Extending the Met Office Weather and Climate Model into the Thermosphere

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- Sun to Earth modelling & motivation for a Whole Atmosphere Model
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- Dynamics for the whole thermosphere – 1st steps
- SWAMI H2020 project

Met Office Space Weather Operations Centre (MOSWOC)

- 24/7 Operations
- Fully integrated within Met Office Operations Centre
- National capability supporting government, military, and critical sectors
- Team includes
  - Space Weather Operational Meteorologists
  - Scientists
  - Programme managers
  - IT developers

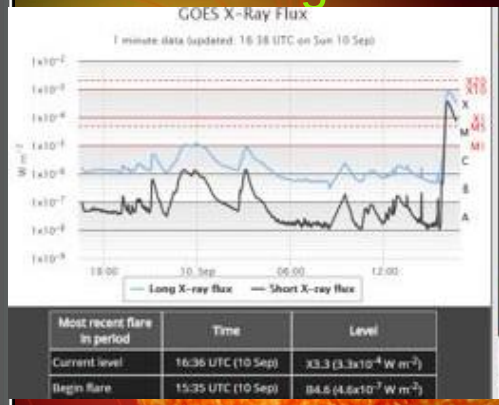
- Set up in response to NRR
- Met Office owns risk on behalf of UK Government (Dept of Business, Energy and Innovation Strategy (BEIS))
- BEIS funds operations and associated research via rolling programme

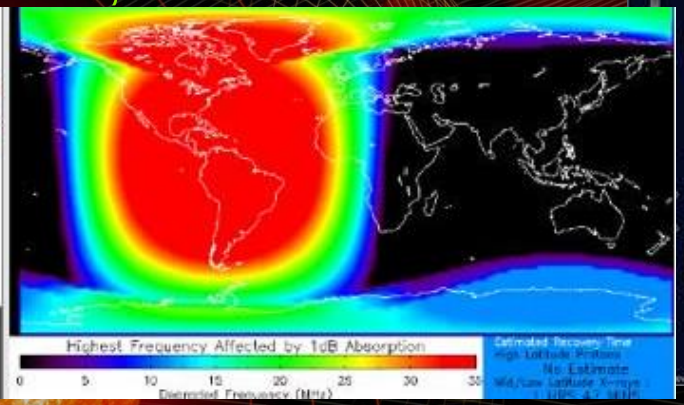
What do forecasters use?

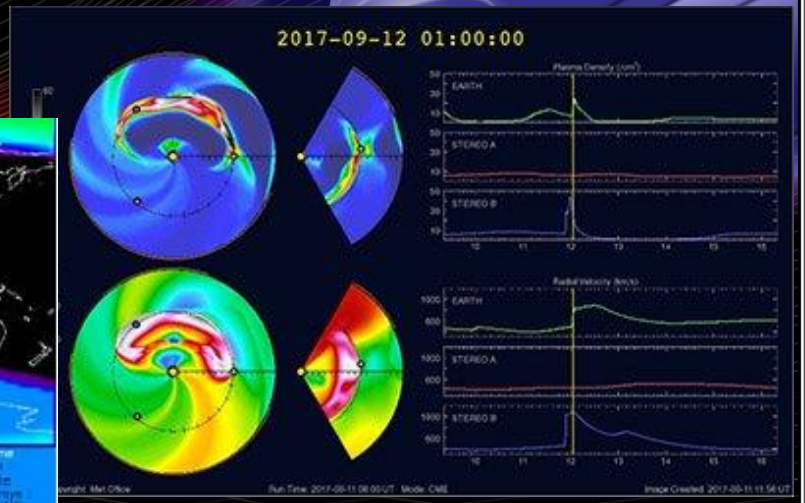
Met Office

Observations

- Solar and corona images and maps (eg SDO, STEREO, SOHO),
- Solar wind on S2E line (ACE, DSCOVR)
- E, p and X-rays at GEO (GOES)
- magnetometers, GPS





