

in Whole Atmosphere Simulations of Unified Forecast System

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Collaborative efforts of NOAA/SWPC, NOAA/NCEP/EMC, CU-CIRES and CUA/NASA (2022-2024)

FV3WAM - *the Whole Atmosphere Model and Space Weather Application of Unified Forecast System (UFS) that build upon on the current operational GFS-v16 (0-80 km) of NOAA/NWS with FV3 dynamics. It will serve for ITM forecasts and data analysis from ~50 km to the exobase.*

FV3WAM is the nonhydrostatic atmosphere model

with top lid at $\sim(10^{-7}\text{Pa}$, or at $\sim 450\text{-}650$ km) with upgrades of operational WAM physics.

Main upgrades of FV3 equations and solvers: variable gravity, molecular weight, heat capacities and **3D Molecular-Eddy Dissipation (MED)** operators as a part of FV3 dynamics to describe the advection-diffusion coupling for resolved dynamics and sub-grid processes above PBL.

FV3WAM configurations across scales: C96(100 km), C192(50 km), C384(25 km), & C768 (12.5 km);
vertical layers: 150L (oper. layers of WAM-IPE) and 196L (match GFS-v16 of NWS).

FV3WAM-v1 (100 km to 25 km) and FV3WAM-SLES (~25 km)

FV3 dynamics: on Eulerian (EL) & Vertically Lagrangian (VL) layers

- 1) NH dycore + Mol. Diff (VL)
- 2) Remap from VL to EL
- 3) Fixers (energy, mass, tracers) EL

Dynamics-Physics Coupling (EL)

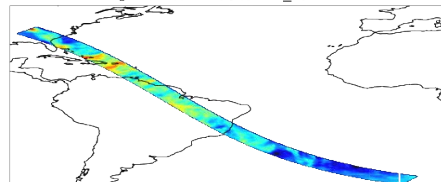
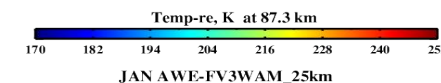
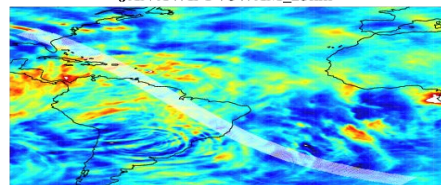
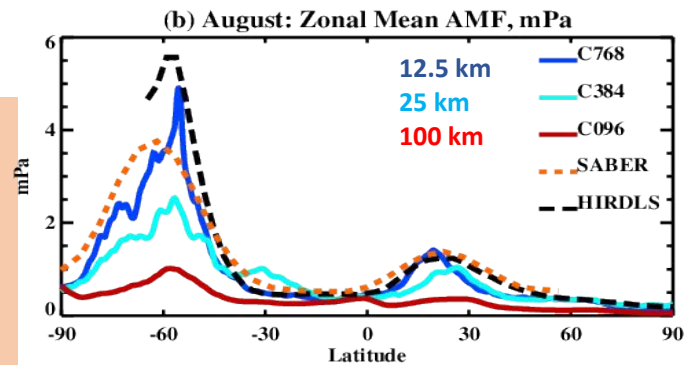
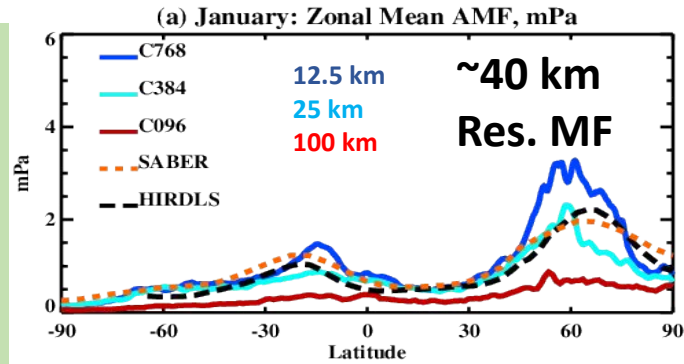
Physics: 3 steps on EL

- 1) Radiation of GFS
- 2) WAM \leq Mol/Eddy Dissipation (MED)
- 3) Standard GFS with UGWP

Dycore and Physics “share” MED operators UGWP acts; Vertical winds are not influenced by vertical part of MED

Uncertainties & Advantages of FV3WAM-v1:

- GW sources and 1-D GW framework;
- WME: absence of molecular & eddy viscosity;
- Scale-aware treatment of GW source fluxes



FV3-SLES : 4 Steps

- 1) NH dycore (VL)
- 2) Remap from VL to EL
- 3) SLES + 3D Mol/Diff (EL)
- 4) Fixers (energy, mass, tracers) EL

Dynamics-Physics Coupling (EL)

Physics: 3 steps on EL

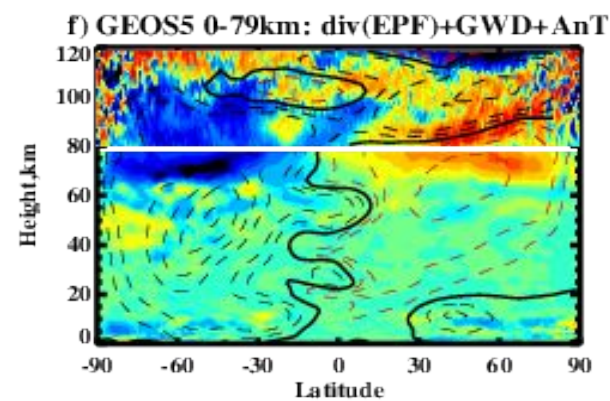
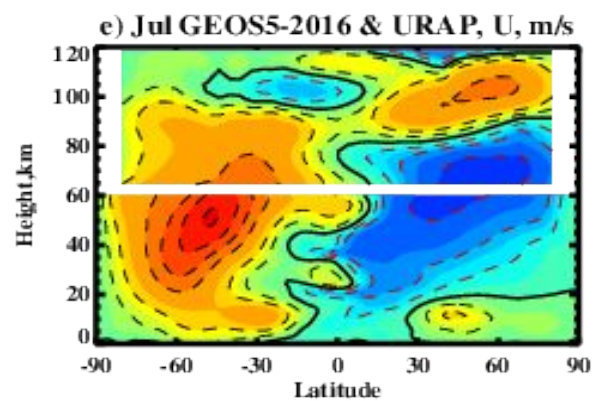
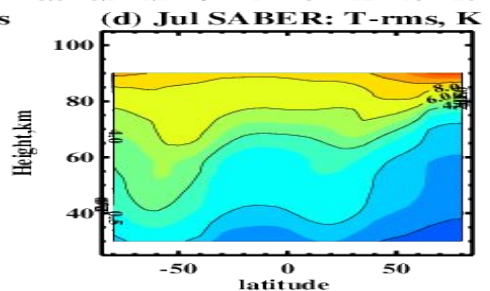
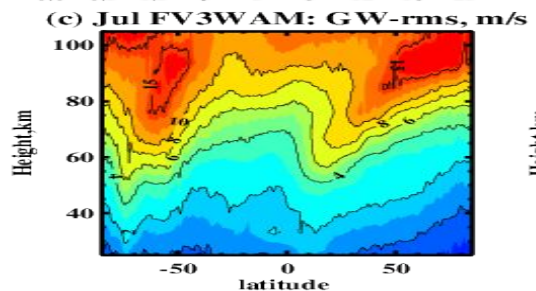
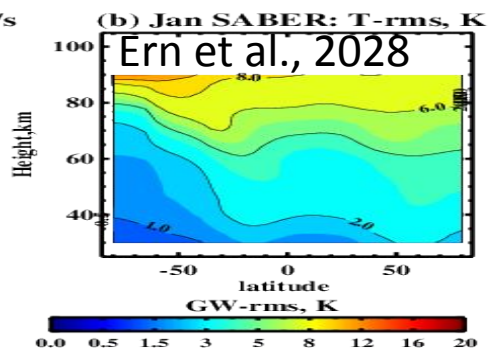
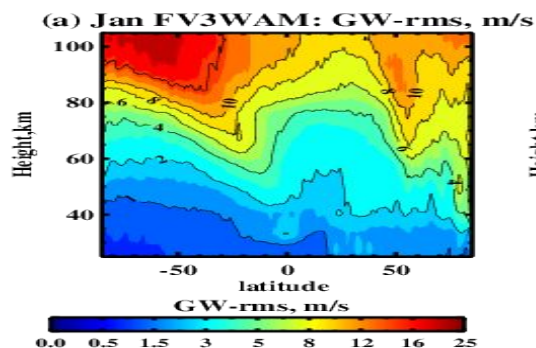
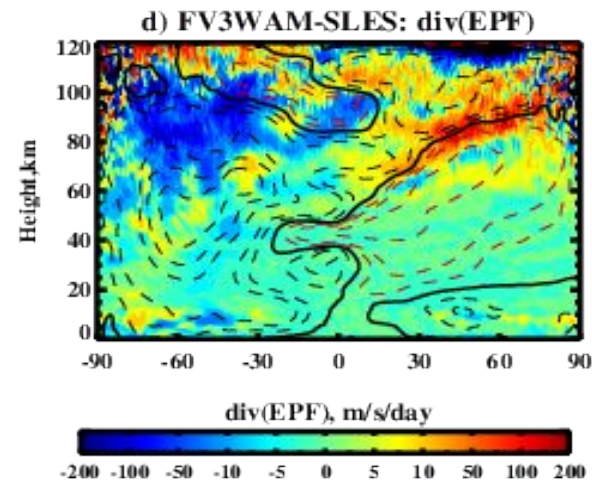
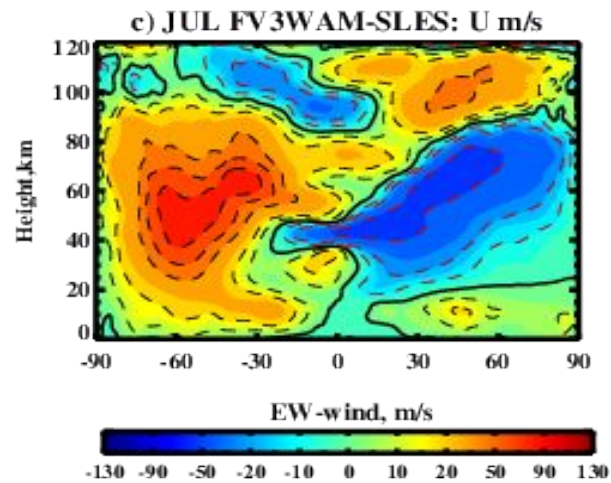
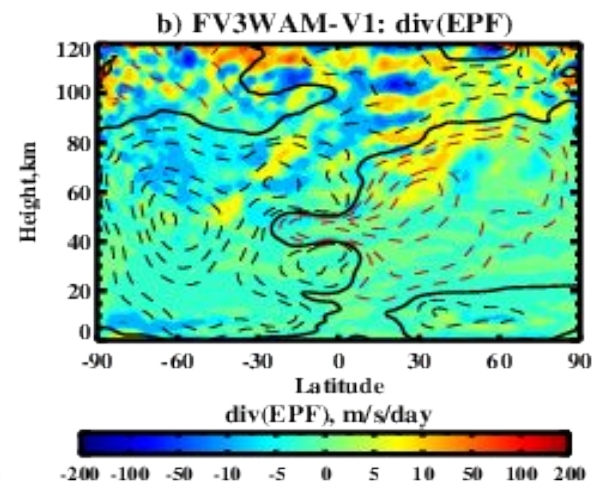
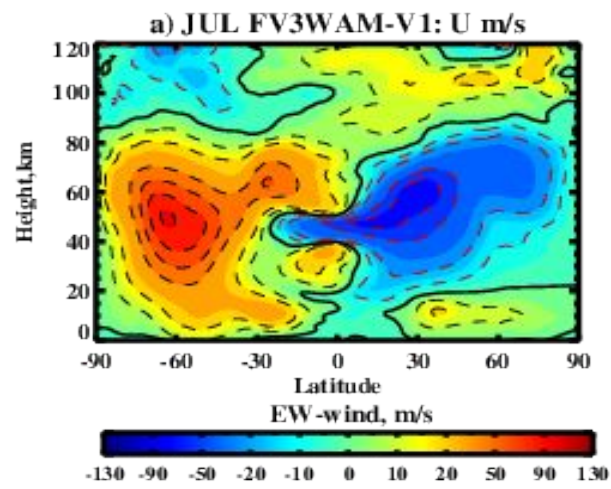
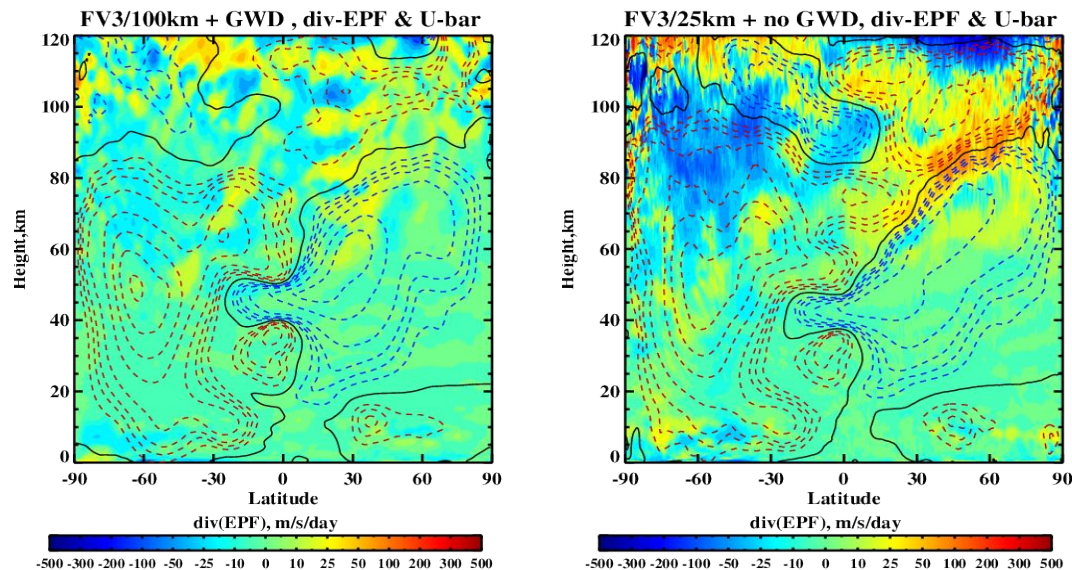
- 1) Radiation of GFS
- 2) WAM without MED processes
- 3) Standard GFS w/o UGWP

3D Smagorinsky (1963) Large Eddy Simulations (SLES) and Molecular dissipation only belong to FV3WAM dycore; UGWP is ‘off’;

