The Met Office Unified Model and its extension to the thermosphere

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Overview

- What is the UM?
- Motivation for coupled models between Sun and Earth
- “whole atmosphere” modelling
  - Motivation
  - Goals and Challenges
- Summary

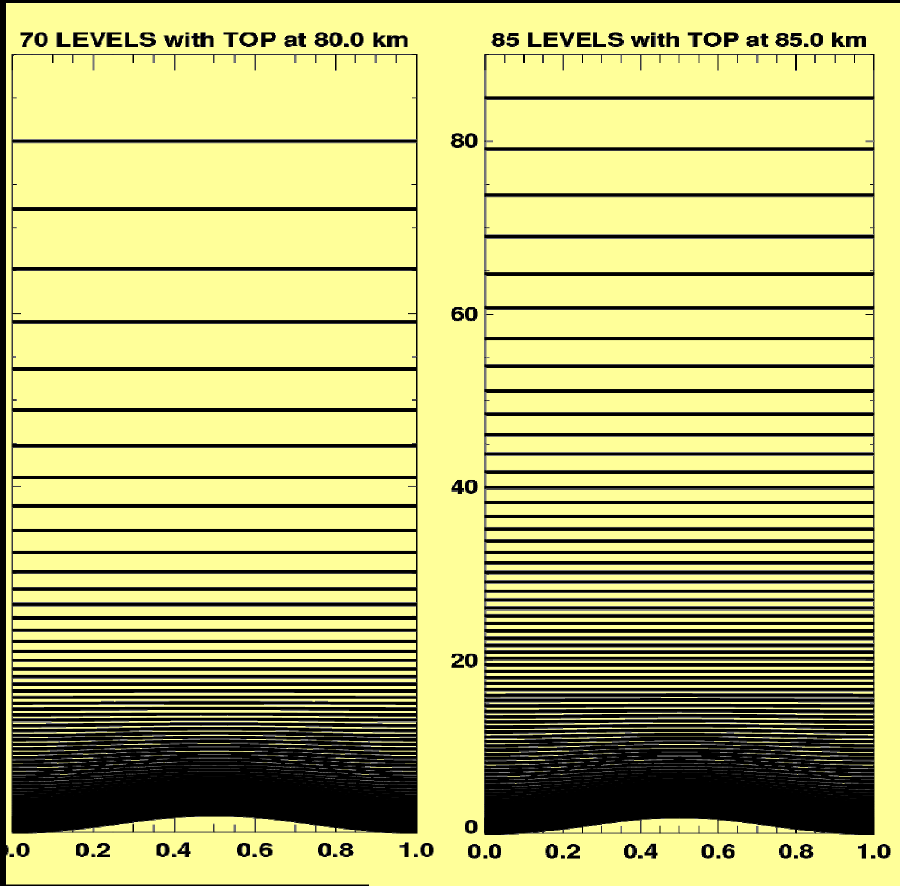
What is the Unified Model (UM)?

- Met Office weather and climate model
- Horizontal resolution N96-N512 (~25-150 km)
- Navier Stokes equations with comprehensive physical parametrizations (radiation, gravity waves..) and coupled chemistry
- Semi-Lagrangian, deep atmosphere, non-hydrostatic dynamical cores (current and “EndGame”)

Vertical levels: 0-~80-85 km

70 and 85-level versions

resolution: ~100m near surface; 4-8 km at top



Coupled "Sun to Earth" models offer great scope for better Space Weather Predictions

Met Office

Current Predictive Capability for geomagnetic storms:
Good but limited

FUTURE

Solar Wind Disturbance Propagation Model (1-4 days lead time)

↓

Geospace Model (lead time as above)

↓

Whole Atmosphere Model (surface to Thermosphere / Ionosphere)

(lead time as above)

NOW

Solar Wind Disturbance Propagation Model (1-4 days lead time)

↓

No indication of CME "geoffectiveness"

↓

ACE observations (L1) – "geoffectiveness" (30-45 mins lead time)

↓

Ionosphere model (nowcast)

↑

No lower atmosphere coupling (~20% of ionospheric variability)

(Geomagnetic storms example)

Motivation for a whole atmosphere model

Met Office

Coupling between lower atmosphere and thermosphere / ionosphere is very important

- Non-migrating tides (DE3) important for w4 structure in EIA
  - non-migrating tide generation linked to zonally-asymmetric forcing due to tropical convection?
- Other studies show strat. sudden warming / ionosphere linkages
- In general, PW / GW / tide interaction need to be properly represented