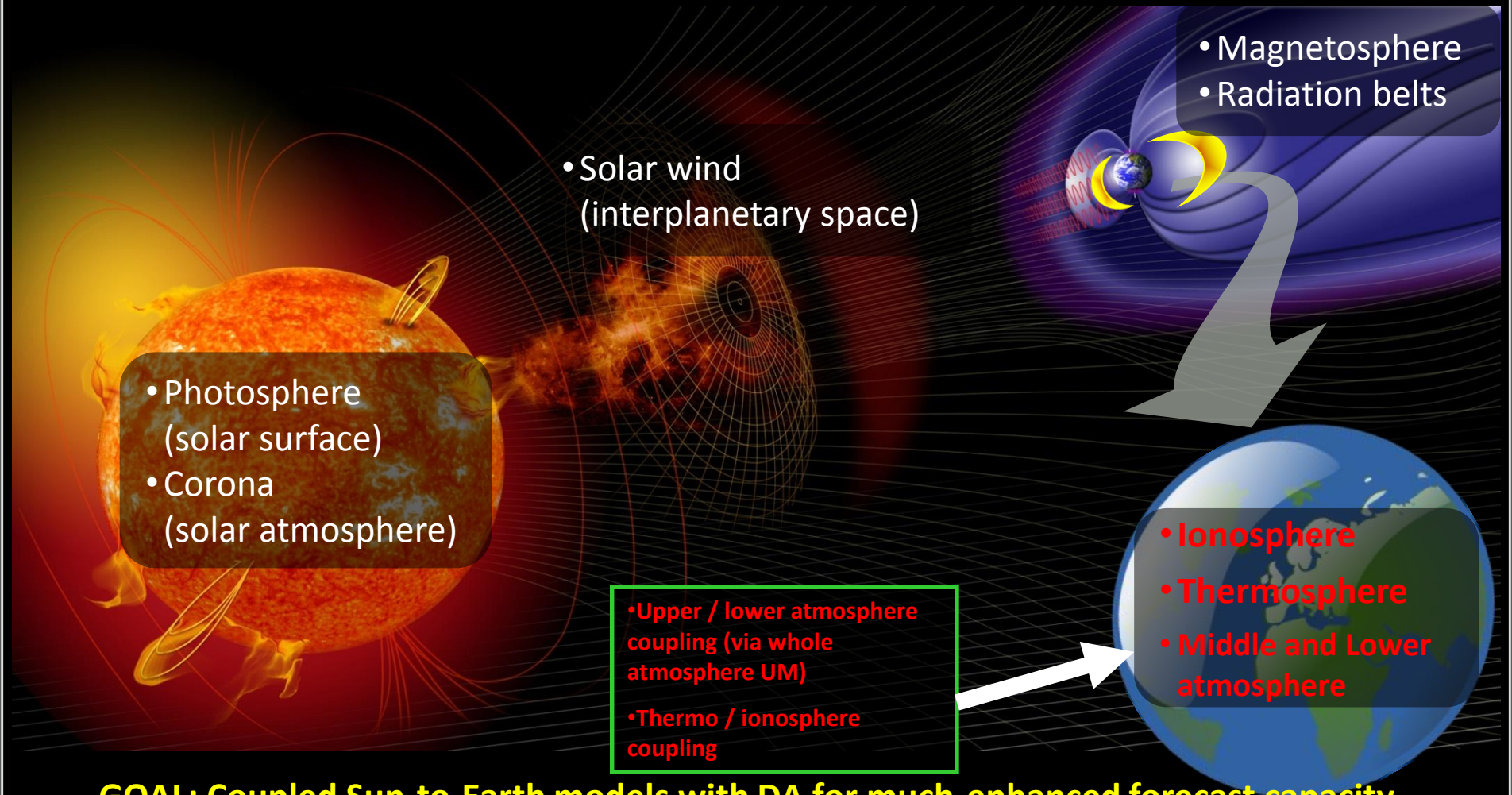


Models

- WSA Enlil: solar wind prediction model; CME predictions
- REFM: >2MeV electron fluence at GEO
- D-RAP: HF absorption due to flares, SEPs
- Bernese: TEC (ionosphere)

- Statistics (eg flares); solar wind persistence model, knowledge

Toward Sun-Earth coupled modelling

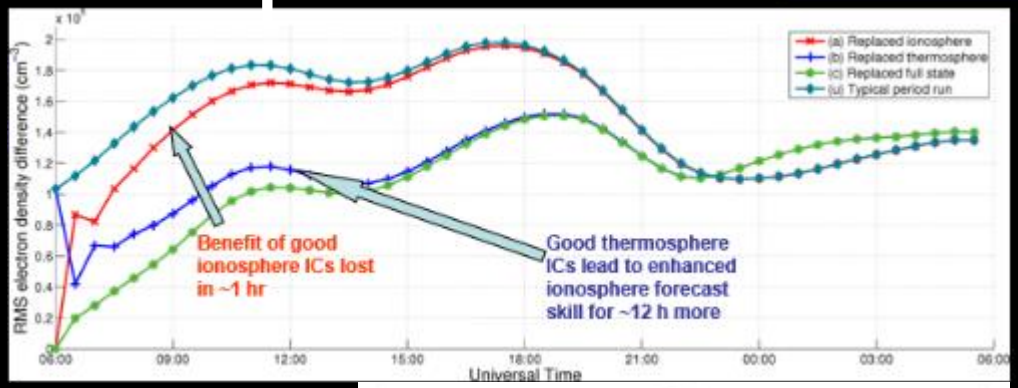


GOAL: Coupled Sun-to-Earth models with DA for much-enhanced forecast capacity

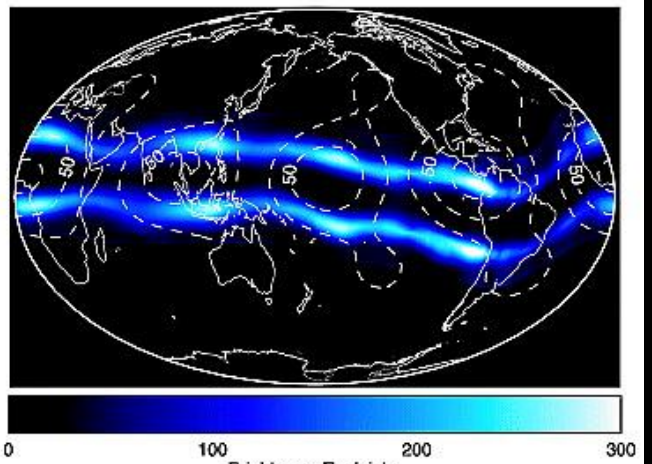
Whole Atmosphere Modelling

A Whole Atmosphere model

- One model from the Earth's surface to exobase
- Motivation:
  - Thermosphere state important for ionospheric evolution
  - Important role of lower level driving in thermos / ionospheric state (convection/tides; SSWs)
  - Lack of thermosphere obs means that lower level driving could be like "free DA"
  - Self-consistent representation of dynamics across whole atmosphere
  - Solar / SEP impact on weather and climate

