Extension of the Met Office Unified Model into the Thermosphere

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Introduction

The Met Office 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

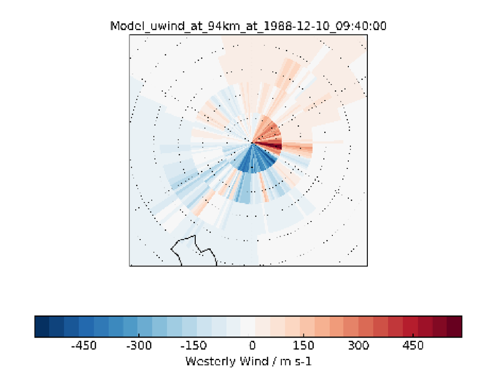

Figure 1: Stereographic plot of westerly wind in a 100km altitude simulation at the top model level at the south pole. (From Matthew Griffith)

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.

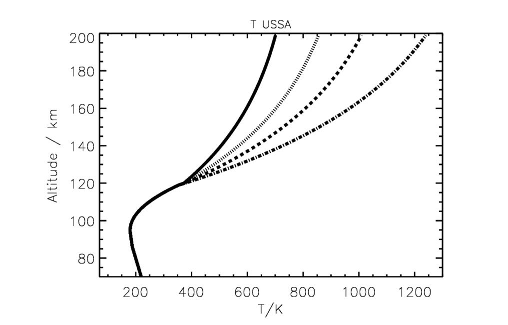

Figure 2: Global mean temperature profile used for the nudging scheme. Exobase temperatures of 800K (solid), 1000K (dotted), 1200K (dashed) and 1500K (dot-dashed) are shown. (From David Jackson)

Extended UM Assessment

The UM now includes:

- Nudging to climatology
- Updated non-LTE (non-local-thermodynamic-equilibrium) radiation scheme (see David Jackson's poster: number 28, 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 one year for different model top boundary heights and vertical/ horizontal resolutions. N96 corresponds to ~400km horizontal grid spacing and N216 corresponds to ~120km horizontal grid spacing. N/A indicates that the simulation could not be completed for any amount of vertical damping.

Model Height	Horizontal Resolution	Vertical Resolution	Minimum vertical damping coefficient
100km	N96	3km	0.05
		1.5km	0.35
	N216	3km	0.4
120km	N96	3km	0.2
		1.5km	N/A
	N216	3km	0.6
135km	N96	3km	0.3
150km	N96	3km	0.6
170km	N96	3km	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 1.5km vertical resolution has a closer wind structure to the climatology, in particular capturing a new feature at the top boundary near the equator.

