Tidal and Mesoscale Dynamics 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 ~(10^{-7}Pa, or at ~450-650 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)

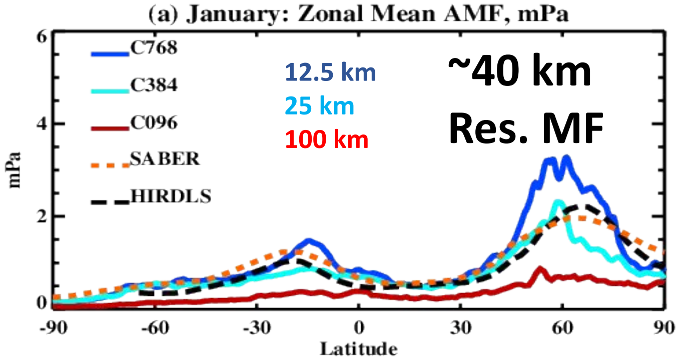
Physics: 3 steps on EL

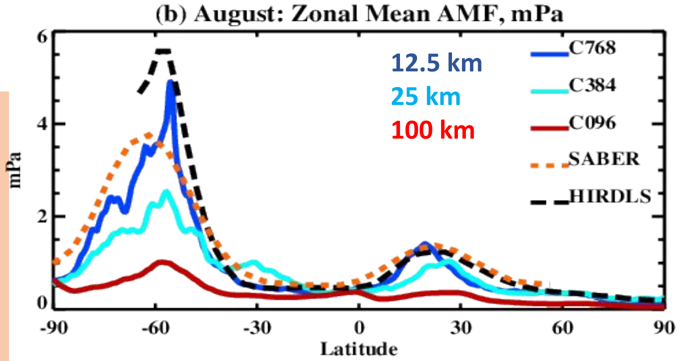
1) Radiation of GFS
2) **WAM <=Mol/Eddy Dissipation (MED)**
3) Standard GFS **with UGWP**

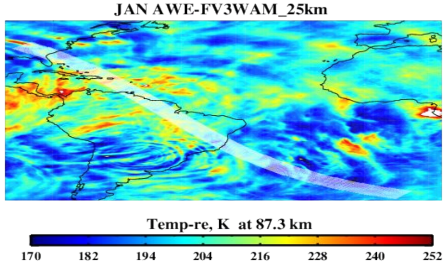
Dycore and Physics "share" MED operators UGWP acts; Vertical winds are not influenced by vertical part of MED

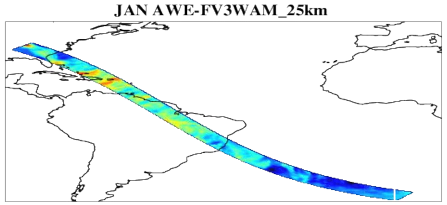
Uncertainties & Advantages of FV3WAM-v1:

- 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

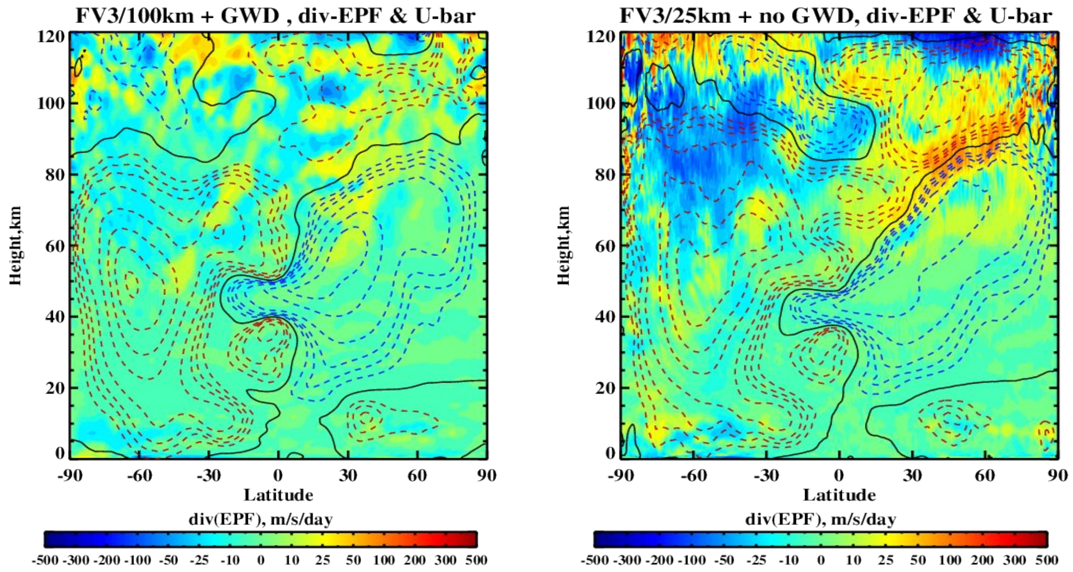
1) Radiation of GFS
2) **WAM without MED processes**
3) Standard GFS **w/o UGWP**

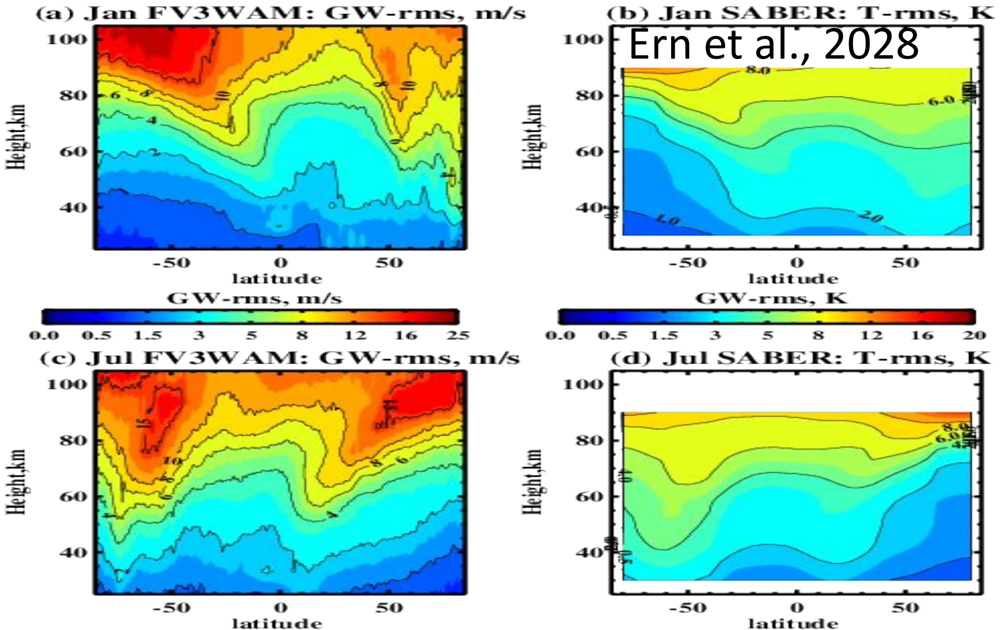
3D Smagorinsky (1963) Large Eddy Simulations (SLES) and Molecular dissipation only belong to FV3WAM dycore; UGWP is 'off';

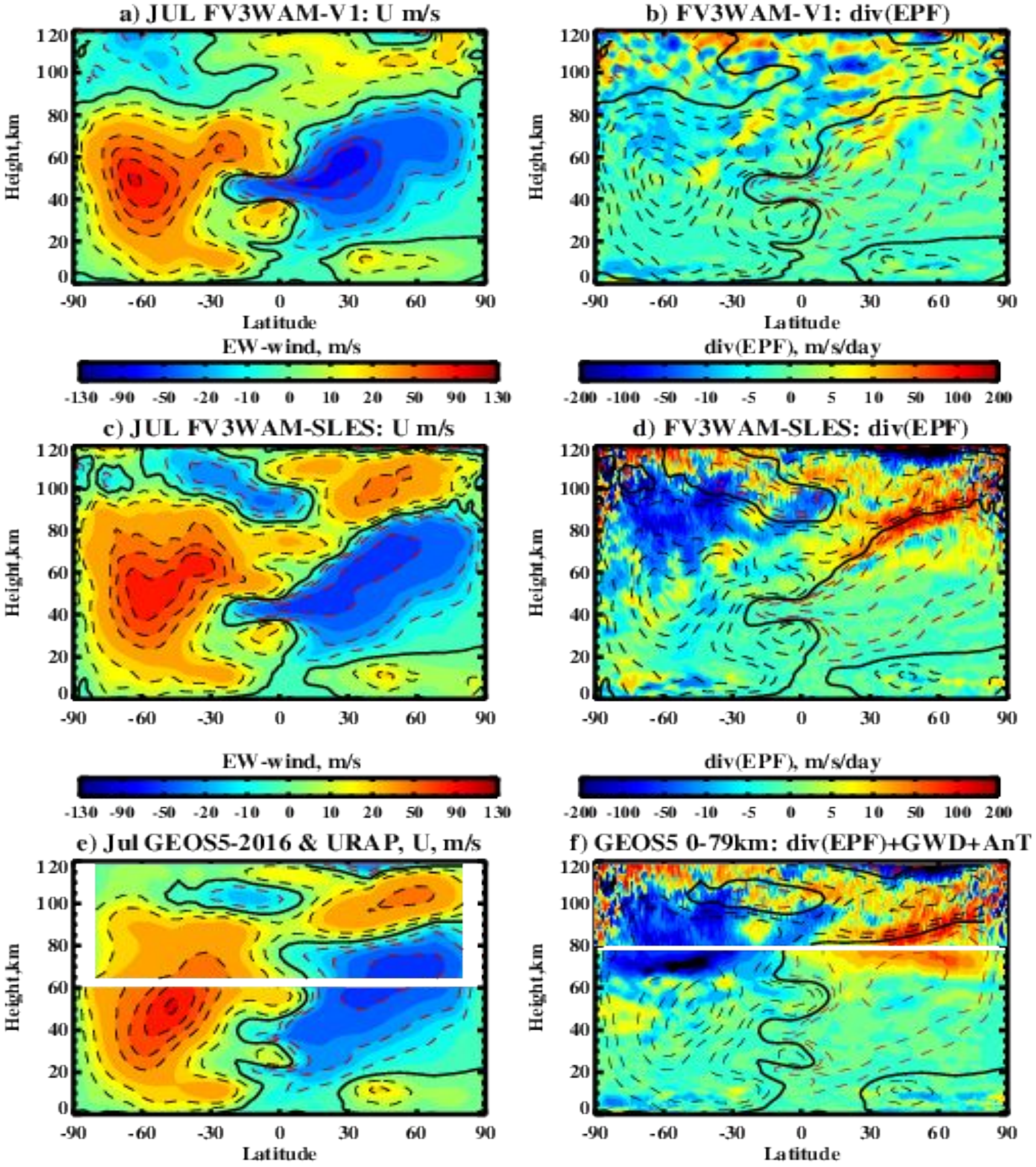
Uncertainties & Advantages of FV3WAM-SLES:

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

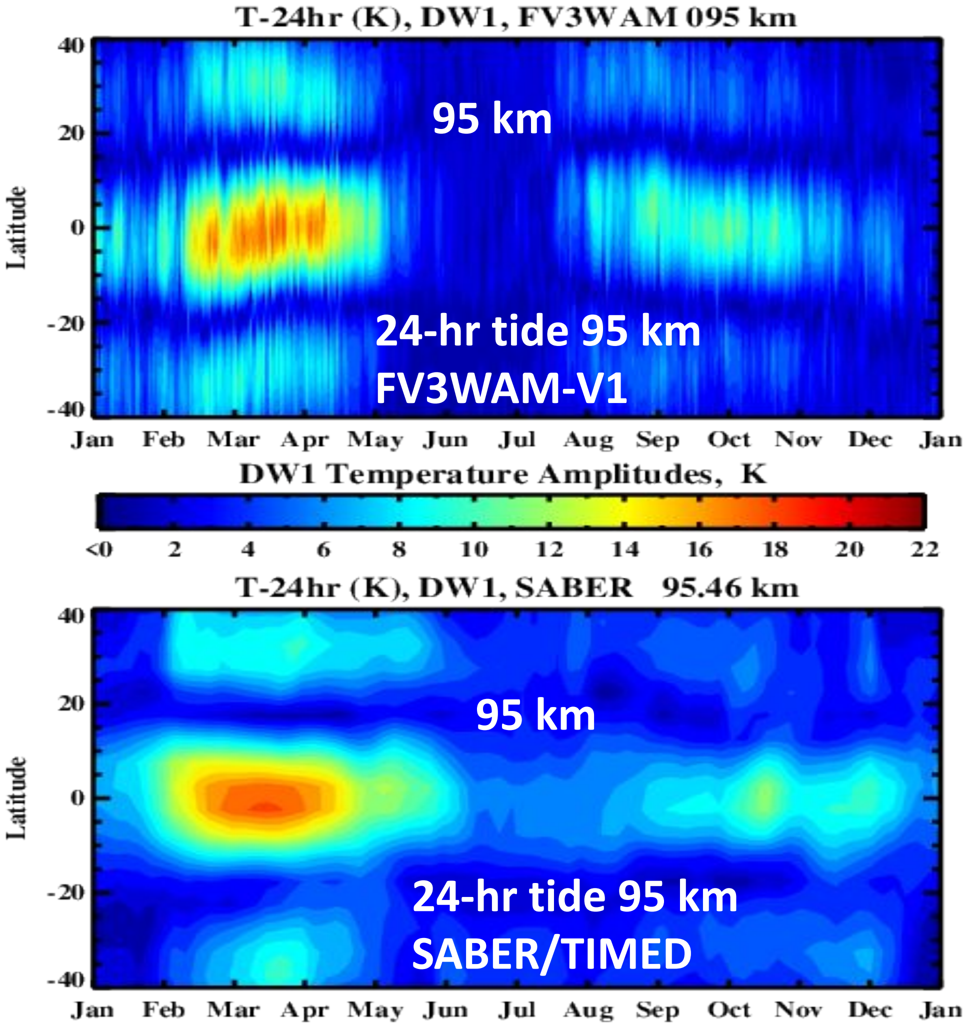
July Zonal Wind and its Wave Forcing:
FV3WAM-100 km vs FV3WAM-SLES (25 km)