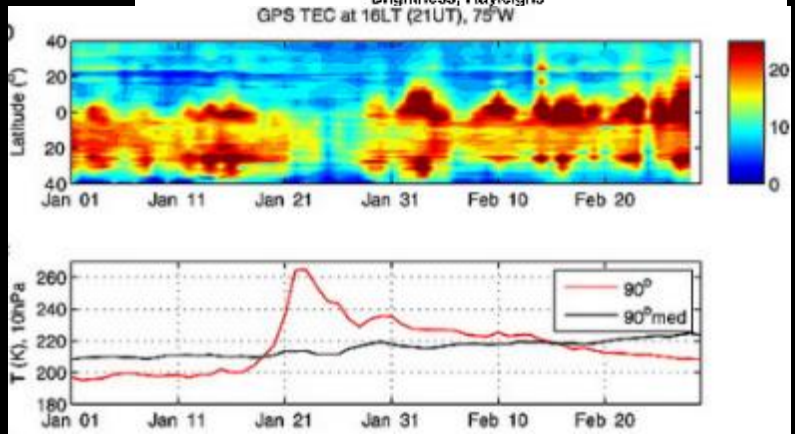


Chartier et al (2013)



Immel et al, 2006

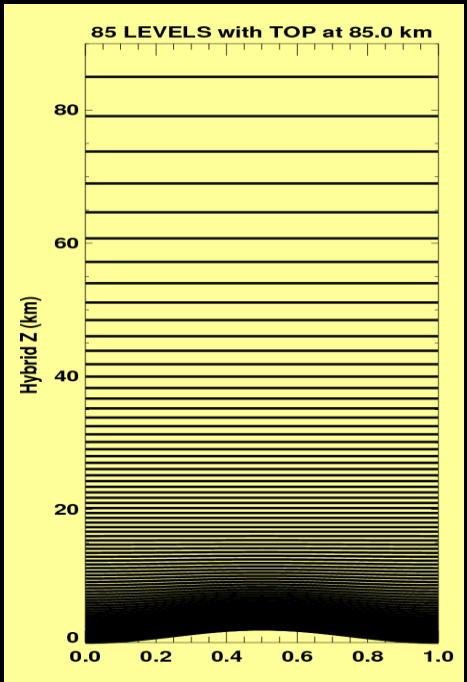
Goncharenko et al, 2010



What model to use?

Vertical levels: 0-~85 km

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

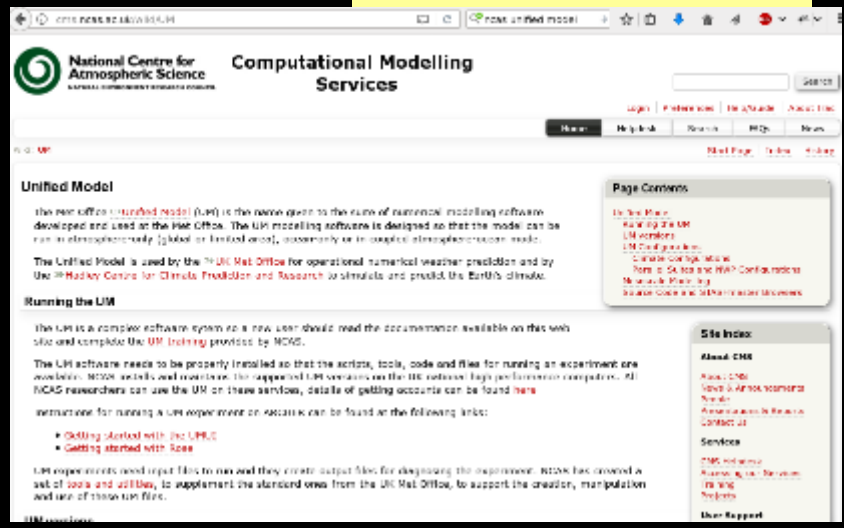


Current whole atmosphere models (surface to around exobase): WAM, WACCM-X, GAIA

Models that include the thermosphere and ionosphere but do not extend all the way down to the surface: CMAT2: 15-~350 km; TIEGCM and GITM – both ~97-~600-700 km

Thanks, but no thanks! – our whole atmosphere model will be based on the Met Office Weather and Climate model (Unified Model – UM)

- Why UM instead of another model?:
  - All other models (except GITM) use hydrostatic dynamics
  - …assumes vertical velocity is negligible – poor in thermosphere
- **Its non-hydrostatic formulation will make the UM unique amongst surface to thermosphere-spanning models.**
- Should lead to
  - more accurate modelling of vertical velocities (and air density) in thermosphere
  - Different interaction between dynamics, radiation and chemistry (possibly benefiting from more accurate dynamics)



Also a UK Community model – hosted by NCAS (NERC)

Extending the UM to the thermosphere

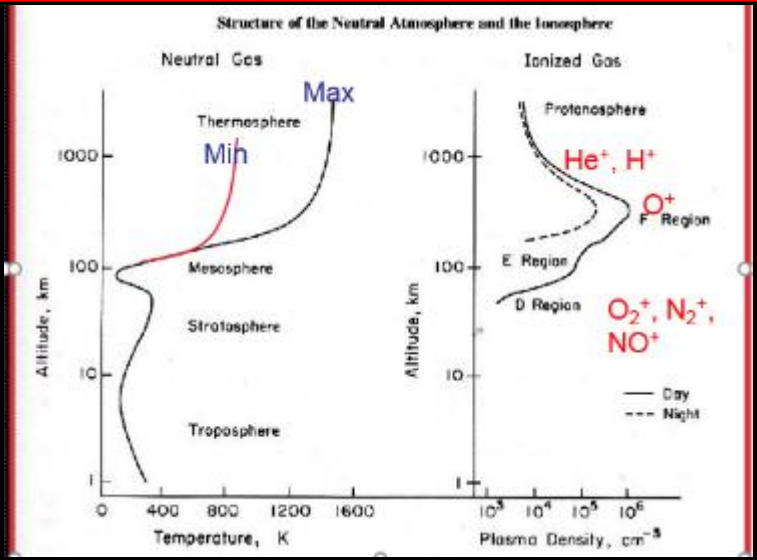
Met Office

Huge task - split into 2 strands:

1. Upward extension ~120-170 km ("Extended UM").
   - Add relevant physics & chemistry; examine dynamical robustness
   - Couple with TIEGCM (LB ~97 km) – pushes ionosphere development to later
2. Develop dynamical core - fast waves (acoustic), new eqns, etc

Eventually blend 1 + 2 => whole atmosphere UM with exobase UB

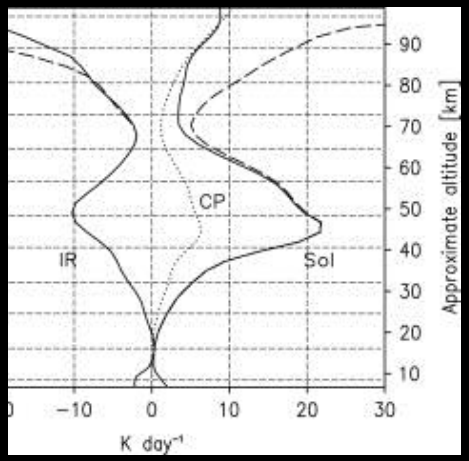
- Radiation scheme – no non-LTE (less accurate MLT heating rates). No scheme in short UV and EUV (photolysis rates for new chemistry)
- Add thermosphere chemistry – for the large rise in T in the MLT,
- No idea how dynamics will work in less dense atmosphere, and above turbopause (~110-120 km)
- No electrodynamics (ionosphere)



Chemical heating dominant in MLT in determining T structure

building

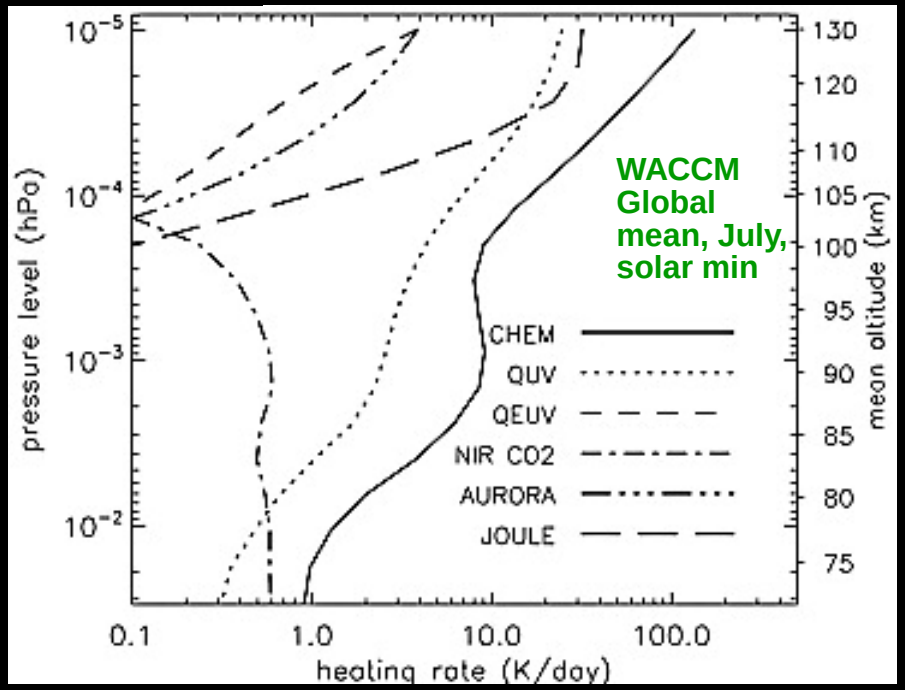
- Current UM chemistry (UKCA) runs up to mesopause but with trop / stratosphere focus
- Chris Kelly (Leeds PhD) developing neutral and ion chemistry for UKCA (based on WACCM). Motivations:
  - Can study impact of EPP on stratosphere and troposphere
  - Will improve MLT simulation (exothermic heating)
  - Examining N2O in WACCM (possible new source)
  - Starting UKCA work with 5 species Na ion chemistry (data for validation available)



SW and LW heating – Fomichev (2009)

schemes for chemical scheme photolysis rates

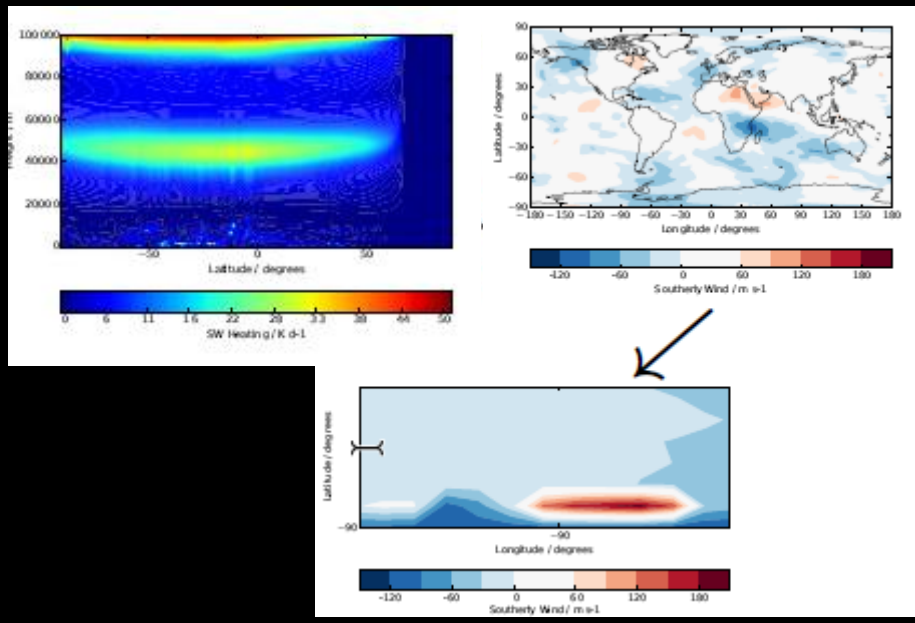
- Need exothermic chemical heating to model large rise in T in MLT



Dynamical Stability – just raise the lid!