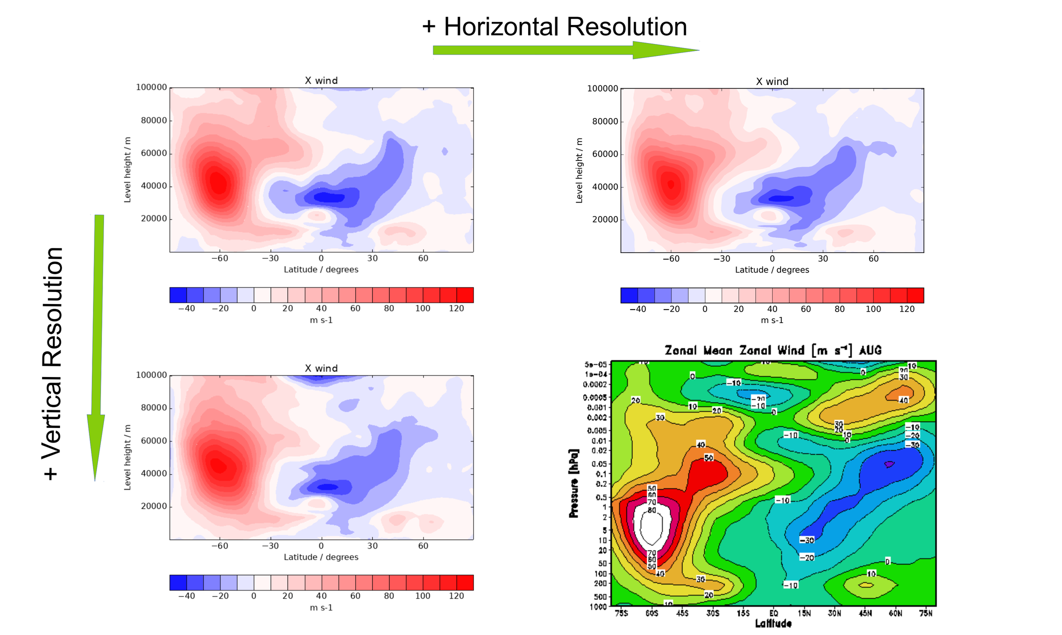

Figure 3: Latitude-altitude plots of 6-hour zonal mean zonal wind after one year of a 100km altitude simulation with
(upper left) 3km vertical resolution and N96 horizontal resolution with damping coefficient 0.05
(upper right) 3km vertical resolution and N216 horizontal resolution with damping coefficient 0.4
(lower left) 1.5km vertical resolution and N96 horizontal resolution with damping coefficient 0.35
(lower right) zonal mean zonal wind climatology in August derived from the UARS Reference Atmosphere Project (URAP) [1].

Figure 4 shows the meridional wind profile at 90km. The main feature this plot demonstrates are the very high polar wind speeds at the south pole.

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.

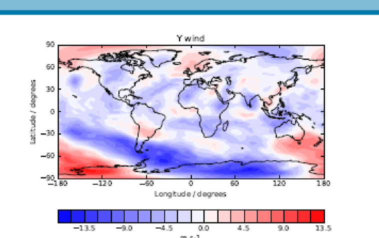

Figure 4: Latitude-longitude plot at 90km altitude of 6-hour mean meridional wind after one year of a 100km altitude simulation with 1.5km vertical resolution and N96 horizontal resolution with damping coefficient 0.35

Figure 5 shows large accelerations that act to decelerate the middle atmosphere extratropical jets, which is the expected behaviour of the UM's gravity wave scheme (USSP). This decreases between 100 and 120km, which is encouraging because gravity waves are expected to break by around the turbopause (~105km).

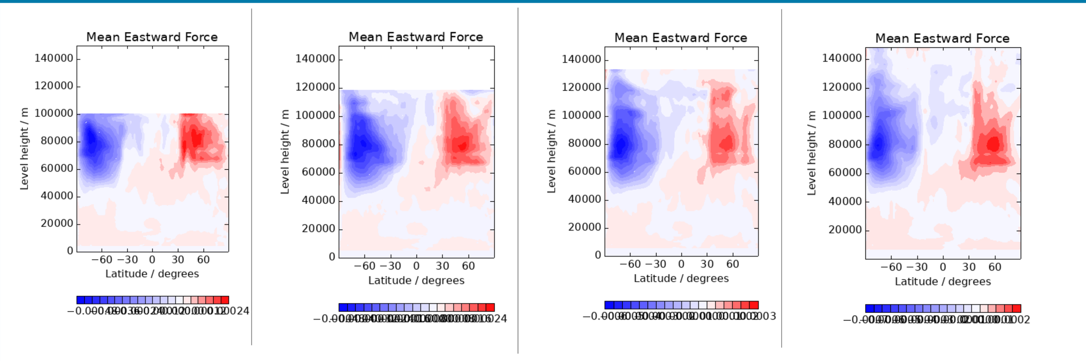

Figure 5: Latitude-altitude plots of the eastward gravity wave acceleration after one year of a simulation with an N96 horizontal resolution, 3km vertical resolution and:
1. 100km altitude with damping coefficient 0.05, 2. 120km altitude with damping coefficient 0.2,
3. 135km altitude with damping coefficient 0.3, 4. 150km altitude with damping coefficient 0.6.

Figure 6 shows that the expected wind reversal above 90km (from climatology in Figure 3) is also captured as the top boundary is raised.

