Development of NCEP FV3 WAM for UFS Space Weather Applications

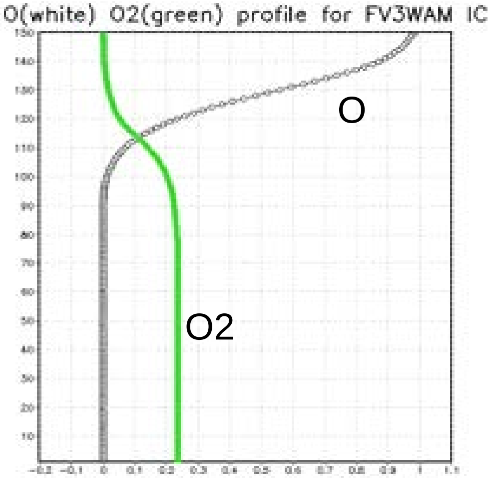
Hann-Ming Henry Juang[1], Sajal Kar[1,2], Vijay Tallapragada[1], Adam Kubaryk[3,4], Tim Fuller-Rowell[3,4], Terry Onsager [4]

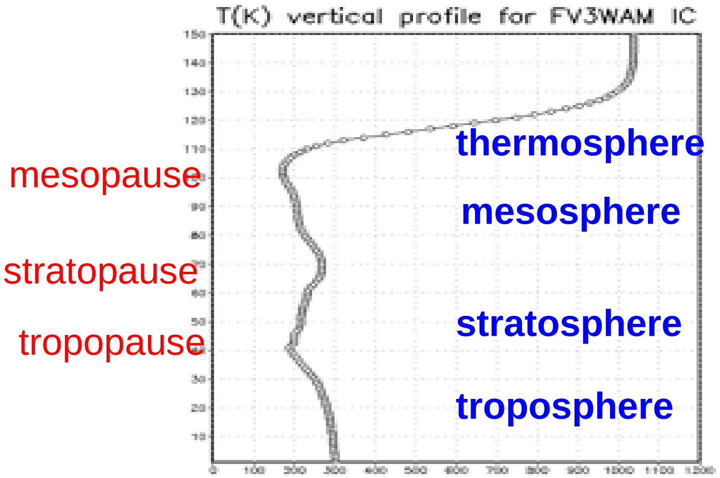
1 Environmental Modeling Center, NCEP, NOAA
2 I. M. Systems Group Inc.
3 CU/CIRES
4 Space Weather Prediction Center, NCEP, NOAA

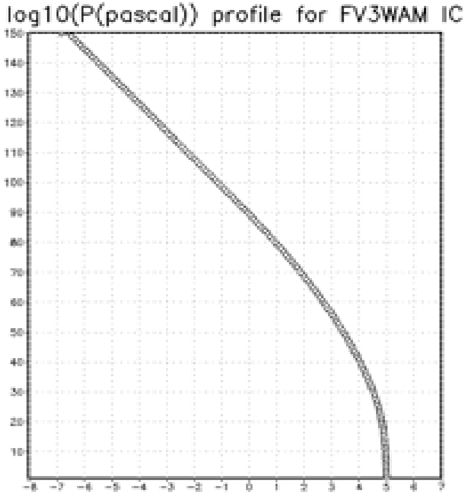
UFS User's Workshop 2020

Background

- NCEP operational atmospheric model, such as GFS, used for weather and climate predictions has a vertical domain covering troposphere, stratosphere and possibly some lower mesosphere with model top around 60 ~ 80 km in height.
- The space weather models cover the thermosphere, ionosphere, plasmasphere, and above, where plasma and electrodynamics are active. So the vertical domain may range from ~100 km to ~10,000 km in height.
- To couple with space weather models, we have to extend atmospheric model top as high as possible to cover space weather model domain.