- With 100 km – stable climatology but fails after a few months – unless timestep is halved
- 105-120 km lids – fails after days/weeks – even with extra diffusion, short timesteps, etc

• SW heating looks too large: due to non-LTE effects being omitted (actually in NIR)
•Could adding non-LTE to UM radiation scheme fix stability issues?

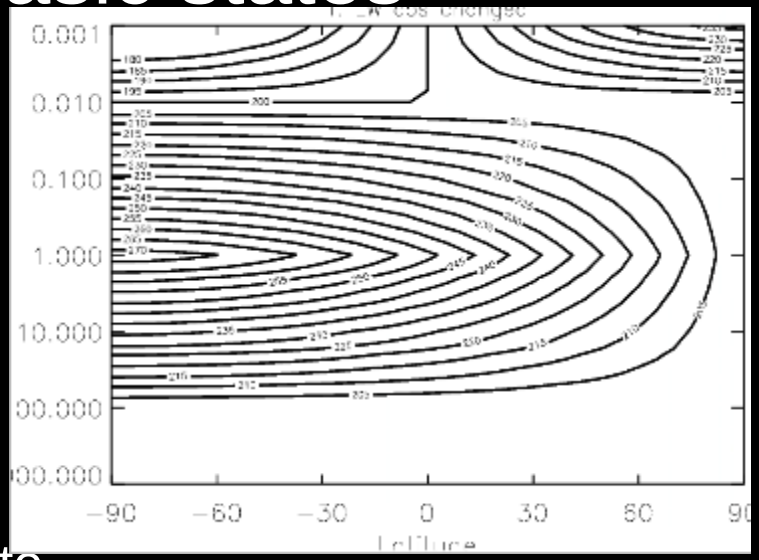


Zonal mean SW heating – lat/pressure section (left). Lat/lon fields meridional winds (right and bottom)

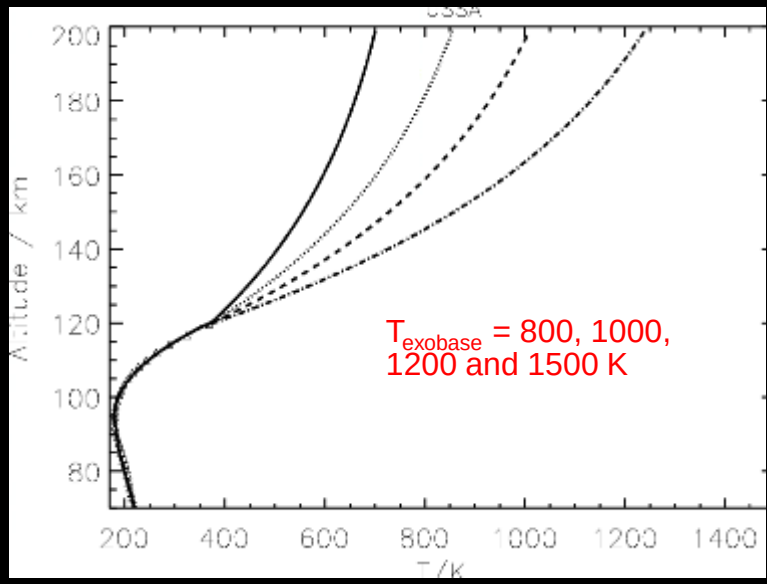
Matt Griffith (Bath)

Dynamical Stability – Basic states

- Try stripped down dynamics only tests
  - Impose climatological T structure
  - Clears out unidentified problems with parametrization schemes (eg gravity waves, diffusion, even convection)
- Builds on well used Held-Suarez tests – relax to Lin-Williamson basic state up to m/pause (radiative timescales)
- Add tidally-locked state for thermosphere – in development – but already applied to exoplanets! (eg Mayne et al, 2014)



Lin-Williamson (Jan)

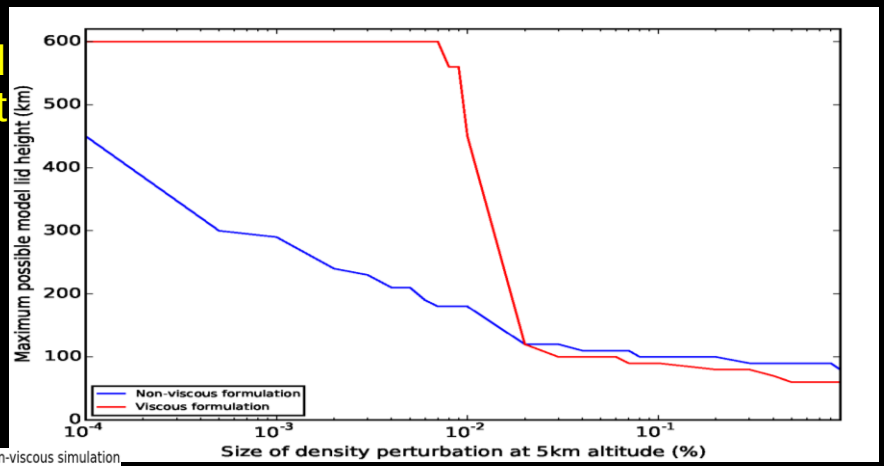


•For "full" UM – relaxation to give realistic basic state while awaiting radiation / chemistry devs (eg in SWAMI)
•Global mean T based on USSA/CIRA and asymptotic relaxation to specified exobase T
•Follows nudging approach (eg Telford et al, 2008)

