Thermosphere-ionosphere integration work with WACCM-X at the Naval Research Laboratory (NRL)

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+ Bottom-side Ionosphere Weather Modeling Team at NRL

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- H.-L. Liu and J. McInerney (HAO)

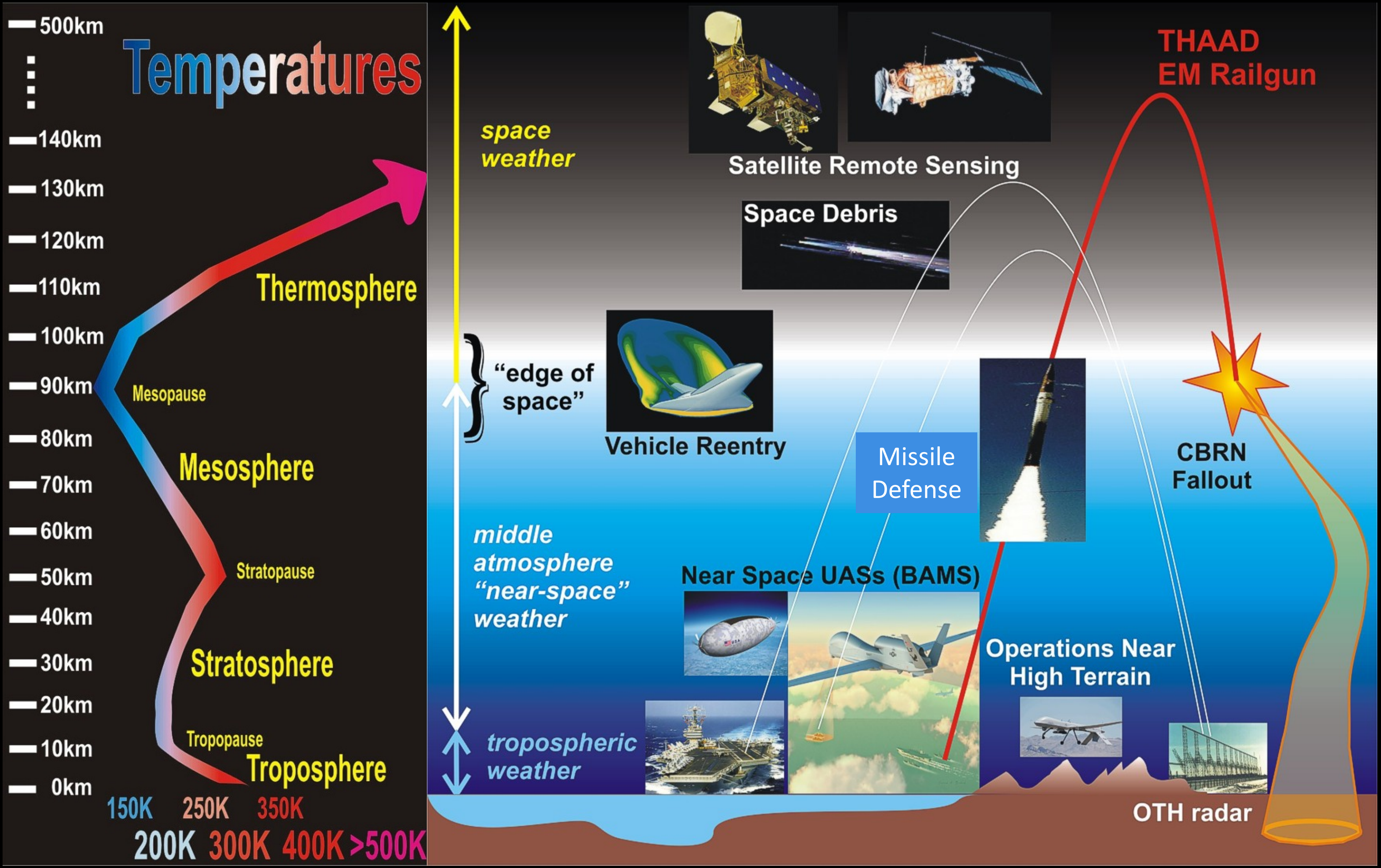
Outline:

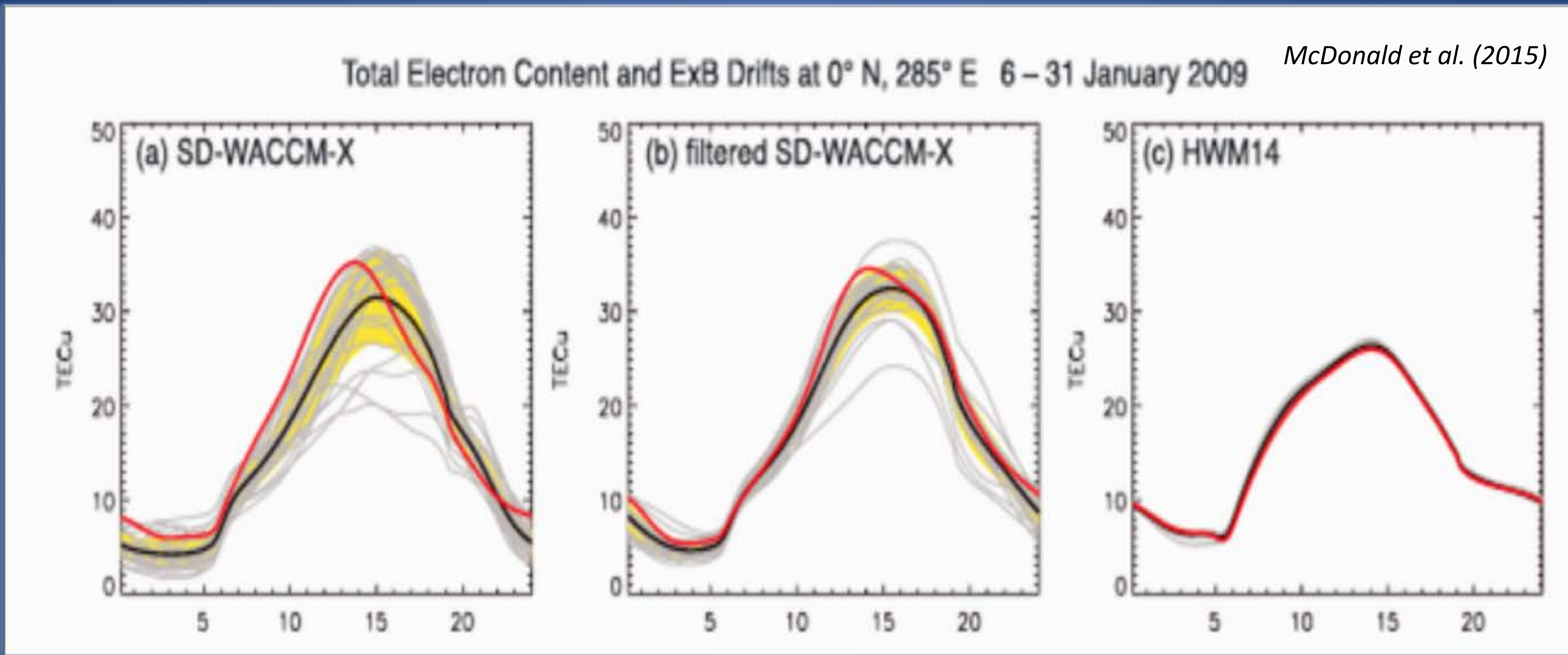
- Motivation
- Technical Approach
- Milestones
- To-do list

Overarching Goals

- The goal is to generate weather forecasts of the ionosphere to investigate:
  - The dynamics that reaches the lower thermosphere and couples the thermosphere with the ionosphere
  - The role of composition of the MLT in changing the characteristics of the D- and E-regions
  - The benefit of including weather at increasing resolution to improve HF radio-wave propagation.

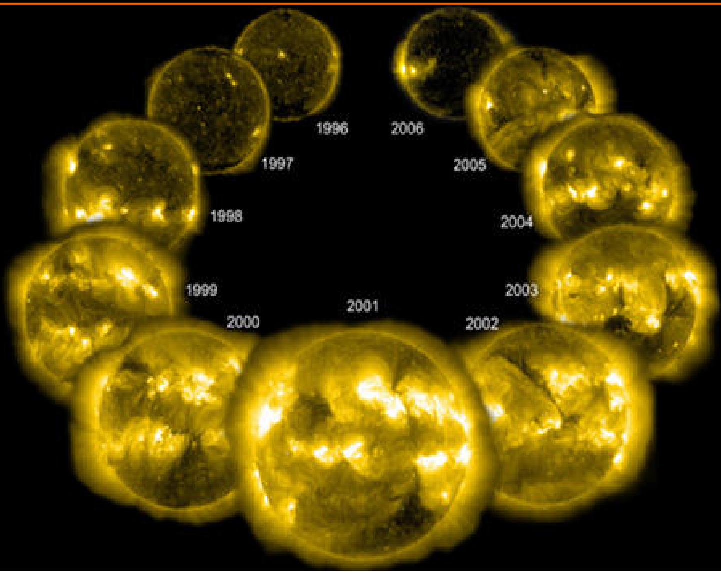
Navy Extended Operational Environment




McDonald et al. (2015)
Total Electron Content and ExB Drifts at 0° N, 285° E 6 – 31 January 2009
(a) SD-WACCM-X
(b) filtered SD-WACCM-X
(c) HWM14
TECu
0
10
20
30
40
50
5
10
15
20

Motivation

Variability of Ionospheric Weather



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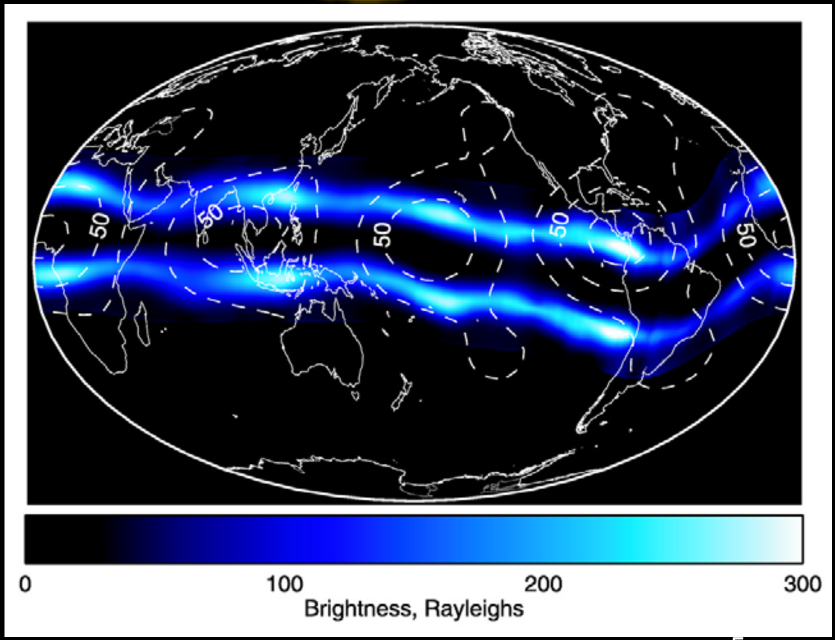
- Solar radiation is the primary driver of ionospheric variation

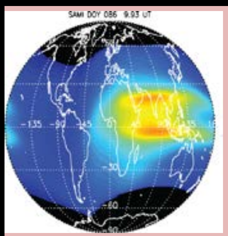
- Lower-atmospheric weather accounts for up to 40% of the day-to-day variability observed in the ionosphere



Immel et al., 2006.

