Extend NCEP FV3 to Cover Thermosphere for Whole Atmospheric Modeling

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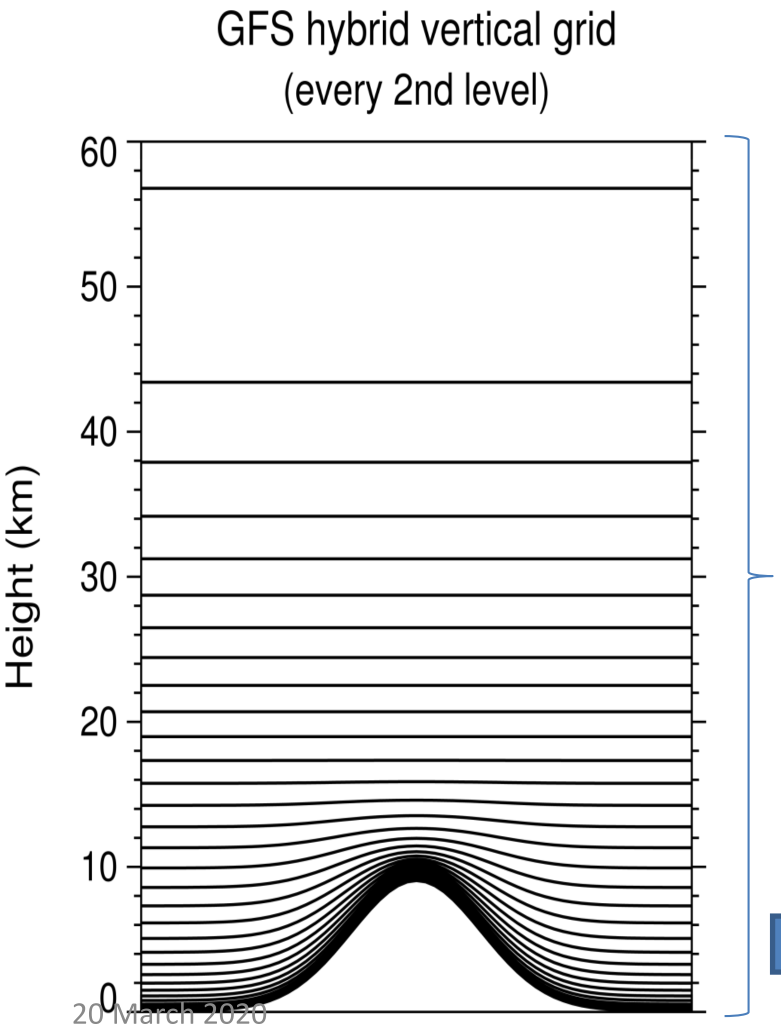
Introduction

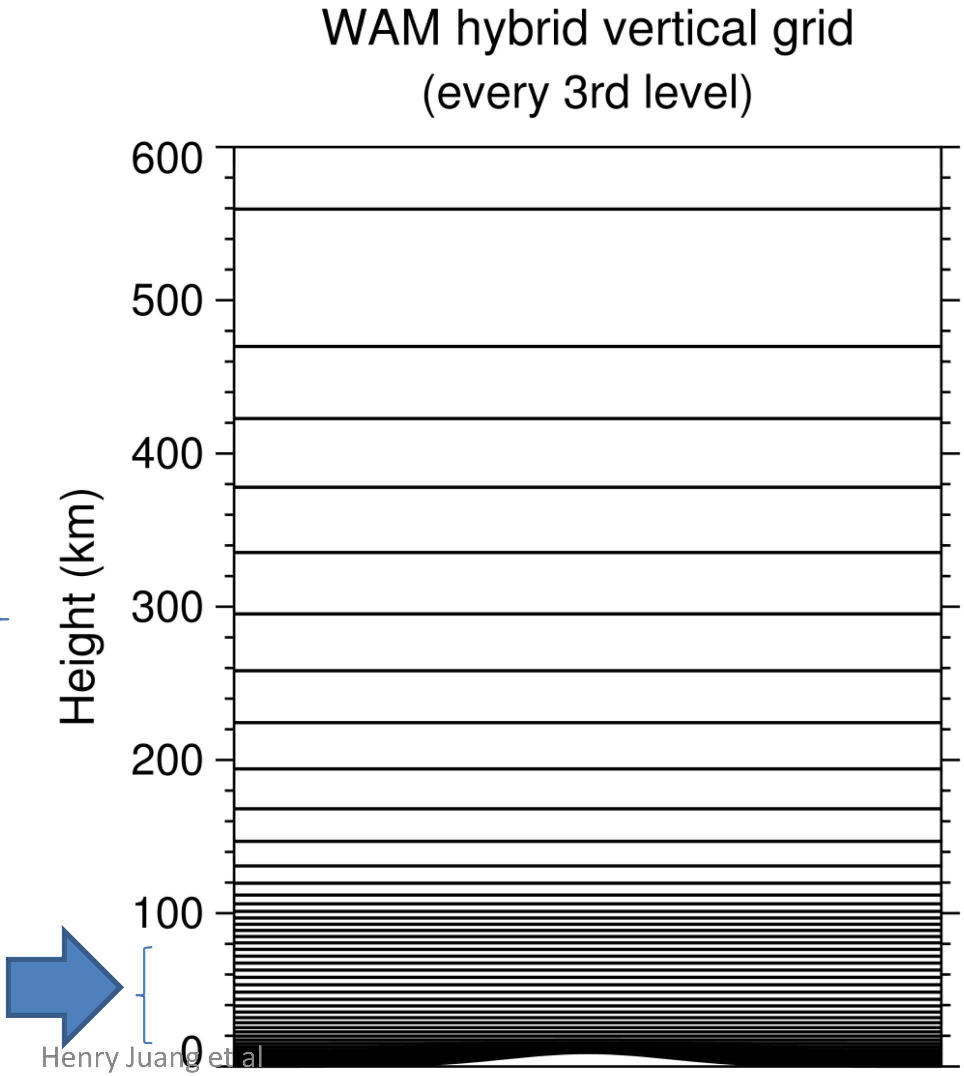
- The model top of NCEP EMC atmospheric weather and climate GFS is around 60 km.
- To couple with NCEP SWPC space weather models, it requires atmospheric model top to be around 600 km to overlay with SWPC IPE.
- We have extended GSM GFS model top about 10 times higher into whole-atmosphere modeling (WAM), and work for next FV3 GFS