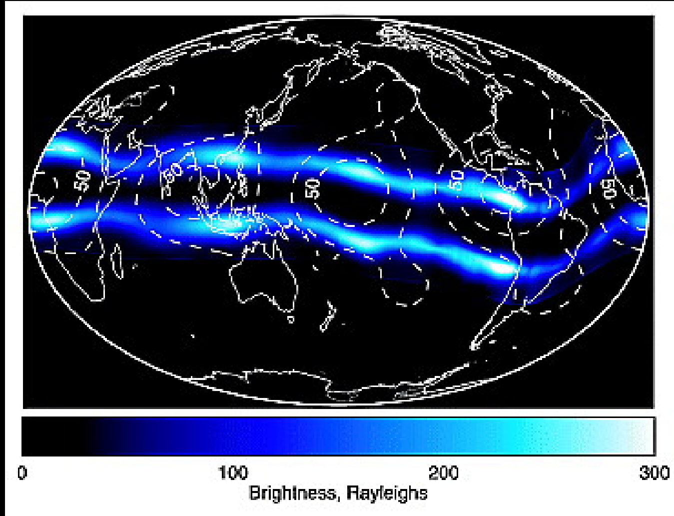


IMAGE composite of 135.6 nm O airglow (350-400km) in March April 2002 and modelled diurnal temperature oscillation at 115 km - Immel et al, 2006

Also impact of SEPs / solar EUV on tropospheric climate & seasonal forecasts

Goals

- Develop a Whole Atmosphere Model of the surface to thermosphere (plus coupled ionosphere model) by extending UM upwards
- Longer term – Incorporate Whole Atmosphere UM into “Sun to Earth” system (other UK / international partners working on the other models)

Whole Atmosphere Specifications

- Height range limited to region where Navier-Stokes equations are valid – the exobase (~600-650 km). Above here molecules follow ballistic trajectories and air no longer can be treated as continuous fluid
- Coupling between lower and upper levels needs to be represented accurately and self-consistently
- Comprehensive physics and chemistry needs to be included (eg gravity waves, non-LTE radiation)
- Coupled ionosphere model

Why is the UM a good basis for a whole atmosphere model?

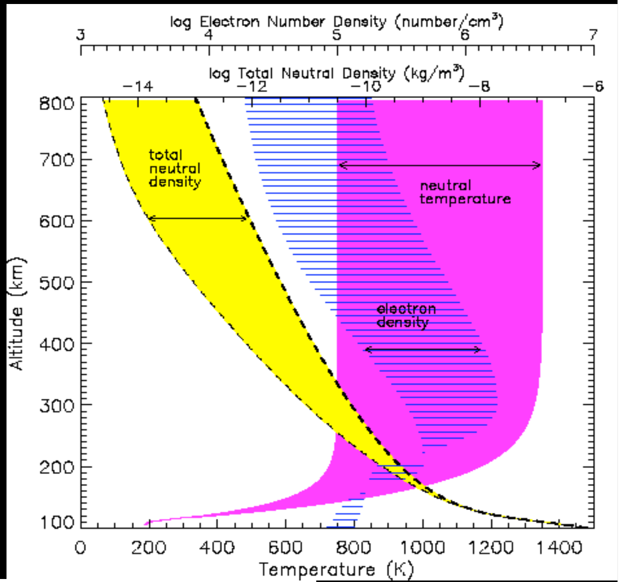
- Dynamical formulation suitable:
  - Non-hydrostatic, deep atmosphere formulation (g(z), r≠a)
  - Many other WA models (eg WAM) and thermosphere models (eg CMAT2) are hydrostatic and/or shallow atmosphere
  - Non-hydrostatic allows simulation of acoustic waves, large vertical velocities that will be important in the thermosphere (eg Deng et al, 2011; Hickey et al, 2001)
- Robust:
  - Used operationally at Met Office and other NMSs
  - Widely used in academic community