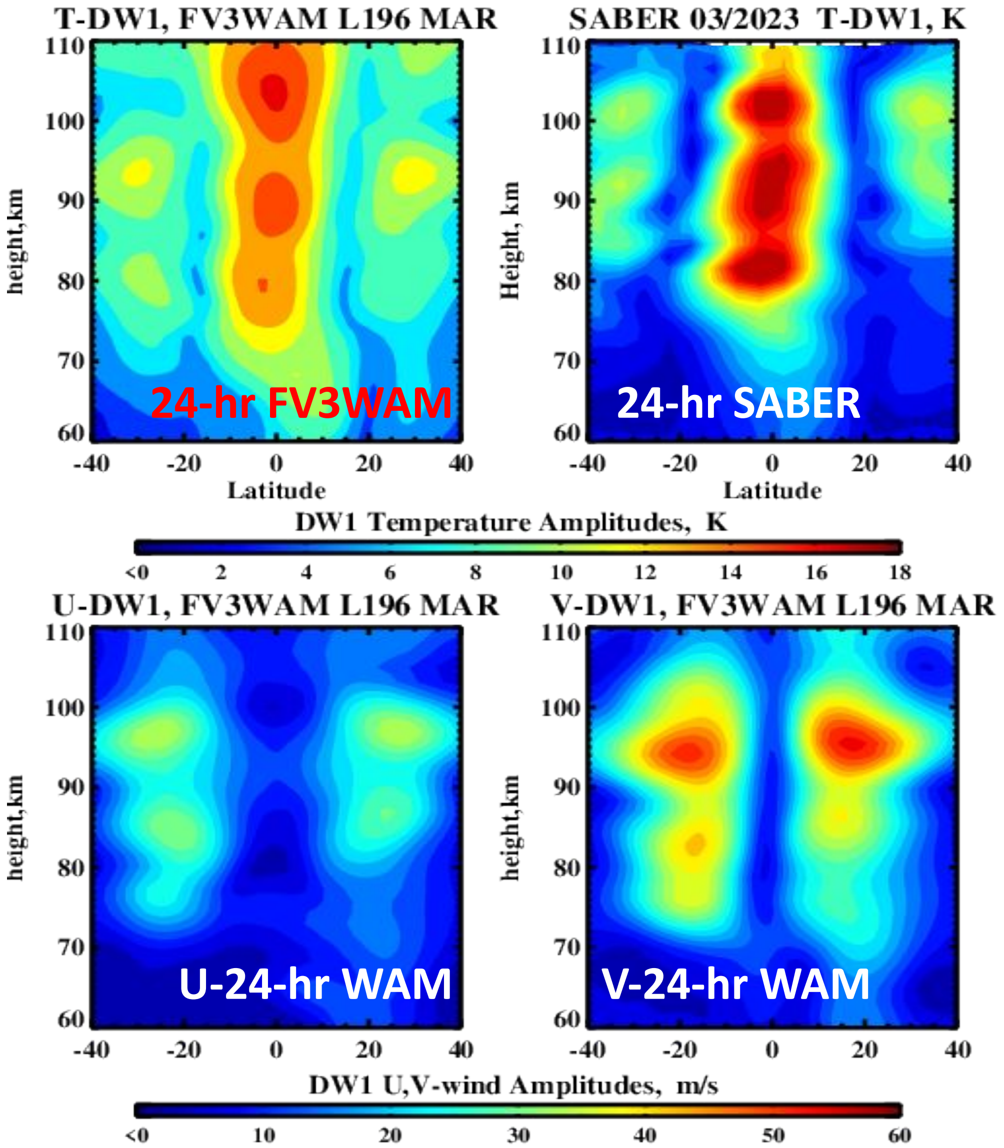




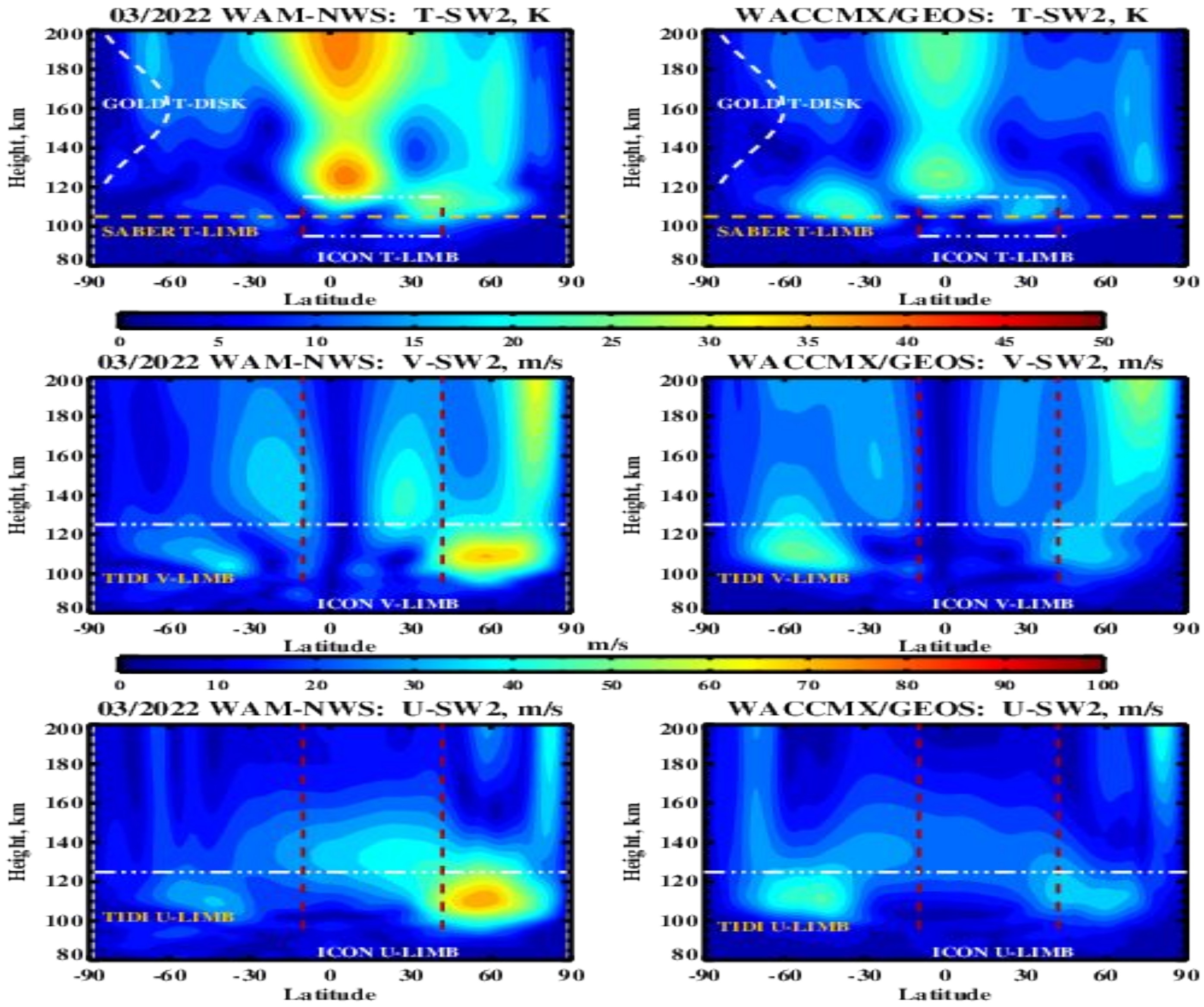


Diurnal Tide: FV3WAM-v1 and SABER/TIMED

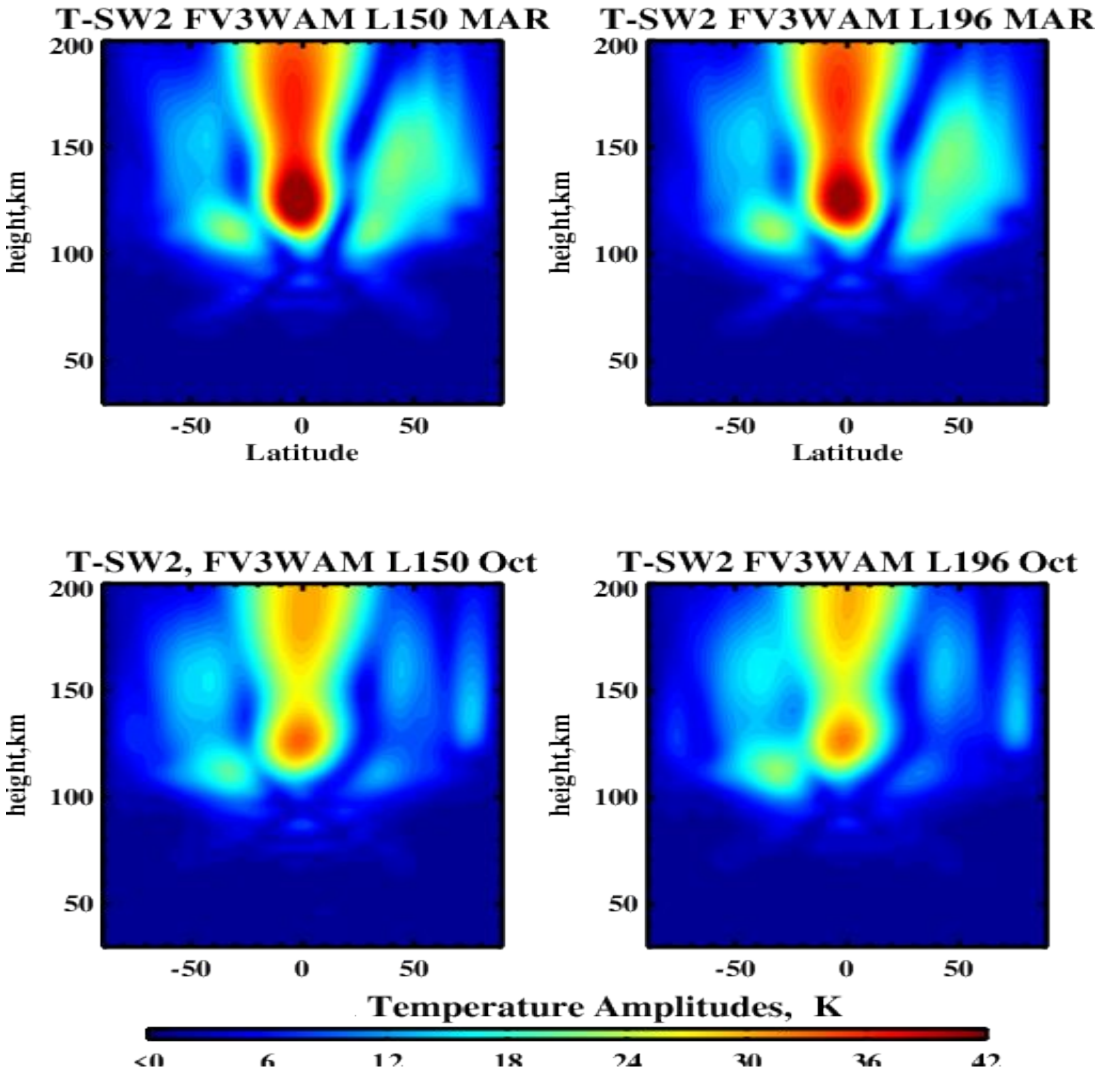




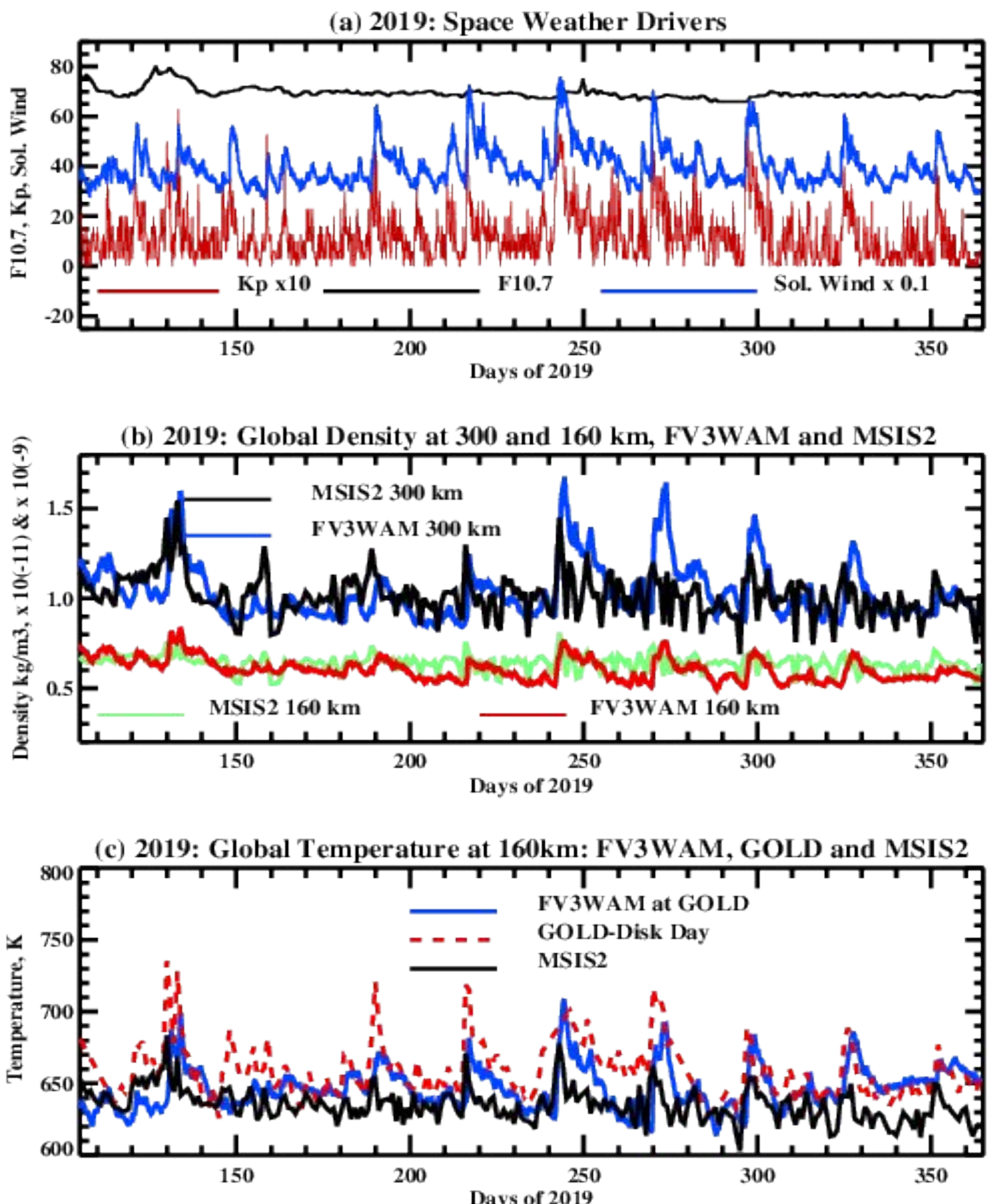