Opr GFS vs GSM WAM

64 layers



150 layers

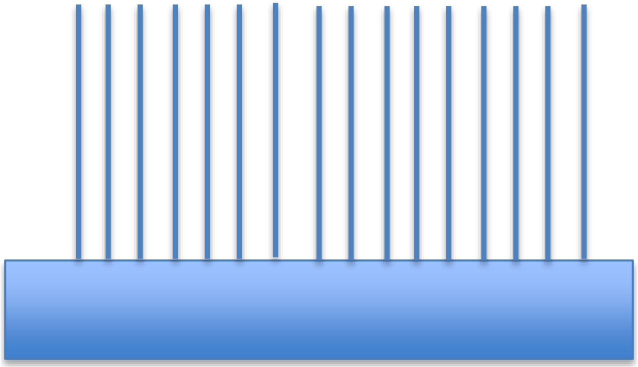


Earth radius a=6371km, r=a+z

Shallow Atmosphere

Assumption r=a

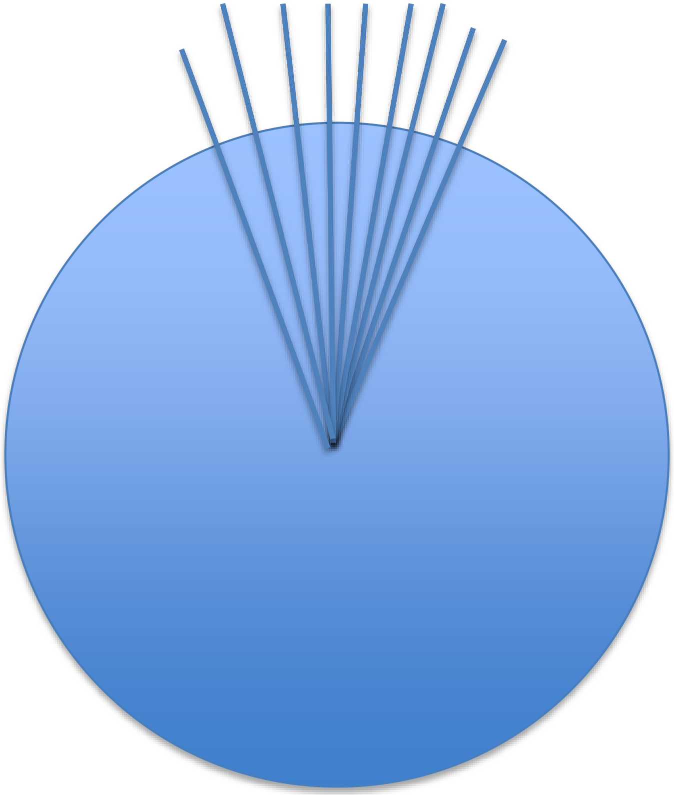
Op GFS z ~ 60km
1% of a



Most of NWP models are
shallow-atmosphere dynamics

Deep Atmosphere

No assumption
r=a+z
WAM z ~ 600 km, 10% of a



Deep-Atmosphere Dynamics (DAD)

While it is not r=a

Equations are fully non-approximation and tends to be complicated

$$r = a + z$$

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

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

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

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

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

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

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

DAD in shallowness form without approximation
(Juang 2017, NOAA Office Note #488)