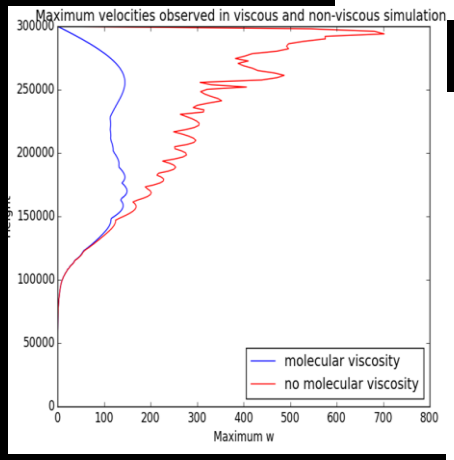
Dynamical stability high higher up - damping via molecular viscosity

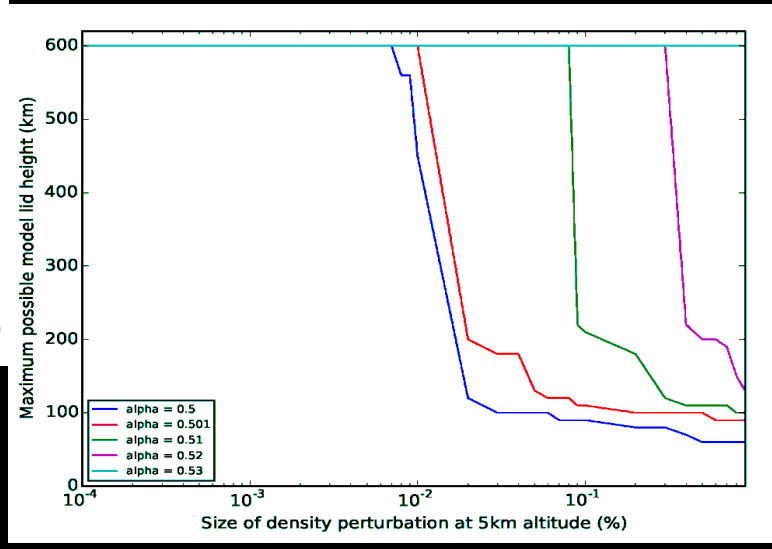
Acoustic waves most challenging to model (fast, rapid amplitude growth, how to represent dissipation?) - but can be important in geomagnetic storms (eg Deng et al)

- Initial simulations with acoustic waves not stable above ~100-120 km (unless amplitude unrealistically small)
- Molecular viscosity is realistic wave damping mechanism important >~ 130 km (t/scale < wave growth t/scale)
- Addition of molecular viscosity into solver (plus use of α≥0.52) appears to decrease wave amplitude in a realistic manner and lead to more stable simulations



Realistic pertbns O(0.01-0.1%)



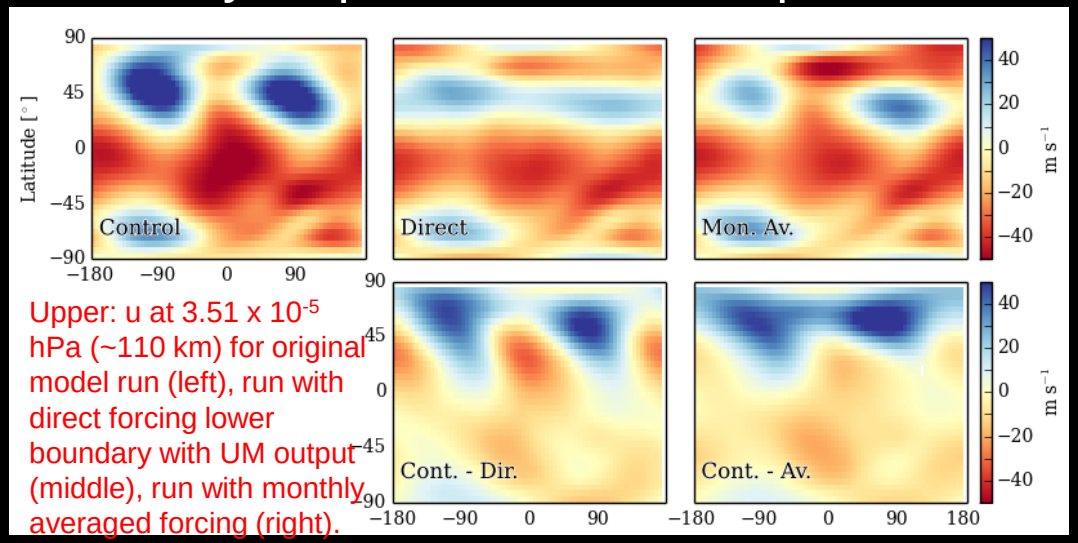


Dan Griffin and John Thuburn: Numerical Effects on Vertical Wave Propagation in Atmospheric Models. QJRMS in prep.

What about the ionosphere?