Semidiurnal Tide, SW2 Mar 2022: WAMGSM-DAS vs WACCM-X/GEOS-5



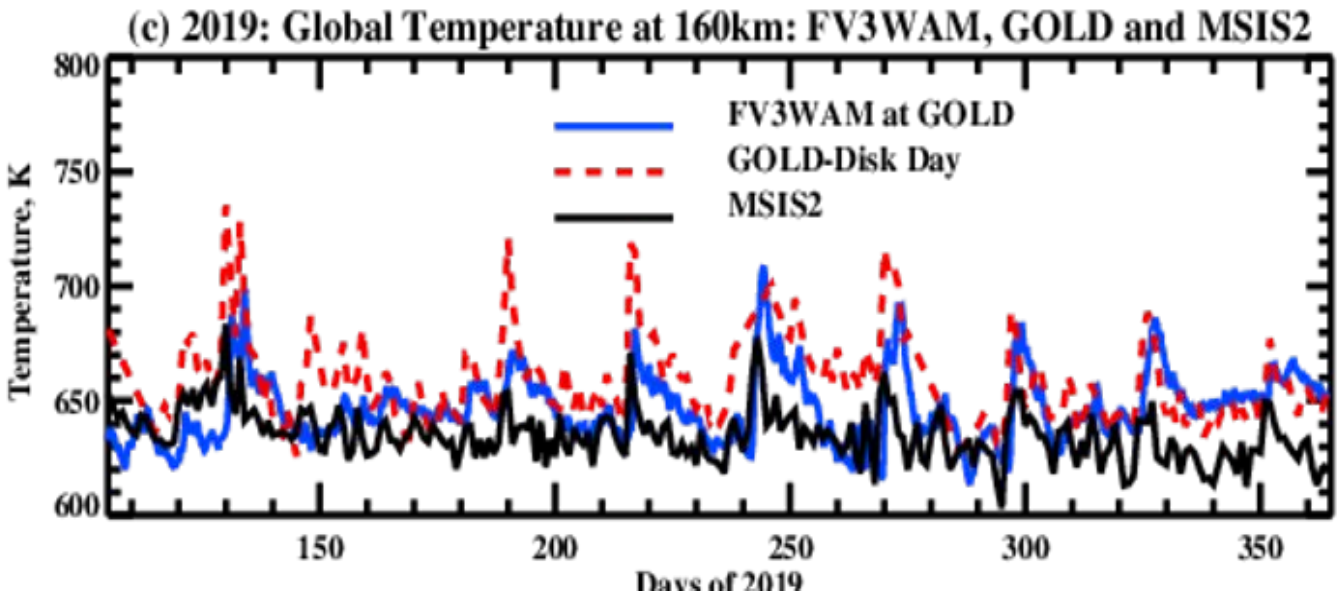
SW2, Mar (top) & Oct (bot) 2018: FV3WAM with 2 vertical resolutions (L150 and L196)