A scaled weighted idea was introduced (Juang 2017)
The so-called smily space simplifies the problem, so you can use

$$\breve{u} = \frac{a}{r} u \quad ; \qquad \breve{v} = \frac{a}{r} v \; ; \quad \breve{w} = \frac{r^2}{a^2} w$$

$$\breve{z} = \frac{r^3 - a^3}{3a^2} = (r - a) \frac{r^2 + ra + a^2}{3a^2}$$

$$\frac{d\breve{p}}{d\breve{z}} = -\rho g_0 \; ; \qquad \rho d\breve{z} = -\frac{d\breve{p}}{g_0}$$

even

$$\boxed{\frac{\partial \frac{\partial \breve{p}}{\partial \zeta}}{\partial t} + m^2 \left(\frac{\partial \frac{\partial \breve{p}}{\partial \zeta} \breve{u}}{a \partial \lambda} + \frac{\partial \frac{\partial \breve{p}}{\partial \zeta} \breve{v}}{a \partial \varphi} \right) + \frac{\partial \frac{\partial \breve{p}}{\partial \zeta} \dot{\zeta}}{\partial \zeta} = 0}$$

The DAD scaled momentum eqns in shallowness form become

$$\frac{d\breve{u}}{dt}=-\left(2\frac{\breve{u}\breve{w}}{\varepsilon^3 a}+f_c^*\frac{\breve{w}}{\varepsilon^3}\right)\delta+f_s\breve{v}-\frac{1}{\varepsilon^2}\left(\frac{1}{\rho}\frac{\partial p}{a\partial\lambda}+\frac{\partial p}{\partial\breve{p}}\frac{\partial\breve{\Phi}}{a\partial\lambda}\right)$$

$$\frac{d\breve{v}}{dt}=-\left(2\frac{\breve{v}\breve{w}}{\varepsilon^3 a}\right)\delta-f_s\breve{u}-m^2\frac{\breve{s}^2}{a}\sin\phi-\frac{1}{\varepsilon^2}\left(\frac{1}{\rho}\frac{\partial p}{a\partial\varphi}+\frac{\partial p}{\partial\breve{p}}\frac{\partial\breve{\Phi}}{a\partial\varphi}\right)$$

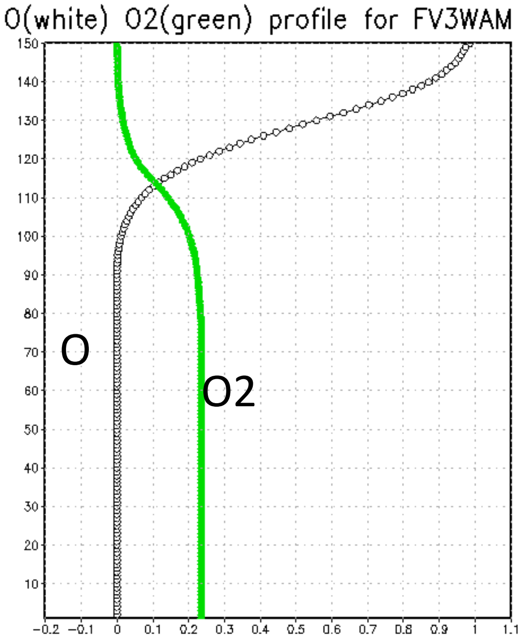
$$\frac{d\breve{w}}{dt}=\left(2\frac{\breve{w}^2}{\varepsilon^3 a}+m^2\varepsilon^3\frac{\breve{s}^2}{a}+m^2\varepsilon^3 f_c^*\breve{u}\right)\delta+g_0\left(\frac{\partial p}{\partial\breve{p}}\varepsilon^4-1\right)$$