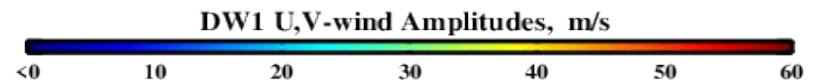
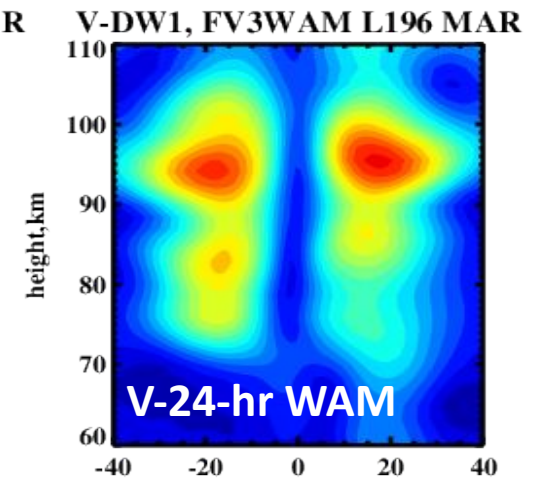
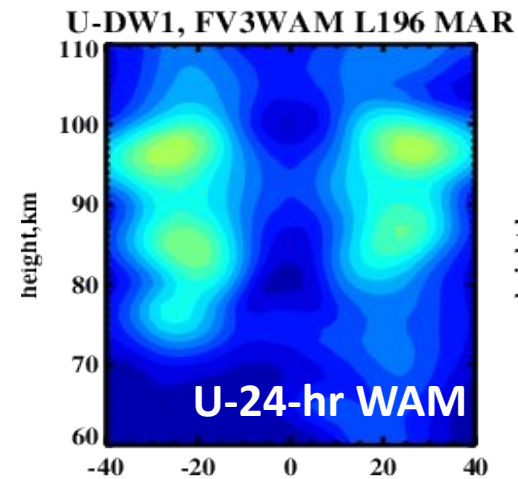
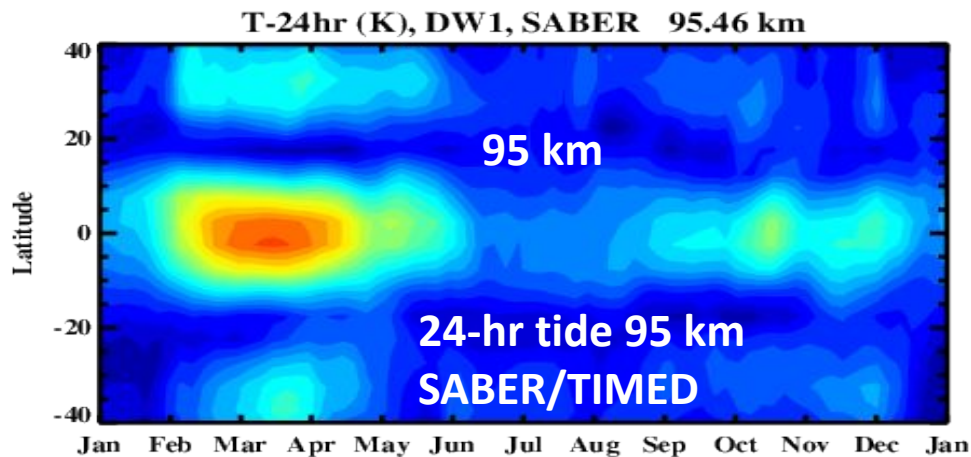
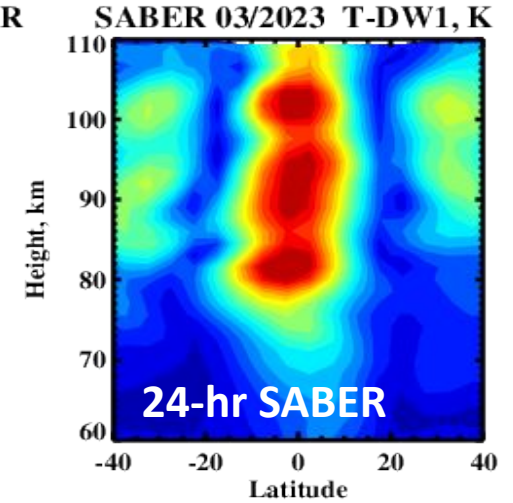
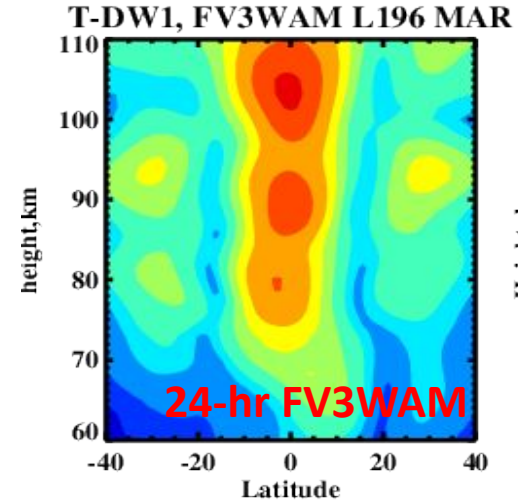
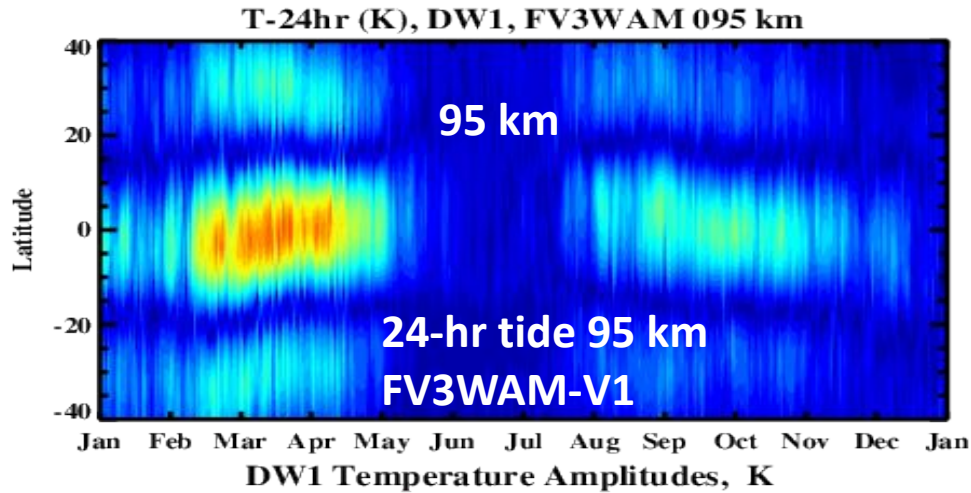
Uncertainties & Advantages of FV3WAM-SLES:

- Eddy mixing/dissipation parameterization
- No needs for GW-sources; WME with MED operators.
- Generation of High-order GWs;
- Scale-aware treatment of eddy mixing

July Zonal Wind and its Wave Forcing: FV3WAM-100 km vs FV3WAM-SLES (25 km)

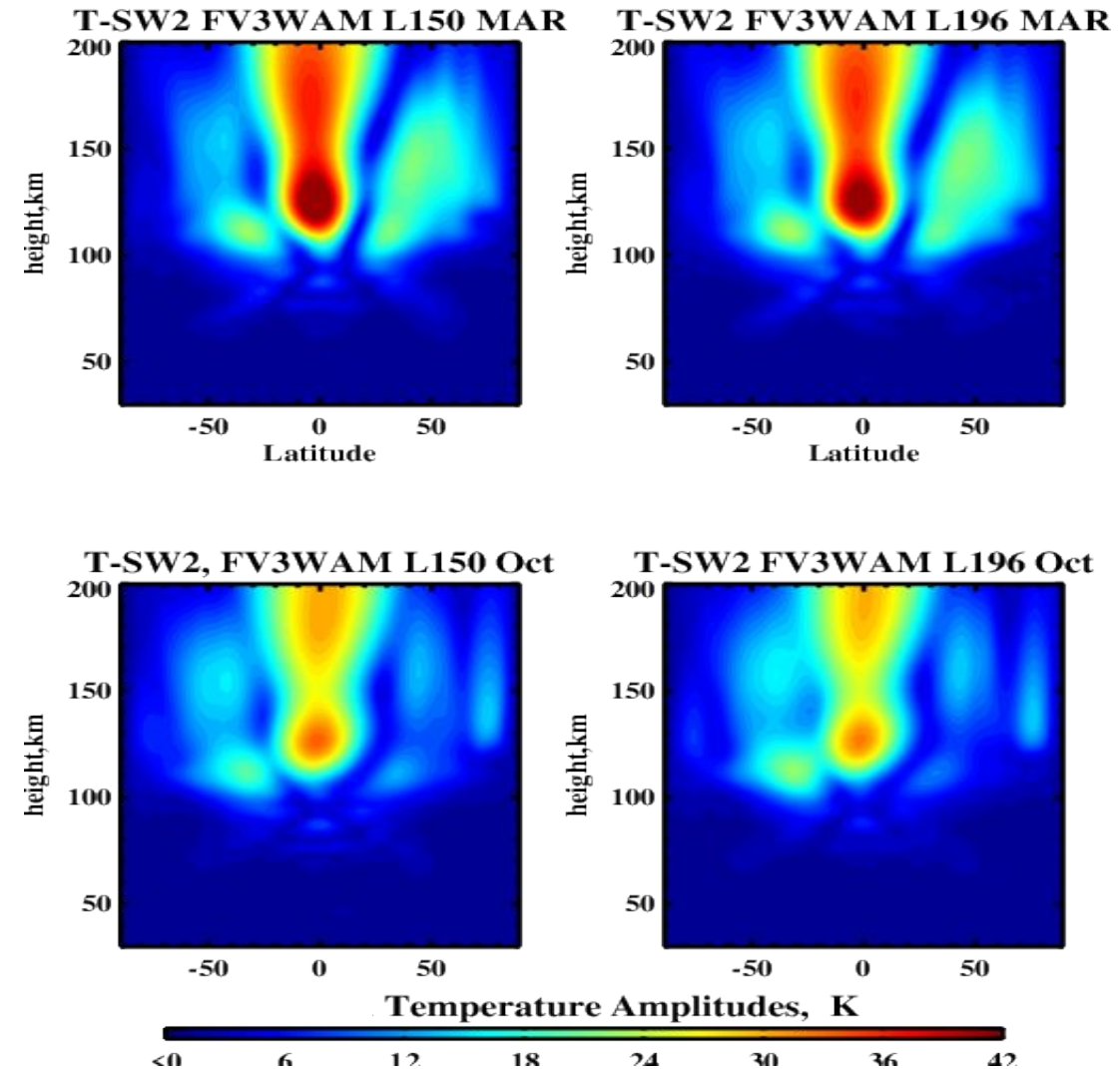
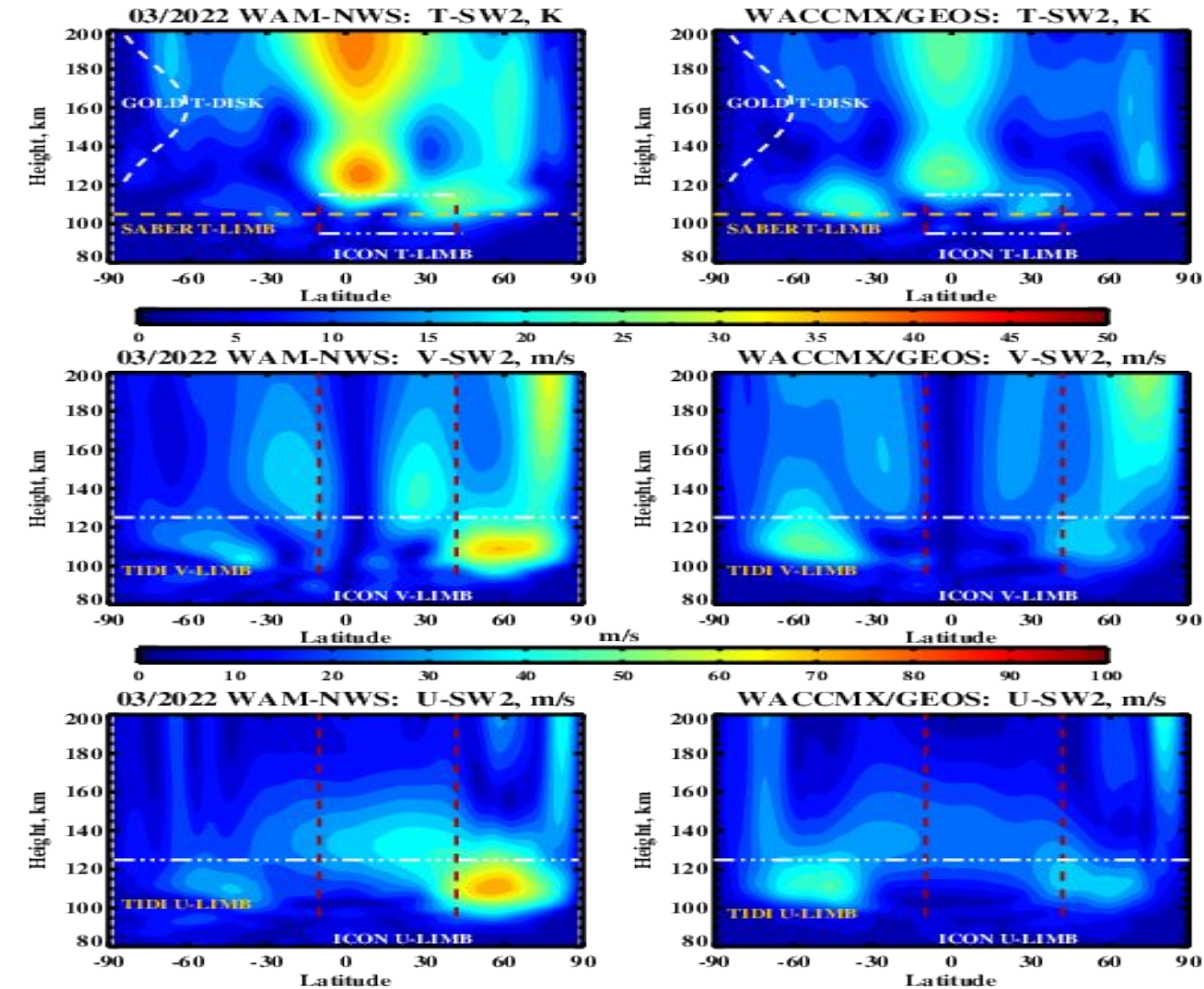