Bottom-side Ionosphere Weather Modeling

How do environmental conditions (chemistry, solar drivers, and meteorology) affect radio-frequency wave propagation?



SAMI3

Physics-based model of the ionosphere.
Dynamics and chemistry of 7 ion species from 85 km to > 20,000 km

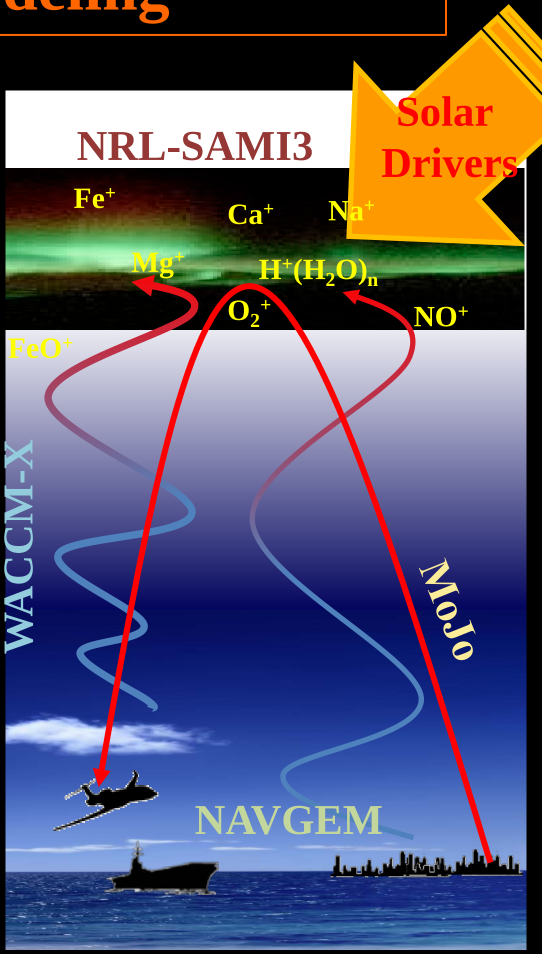
Full Coupling

WACCM – Whole Atmosphere Community Climate Model

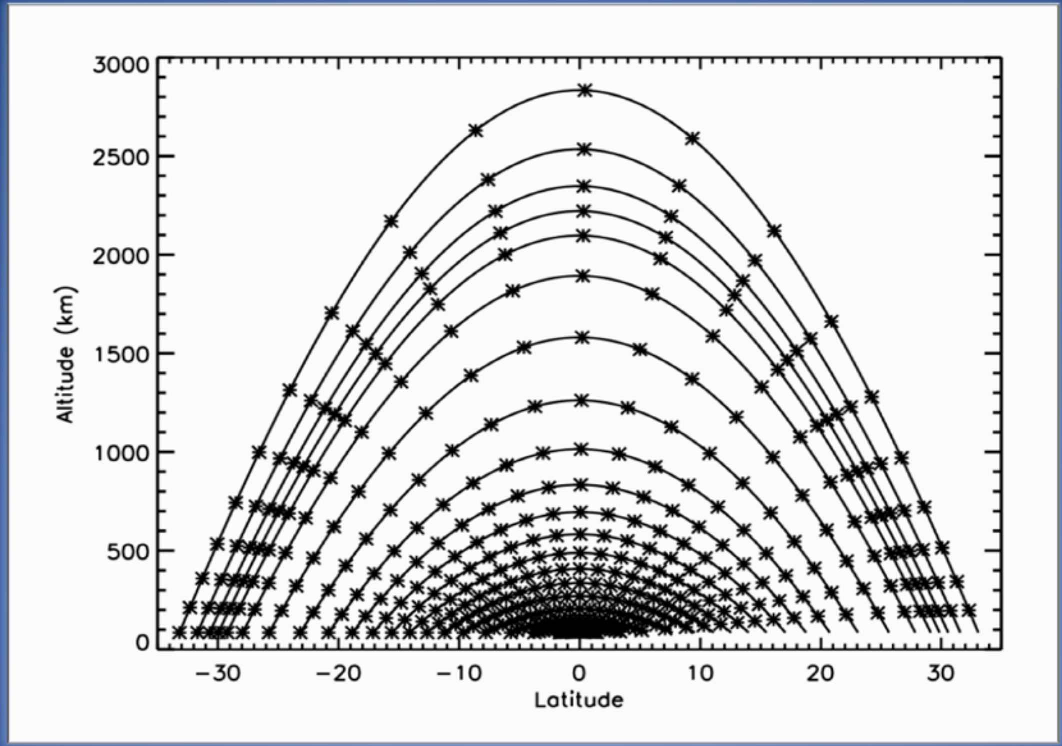
Global climate-chemistry model
Solves dynamics, physics and chemistry globally from ground to ~500 km

NAVGEM – Navy Global Environmental Model

NAVGEM: Operational Navy Analysis
(ground to ~92 km)
4DVAR Hourly data assimilation products



MoJo
Radio-wave propagation code.
Includes updated dispersion and attenuation.
Capable of using observations & model data.
Produces ionograms (WSBI) for verification.