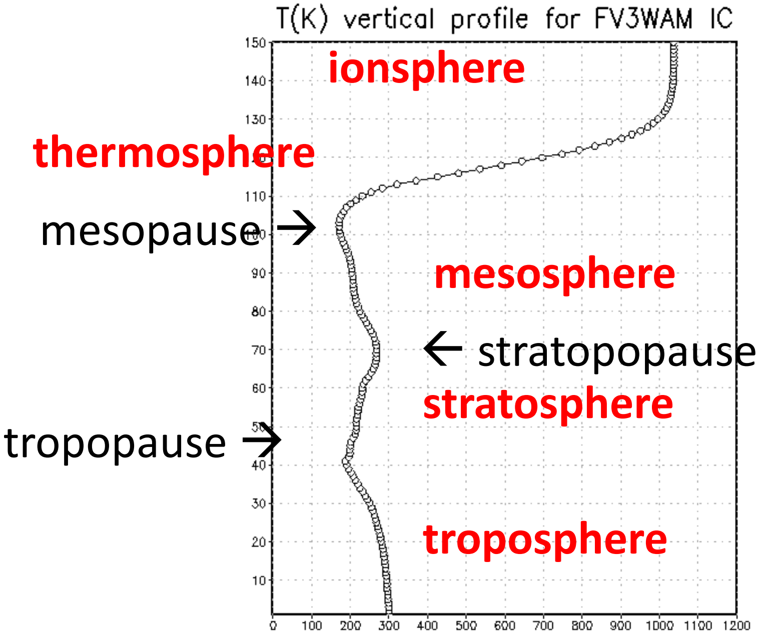
All terms with

$\varepsilon=r/a$ and $\delta=1$ are additions to shallow atmosphere dynamics

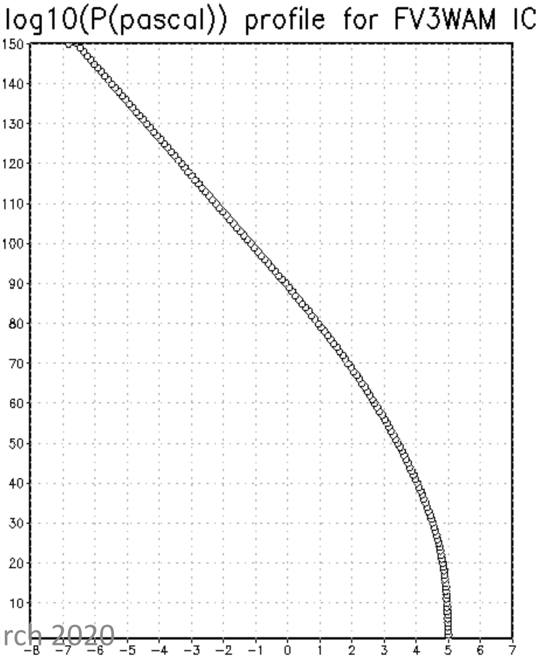
while $\varepsilon=1$ and $\delta=0$ All eqns are back to shallowness

And it is possible to define hydrostatic pressure as $\frac{\partial\bar{p}}{\partial\breve{p}}\varepsilon^4-1=0$





FV3WAM IC



FV3WAM Initial Condition
at lat=0 and lon=180
cold start with standard T, P, O, and O2
other fields, wind, and q are gradually decreasing to zero at top
top pressure is about 1.E-7 Pa close to 500~600 km

Opr GFS

	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

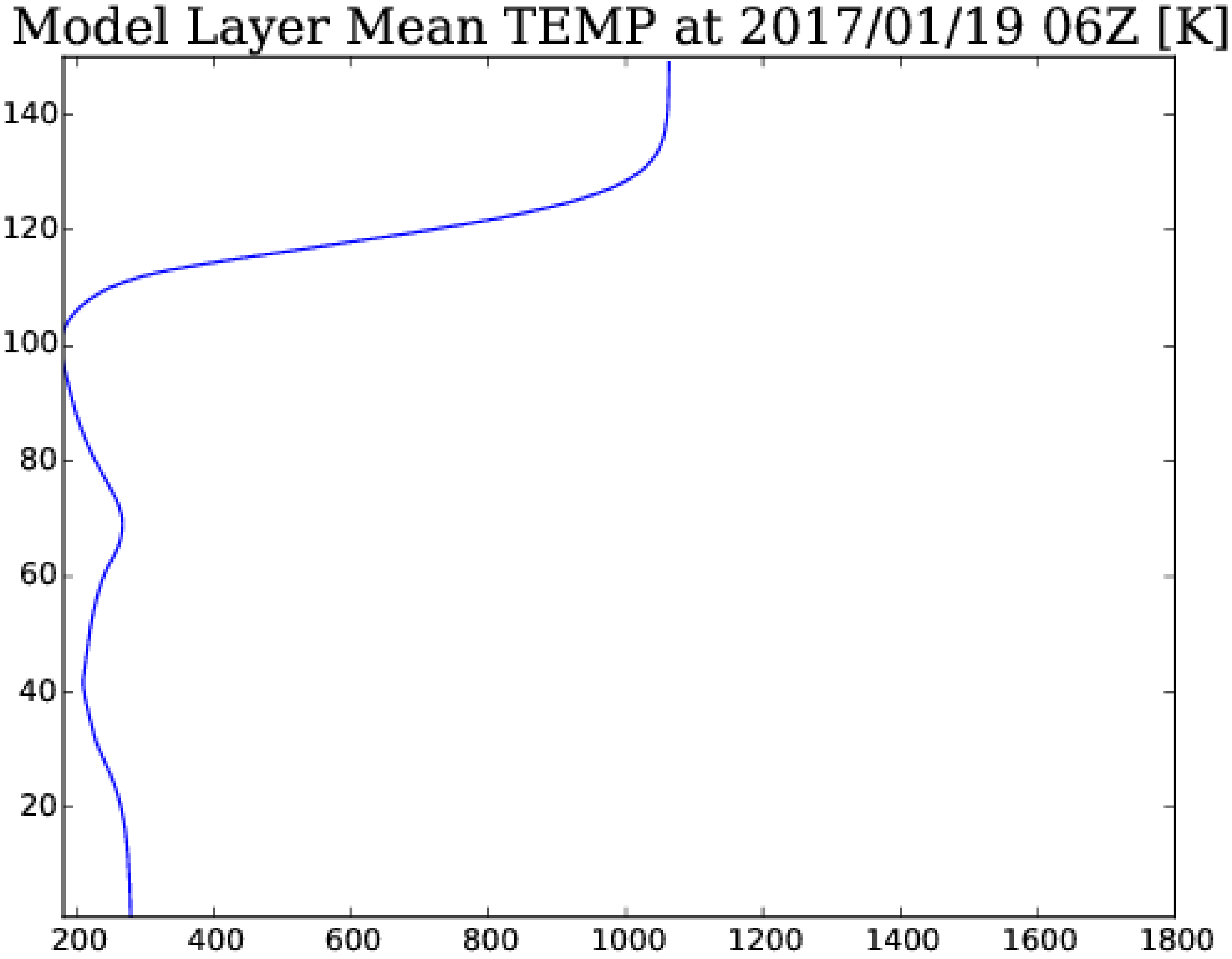
$$p = \rho R T = \rho R_d T_v \;; \qquad T_v = \frac{\sum_{i=0}^{N} q_i R_i}{R_d} T \;; \qquad \theta_v = T_v \left(\frac{p}{p_0} \right)^{-\frac{R}{C_P}}$$