Diurnal Tide: FV3WAM-v1 and SABER/TIMED

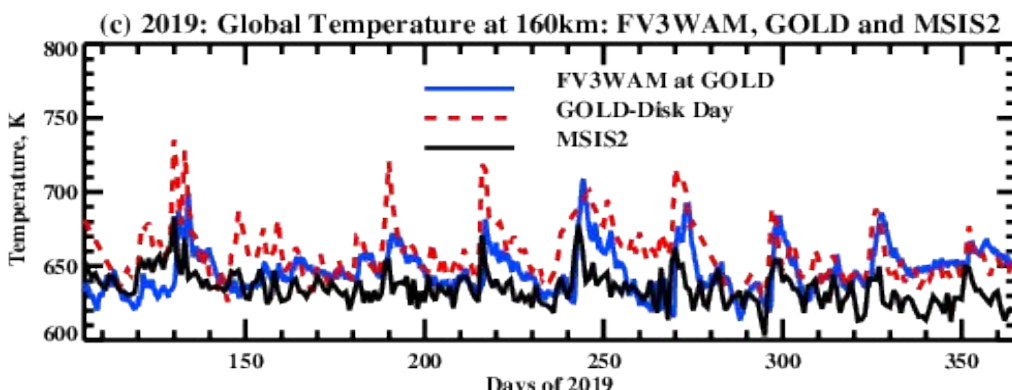
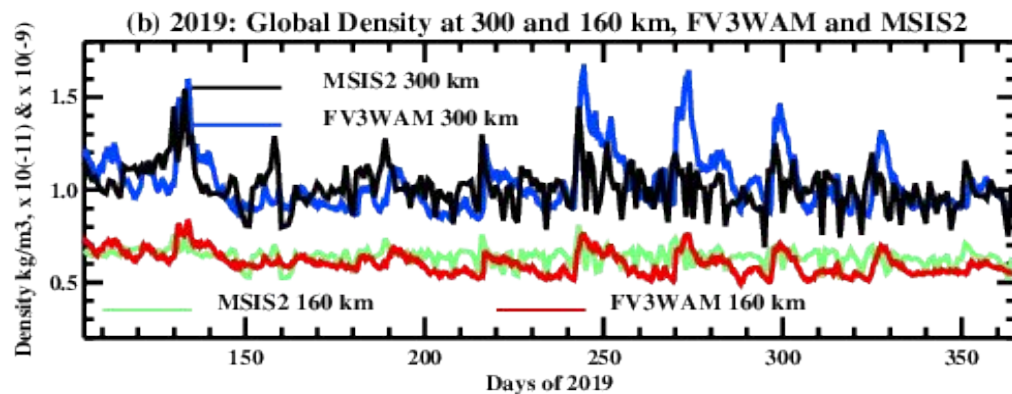
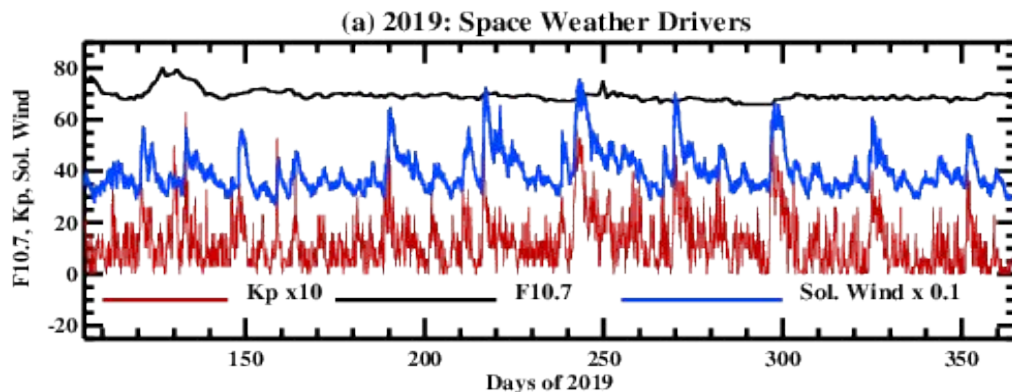


Semidiurnal Tide, SW2 Mar 2022: WAMGSM-DAS vs WACCM-X/GEOS-5

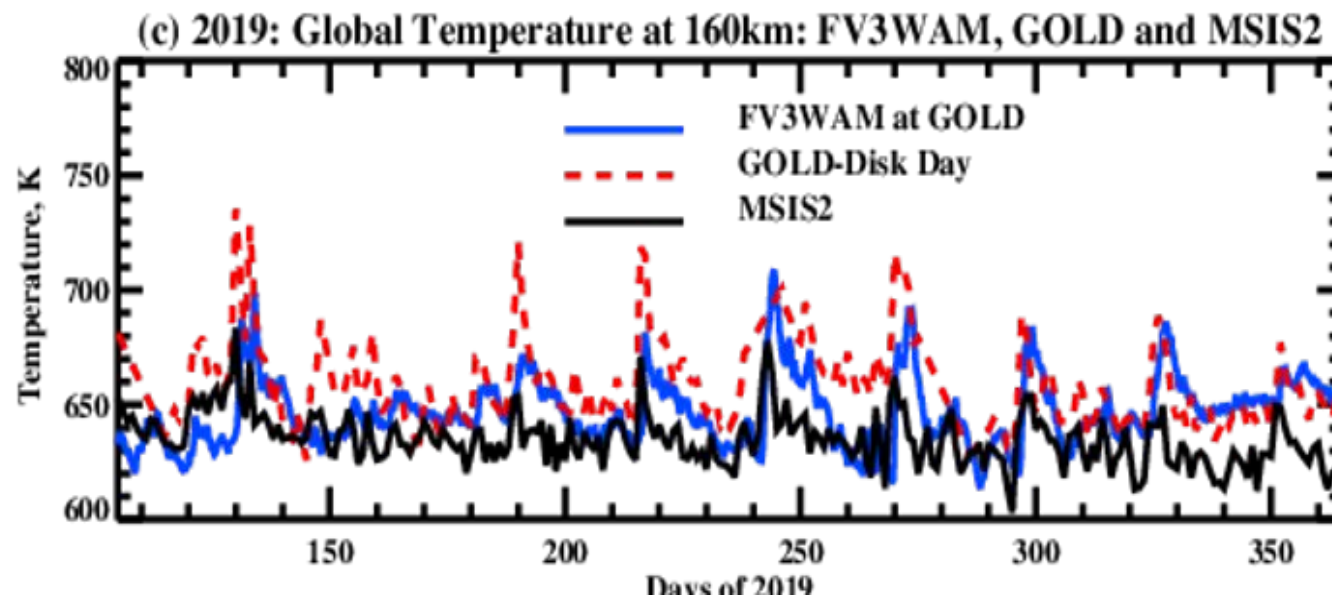
SW2, Mar (top) & Oct (bot) 2018: FV3WAM with 2 vertical resolutions (L150 and L196)



FV3WAM-v1 2019-Run with SW Drivers of SWPC (SMIN)



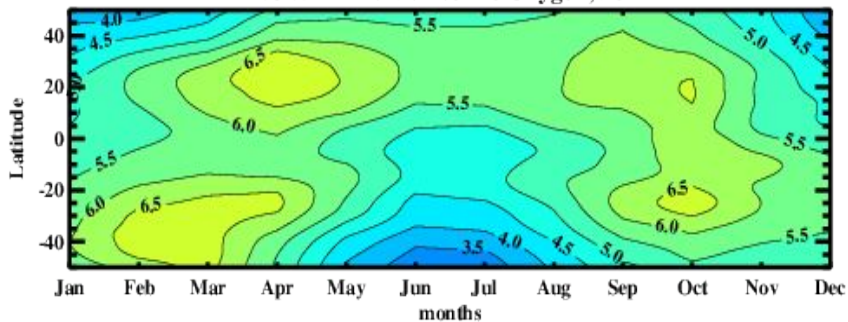
Comparison between
FV3WAM-T (160 km), MSIS_V2 and **GOLD-Tdisk**



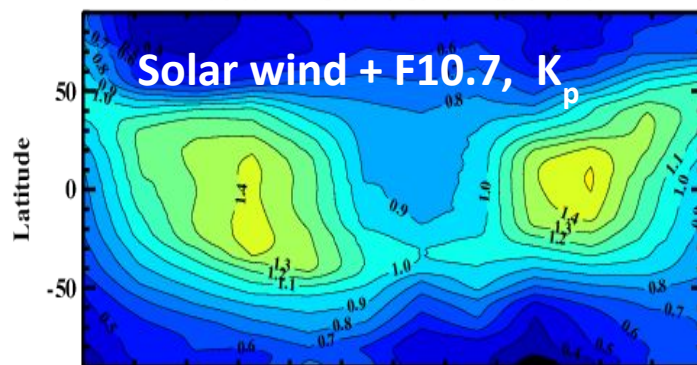
Comparison with GOLD T-disk needs applications of the averaging kernels to map MSIS and FV3WAM simulations
=> T-disk data space of GOLD

Composition: FV3WAM 2019 Annual Run with SWD of SWPC/NOAA

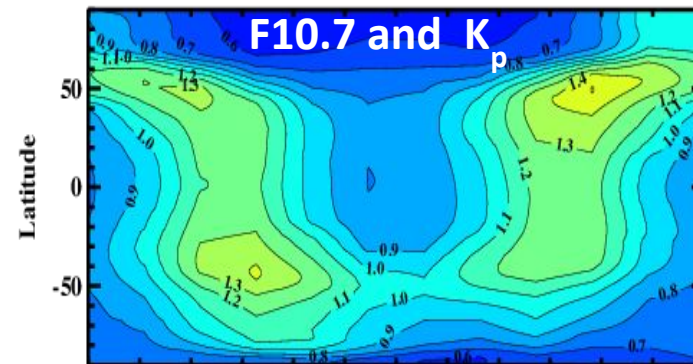
FV3WAM-2019: Atomic Oxygen, 98km



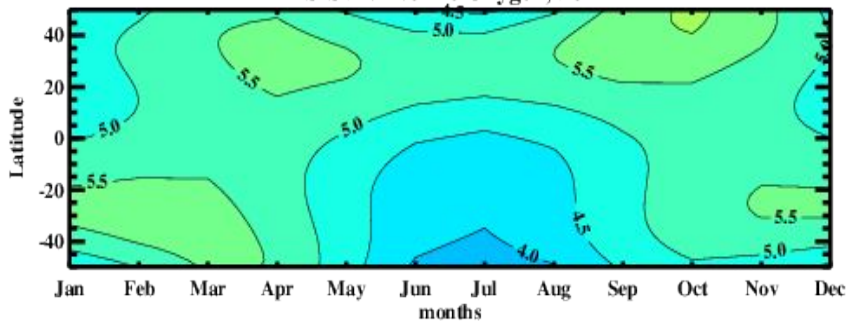
FV3WAM-SWD: O/N2 Ratio 2019



FV3WAM: O/N2 Ratio 2019



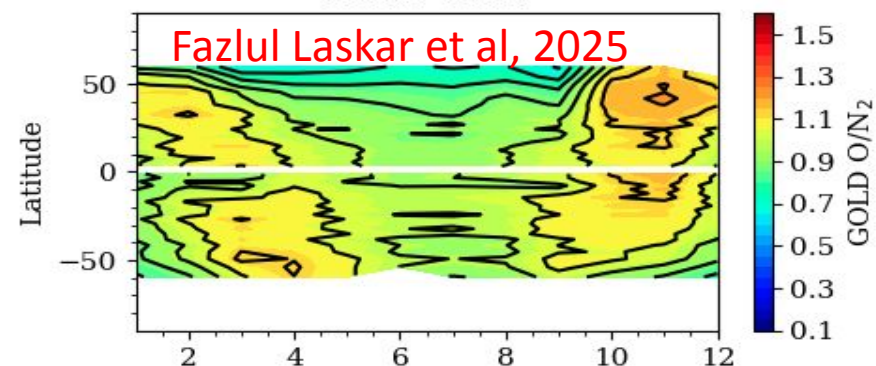
MSISv2: Atomic Oxygen, 98km



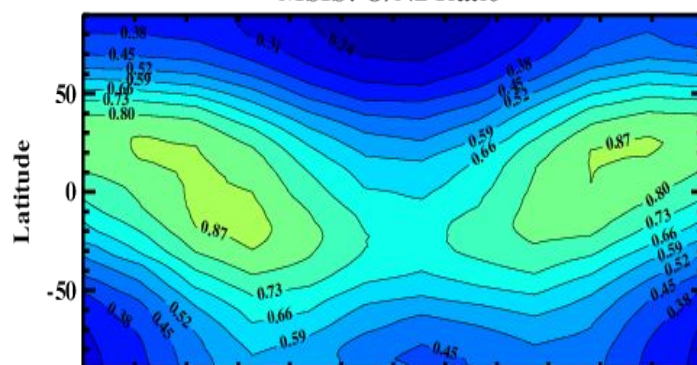
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month