R&D Challenges

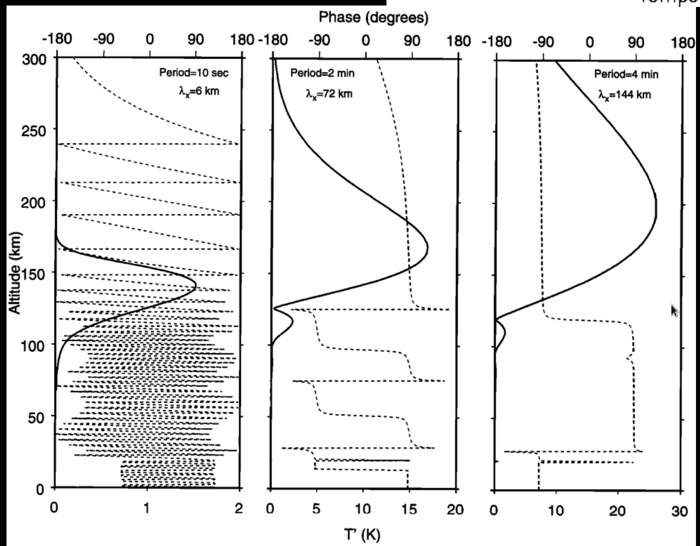
- Lot of work involved!
- Focus on two areas initially
  - Robustness and Extension of Dynamical Core
  - Existing UM tidal (and other wave) climatology and physics
- (Implementations of comprehensive thermospheric physics & chemistry, and ionosphere, can come later)

Robustness and Extension of Dynamical Core

- Test robustness of solver, model formulation (ρ`,Θ`). Modify density-theta formulation at higher levels?
- New equations for constituents needed above turbopause
- Upper boundary conditions, eg do acoustic waves bounce off the upper boundary or refract?
- Add implicit damping of large amplitude waves at higher levels?
- Add molecular diffusivity to implicit timestep?
- Appropriate horizontal and vertical resolutions to resolve important waves (Lindzen & Fox-Rabinowitz??)



(Forbes, 2007)



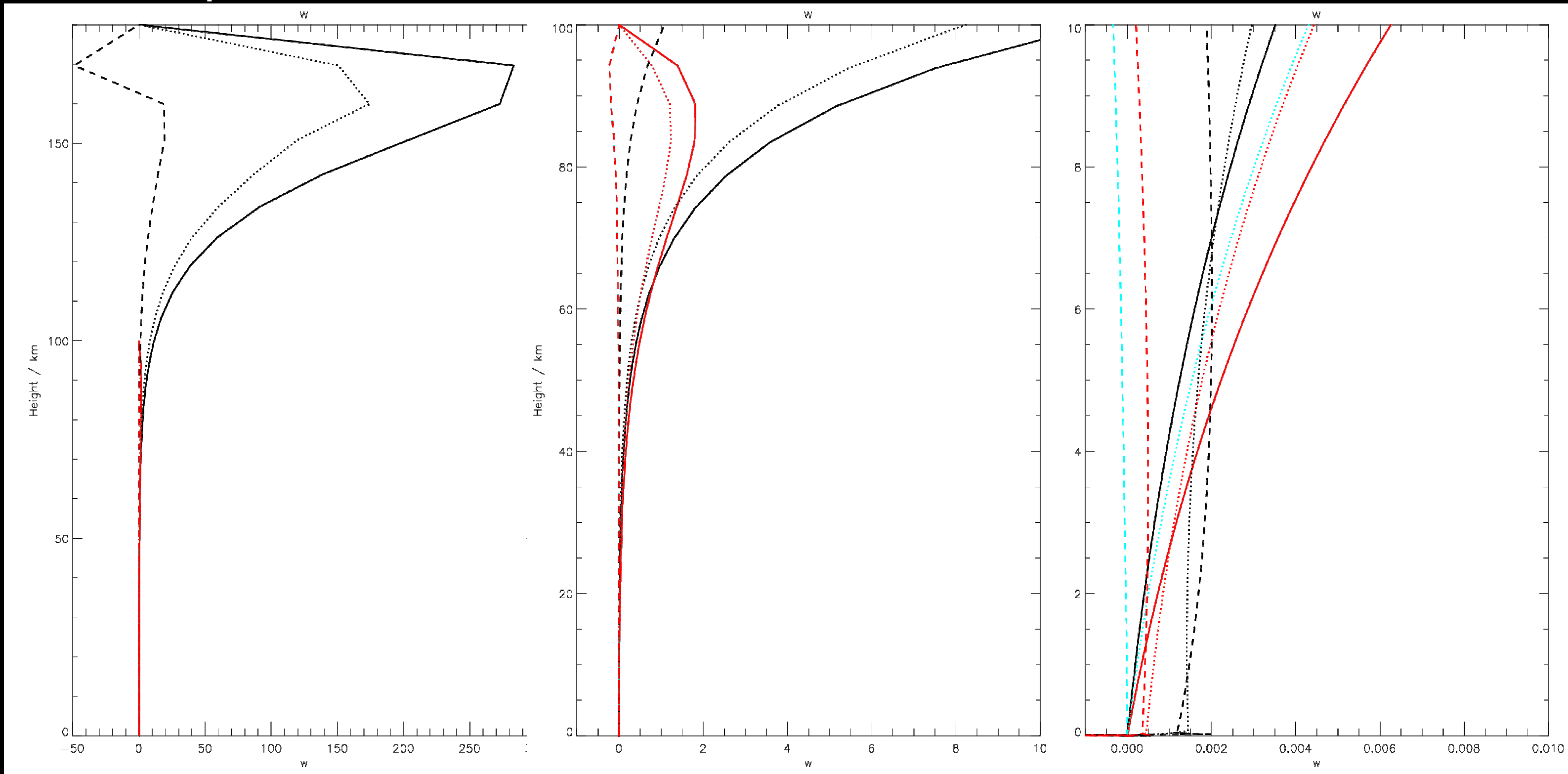
Hickey et al (2001): Viscous dissipation included, leading to amplitude maximum (which increases with wave period) and associated large heating rates.