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

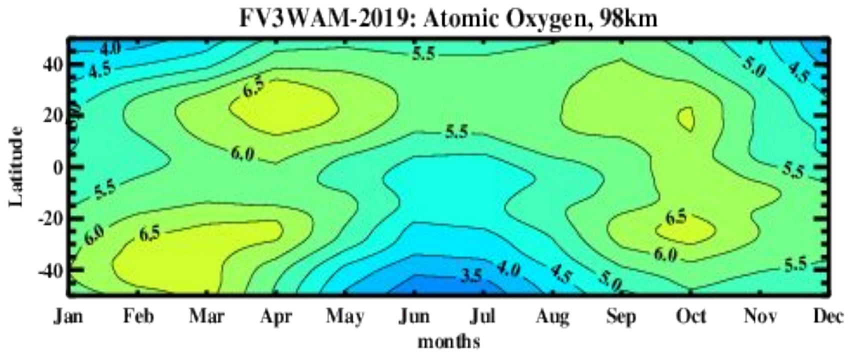


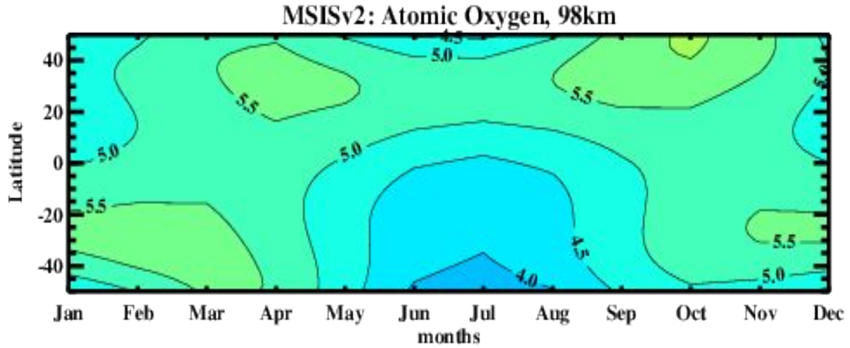
Comparison between
FV3WAM-T (160 km), MSIS_V2 and **GOLD-Tdisk**

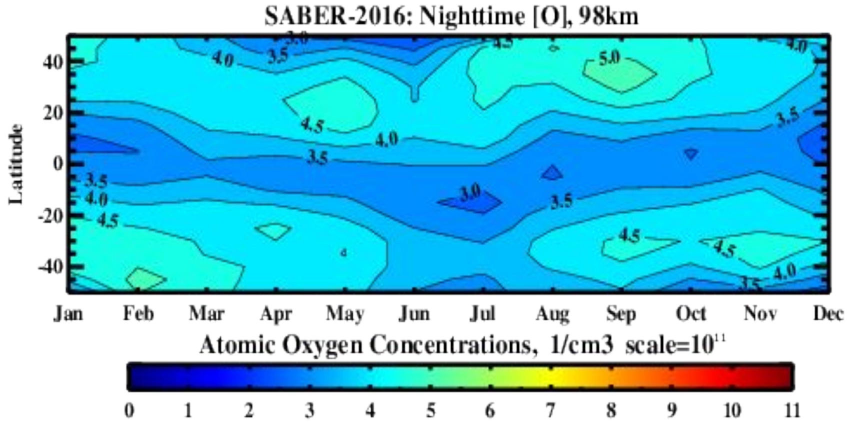


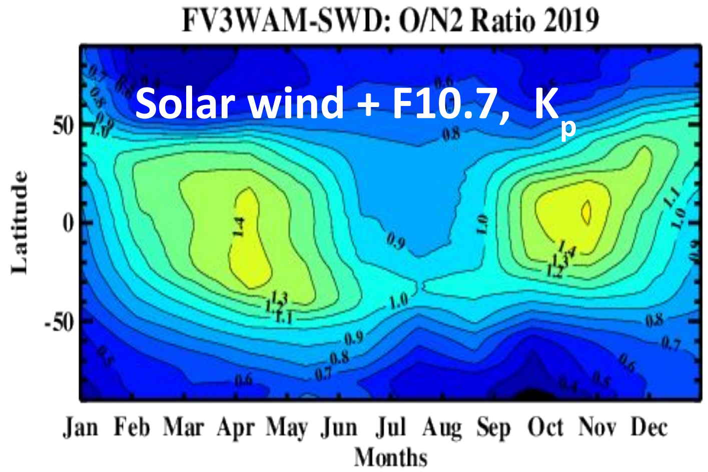
Comparison with GOLD T-disk needs applications of the averaging kernels to map MSIS and FV3WAM simulations => T-disk data space of GOLD

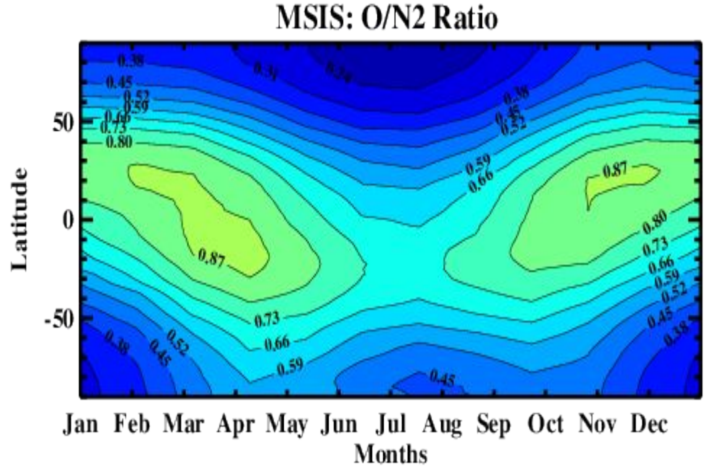
Composition: FV3WAM 2019 Annual Run with SWD of SWPC/NOAA