Technical Approach

NRL SAMI3

Time Management

Photochemistry

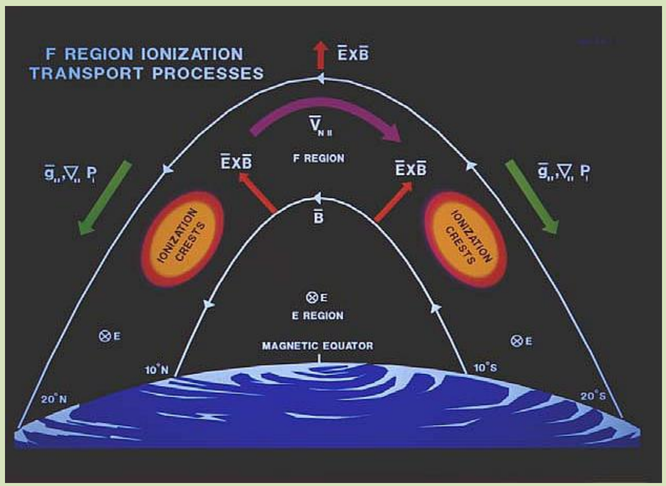
Parallel Transport
(motion along **B**)
$t_0 + \Delta t \rightarrow t^*$

Electric Potential Solver
($\nabla \cdot \boldsymbol{J}=0$)

Perpendicular Transport
$t^* + \Delta t \rightarrow t_1$

I/O:
N_i, N_e, T_i, T_e
Ion V (δV)
Heating (δT)

Update Neutrals



External Drivers

Solar Irradiances
(NRLSSI)

Neutrals
(from atmospheric meteorology or climatology)

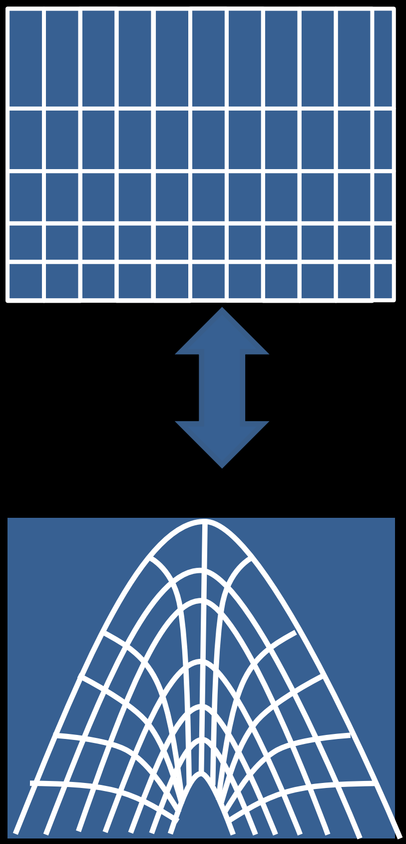
Solar params
(F10.7, Ap)

Regridding using ESMF

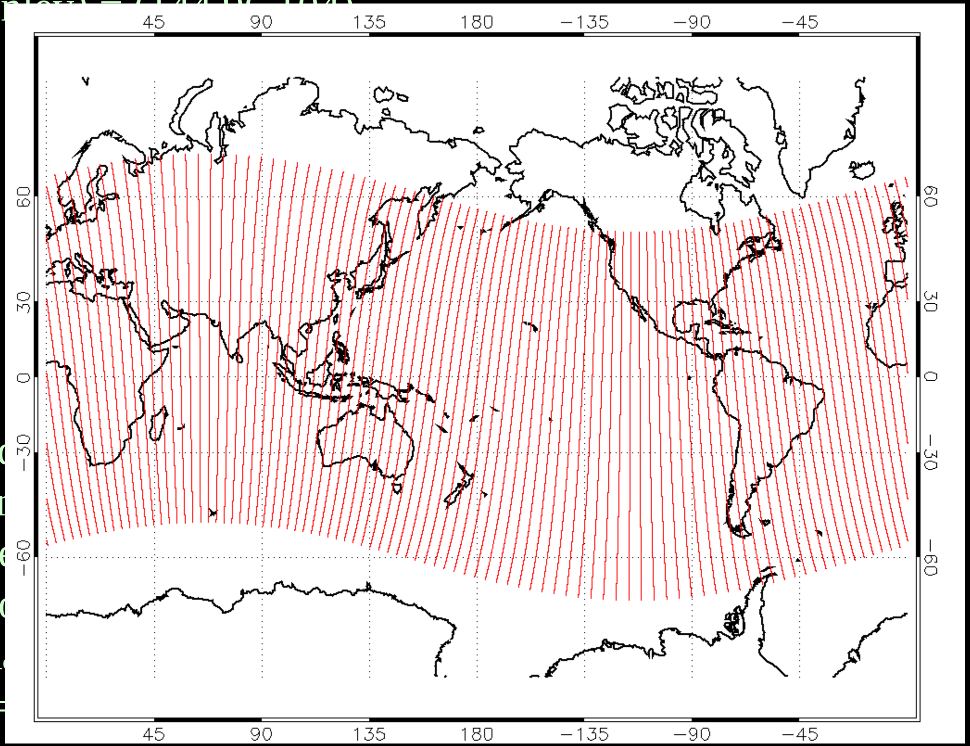
We are taking advantage of the ESMF toolkit to handle regridding between the WACCM-X and SAMI3 models.

