top model boundaries and higher resolutions, it becomes more difficult to complete simulations without numerical damping.

Table 1: This table shows the minimum vertical damping coefficient required for the Extended UM to remain stable for a year for different model top boundary heights and vertical resolutions.
All simulations are performed with N96 horizontal resolution (which corresponds to ~400km horizontal grid spacing).

N/A indicates that the simulation could not be completed for any amount of vertical damping.

Model Height	Vertical Resolution	Nudging Height	Minimum vertical damping coefficient
100km	3km	No nudging	0.05
	1.5km	No nudging	0.55
		70km	0.15
		90km	0.55
120km	3km	70km	0.1
		90km	0.15
	1.5km	70km	0.7
		90km	N/A
135km	3km	70km	0.35
		90km	0.55
	1.5km	70km	N/A
150km	3km	70km	N/A

Figure 3 shows zonal wind profiles for different resolutions, and a climatology to compare it against. It can be seen here that the various vertical and horizontal resolutions considered all give wind structures that resemble the climatology. Therefore, the coarser N96 horizontal and 3km vertical resolutions should be sufficient to capture circulation in the MLT region. (Note that here, N represents the maximum number of zonal 2 grid-point waves that can be represented)

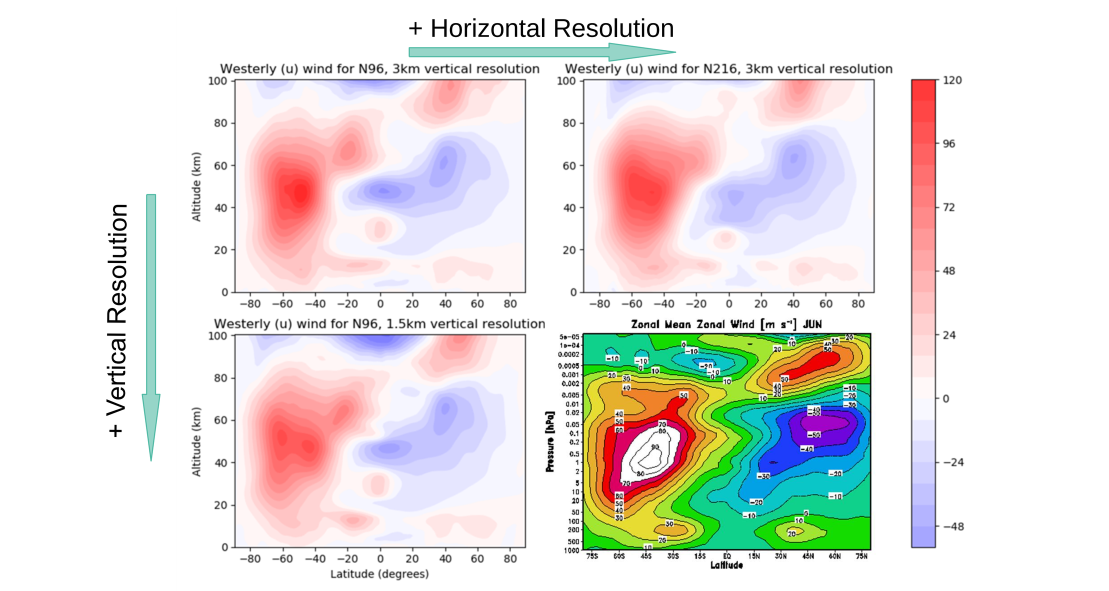


Figure 3: Latitude-altitude plots of 6-hour zonal mean zonal wind in June for 100km altitude simulations with no nudging and:
(upper left) 3km vertical resolution and N96 horizontal resolution with damping coefficient 0.05.
(upper right) 3km vertical resolution and N216 horizontal resolution with damping coefficient 0.6.
(lower left) 1.5km vertical resolution and N96 horizontal resolution with damping coefficient 0.55.
(lower right) zonal mean zonal wind climatology in June derived from the UARS Reference Atmosphere Project (URAP) [1].

Figure 4 shows the meridional wind profile in a simulation with a 135km model top boundary. The main feature this plot demonstrates are the high polar wind speeds in the MLT region.