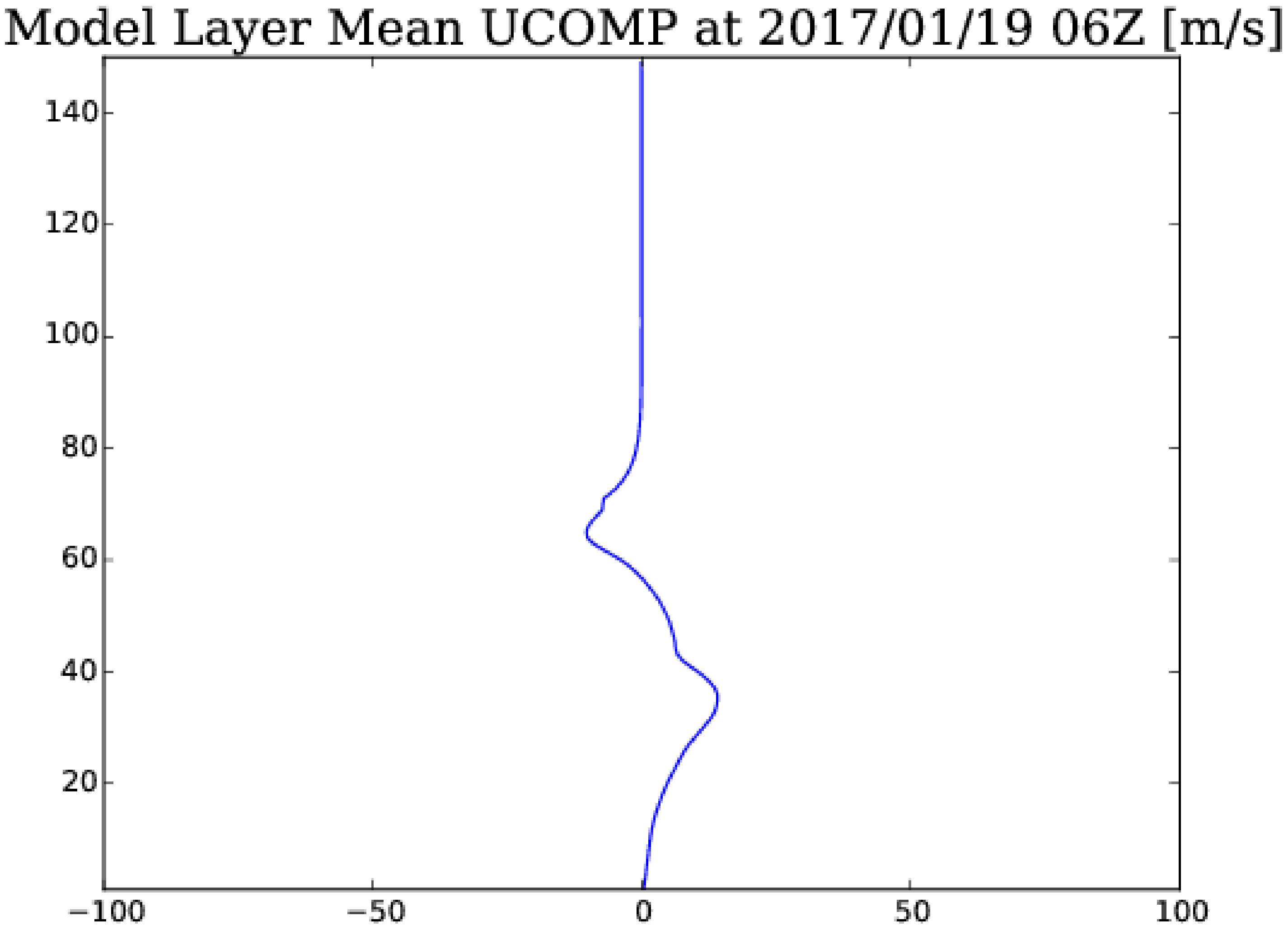
Implementation steps

- Extend FV3 vertical domain to be the same as GSM WAM
  - Adiabatic mode of FV3
  - Extend to WAM domain with WAM cold-start IC
  - Use GFS physics with Rayleigh damping
  - Implement multi gases thermodynamics
  - Add WAM physics
  - Add diffusivity, conductivity, viscosity for upper-layer integration
  - Add deep-atmosphere dynamics

Adiabatic L149

- Create WAM IC with LEVS=149 through global chgres to run C48 & C96
- FV3 can run adiabatic in weather mode with LEVS=63 about 60km
- However, the same configuration of FV3 cannot run adiabatic mode with LEVS=149 about 600km without stronger Rayleigh damping


Model Layer Mean TEMP at 2017/01/19 06Z [K]
140
120
100
80
60
40
20
200
400
600
800
1000
1200
1400
1600
1800