Sponsored by DoD,
NASA, NSF and NOAA

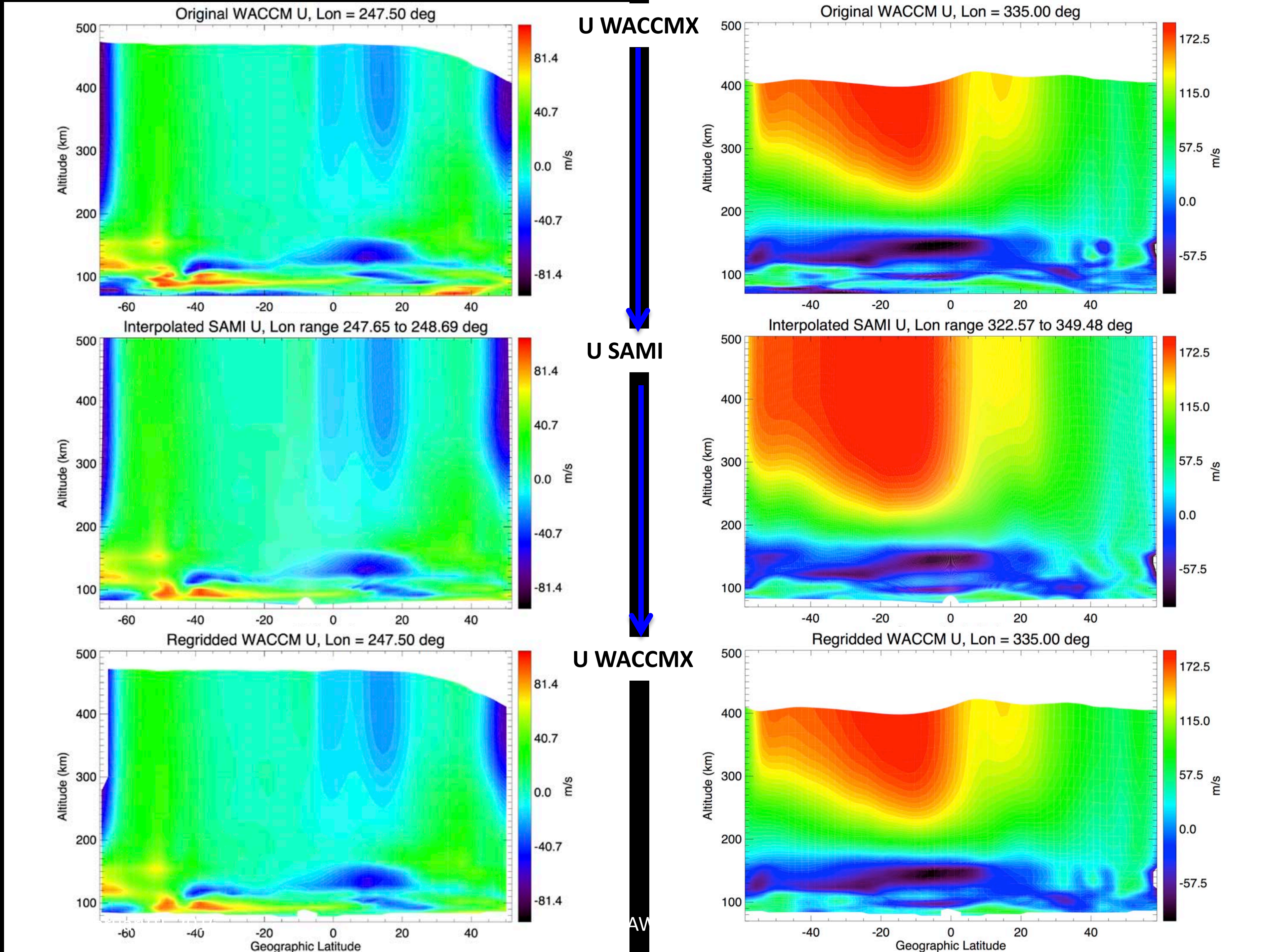
WACCM-X grid



Pressure grid
1.9° ×2.5°
(nlon, nlat, nlev) = (144,96,104)