The UM runs on multiple processors, each with a 'halo' to account for semi-Lagrangian trajectories that originate outside their processing areas. This is usually restricted in the North-South direction as most horizontal motion is in the East-West direction. These large North-South velocities may not be unphysically large, but they generate many North-South halo advection errors that cause UM simulations to fail.

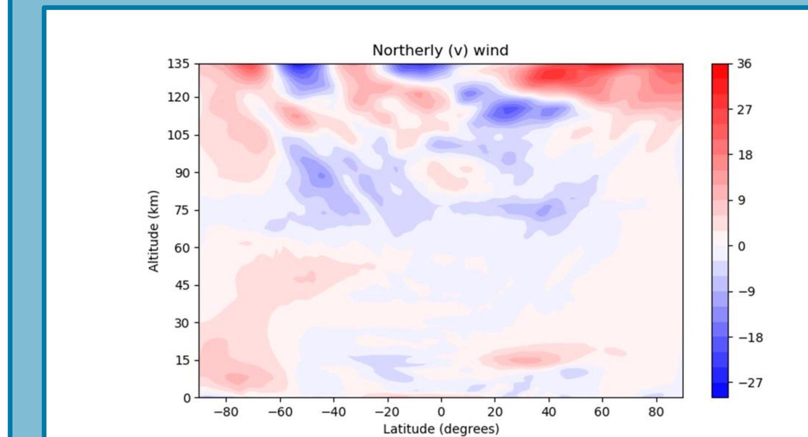


Figure 4: Latitude-altitude plot of 6-hour zonal mean meridional wind in June for a 135km altitude simulation with N96 horizontal and 1.5km vertical resolution, with nudging to climatology from 90km with a 10km gradual linear introduction of nudging, and damping coefficient 0.55.

Figure 5 shows that the expected wind reversal above 90km (from the climatology shown in Figure 3) is also captured as the top boundary is raised up from 100km to 135km.

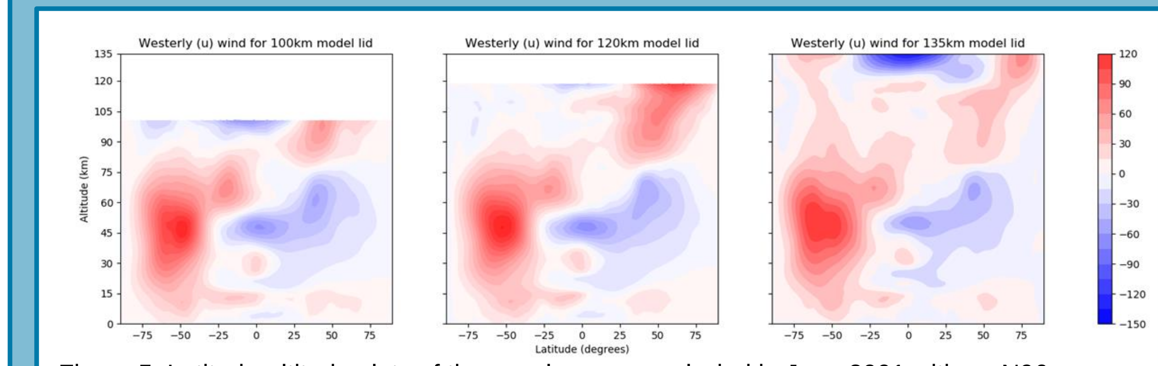


Figure 5: Latitude-altitude plots of the zonal mean zonal wind in June 2001 with an N96 horizontal resolution, 3km vertical resolution and nudging applied from 90km altitude with:
1. 100km altitude top boundary with a damping coefficient of 0.05,
2. 120km altitude top boundary with a damping coefficient of 0.2,
3. 135km altitude top boundary with a damping coefficient of 0.55.

Figure 6 shows the sharp rise in the temperature profile as the top boundary is raised. This is captured effectively with a combination of the NLTE radiation scheme and the nudging to the thermosphere climatology.