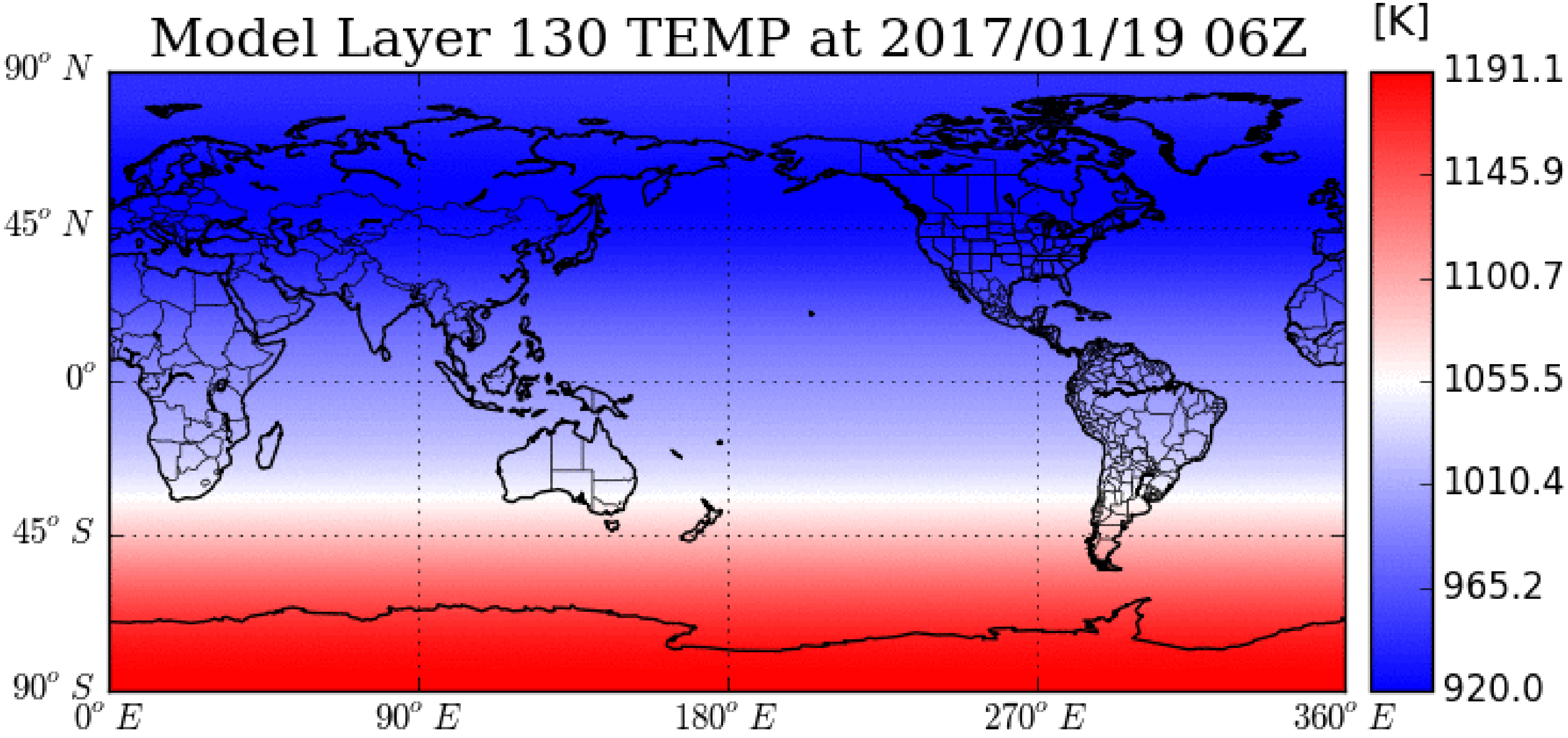


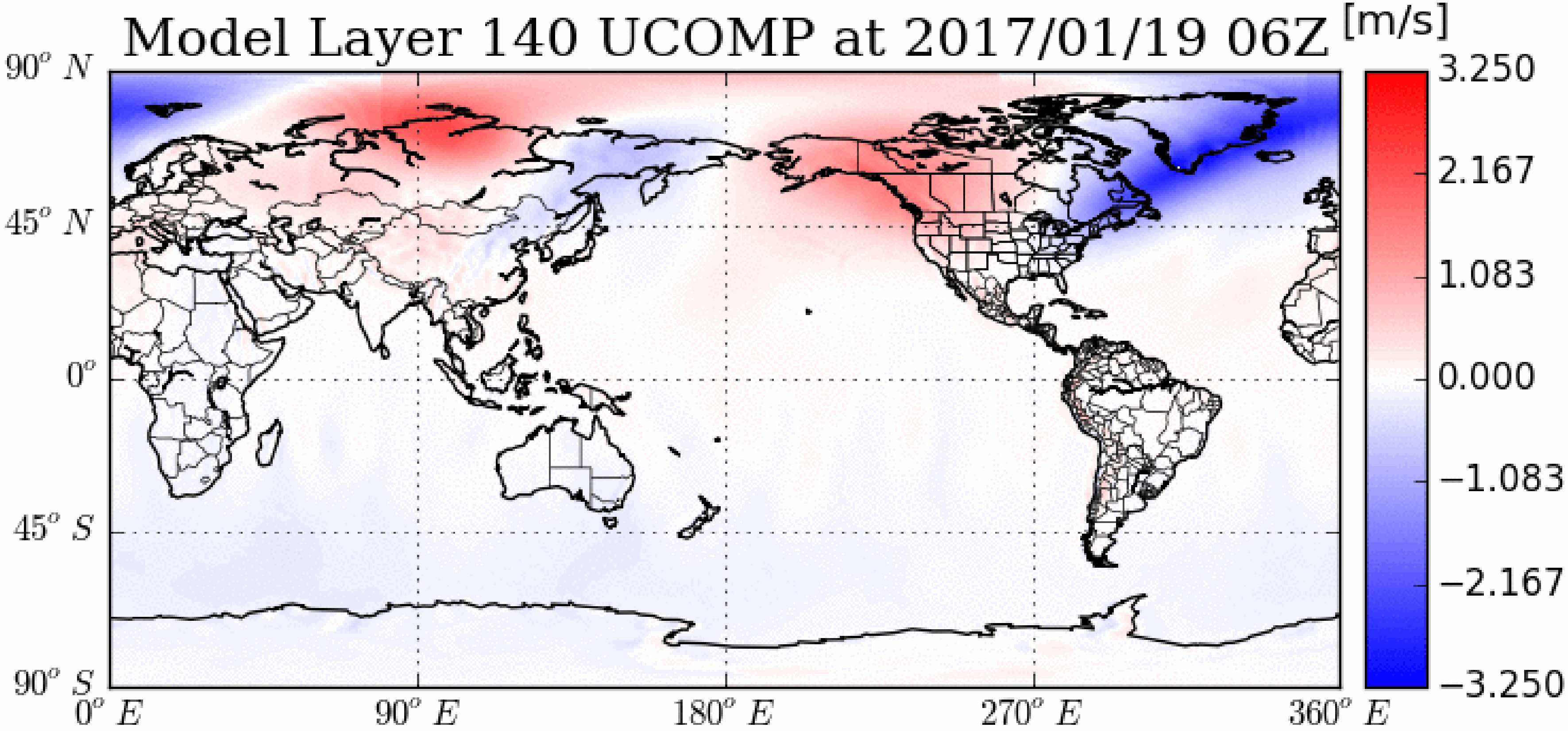
Model Layer Mean UCOMP at 2017/01/19 06Z [m/s]