Model Initial condition started from

No wind, mean standard temperature

Mean gas variation of O and O2

top pressure is about 1.E-7 Pa

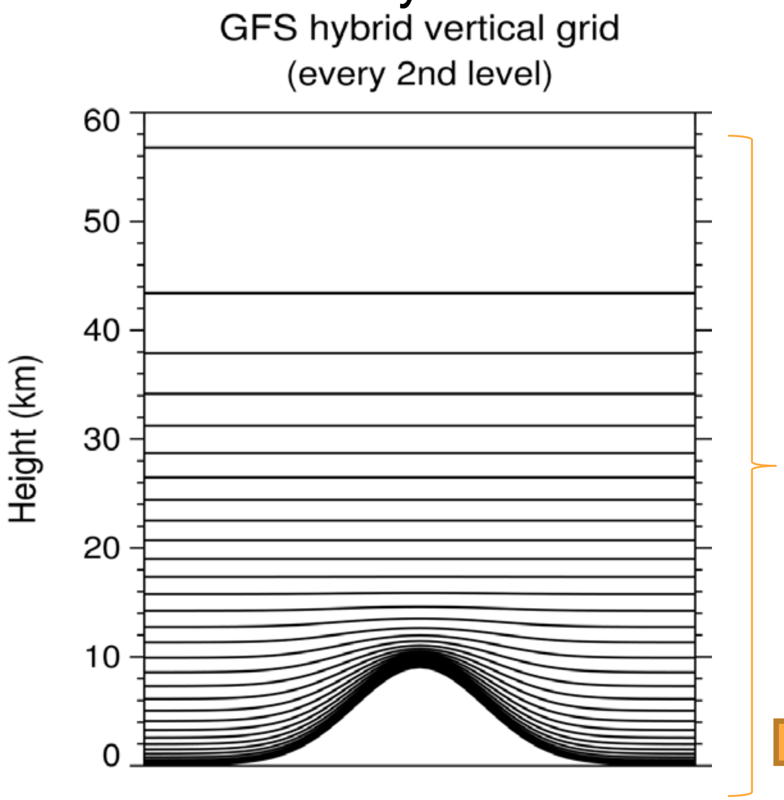
close to 500~600 km

Build a WAM

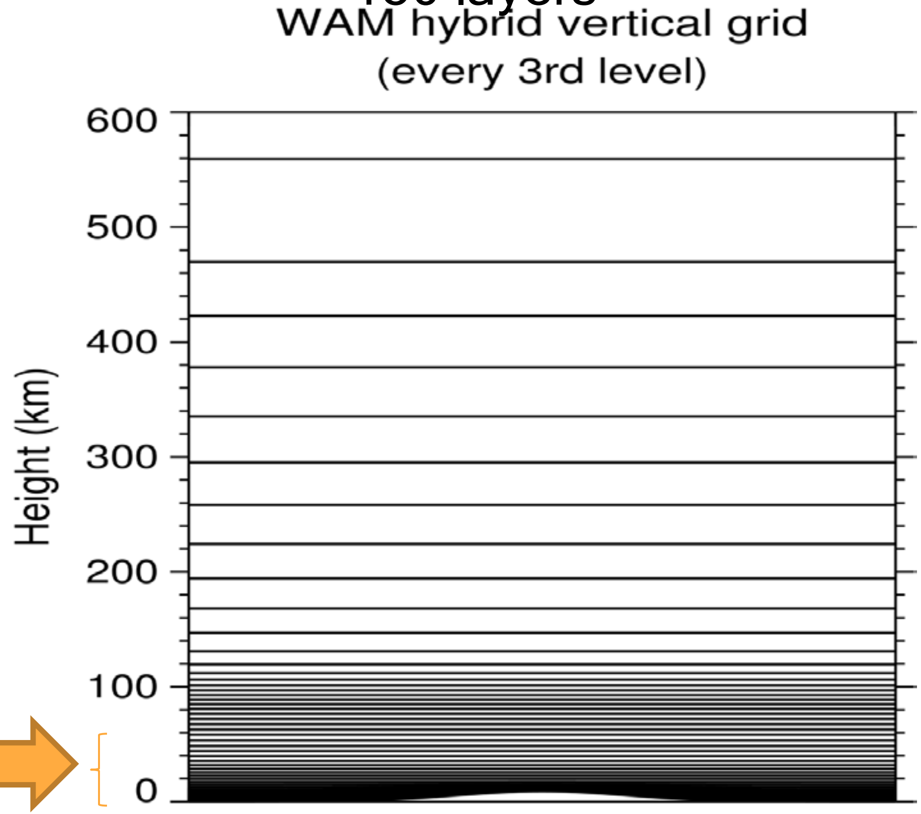
- NCEP has a WAM (Whole-Atmosphere Model) developed in EMC.
- It is based on enthalpy version of NCEP Global Spectral Model (GSM) in generalized vertical coordinates (Juang 2011), called GSMWAM.
- Enthalpy as thermodynamics variable plays a major role to take care of the variation of atmospheric constituents covering troposphere, stratosphere, mesosphere, and up to the thermosphere.
- GSMWAM has a molecular diffusion which plays another major role to stabilize upper-layer disturbances to have longer-time integrations.
- Also GSMWAM has a mesosphere-thermosphere physics package to extend the physics of GSM.