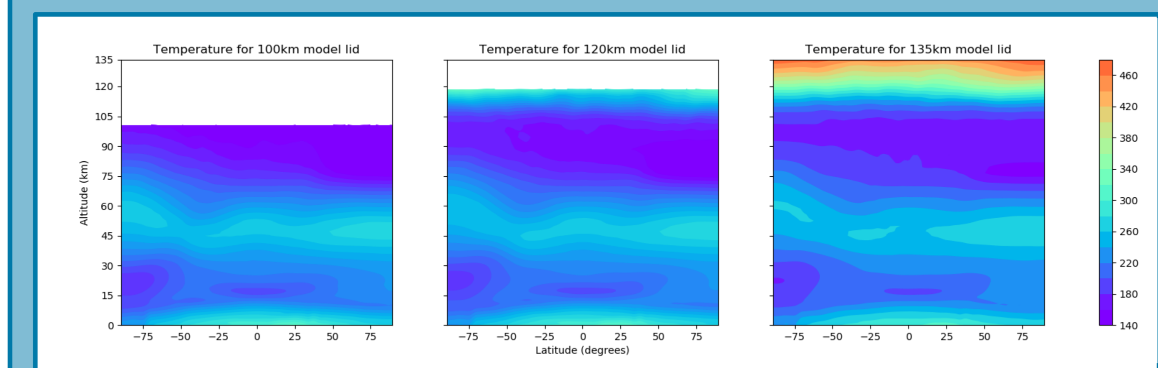


Figure 6: Latitude-altitude plots of the zonal mean temperature in June 2001 with an N96 horizontal resolution, 3km vertical resolution and nudging applied from 90km altitude with:
1. 100km altitude top boundary with a damping coefficient of 0.05,
2. 120km altitude top boundary with a damping coefficient of 0.2,
3. 135km altitude top boundary with a damping coefficient of 0.55.

Summary

The UM can reliably remain stable with low resolutions up to 135km, but large amounts of vertical damping are needed for higher altitudes. However, it matches up well when compared with climatologies.
This is sufficient to allow the UM to be merged with a thermosphere model (DTM [2]) for the SWAMI project.

Molecular Viscosity and Diffusion

Molecular viscosity and diffusion are real physical processes that have a significant damping effect on vertically propagating waves in the thermosphere (above 130km). The non-hydrostatic formulation of the UM allows for high-frequency acoustic waves. These are challenging to simulate, but they are important in geomagnetic storms and need to be represented realistically as the UM is extended upwards.

Idealised tests have been performed with a stand-alone version of the ENDGame dynamical core (the part of the UM that just solves the Euler equations for fluid dynamics) that includes vertical molecular viscosity and diffusion. Figure 7 shows the damping effect that molecular viscosity and diffusion have on vertically propagating waves. The stability of ENDGame is improved greatly too: much less numerical damping (in the form of off-centering of ENDGame's semi-implicit timestepping scheme) is required in order to extend the top model boundary of ENDGame to over 200km.