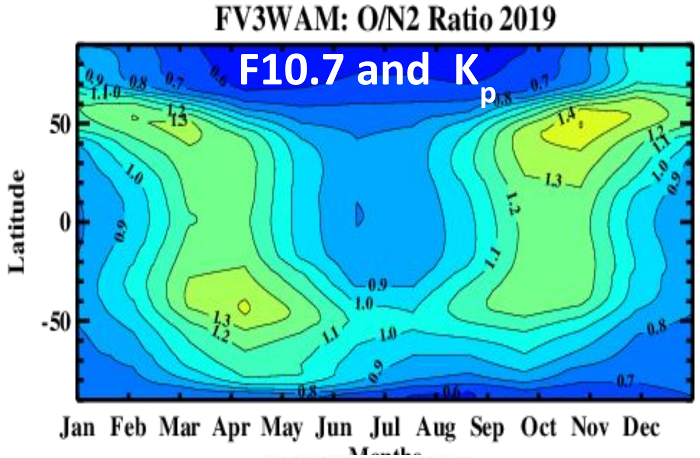


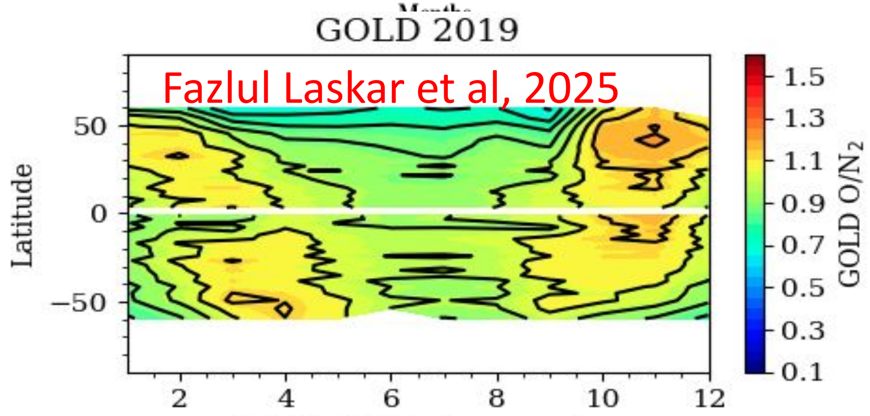


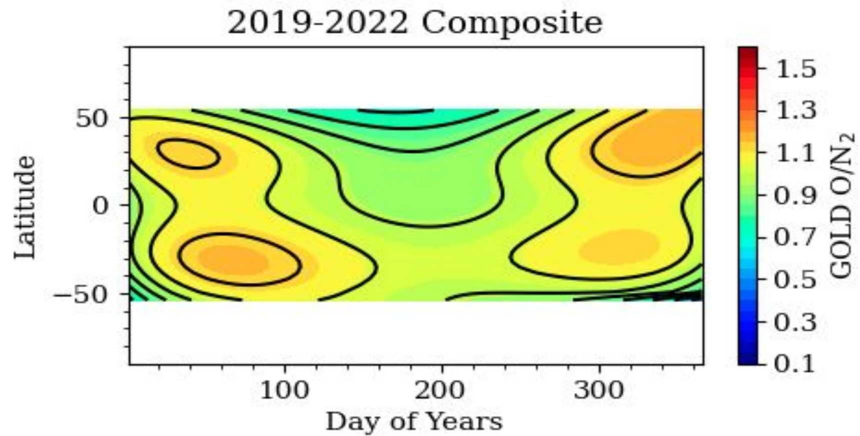




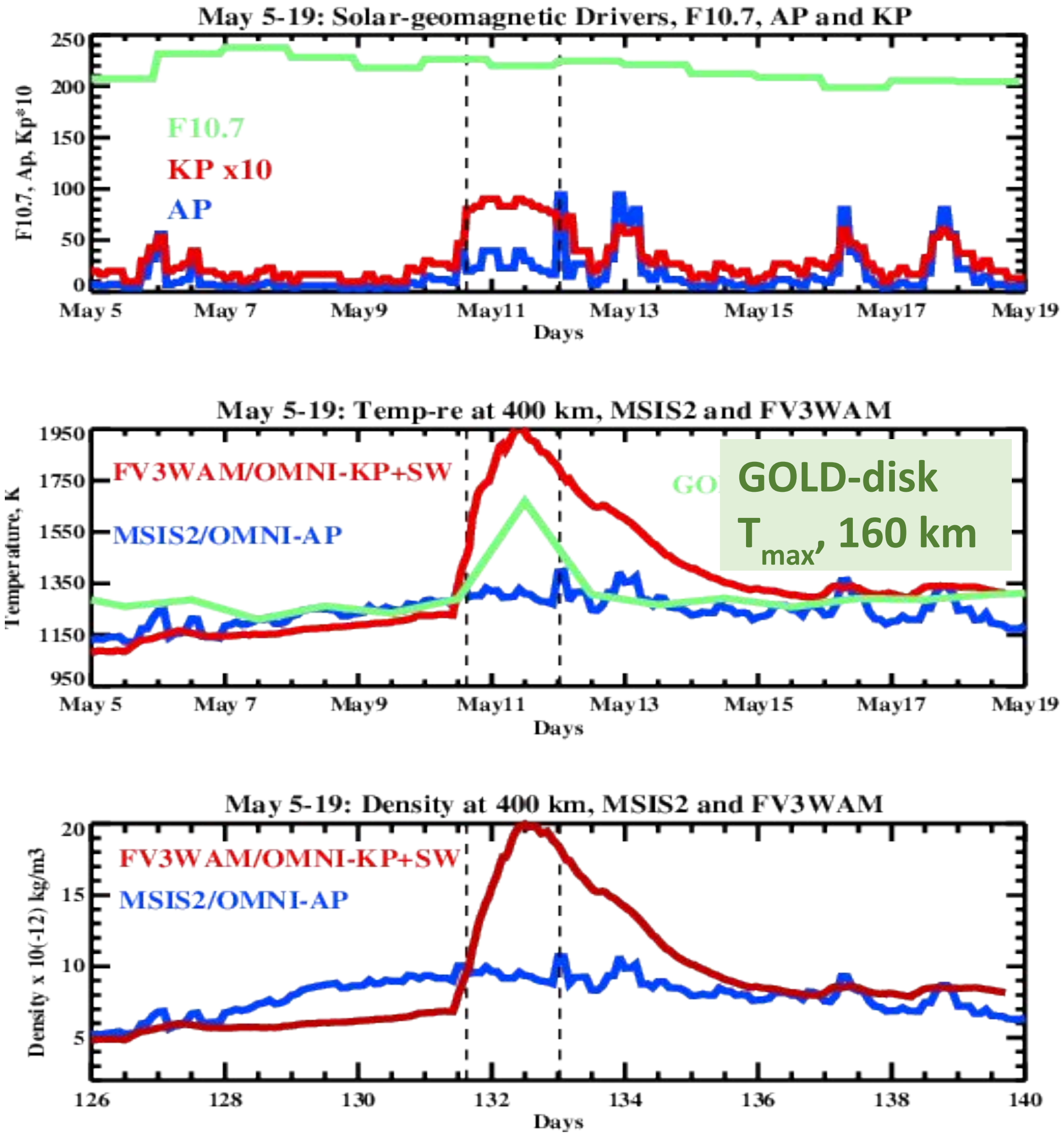


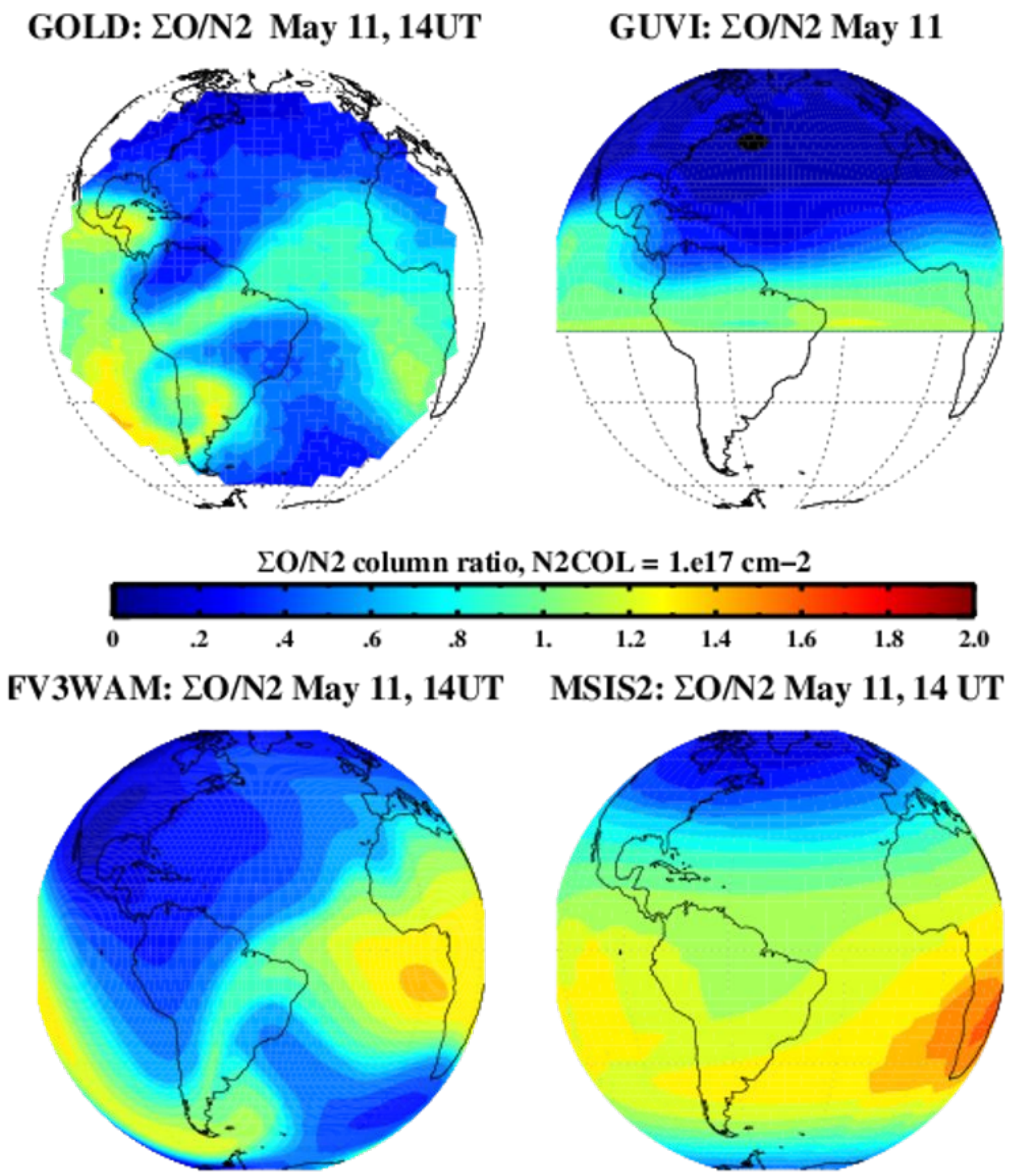






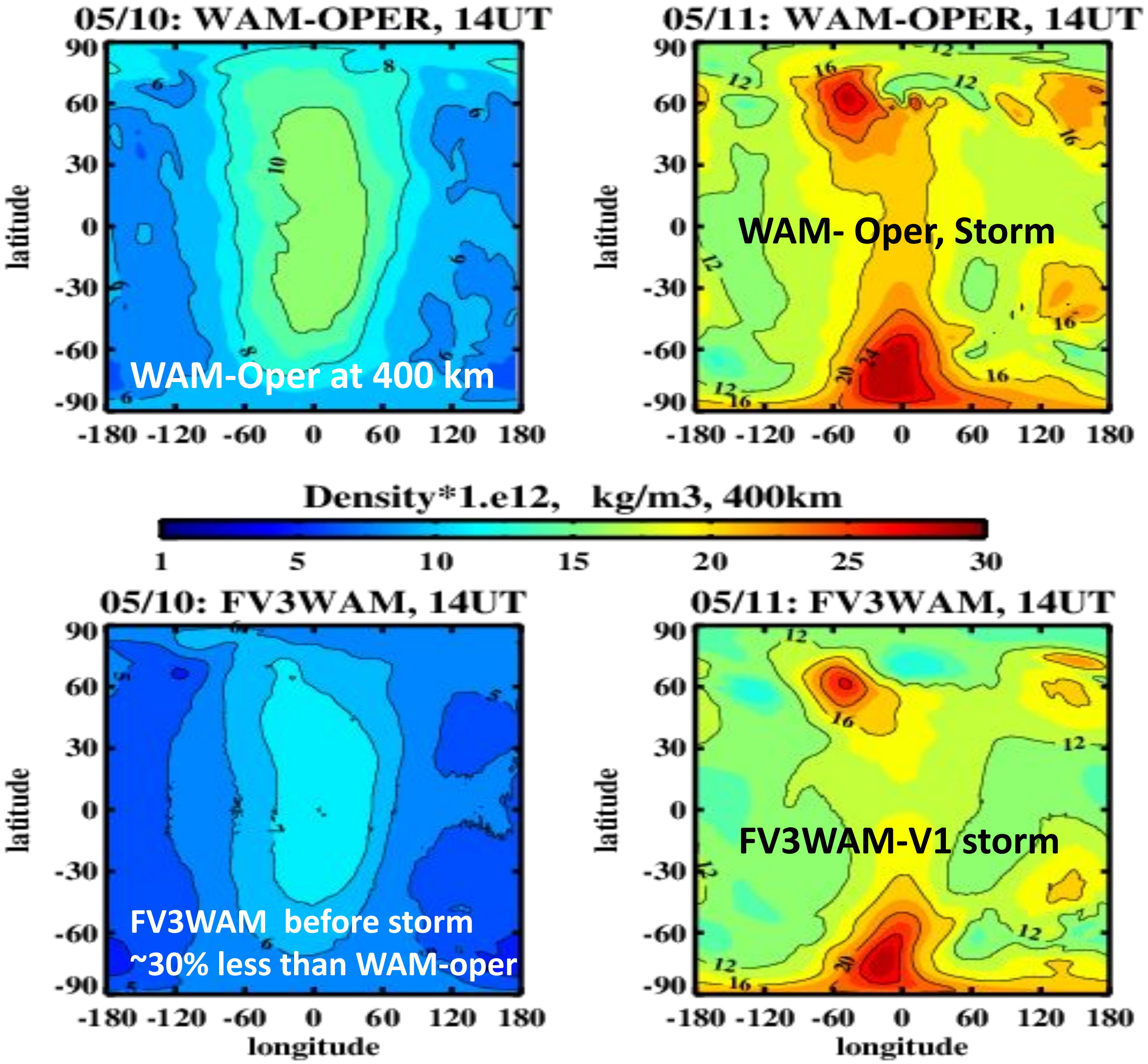
May 2024 Super Storm: First Simulations of FV3WAM-V1