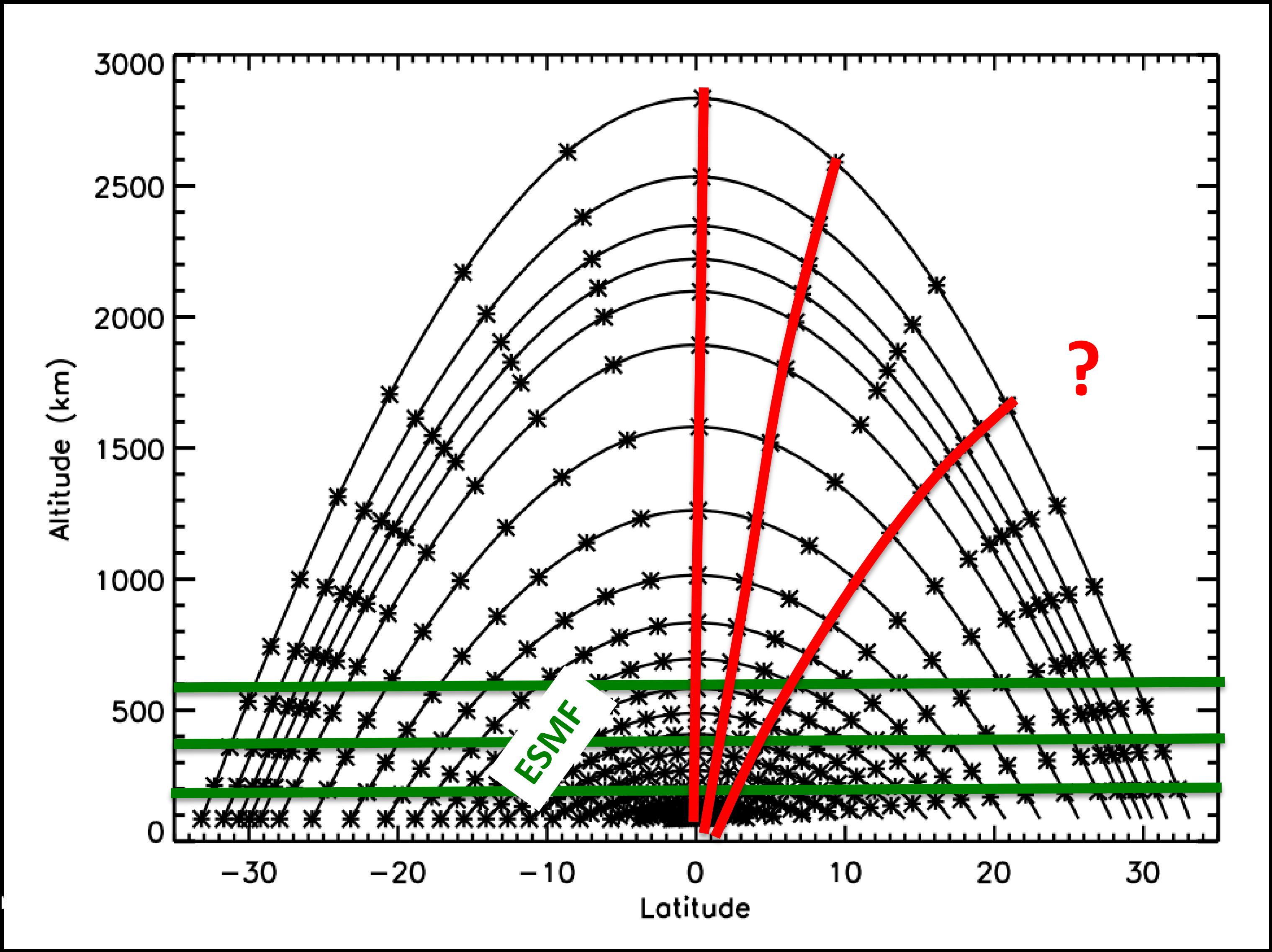


Offset, tilted
Non-uniforn
Nf = # of fie
Nz = # of p
Nl = # of m
(nz, nf, nl) =



U WACCMX
U SAMI
U WACCMX
Original WACCM U, Lon = 247.50 deg
Interpolated SAMI U, Lon range 247.65 to 248.69 deg
Regridded WACCM U, Lon = 247.50 deg
Original WACCM U, Lon = 335.00 deg
Interpolated SAMI U, Lon range 322.57 to 349.48 deg
Regridded WACCM U, Lon = 335.00 deg
Altitude (km)
Geographic Latitude
m/s
500
400
300
200
100
-60
-40
-20
0
20
40
81.4
40.7
0.0
-40.7
-81.4
172.5
115.0
57.5
0.0
-57.5

A Slight complication



Solution: An analytical formulation (consisting of a horizontal projection and a vertical extension) for temperature, constituent densities and winds: based on diffusive equilibrium profiles and an orthonormal set of basis functions. Algorithm developed following *Drob et al.* (2003) for the NRL/G2S model.

Horizontal Projection

We seek a decomposition of temperature, constituents and winds in terms of spherical harmonics:

$$T(\lambda,\theta) = \sum_{n=0}^{N} \sum_{m=-n}^{+n} \mathrm{T}_{m,n} \, Y_{m,n}(\lambda,\theta)$$

where λ is the longitude and θ is the co-latitude.

$$Y_{m,n}(\lambda,\theta) = \; Y_{m,n}^{0} e^{im\lambda} \mathcal{L}_{m,n}(\cos(\theta))$$

Vertical Extension: Bates profiles

Assuming diffusive equilibrium, Bates vertical profiles describe the equilibrium temperature and densities. For temperature:

$$T(\zeta) = T_{ex} - (T_{ex} - T_0)e^{-\sigma(\zeta - \zeta_0)}$$

where T_{ex} is the exospheric temperature, T_0 is the temperature at a reference level ζ_0.