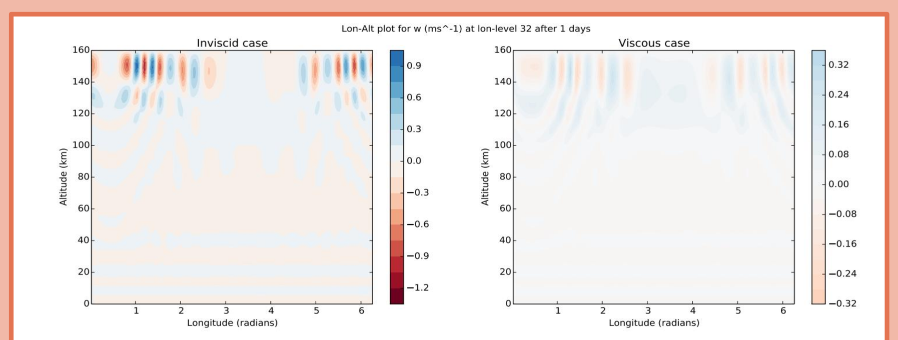
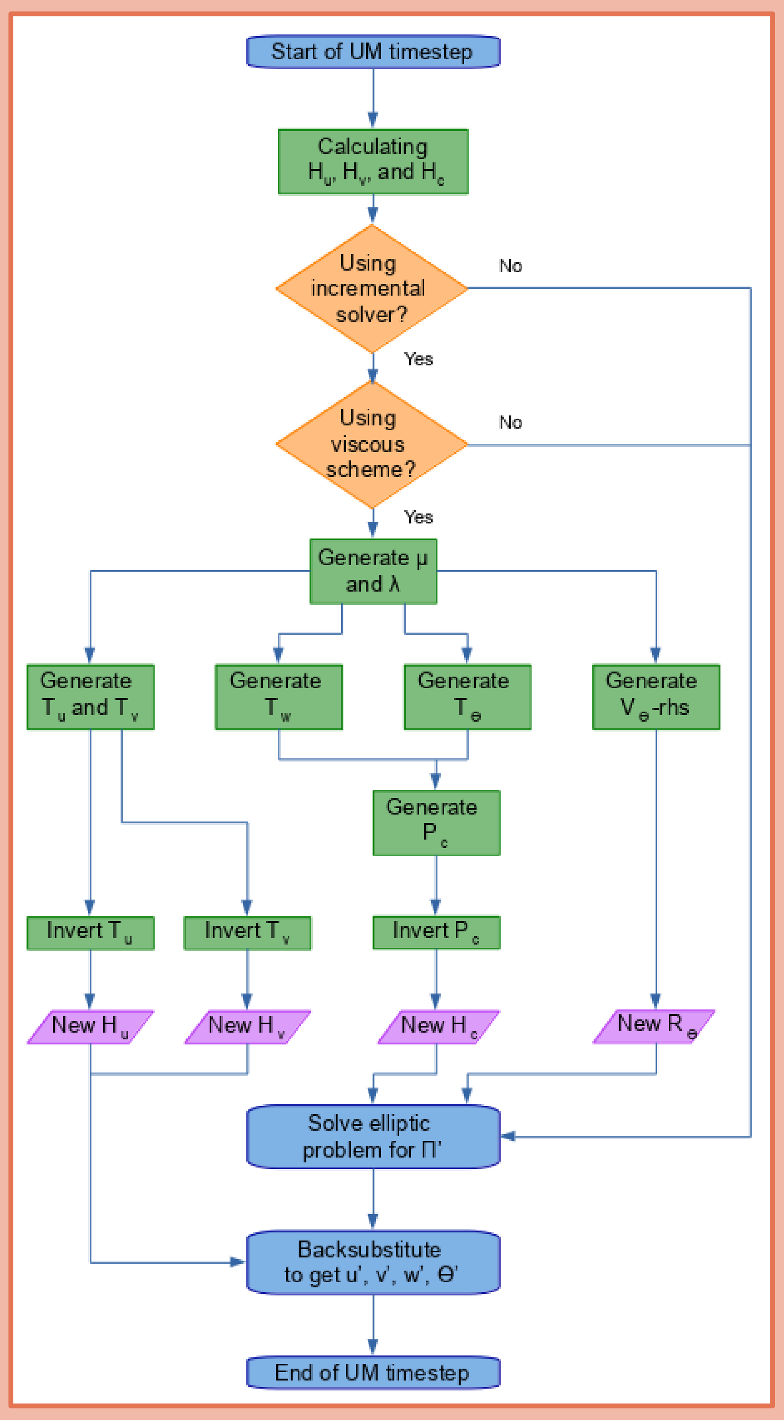


Figure 7: Longitude-altitude plots at the equator of vertical velocities from the stand-alone version of ENDGame after one day for a baroclinic wave test with (left) the original formulation and (right) the new formulation with vertical molecular viscosity and diffusion with 30 minute timesteps. The muted colours above 130km in the right-hand plot illustrate the damping effect of vertical molecular viscosity and diffusion [3].

As this worked very well for the stand-alone ENDGame, it will be implemented in the UM as well. It is also envisaged that its inclusion will negate the need for the sponge layer in the UM in simulations with a top model boundary higher than 130km.

The flowchart below illustrates the structure that the viscous scheme will have within the UM. The UM's incremental solver itself is not changed: this scheme finds new operators that account for the viscous terms, that are used as inputs by the incremental solver and backsubstitution routines.



References and Acknowledgments

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