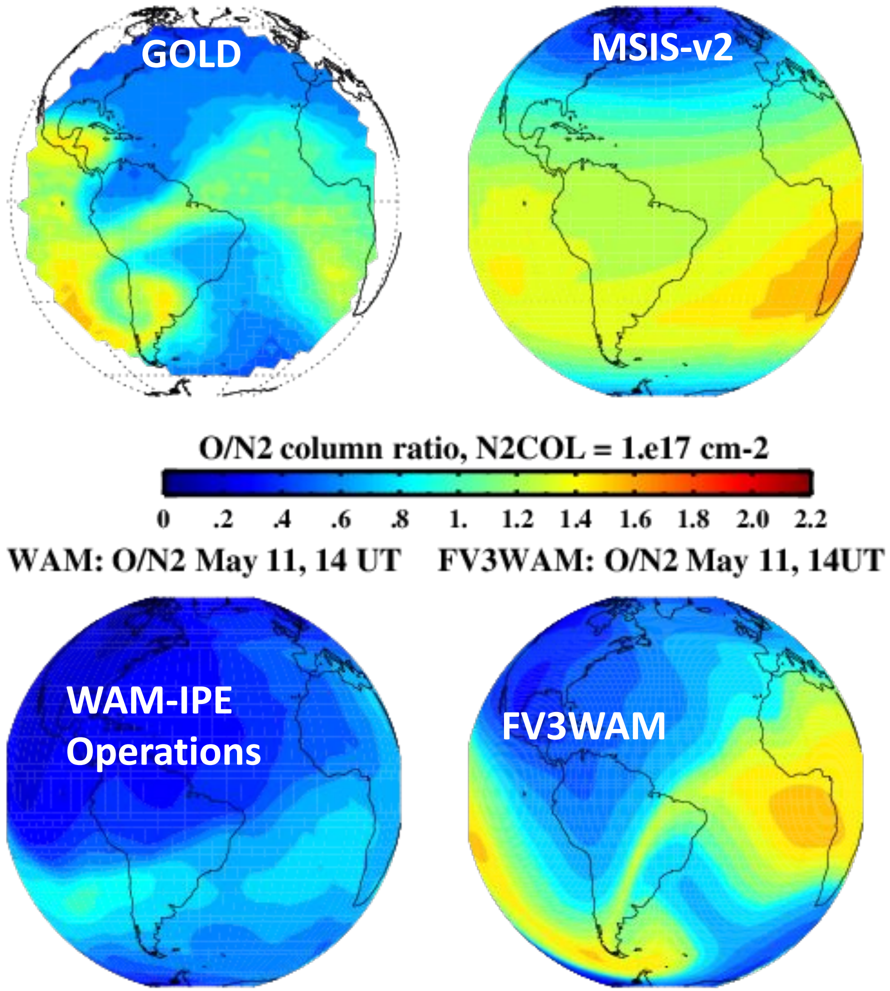


May Storm: WAM-IPE/NWS vs FV3WAM, Density and $\Sigma O/N_2$

Density: PRE-STORM STORM-14UT, as in GOLD O/N_2

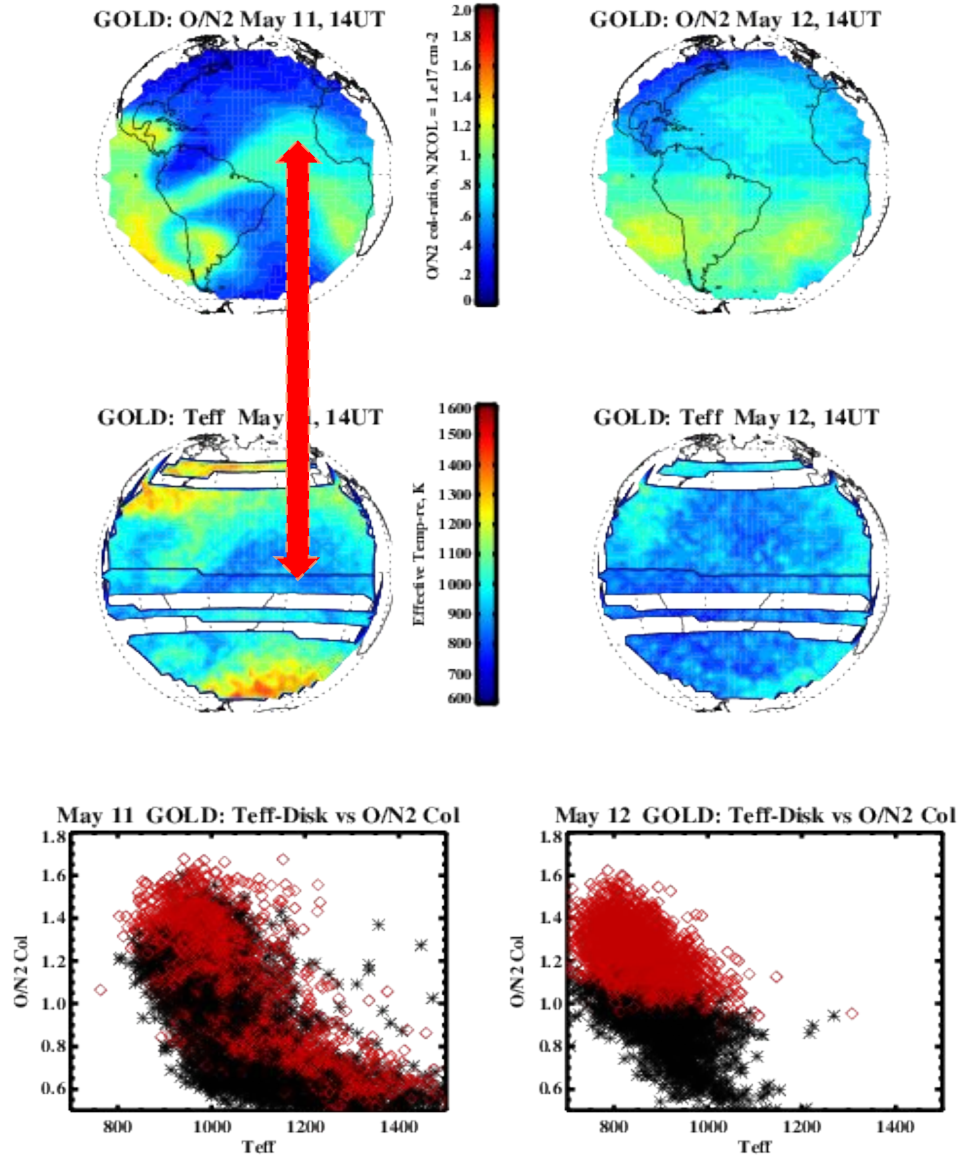


$\Sigma O/N2$: Storm May 11, 14 UT



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 Data
& WA models

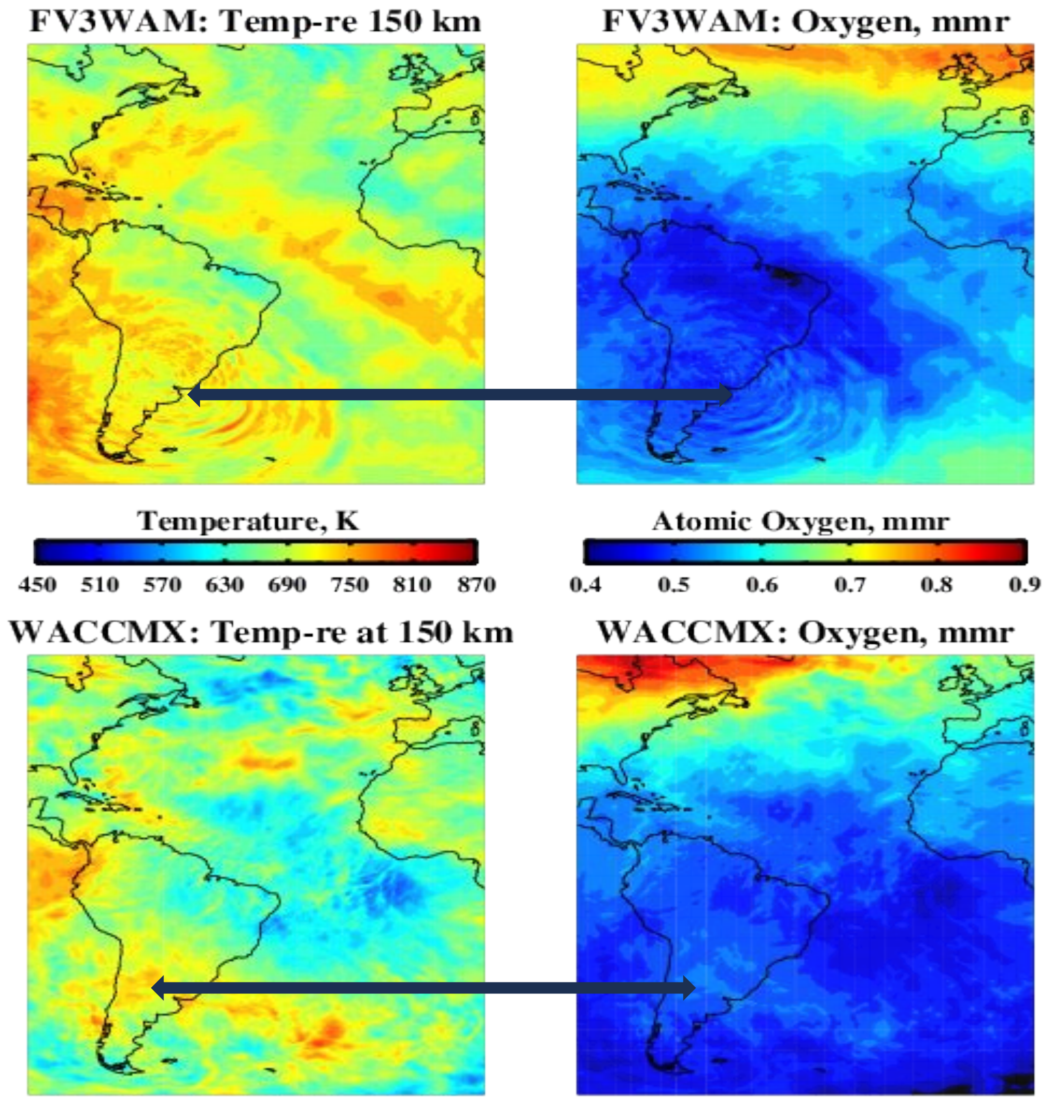
display
anti-correlation

between

Oxygen and

Temperature

at the peak of
the GOLD FUV
emissions



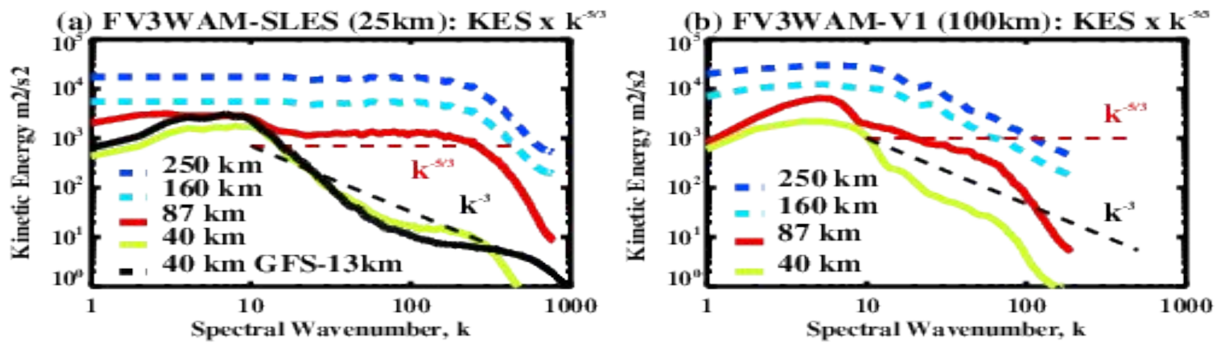
FV3 Mesoscale Dynamics: GW Explicit Simulations

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

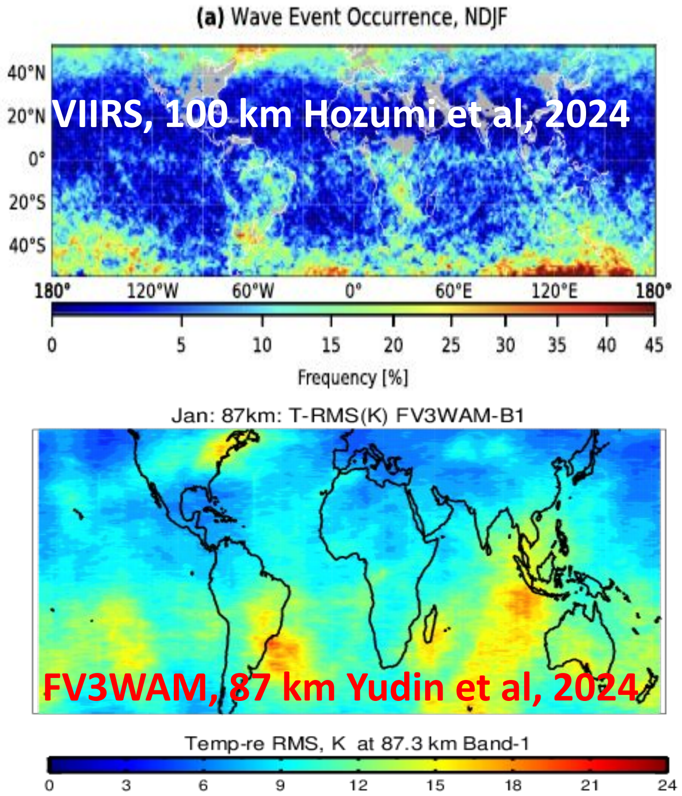
FV3WAM-25 km to resolve seasonal migration of GW hotspots at ~40 km observed by **HIRDLS EOS Aura;**

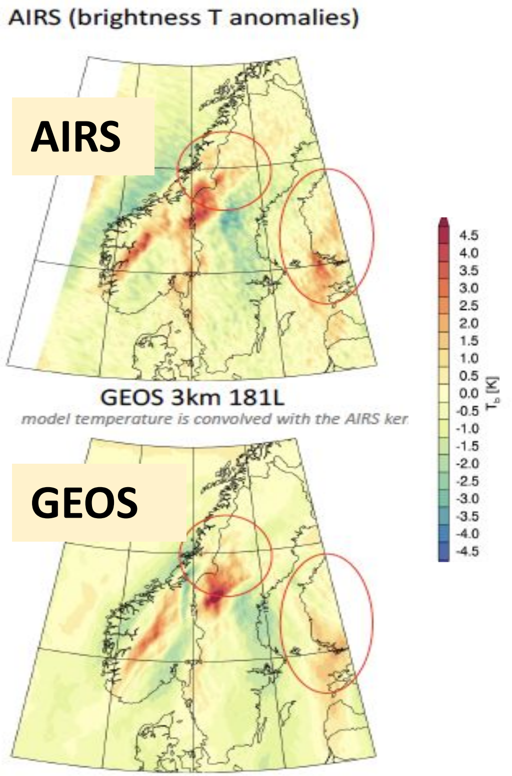
GEOS-5/3km match the OGW patterns seen by NASA **AIRS**