- For now, couple extended UM and TIEGCM
  - Global 3-D physics-based model of thermo/ionosphere (~97 - ~600 km). **Used at Met Office in thermosphere DA and ionosphere nowcasts**
  - Provides contribution to MLT budget via Joule heating (collisions between ions and neutral gases)
  - Electric field model required – currently empirical, based on Kp or solar wind at high latitudes)

Coupling extended UM with TIEGCM (direct or "nudging") already coded



Upper: u at 3.51 x 10^{-5} hPa (~110 km) for original model run (left), run with direct forcing lower boundary with UM output (middle), run with monthly averaged forcing (right).

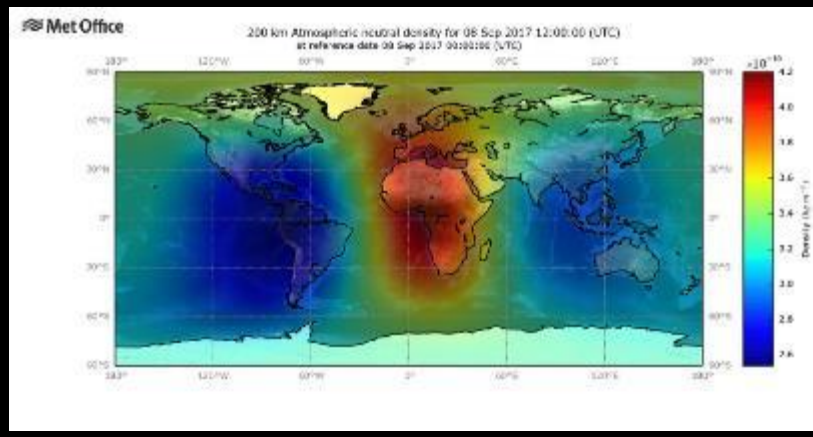
New developments:

- Improved JH and E field model
- Ionospheric DA and low level coupling

SWAMI

New Horizon 2020 project (Jan 2018 – Dec 2020)

- Met Office aims
  - Add new radiation schemes to UM
  - Build and test (+ dynamics and chemistry changes) => stable, validated Extended UM
- Blend with DTM => “whole atmosphere” model with quick use option for satellite launch and re-entry
- Driven by higher cadence Kp nowcasts & improved Kp forecasts



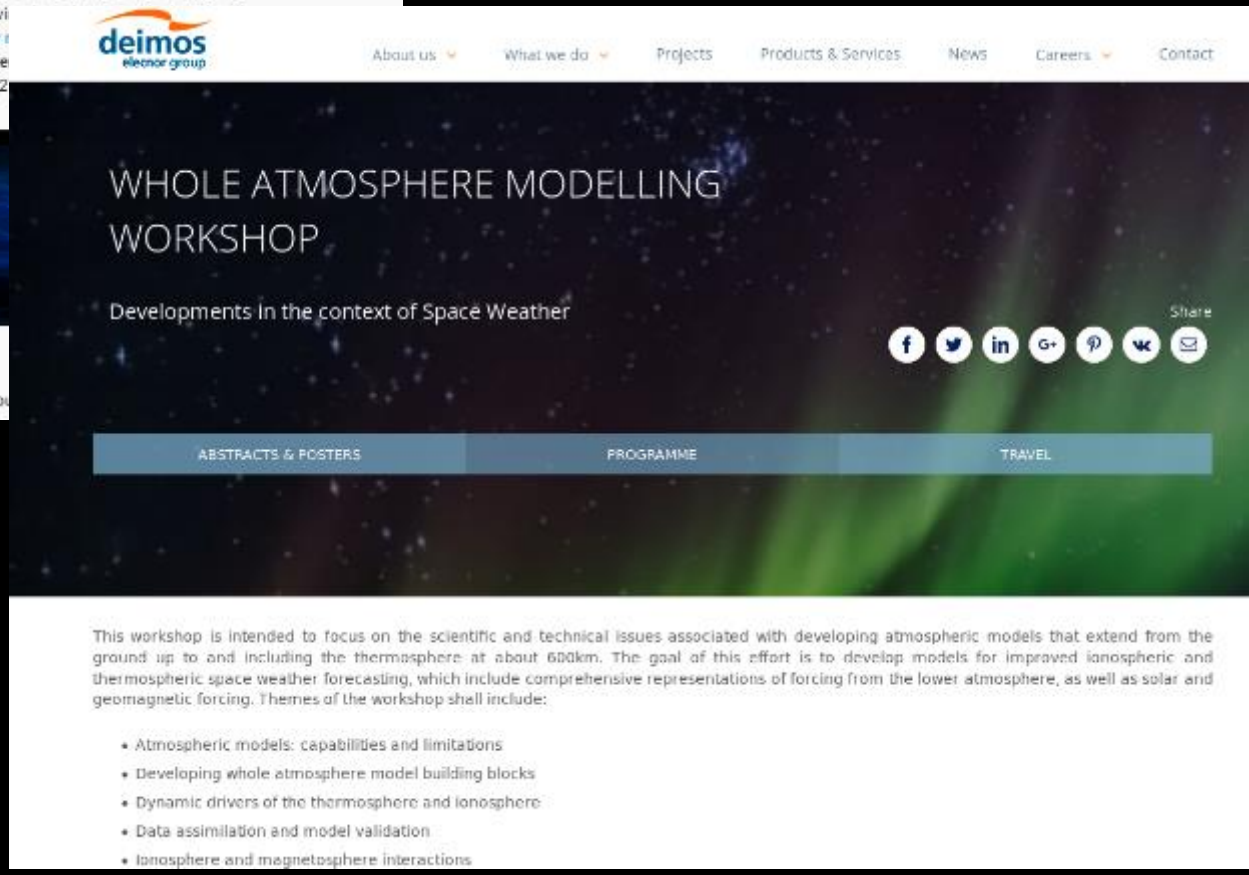
Conclusions

- Whole Atmosphere UM important part of coupled Sun to Earth system:
  - better lower / upper atmosphere coupling => improved thermosphere / ionosphere
- Initial focus on Extended UM:
  - Range of projects – dynamics, chemistry and radiation, coupled UM / TIEGCM
  - SWAMI provides resources and focus leading to 1st stable, verified Extended UM version
- Pathway to Whole Atmosphere (full thermosphere / ionosphere) UM and coupled S2E modelling system.