Operational GFS vs WAM-GSM

64 layers



150 layers



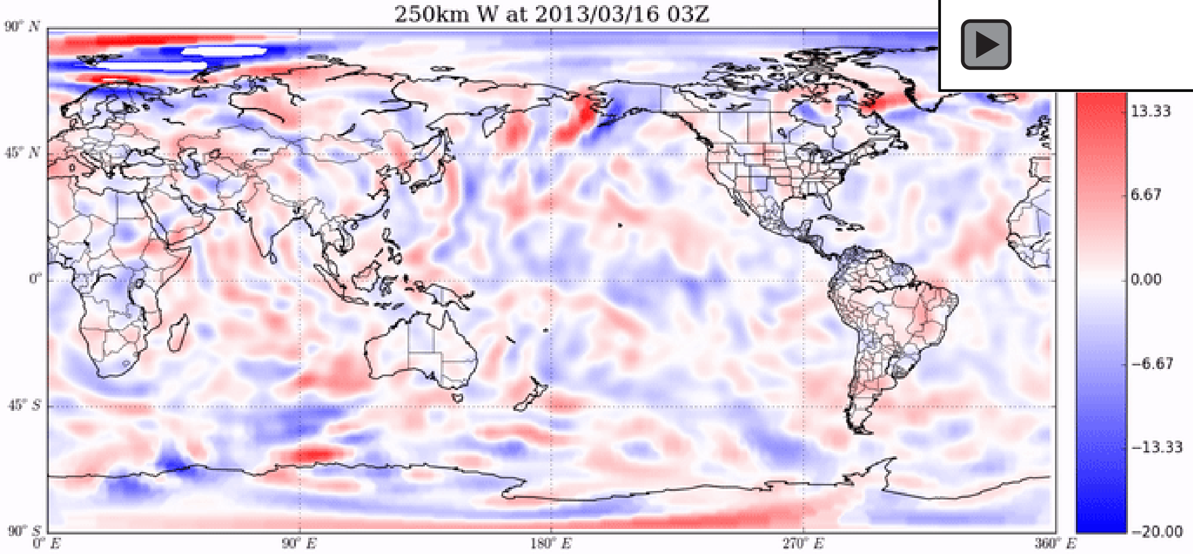
Operational GSM

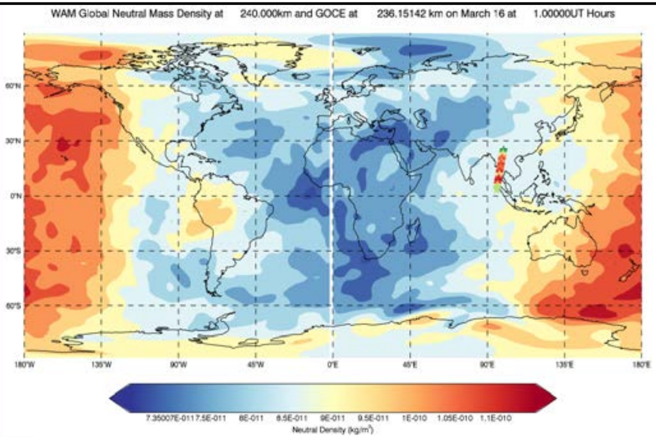
	R	Cp
O3	173.225	820.239
All other dry gases	286.05	1004.60
Water vapor	461.50	1846.00

WAM

	R	Cp
O	519.674	1299.18
O2	259.837	918.096
O3	173.225	820.239
All other dry gases	296.803	1039.64
Water vapor	461.50	1846.00

Structure and variability of vertical wind, temperature, and density at 250 km altitude in response to waves from lower atmosphere (courtesy: WAM-IPE Team)





Replicate GSMWAM in FV3

- FV3 is now NCEP’s operational atmospheric model, and its vertical coverage is the same as GSM including troposphere and stratosphere. And it uses standard atmospheric constituents without consideration of their variations as shown in thermosphere.
- Thus, the same work as done for GSMWAM should be repeated in FV3 to build a FV3WAM. The work details include; extend model top domain to cover thermosphere, consider gas constituents variation, and add molecular diffusion to have stable time integration in FV3WAM.

Extend FV3 model top

- First we made FV3 run in an adiabatic mode without model physics.
- Then extended model top to the thermosphere, with 150 layers.
- Turned on model physics with radiation option to use mean values of radiation computation from layer 90 to layer 150.