Robustness and Extension of Dynamical Core

- Develop 1D dynamical core to examine large upper level amplitudes and UBCs
- Set up dynamical core for quick 3D tests
  - simple acoustic wave and other standard tests
  - Forcing from WAM, MSIS, simplified physics (Newtonian cooling, etc)
- Use these 2 tools to answer questions from previous page
- Cross-over to full UM after dynamics questions tested and sufficiently well answered

Simple acoustic wave test with 3D TestBed

- Only works up to 140 km (180 km) for 60 (250) levels (further trials with different distributions of level sets needed)
- w=0 upper BC and no damping
- impact of wave reflection and resolution seen



L250 z=180 km

L250 z=100 km

L100 z=100 km

solid: IC;
dot: t/step 1;
dash: t/step 2

Existing UM tidal (and other wave) climatology and physics

- Tides very important for lower/upper atmosphere coupling – need to be well represented in existing UM
- Observed tidal amps maximise near 100 km. Existing UM has UB near 85 km, which affects interpretation. Do simulation with "intermediate" UM with UB around 120-140 km?
- UB with 140 km UB set up but fails after few days – probably due to lack of balance in initial conditions
- Such a model can also be used to test:
  - Radiation – no non-LTE in current UM. Start with simple merge to different scheme in MLT?
  - Gravity waves – also important for coupling. Is existing UM scheme too tuned for middle atmosphere?

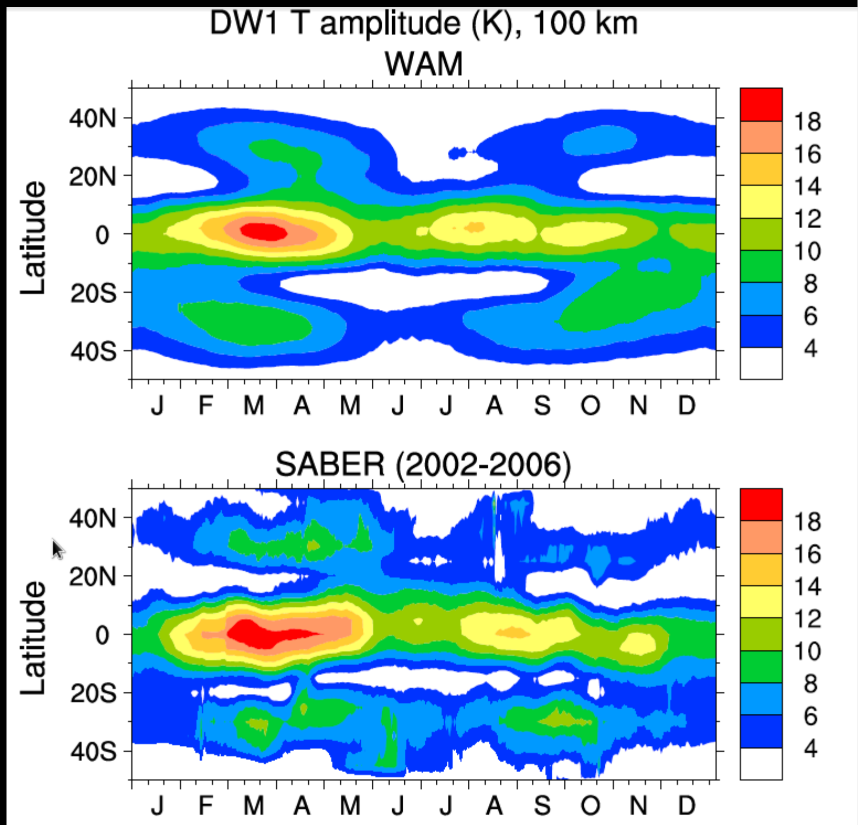


Figure 7. Diurnal migrating DW1 temperature amplitude (K) near 100 km as a function of latitude and season: (top) WAM simulation and (bottom) SABER observations [*Akmaev et al.*, 2008].