Come and join us!

Extended UM Slack group

(Met Office, Bath, Exeter, Leeds, UCL, Lancaster, B'ham..)



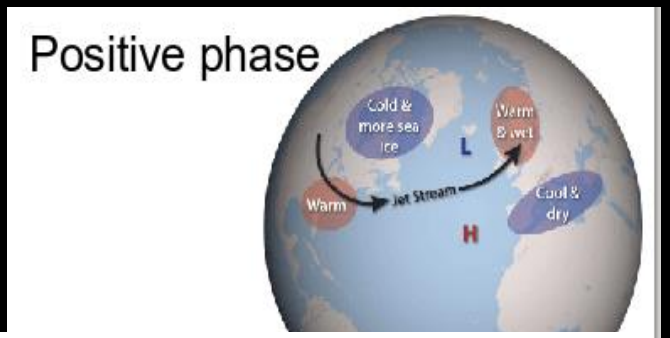
WA Modelling Workshop: Madrid, 13-15/06/18

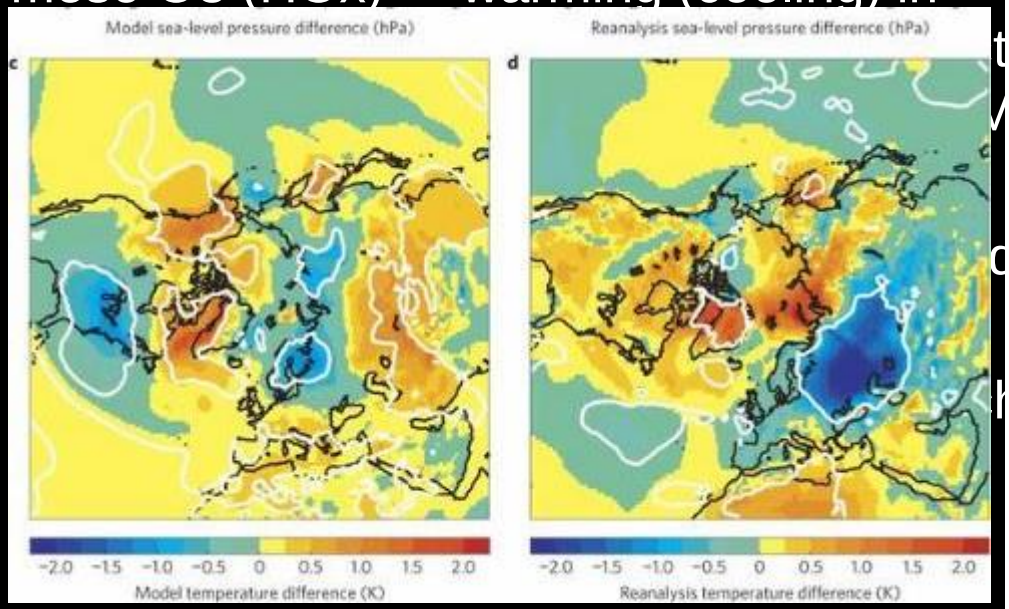
http://www.elecnor-deimos.com/wam-workshop-2018/

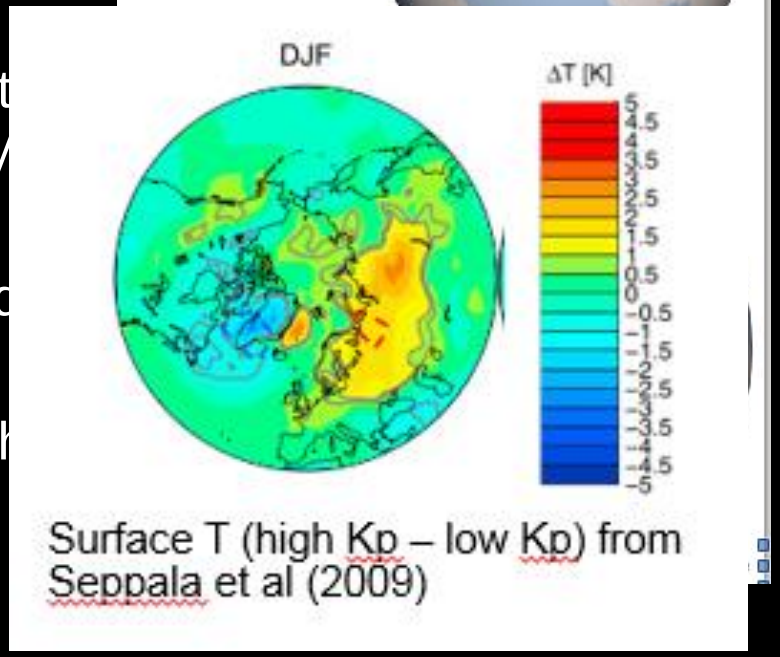
Extra slides

Motivation: Impact on tropospheric climate & seasonal forecasts?

- Solar cycle in UV => increased heating via o3 (at solar max) =>stronger meridional T gradient and stronger polar vortex
- EPP reduces strat O3 (NOx + t/port) and meso O3 (HOx) -> warming (cooling) in







Solar min – Solar max for near-surface temperature for UM (left) ERA (right) Ineson et al (2011)