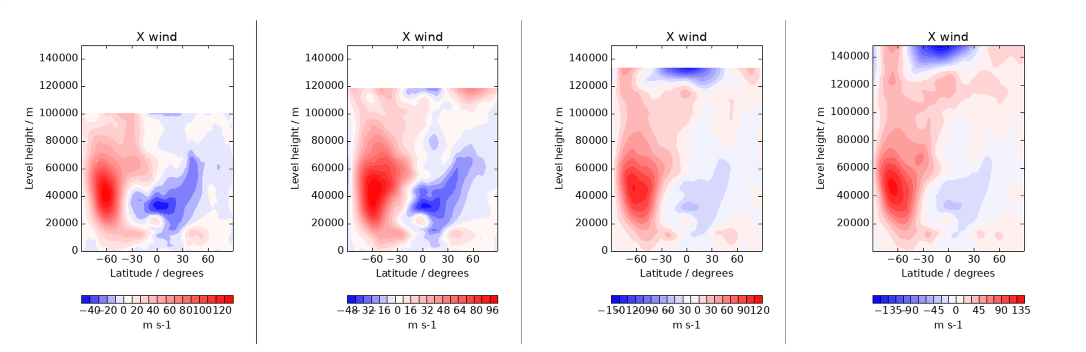

Figure 6: Latitude-altitude plots of the zonal mean zonal wind after one year of a simulation with an N96 horizontal resolution, 3km vertical resolution and:
1. 100km altitude with damping coefficient 0.05, 2. 120km altitude with damping coefficient 0.2,
3. 135km altitude with damping coefficient 0.3, 4. 150km altitude with damping coefficient 0.6.

Summary

The UM can remain stable with low resolutions up to 150km, but large amounts of vertical damping are needed for the higher altitudes. 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). These are very important for the accuracy and the stability of the the UM as it 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 ENDGame up to over 200km.

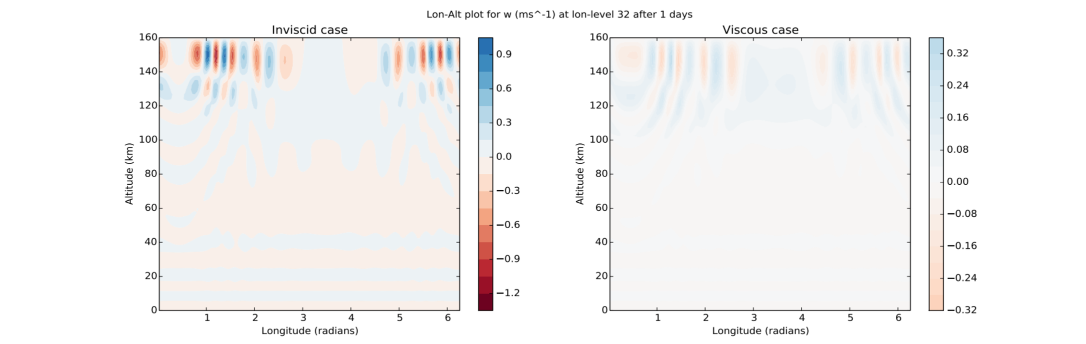

Figure 7: Longitude-altitude plots at the equator of vertical velocities from the stand-alone version of ENDGame after one day for a baroclinic wave test with (left) the original formulation and (right) the new formulation with vertical molecular viscosity and diffusion with 30 minute timesteps. The 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 may even negate the need for a sponge layer at the top of the model atmosphere.

Molecular viscosity and diffusion are very fast processes, so must be incorporated into the UM solver fully coupled to the dynamics. This makes coding the scheme very complex. In addition, the full UM uses a different solver (incremental) to that used by the stand-alone version of ENDGame (multigrid), so this needs to be re-implemented.

This scheme has been derived, and work on implementing and testing it will begin soon.

References and Acknowledgments

[1] Swinbank R. & Ortland D. A. 2003. Compilation of wind data for the Upper Atmosphere Research Satellite (UARS) Reference Atmosphere Project. Journal of Geophysical Research, **108**(D19).

[2] Bruinsma S. 2014. The DTM-2013 thermosphere model. Journal of Space Weather and Space Climate, **5**(A1).

[3] Griffin D. J. 2018. The Extension of a Non-Hydrostatic Dynamical Core into the Thermosphere. Ph.D. thesis, The University of Exeter.

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