- Required very strong Rayleigh damping for numerical instability, which drastically reduced wind strength, not realistic.

Potential Temperature instead of enthalpy

- FV3 dynamics is using virtual potential temperature as a prognostic thermodynamic variable, unlike the GSMWAM using enthalpy. It may not be easy to recode FV3 in term of enthalpy, which will require lots of model numerical technique developments.
- So instead of recoding FV3 thermodynamics system as in GSMWAM with enthalpy as prognostic variable, we implemented a multi-gas option directly in the thermodynamics system to have all gas related parameters, as R and Cp etc.

$$p = \rho R T = \rho R_d T_v \ ; \qquad T_v = \frac{\sum_{i=0}^{N} q_i R_i}{R_d} T \ ; \qquad \theta_v = T_v \left(\frac{p}{p_0} \right)^{-\frac{R}{C_P}}$$

Molecular Diffusion

- In GSMWAM, we have used implicit molecular diffusion to smooth thermosphere disturbances for stable time integration.
- The molecular diffusion coefficients; viscosity for momentum, conductivity for temperature, and diffusivity for tracers, are very large in the thermosphere.
- Use of implicit molecular diffusion in GSMWAM with large coefficients is possible because GSM is a spectral model. but not in FV3 as it is a grid-point model.
- So we used explicit molecular diffusion with weighting to tune the coefficients.

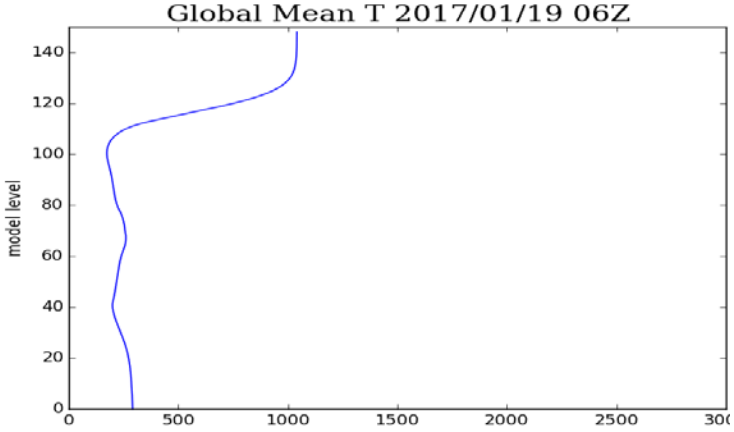
Vertical profiles of molecular diffusion coefficients