GOLD 2019

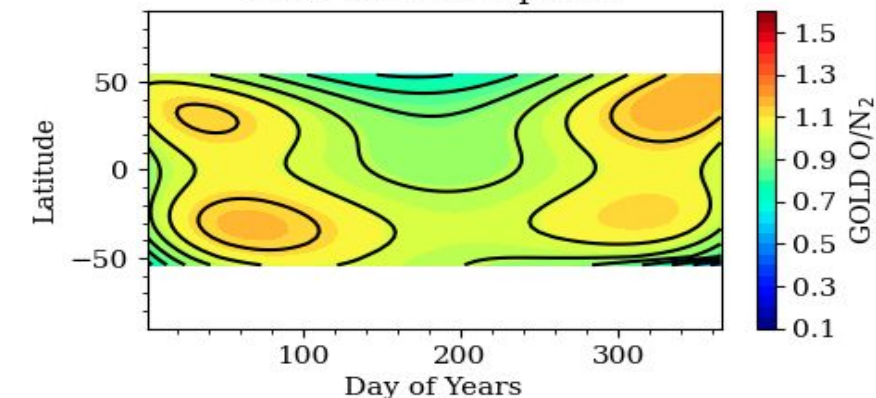


MSIS: O/N2 Ratio

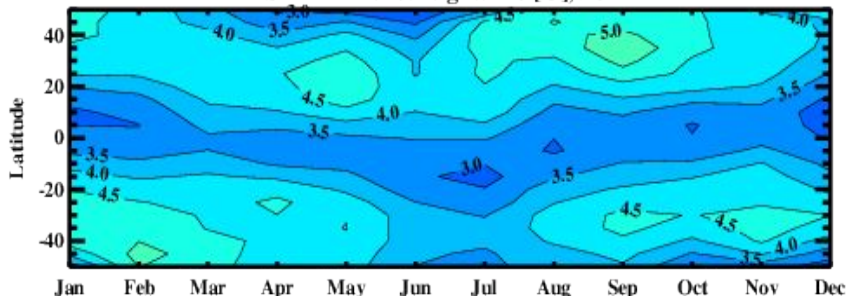


Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months

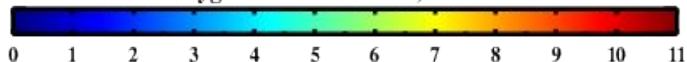
2019-2022 Composite



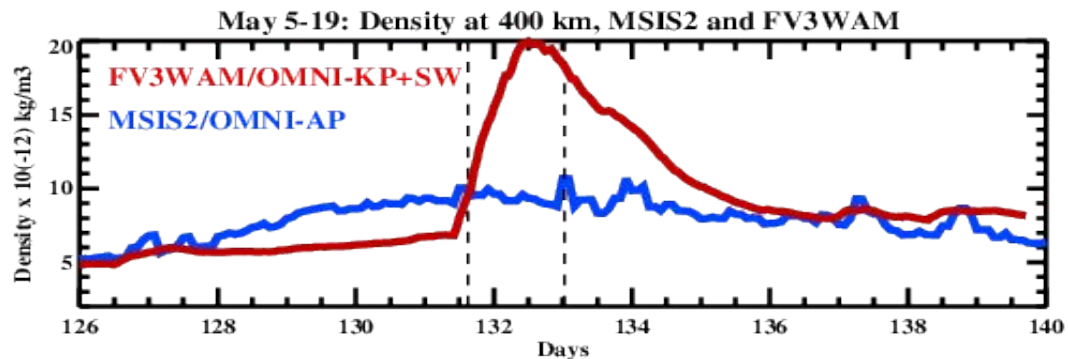
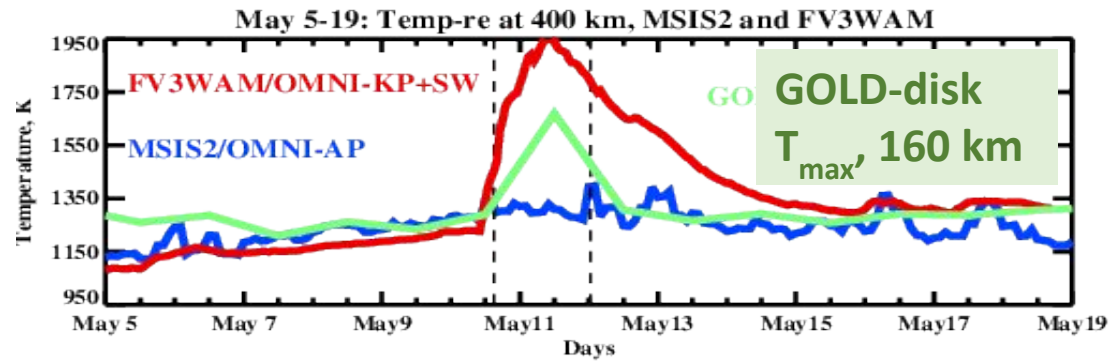
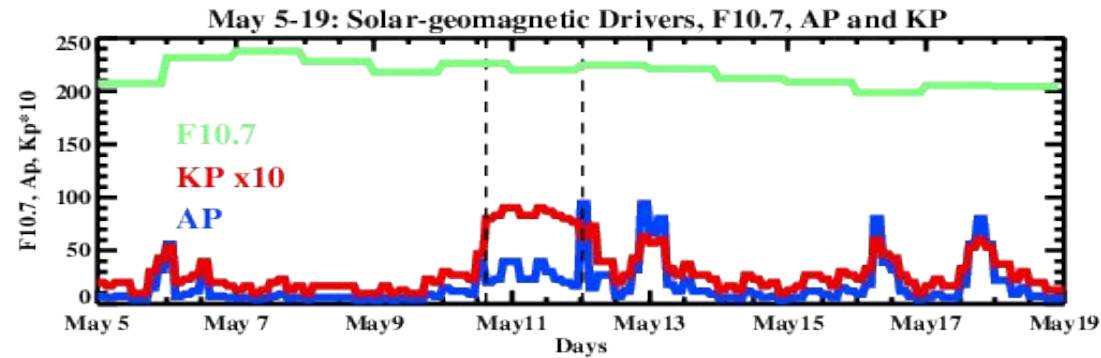
SABER-2016: Nighttime [O], 98km



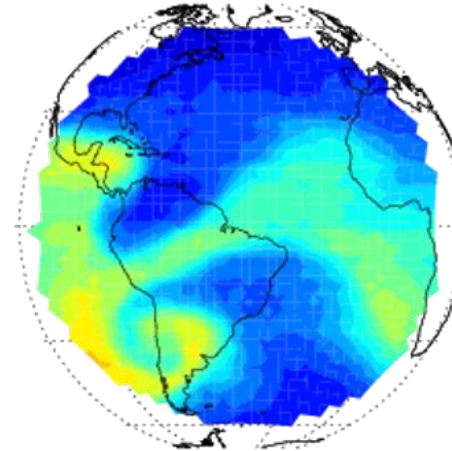
Atomic Oxygen Concentrations, 1/cm3 scale=10¹¹



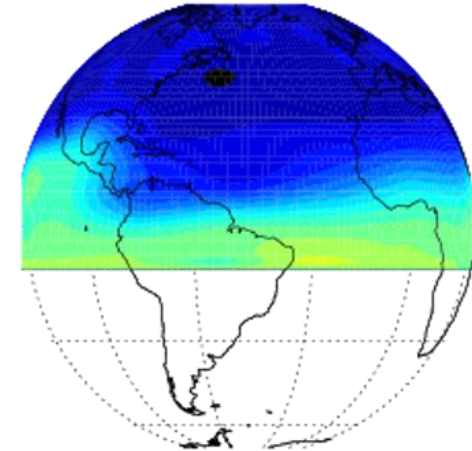
May 2024 Super Storm: First Simulations of FV3WAM-V1



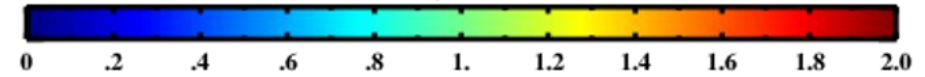
GOLD: $\Sigma\text{O}/\text{N}_2$ May 11, 14UT



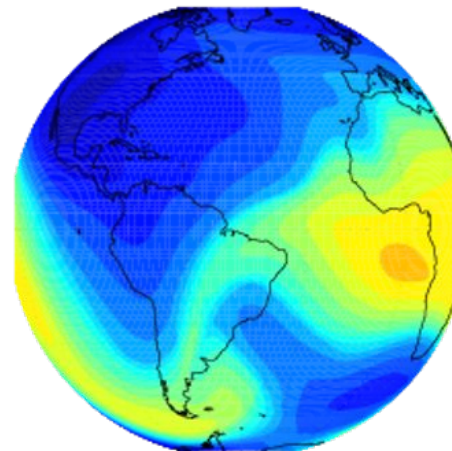
GUVI: $\Sigma\text{O}/\text{N}_2$ May 11



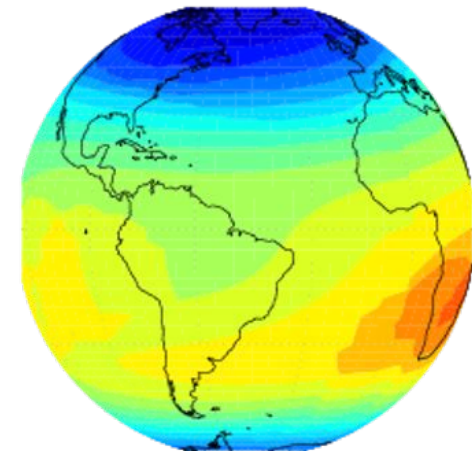
$\Sigma\text{O}/\text{N}_2$ column ratio, $\text{N}_2\text{COL} = 1.e17 \text{ cm}^{-2}$



FV3WAM: $\Sigma\text{O}/\text{N}_2$ May 11, 14UT



MSIS2: $\Sigma\text{O}/\text{N}_2$ May 11, 14 UT

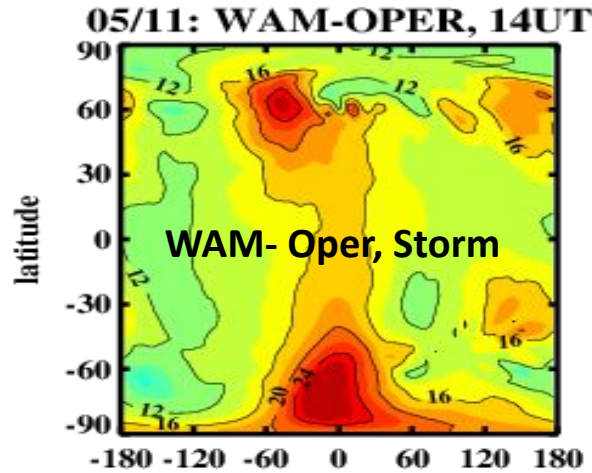
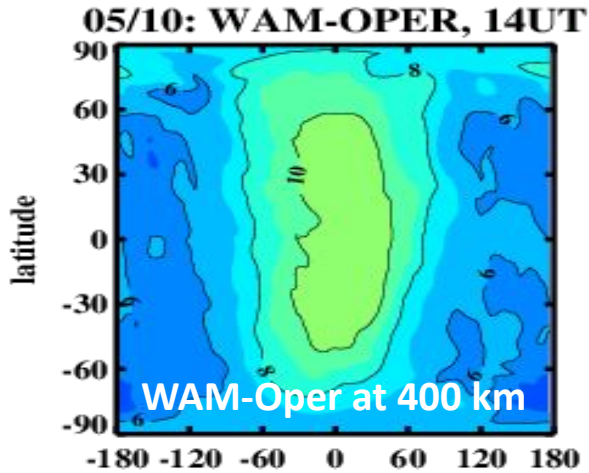


May Storm: WAM-IPE/NWS vs FV3WAM, Density and $\Sigma O/N_2$

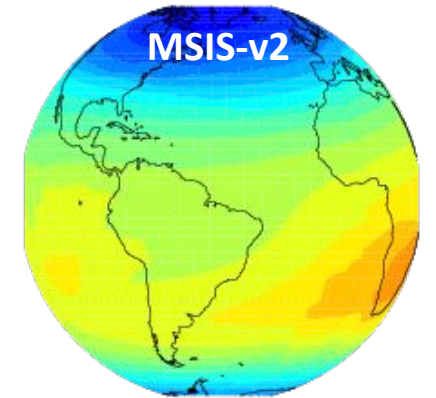
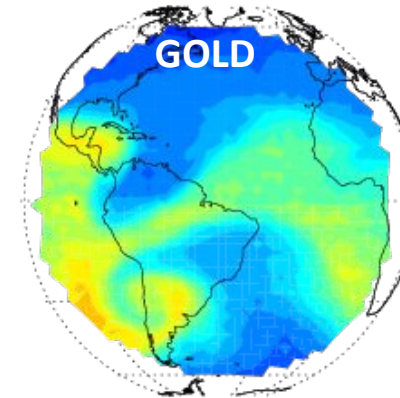
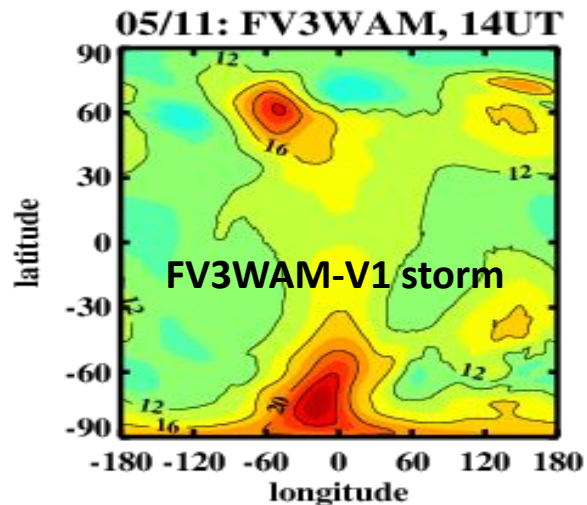
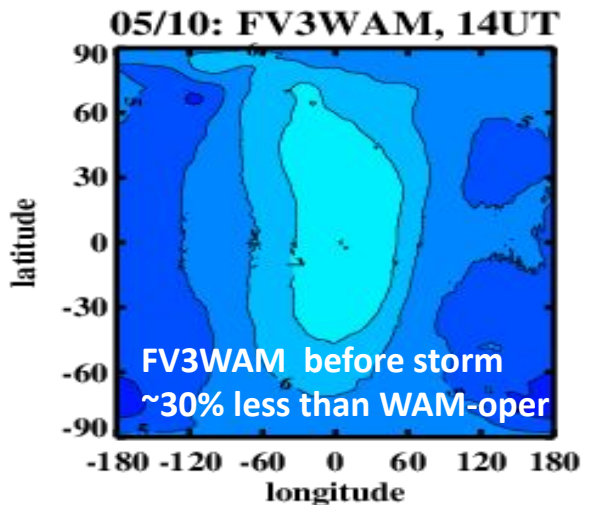
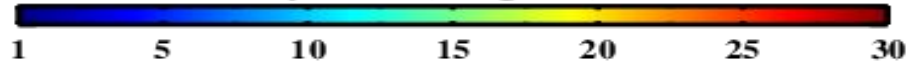
Density: PRE-STORM

STORM-14UT, as in GOLD O/N_2

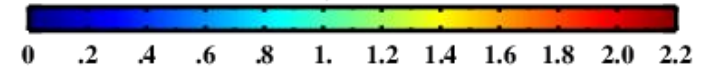
$\Sigma O/N_2$: Storm May 11, 14 UT



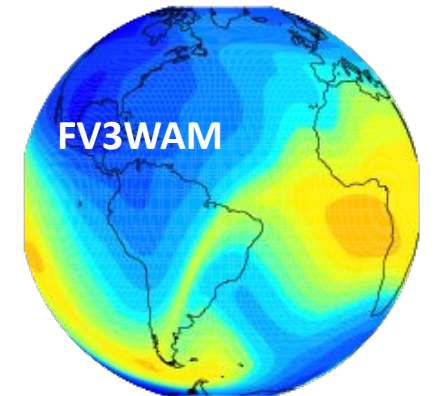
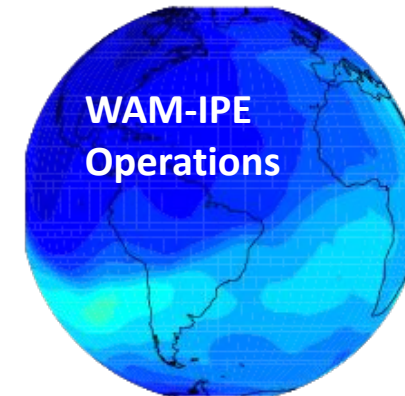
Density*1.e12, kg/m3, 400km



O/N_2 column ratio, $N_2COL = 1.e17 \text{ cm}^{-2}$



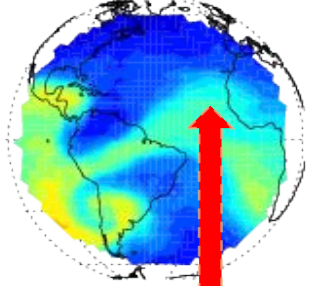
WAM: O/N_2 May 11, 14 UT FV3WAM: O/N_2 May 11, 14 UT