Summary

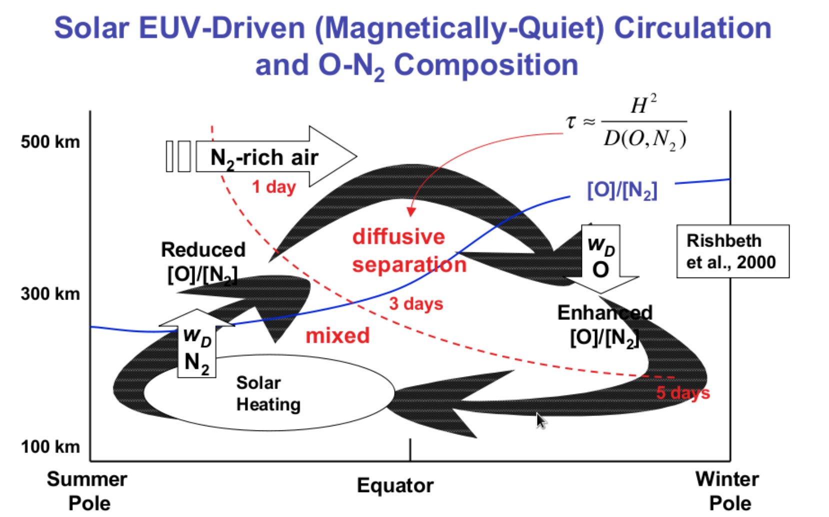
- For improved space weather forecasts in the long term, a coupled Sun-to-Earth modelling system is needed
- An important component is a Whole Atmosphere model – enables the lower / upper atmosphere coupling to be well represented.
- We are started to develop a Whole Atmosphere version of the UM
- Initial development should focus on dynamical issues:
  - Use 1d and 3d Test Beds to answer range of dynamics questions (eg robustness, upper boundary conditions, thermospheric constituent equations)
- Use full UM with slightly raised upper boundary (120-140km) to validate tides and other waves. Also use this to test radiation and GW parametrizations
- Some initial steps taken, but considerable resources needed for full R&D

Questions and answers

Challenges

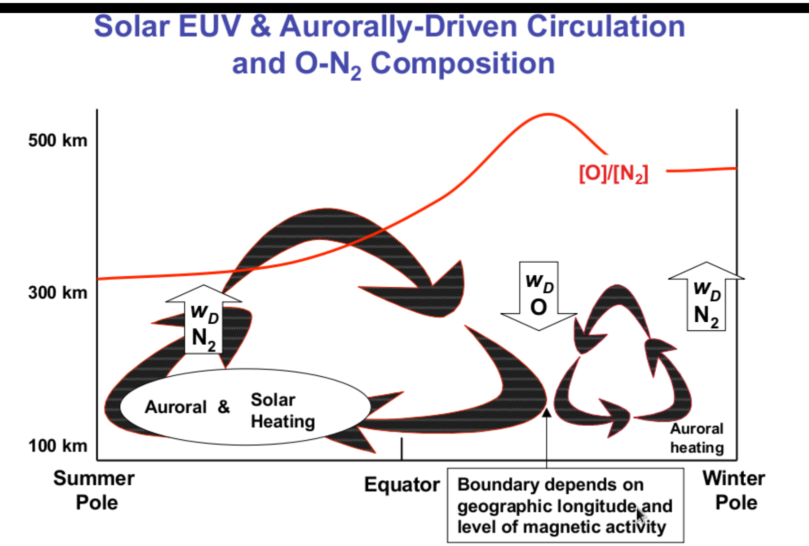
- Need to represent constituents:–
  - separate equations above the turbopause.
  - Chemical changes important

- Need to represent the ionosphere and its interactions with the thermosphere
  - The O/N2 ratio influences the plasma density of the F-region;hence regions of enhanced O/N2 tend to have higher plasma densities, and vice-versa
  - Therefore, seasonal-latitudinal and longitudinal variations in O/N2 ratio also tend to be reflected in F-layer plasma densities.



Upwelling occurs in the summer hemisphere, which upsets diffusive equilibrium.

Molecular-rich gases are transported by horizontal winds towards the winter hemisphere, where diffusive balance is progressively restored, from top (where diffusion is faster) to bottom



A secondary circulation cell exists in the winter hemisphere due to upwelling driven by aurora heating. The related O/N_2 variations play an important role in determining annual/semiannual variations of the thermosphere & ionosphere.