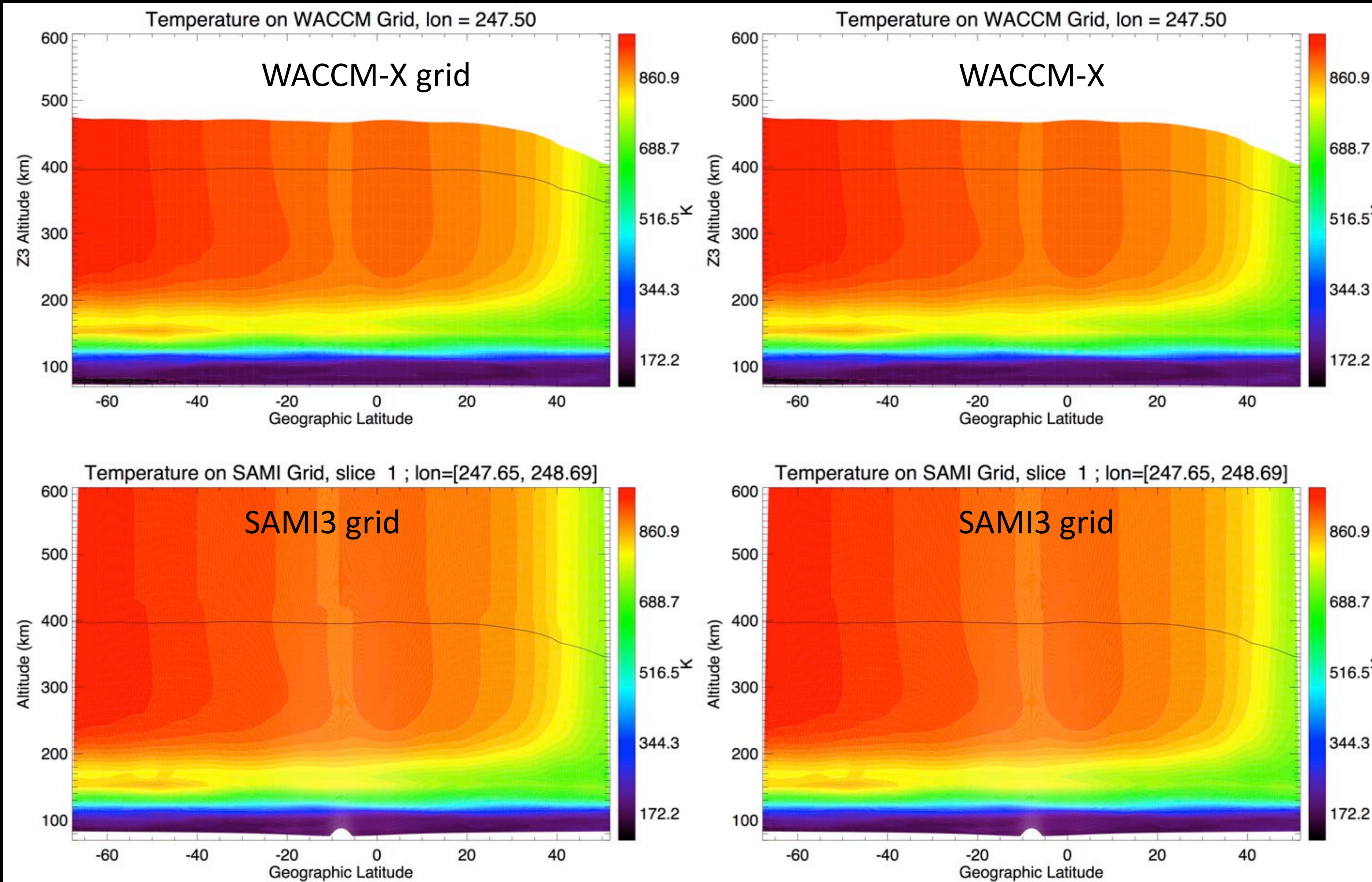
For densities (with n_{x0} a reference density profile):

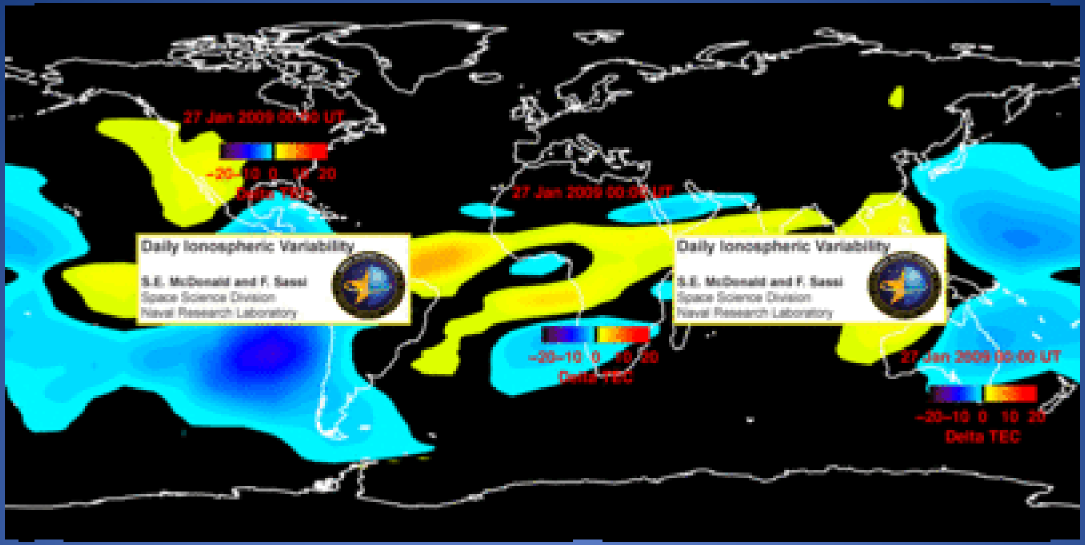
$$n_x(\zeta) = n_{x0}\left[{}^{T_0}/_{T(\zeta)}\right]^{1+\gamma} e^{-\sigma\gamma(\zeta - \zeta_0)}$$

with: $$\gamma = \frac{m_x g}{\sigma k_b T_{ex}} \qquad \sigma = \frac{(T_z)|_{\zeta_0}}{T_{ex} - T_0}$$

Zonal and meridional winds are assumed constant in altitude above the exobase.