*WAM-IPE has "negative" bias vs Data $\Sigma O/N_2$ (GOLD);
FV3WAM-v1 (same SW drivers) can match GOLD in some parts*

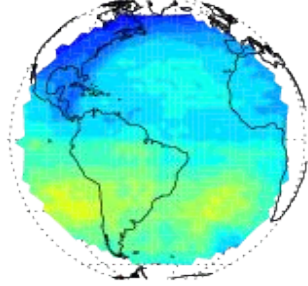
Composition (Oxygen) vs Temperature in the GOLD Layers

GOLD: O/N2 May 11, 14UT

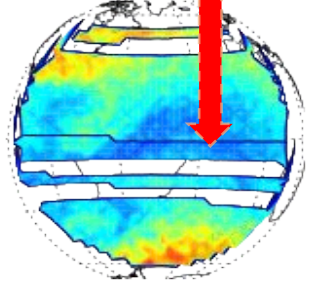


O/N2 col-ratio, NCOL = $1 \cdot 10^{17}$ cm⁻²

GOLD: O/N2 May 12, 14UT

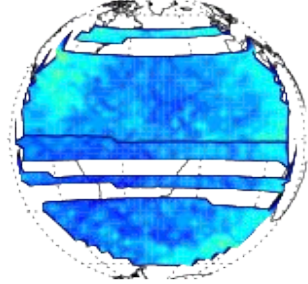


GOLD: Tefl May 11, 14UT



Effective Temp-re, K

GOLD: Tefl May 12, 14UT



GOLD Data
& WA models

display
anti-correlation

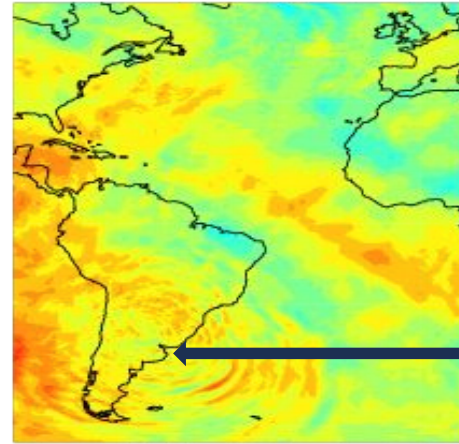
between

Oxygen and

Temperature

at the peak of
the GOLD FUV
emissions

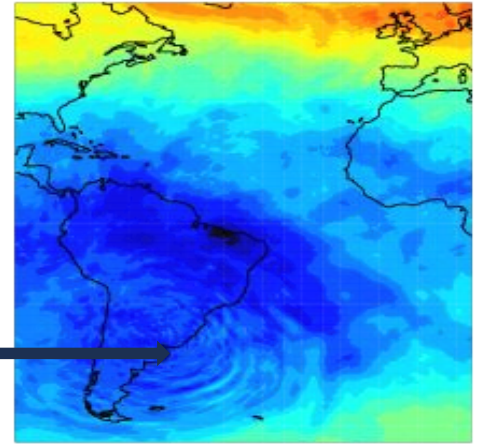
FV3WAM: Temp-re 150 km



Temperature, K

450 510 570 630 690 750 810 870

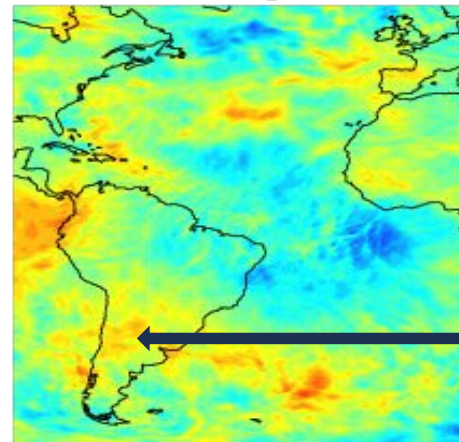
FV3WAM: Oxygen, mmr



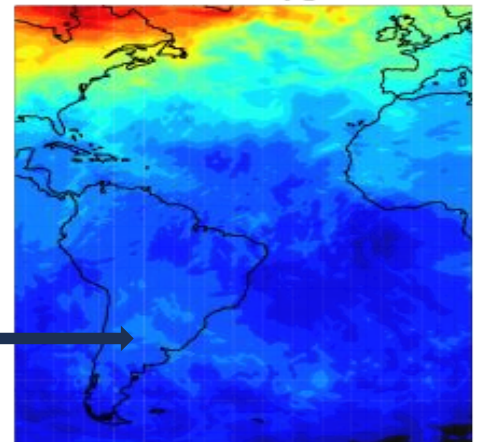
Atomic Oxygen, mmr

0.4 0.5 0.6 0.7 0.8 0.9

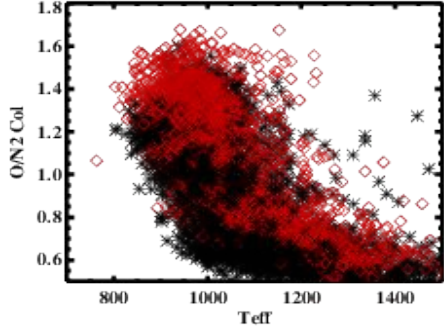
WACCMX: Temp-re at 150 km



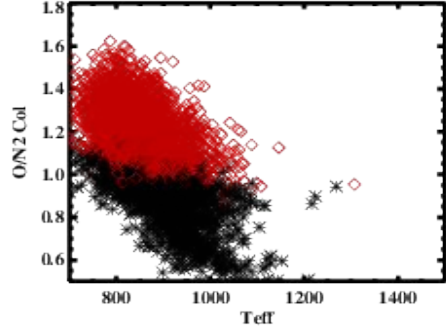
WACCMX: Oxygen, mmr



May 11 GOLD: Tefl-Disk vs O/N2 Col



May 12 GOLD: Tefl-Disk vs O/N2 Col



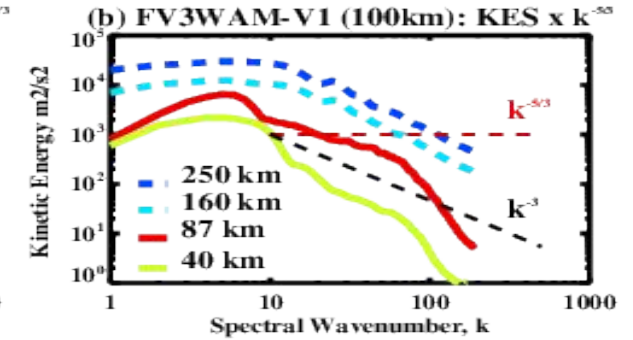
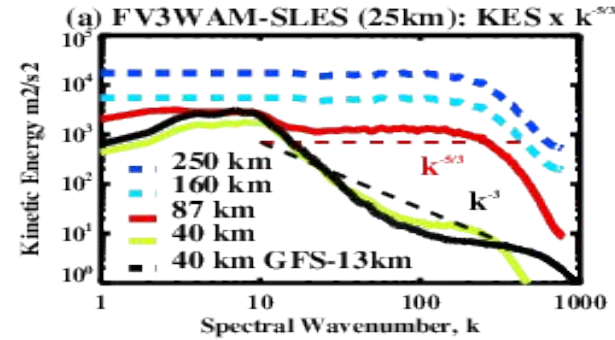
FV3 Mesoscale Dynamics: GW Explicit Simulations

FV3-based Models reproduce the mesoscale GW patterns observed from the troposphere to upper thermosphere.

FV3WAM-25 km to resolve seasonal migration of GW hotspots at ~40 km observed by **HIRDLS EOS Aura**;

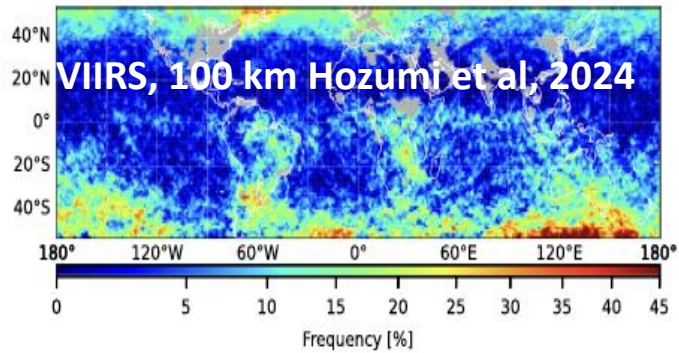
GEOS-5/3km match the OGW patterns seen by NASA **AIRS**

FV3WAM-25 km at ~87 km 'fit' GW events seen by **VIIRS** radiances at ~100 km.

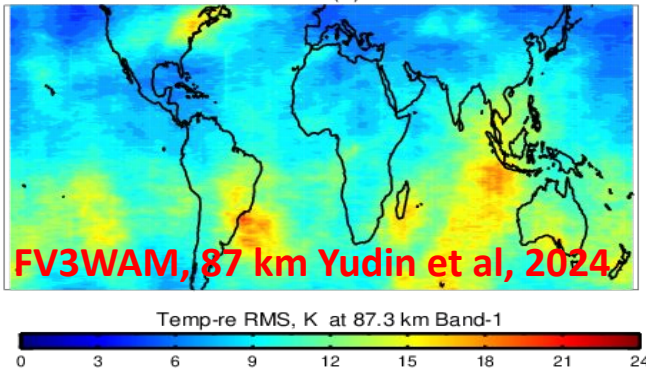


Putman et al., 2022

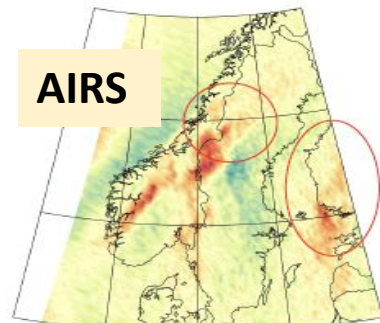
(a) Wave Event Occurrence, NDJF



Jan: 87km: T-RMS(K) FV3WAM-B1

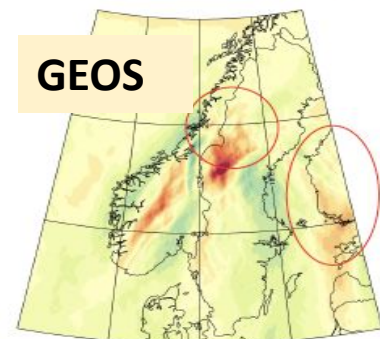


AIRS (brightness T anomalies)



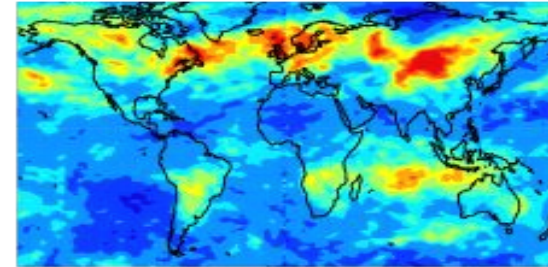
GEOS 3km 181L

model temperature is convolved with the AIRS ker

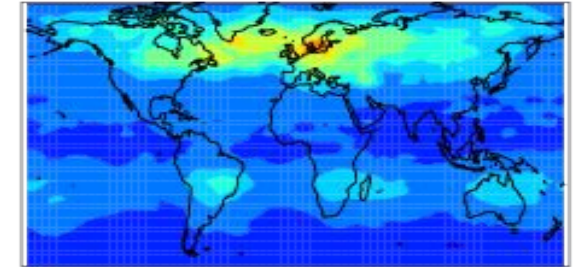


HIRDLS

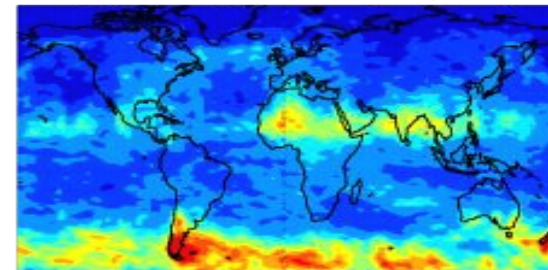
(c) Jan: FV3WAM, AVMF, mPa



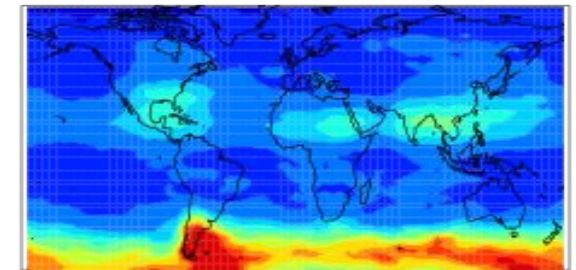
(d) Jan: HIRDLS, AVMF, mPa



(e) Jul: FV3WAM AVMF, mPa

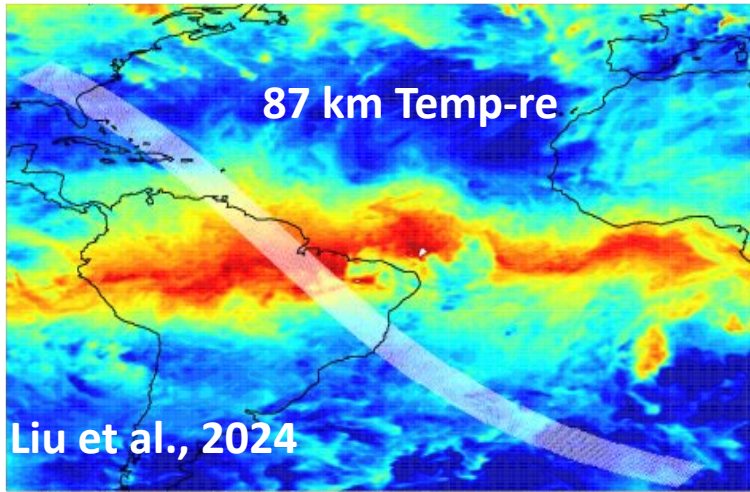


(f) Jul: HIRDLS, AVMF, mPa

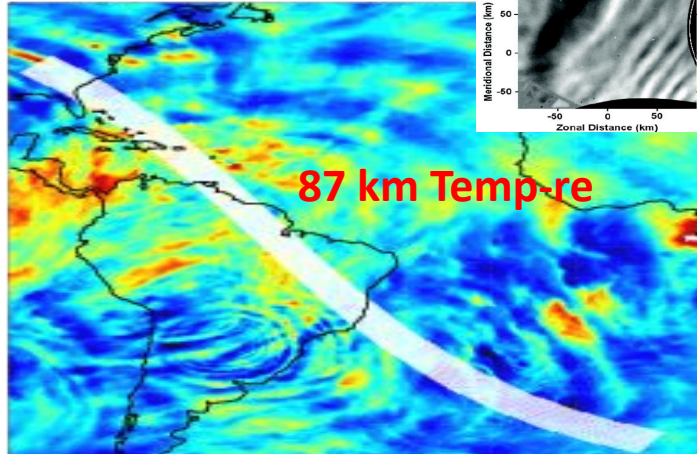


WACCM-X/SE and FV3WAM-SLES (25 km) at 87 (AWE) and 80 (EZIE) km: Mesoscale Wave Patterns in Temperature and Horizontal Winds