Turn on GFS physics

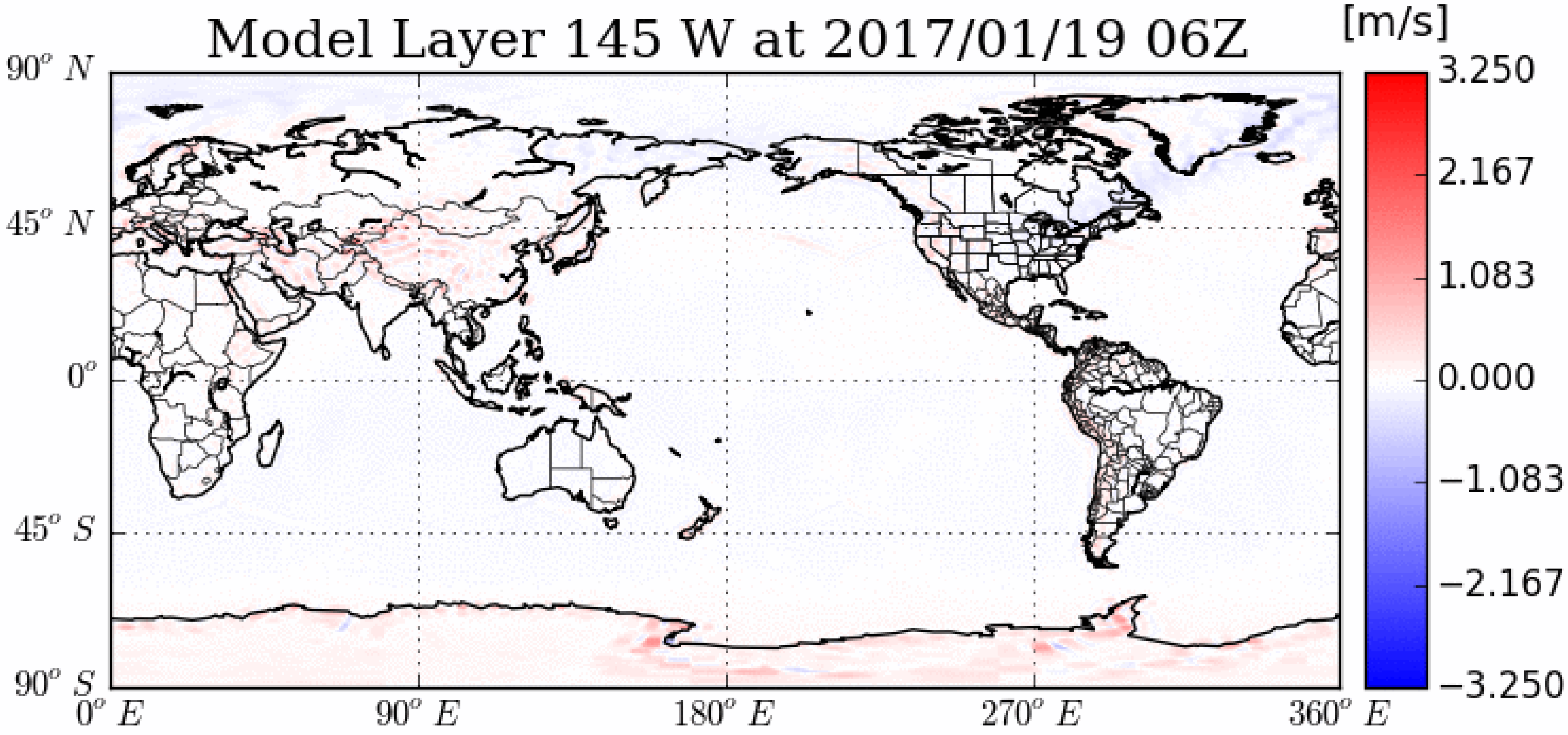
- With all namelist option for L149 adiabatic and turn on physics
- Mean upper layers gsm radiation calculation
- Then FV3 can integrate stably with the same Rayleigh damping as GSM
- The WAM physic called IDEA PHYS has not implemented into FV3 yet.

C96 FV3 L149 gfs-physics with strong Rayleigh damping
5-day integration at layer 130




Model Layer 140 UCOMP at 2017/01/19 06Z
[m/s]
90° N
45° N
0°
45° S
90° S
0° E
90° E
180° E
270° E
360° E
3.250
2.167
1.083
0.000
−1.083
−2.167
−3.250

C96 FV3 L149 gfs-physics with strong Rayleigh damping 5-day integration at layer 145



summary

- While extending atmospheric models to whole atmosphere, we consider (1) deep atmospheric dynamics and (2) multi-gases thermodynamics equation.

- FV3 has been extended to WAM with preliminary results of stable integration by Rayleigh damping.

- Multi-gases option has been implemented into FV3 for WAM, and it also benefits to GFS.

- Based on Juang (2017) NOAA Office Note #488, DAD equation can be converted to shallow-atmosphere form without approximation for easy implementation.

Future Works

- Implement molecular diffusion to remove or reduce the too-much Rayleigh damping for thermosphere wind.

- Implement IPE (Idea) model physics, especially the radiation of multi-gases into WAMFV3.

- Implement deep-atmosphere dynamics, which should be good for WAM as well as GFS.