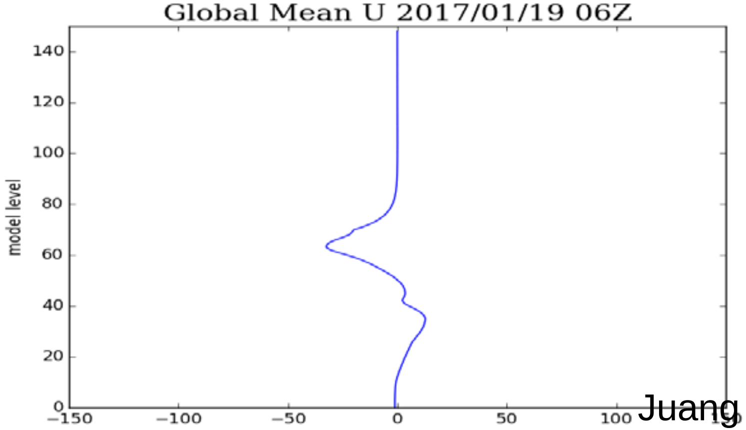
# from top	viscosity	conductivity	diffusivity
1	**4.e7**	**7.e7**	**1.e8**
10	**4.e6**	**7.e6**	**1.e7**
20	**3.e5**	**5.e5**	**8.e5**
30	**1.e4**	**2.e4**	**3.e4**
40	**2.e2**	**3.e2**	**4.e2**
50	**10**	**1.e1**	**1.e1**
70	1.e-1	1.e-1	2.e-1
80	1.e-2	1.e-2	3.e-2
90	1.e-3	1,e-3	4.e-3
100	1.e-4	1.e-4	7.e-4
120			
149	1.e-5	1.e-5	3.e-5

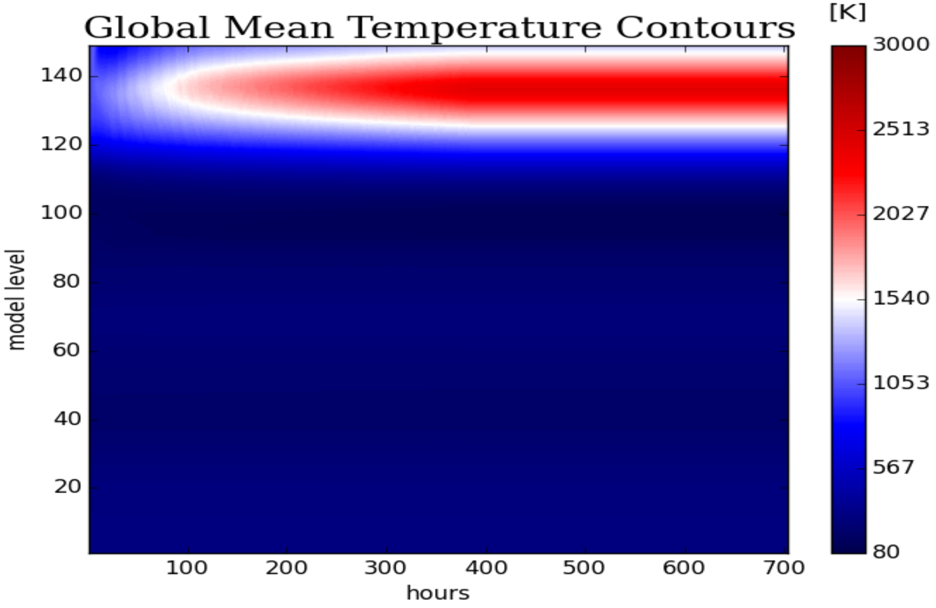
WAM

GFS

C96 FV3 L149 gfs-physics with molecular-diffusion & reduced Rayleigh damping







Juang et al. 2020

Mesosphere-Thermosphere Physics

- The last step of replicate GSMWAN in FV3WAM is to add physics for mesosphere and thermosphere to extend GFS physics.
- We are implementing the package used in GSMWAM called IDEA Physics to FV3 with Interoperable Physics Driver (IPD) and later with CCPP.