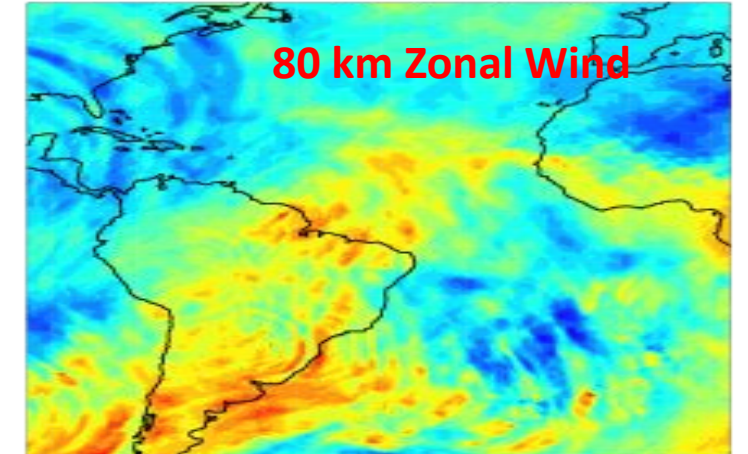
JAN 20/0Z WACCMX_25km



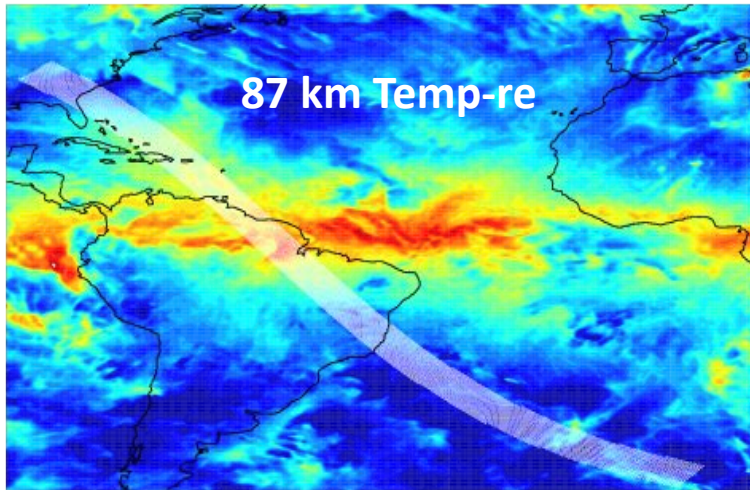
AWE-87km: FV3WAM-25km



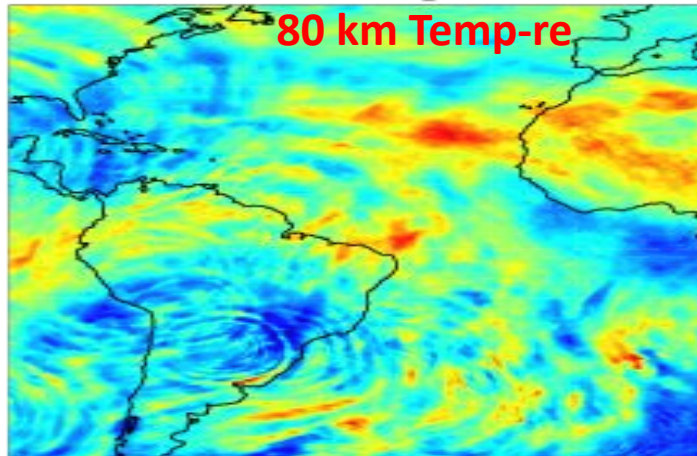
EZIE-80km: EW-wind FV3WAM



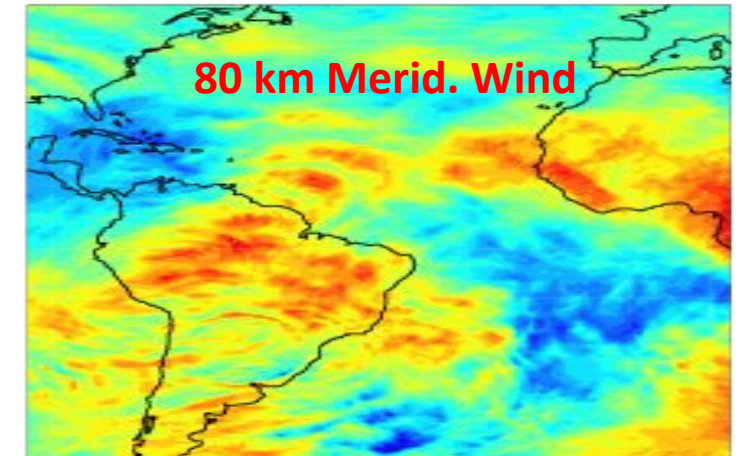
JAN 21/0Z WACCMX_25km



EZIE-80km: Temp FV3WAM



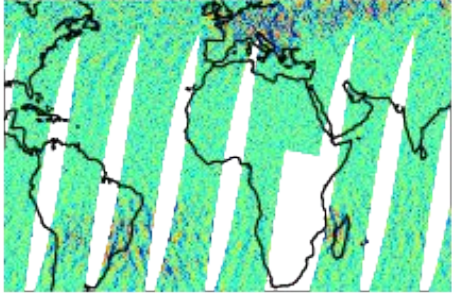
EZIE-80km: NS-wind FV3WAM



AWE Temp-res and EZIE Secondary Products (Winds-80 km and Temp-re 60-80km) will provide data for Meso-Dynamics

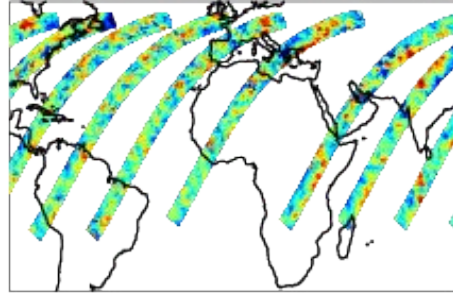
Dec 30 2023: Sampling Orbital Swaths of AIRS (15 $\mu\text{k CO}_2$, 42 km peak) and AWE (OH-emission, 87 km)

a) 2023-12-30 AIRS, ~42 km: T-pert, [%]



AIRS Temp-re Perturbations, [%], 42 km
-0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5

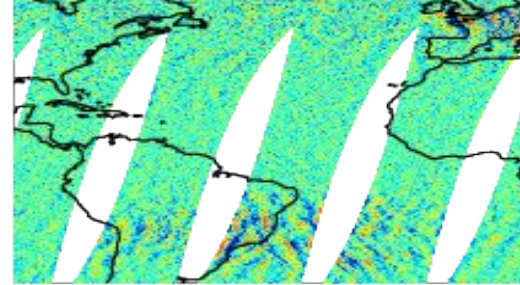
d) 2023-12-30 AWE 87 km: T-pert, [%]



AWE Temp-re Perturbations, [%], 87 km
-8 -6 -4 -2 0 2 4 6 8

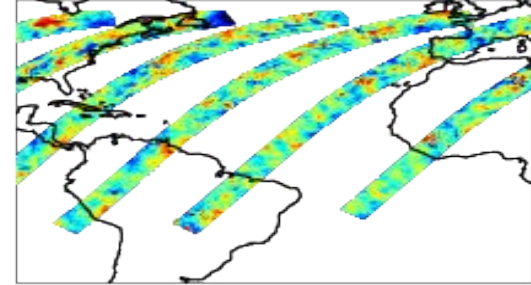
Data
T'/T, %

a) 2023-12-30 AIRS, ~42 km: T-pert, [%]



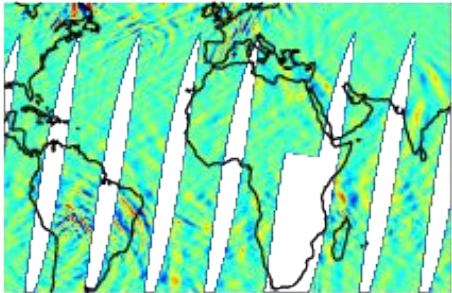
AIRS Temp-re Perturbations, [%], 42 km
-0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5

d) 2023-12-30 AWE 87 km: T-pert, [%]



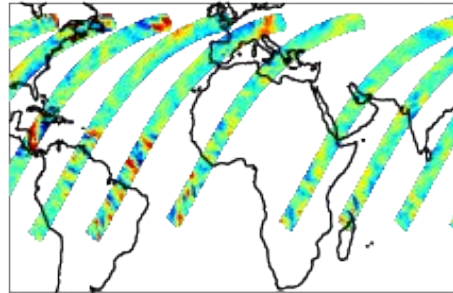
AWE Temp-re Perturbations, [%], 87 km
-8 -6 -4 -2 0 2 4 6 8

b) FV3WAM at AIRS (~42 km): T-pert, [%]



Temp-re Perturbations, [%], 42 km
-1.5 -1.2 -0.9 -0.6 -0.3 0 0.3 0.6 0.9 1.2 1.5

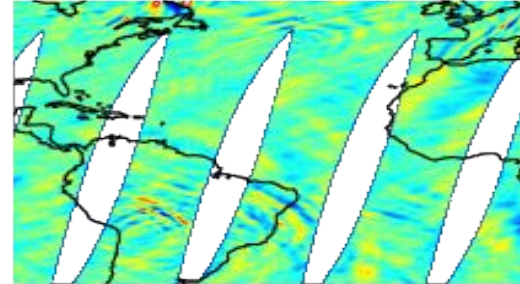
e) FV3WAM at AWE: T-pert, [%]



Temp-re Perturbations, [%], 87 km
-10 -8 -6 -4 -2 0 2 4 6 8 10

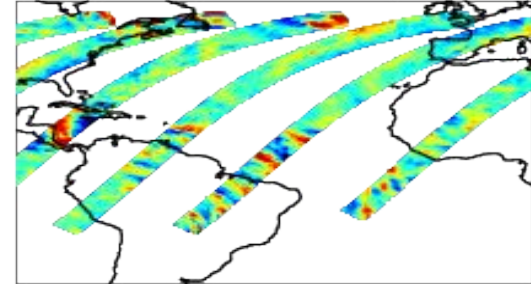
FV3WAM
T'/T, %

b) FV3WAM at AIRS (~42 km): T-pert, [%]



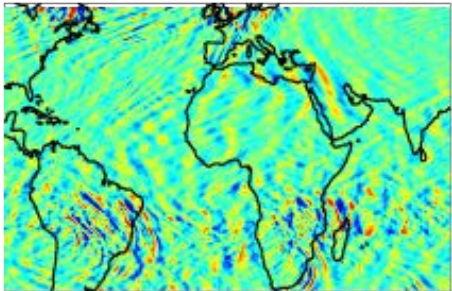
Temp-re Perturbations, [%], 42 km
-1.5 -1.2 -0.9 -0.6 -0.3 0 0.3 0.6 0.9 1.2 1.5

e) FV3WAM at AWE: T-pert, [%]

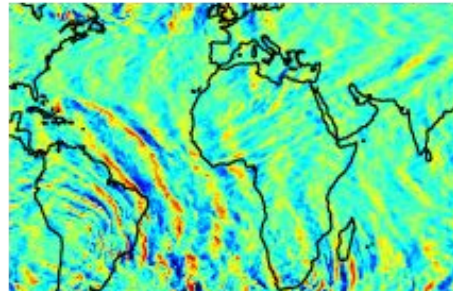


Temp-re Perturbations, [%], 87 km
-10 -8 -6 -4 -2 0 2 4 6 8 10

c) FV3WAM 42 km, 00Z: T-pert, [%]

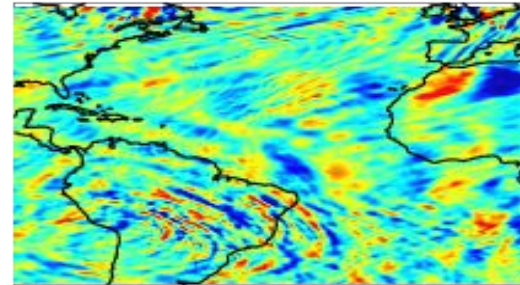


f) FV3WAM 87 km, 00Z: T-pert, [%]

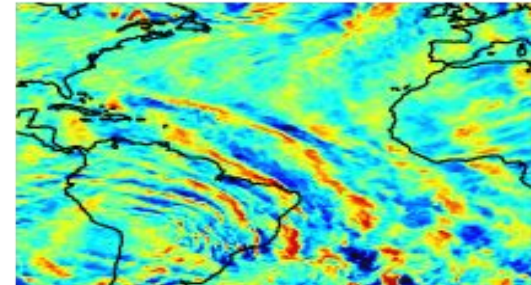


FV3WAM
T'/T, %
00Z

c) FV3WAM 42 km, 00Z: T-pert, [%]



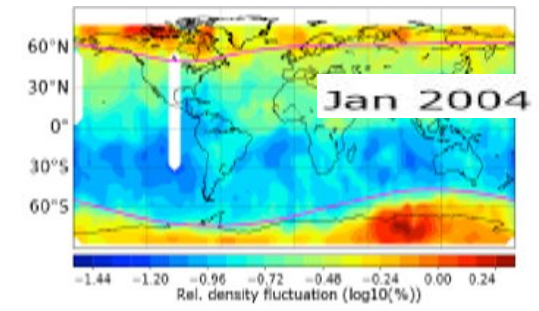
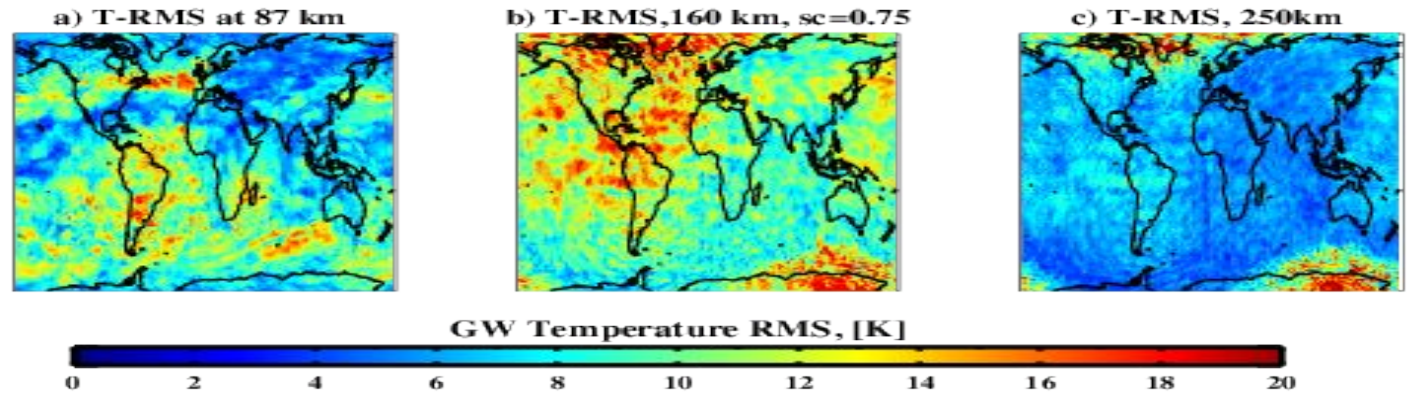
f) FV3WAM 87 km, 00Z: T-pert, [%]