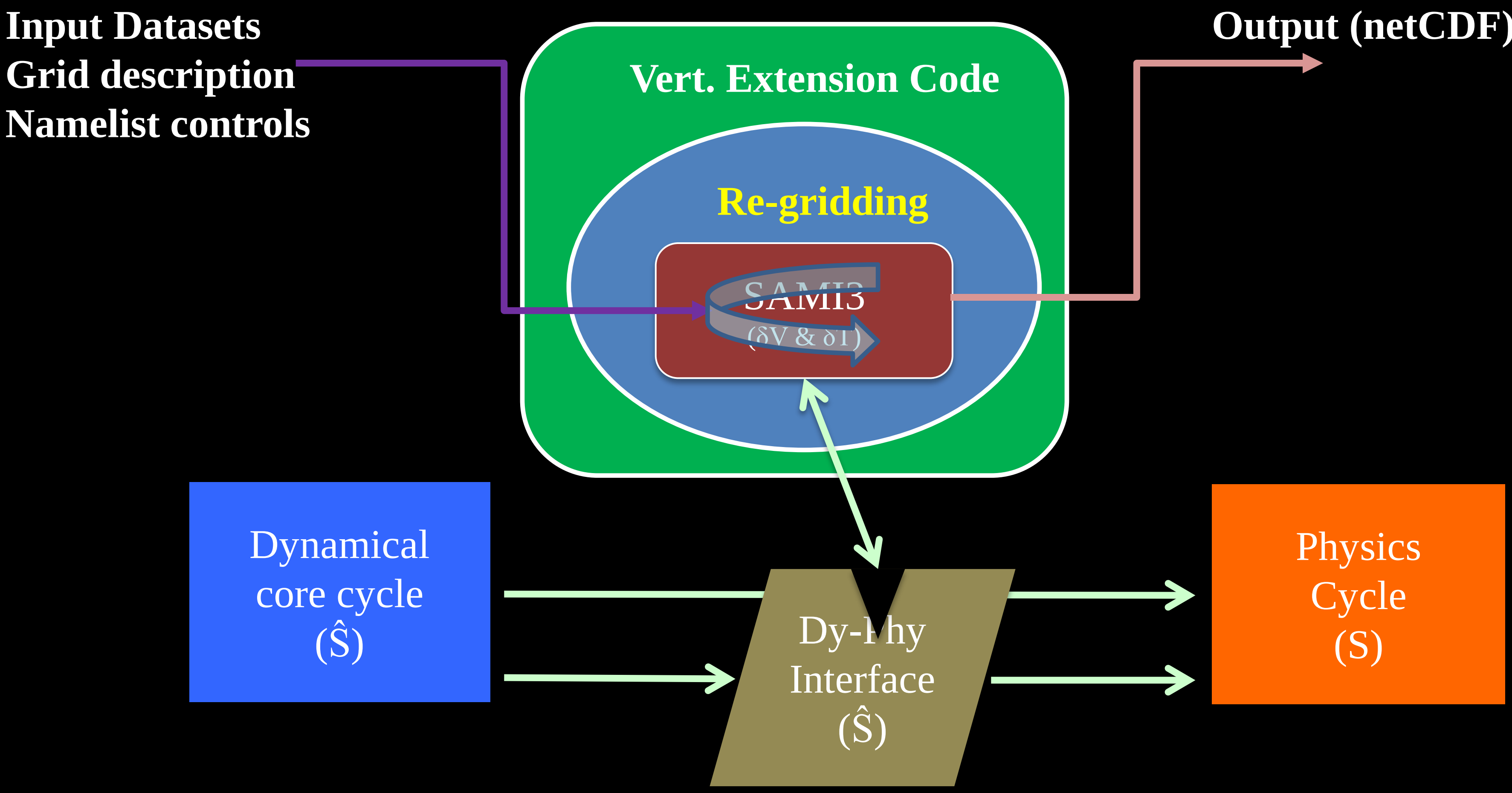
N = 15 N = 31


Temperature on WACCM Grid, lon = 247.50
WACCM-X grid
WACCM-X
Z3 Altitude (km)
Geographic Latitude
Temperature on SAMI Grid, slice 1 ; lon=[247.65, 248.69]
SAMI3 grid
Altitude (km)
K
860.9
688.7
516.5
344.3
172.2
600
500
400
300
200
100
-60
-40
-20
0
20
40


27 Jan 2009 00:00 UT
−20 −10 0 10 20
Delta TEC
Daily Ionospheric Variability
S.E. McDonald and F. Sassi
Space Science Division
Naval Research Laboratory

Milestones

WACCM-X


Input Datasets
Grid description
Namelist controls
Vert. Extension Code
Output (netCDF)
Re-gridding
SAMI3
(δV & δT)
Dynamical
core cycle
(Ŝ)
Dy-Phy
Interface
(Ŝ)
Physics
Cycle
(S)

Milestones

- ✓ Regridding: ESMF
- ✓ Vertical extension: Analytical formulation
- ✓ Optimization: MPI (longitude) & OpenMP (field-line transport)
- ✓ Restart facility
- ✓ netCDF output
- ➢ namelist controls
- ❑ Ions
- One-way coupling (WACCM-X → ionosphere) is completed.

To-do List

TBD in FY16

- Two-way coupling:
  - Ion drag (momentum tendency)
  - Electron temperature heating (temperature tendency)

Summary & Final Thoughts

- NRL /Space Science Division is coupling the WACCM-X thermosphere with the ionosphere of the NRL/SAMI3 model:
  - Scientific challenges: Coupling the thermosphere up to the exobase with the ionosphere to 8 R_e
  - Computational challenges: Achieving code efficiency and accuracy
  - Operational challenges: Atmospheric weather effects on the D-region absorption and E-regions HF transmission.
- One-way coupling is close to completion and includes:
  - Full re-gridding between the WACCM grid and the field-lines grid.
  - Analytical formulation of vertical extension for neutrals above the WACCM-X lid
  - NetCDF output and namelist controls
  - Initial MPI and OpenMP implementations, but more work needs to be done
  - An exhaustive comparison of the SAMI3 ions to WACCM's has not been done yet.
- A two-way coupling is next and should (!) be relatively straightforward.