Earth radius $a = 6371$ km, $r = a + z$

Shallow atmosphere

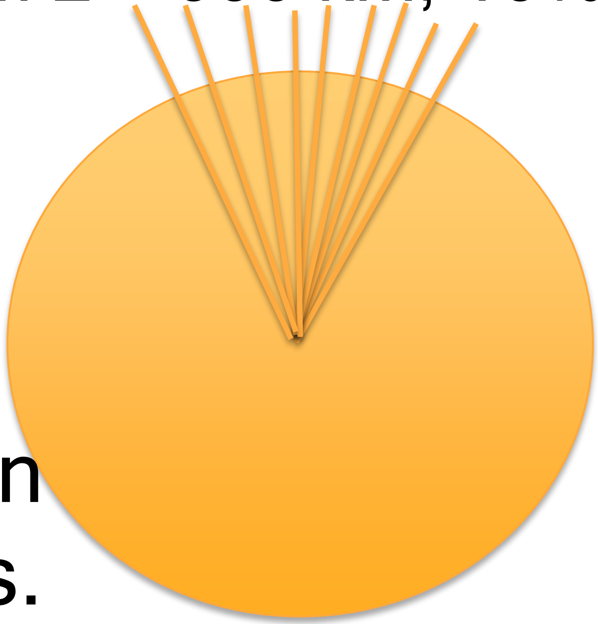
Assumption: $r = a$

Op GFS $z \sim$ 60km, 1% of a

Deep atmosphere

No assumption: $r = a + z$

WAM $z \sim$ 600 km, 10% of a



Most NWP models are based on shallow-atmosphere dynamics.

Deep-Atmosphere Dynamics (DAD)

Approximations: spherical earth & radial variation of gravity

Notice additional Coriolis, metric, and vertical-divergence terms

$$r = a + z$$

$$u = r\cos\phi\frac{d\lambda}{dt}$$

$$\frac{dA}{dt} = \frac{\partial A}{\partial t} + u\frac{\partial A}{r\cos\phi\,\partial\lambda} + v\frac{\partial A}{r\partial\phi} + w\frac{\partial A}{\partial r}$$

$$v = r\frac{d\phi}{dt}$$

$$\frac{du}{dt} - \frac{uv\tan\phi}{r} + \frac{uw}{r} - (2\Omega\sin\phi)v + (2\Omega\cos\phi)w + \frac{1}{\rho}\frac{\partial p}{r\cos\phi\,\partial\lambda} = F_u$$

$$\frac{dv}{dt} + \frac{u^2\tan\phi}{r} + \frac{vw}{r} + (2\Omega\sin\phi)u + \frac{1}{\rho}\frac{\partial p}{r\partial\phi} = F_v$$

$$\frac{dw}{dt} - \frac{u^2+v^2}{r} - (2\Omega\cos\phi)u + \frac{1}{\rho}\frac{\partial p}{\partial r} + g = F_w$$

$$\frac{\partial\rho}{\partial t} + \frac{\partial\rho u}{r\cos\phi\,\partial\lambda} + \frac{\partial\rho v\cos\phi}{r\cos\phi\,\partial\phi} + \frac{\partial\rho r^2 w}{r^2\partial r} = F_\rho$$

Summary

- We have finished the first version of FV3WAM dynamics extending to thermosphere with multi-gas variation in thermodynamics and an explicit molecular diffusion for stable time integrations.
- We are in the process of implementing the mesosphere- and thermosphere- physics within the IPD and CCPP frameworks.
- We are looking for funding supports to implement a deep atmospheric dynamics into FV3WAM and used for all UFS applications.