January FV3WAM-SLES GW Regional Activity in 3 Layers

AWE (87km), GOLD (160 km) & GOCE (250 km) /Data Analysis/

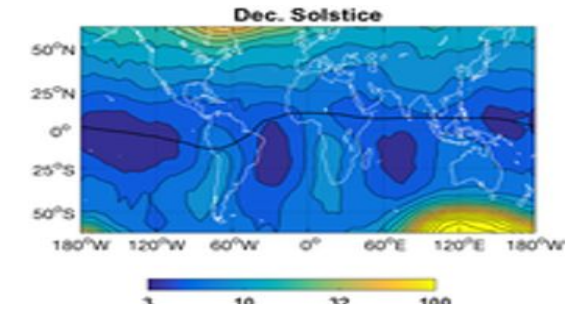
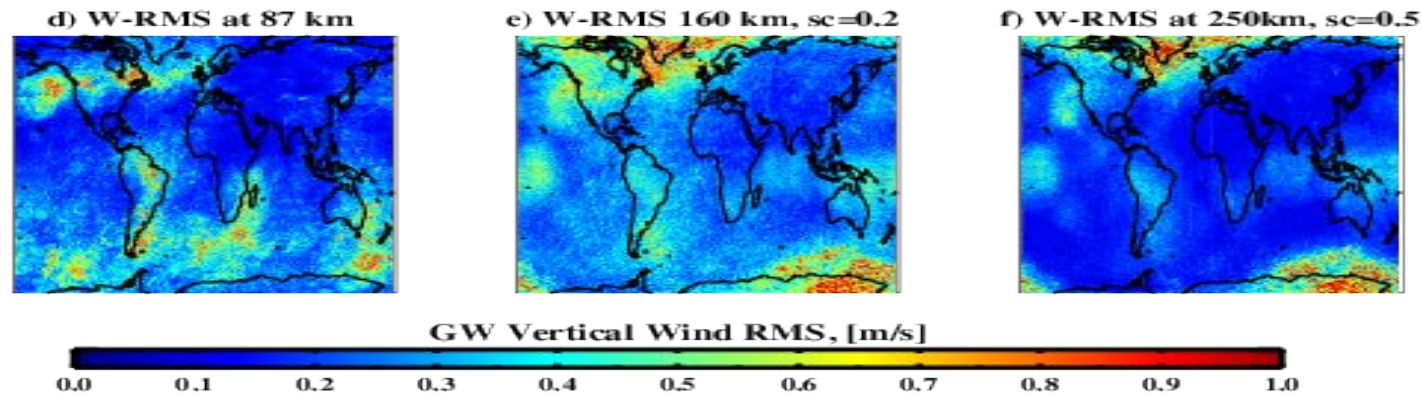
Temp-re



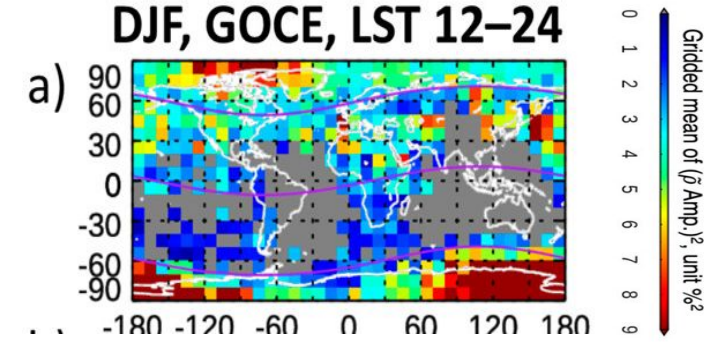
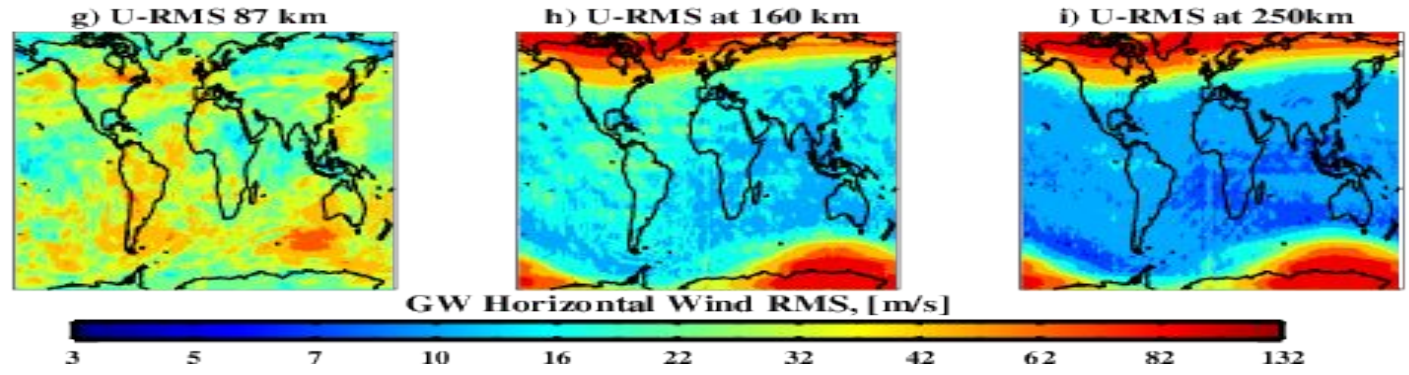
CHAMP Trinh et al., 2018

GOCE: Huixin Liu et al. 2017

Vertical wind

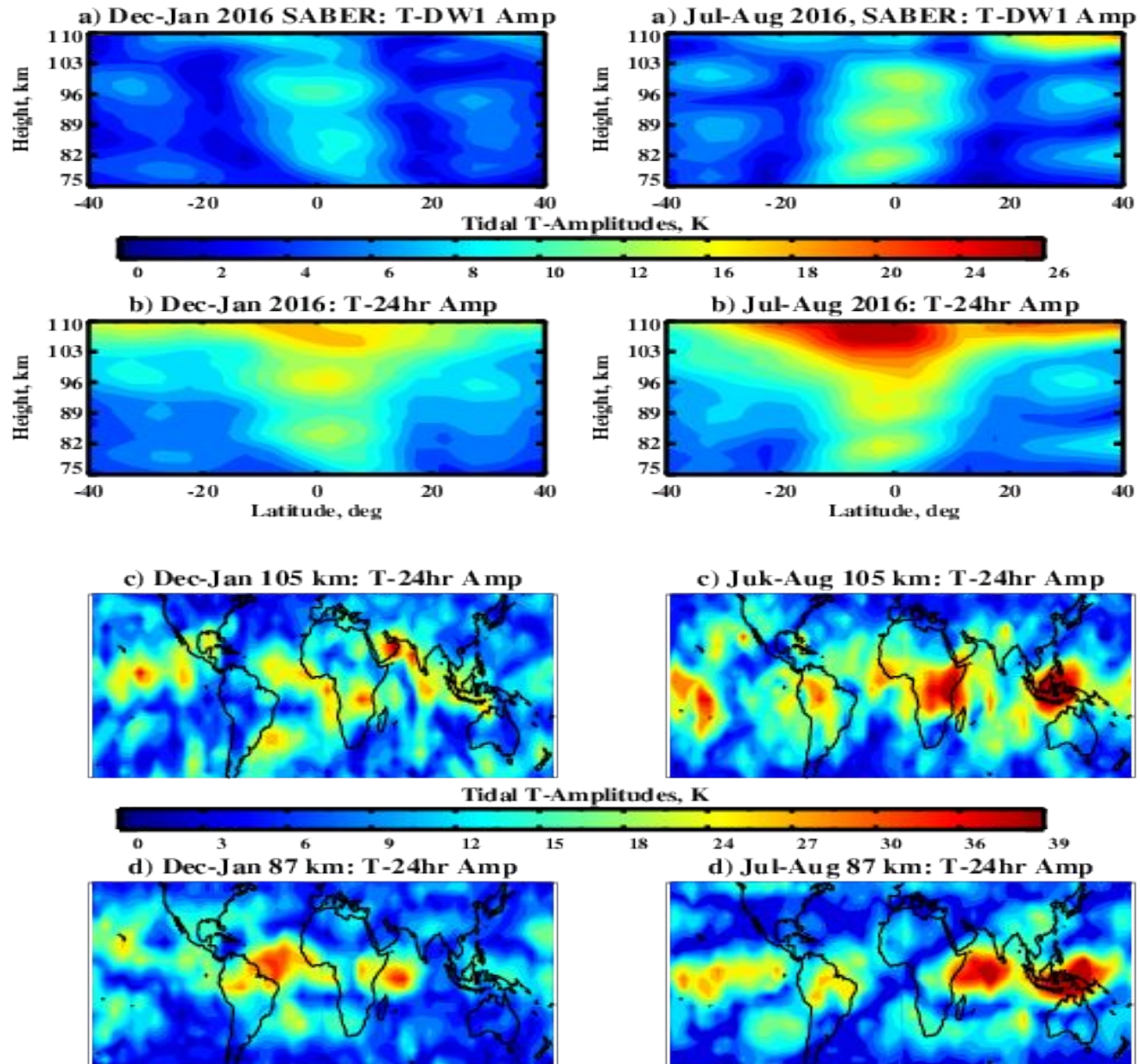


Horizontal winds

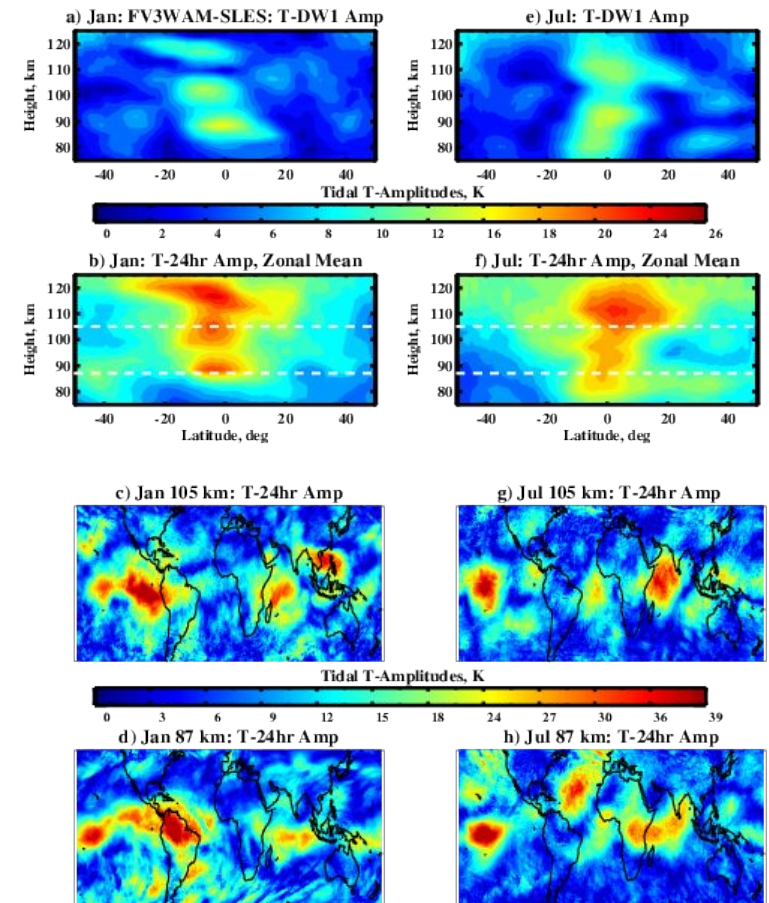


Xu et al., 2024

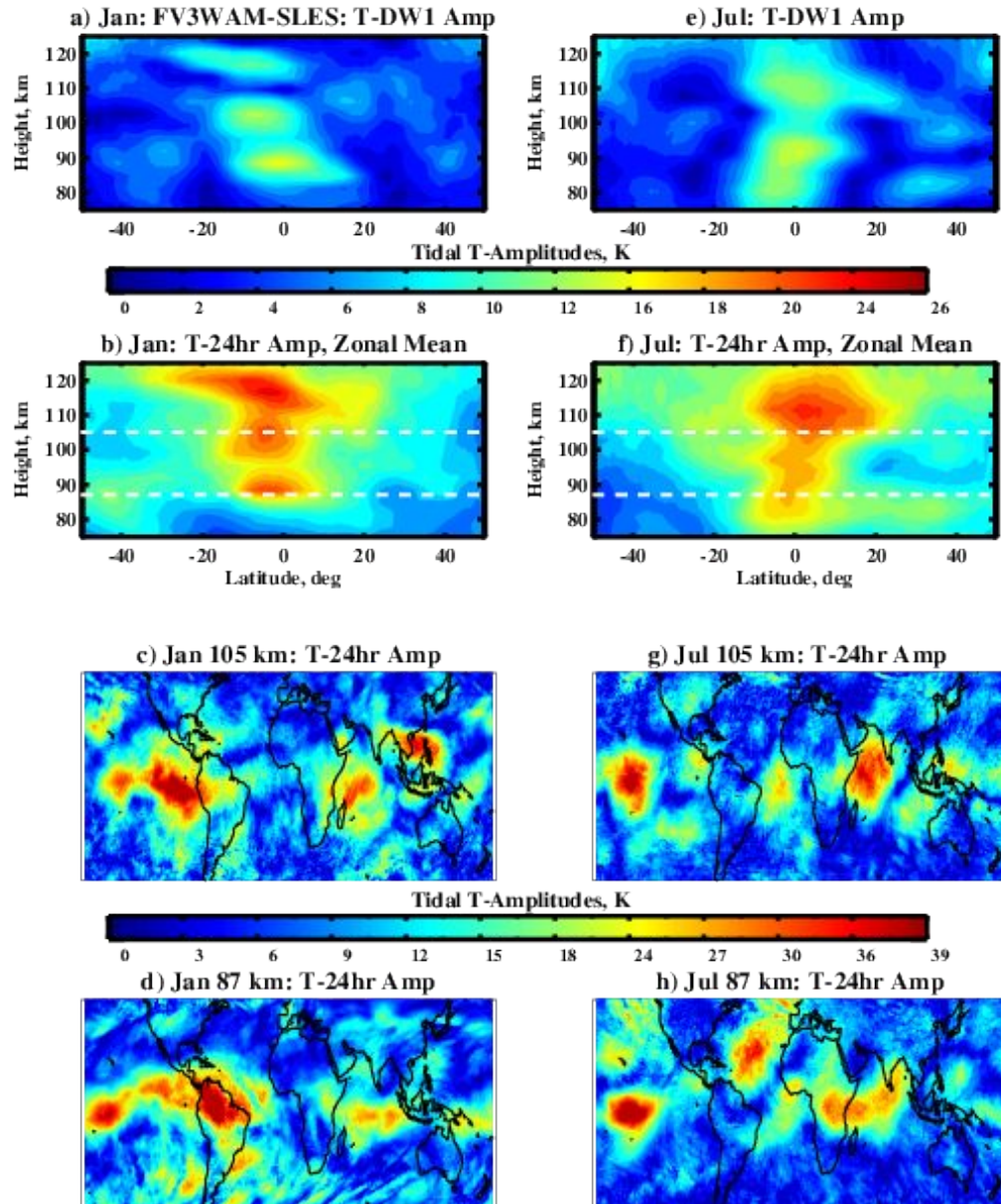
SABER/TIMED: Seasonal Variability of Diurnal Tide in MLT



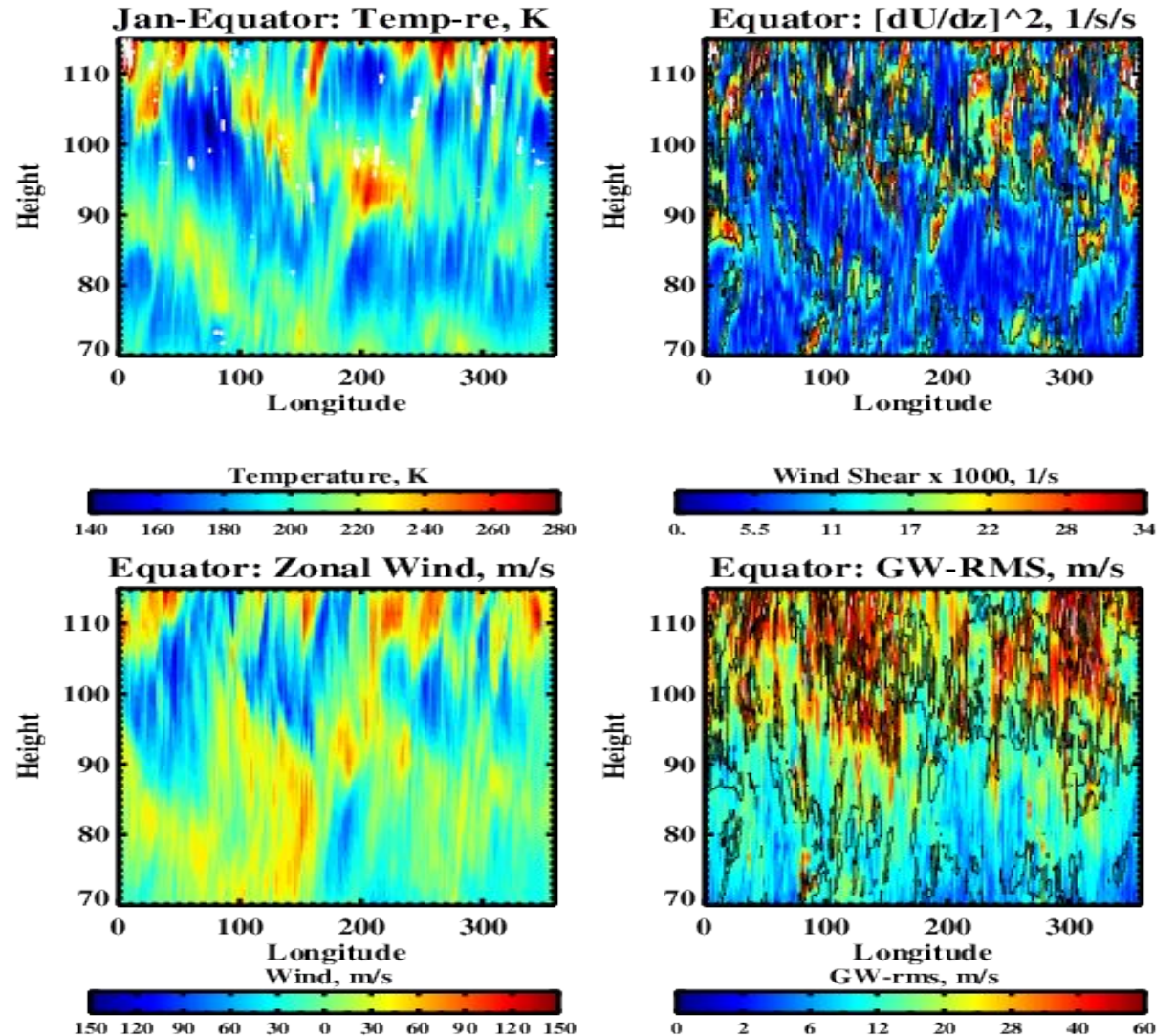
FV3WAM-SLES, Diurnal Tide



FV3WAM-SLES: Seasonal Variability of Diurnal Tide in MLT

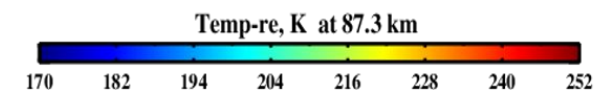
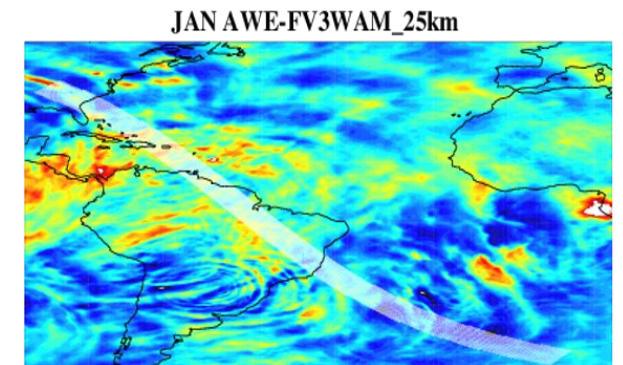
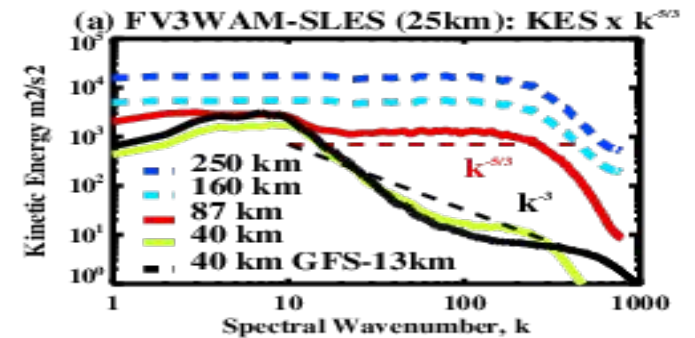
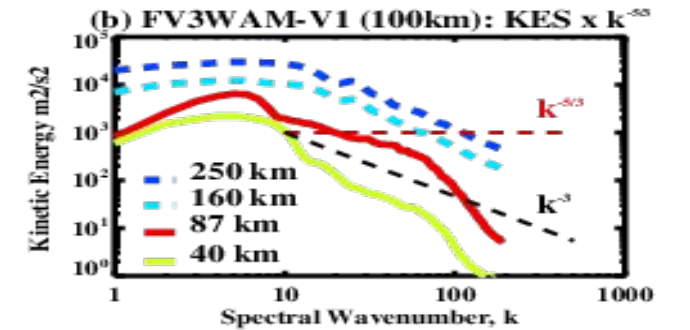


Possible Mechanism for the Multi-Peak Amplitudes of Tidal Amplitudes at the Equator : GW-Tidal interactions and Dynamical Inst



Summary: FV3WAM in UFS and Next Steps

1. Two configurations of FV3WAM as the Space Weather Application of UFS were designed and assessed.
2. FV3WAM-v1 (100 km) will be in the next UFS community release.
3. Combination of two FV3WAM-v1 resolutions (100 km and 50 km) are planned for the JEDI data assimilation with the 1-hour analysis-forecast cycling with retrospective ITM observations.
4. FV3WAM-SLES (25 km) will be further tested and promoted as the Nature Run (NR) simulations for OSSEs for SW-oriented missions.
5. Twin-OSSE (WACCM-X/SE 25 km) & FV3WAM-SLES (25 km) design will support next SW-oriented missions:
EZIE, DYNAGLO, WindCube, GDC and DYNAMIC



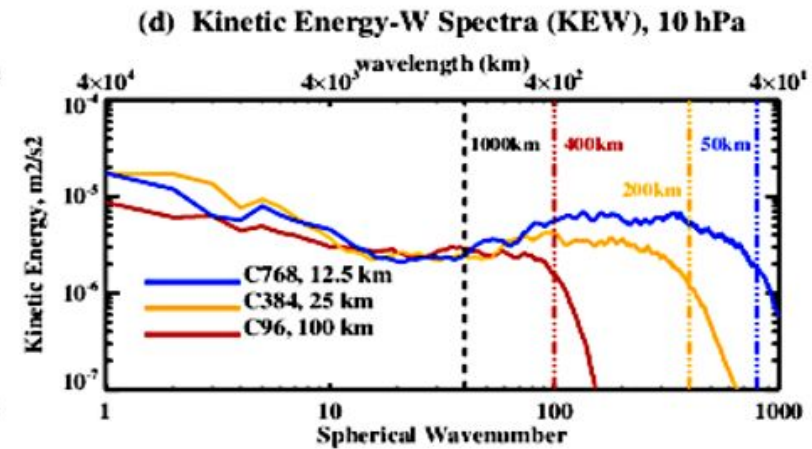
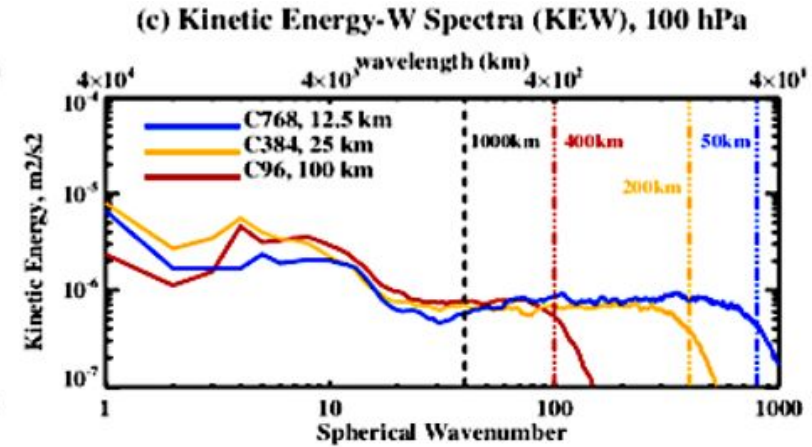
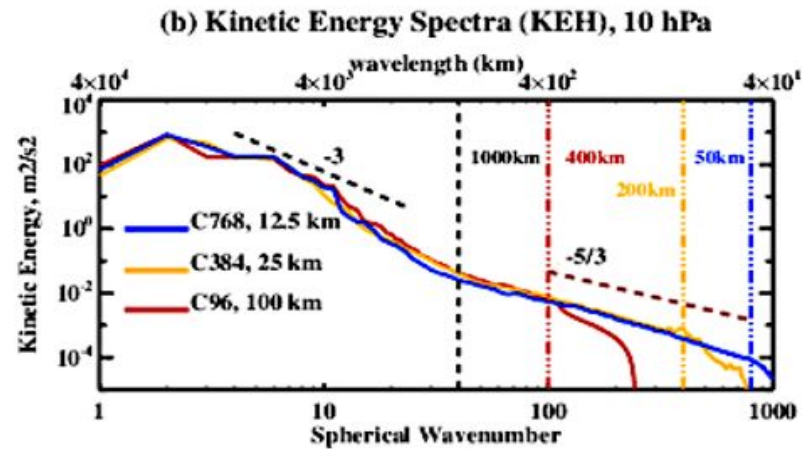
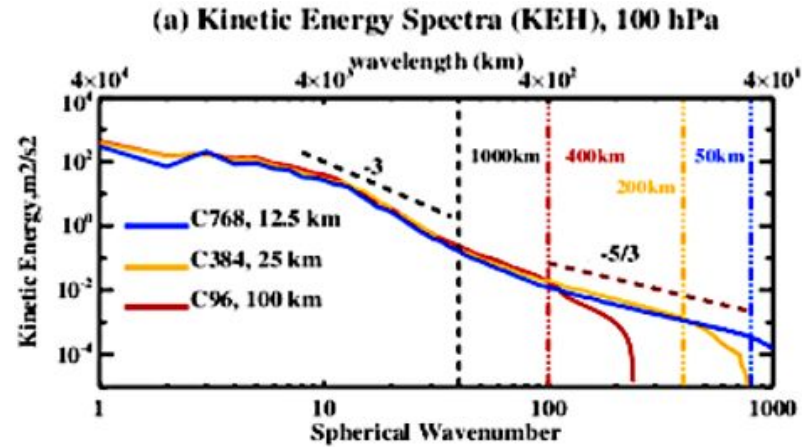
FV3WAM: Kinetic Energy Spectra and Scale-Aware GW Physics

FV3 dycore resolves the medium- and mesoscale waves in the horizontal & vertical energy spectra=> (4-6)dx perturbations.

FV3WAM-v1 at moderate (100-km, 50-km) resolutions have been used in the multi-year runs to evaluate the seasonal variability of the zonal mean flow, meridional transport circulation, PWs, and tides. The UGWP-v1 of GFS (Yudin et al., 2020) adapted to the ITM layers in the scale-aware fashion.

FV3WAM-SLES have been tested with and without GW physics. The Smagorinsky Large-Eddy-Simulation (SLES) framework (1963) in FV3 dycore replaces the column GW physics of GFS.

FV3WAM-SLES is capable to perform GW Explicit Simulations without specifications of any types for "sub-grid" sources of waves.



$$\tau_{unres} \approx \rho E_{hu}^{\frac{1}{2}} E_{wu}^{\frac{1}{2}} \sim \rho \left(k_c^{-\frac{2}{3}} - k_d^{-\frac{2}{3}} \right)^{1/2} (k_d - k_c)^{1/2} \sim \rho k_c^{-1/3} k_d^{1/2} \quad (C1)$$

$k_c = 1/L_{hc}$ 'cut-off' lengths (resolution) define the source strength