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

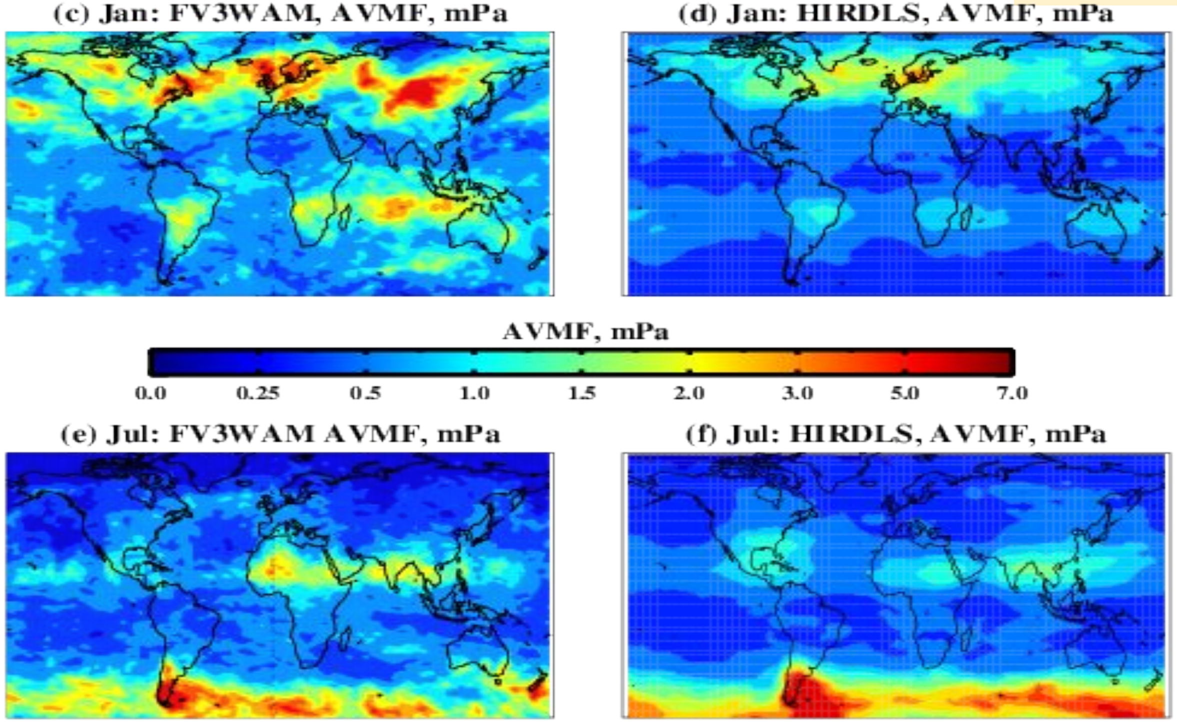


Putman et al., 2022

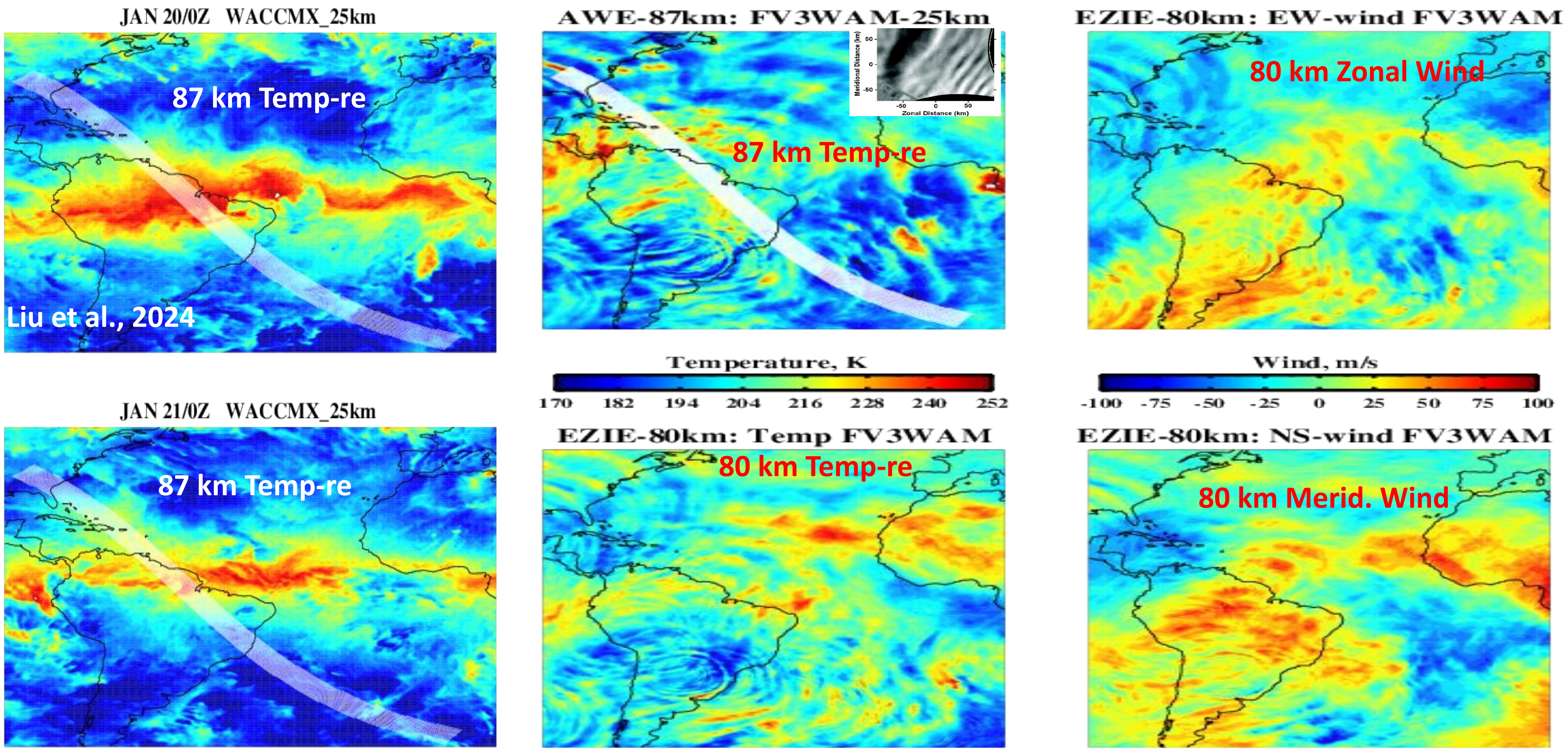




HIRDLS

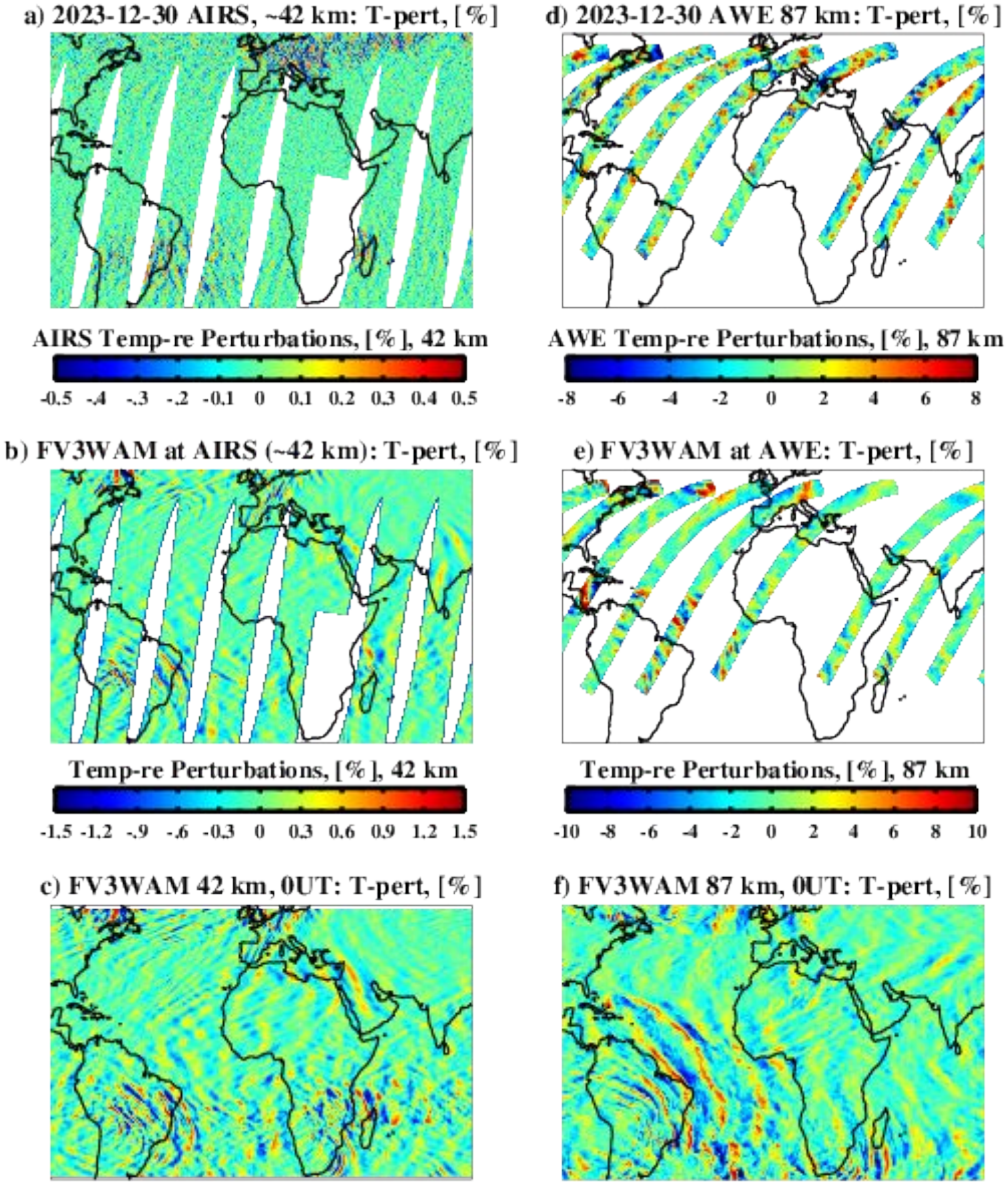


WACCM-X/SE and FV3WAM-SLES (25 km) at 87 (AWE) and 80 (EZIE) km: Mesoscale Wave Patterns in Temperature and Horizontal Winds



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

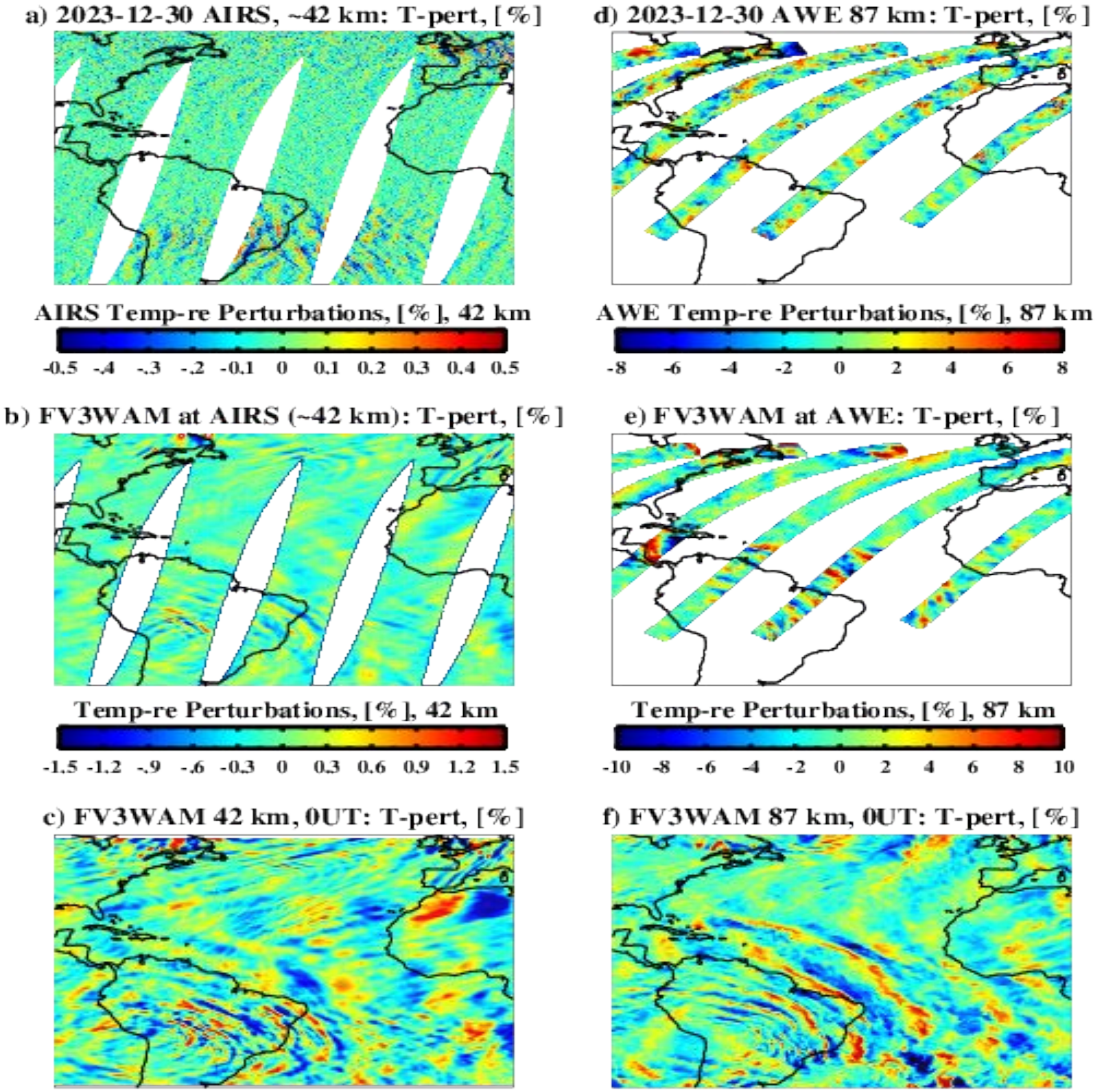
Dec 30 2023: Sampling Orbital Swaths of AIRS (15 µk CO2, 42 km peak) and AWE (OH-emission, 87 km)



Data
T'/T, %

FV3WAM
T'/T, %

FV3WAM
T'/T, %
00Z

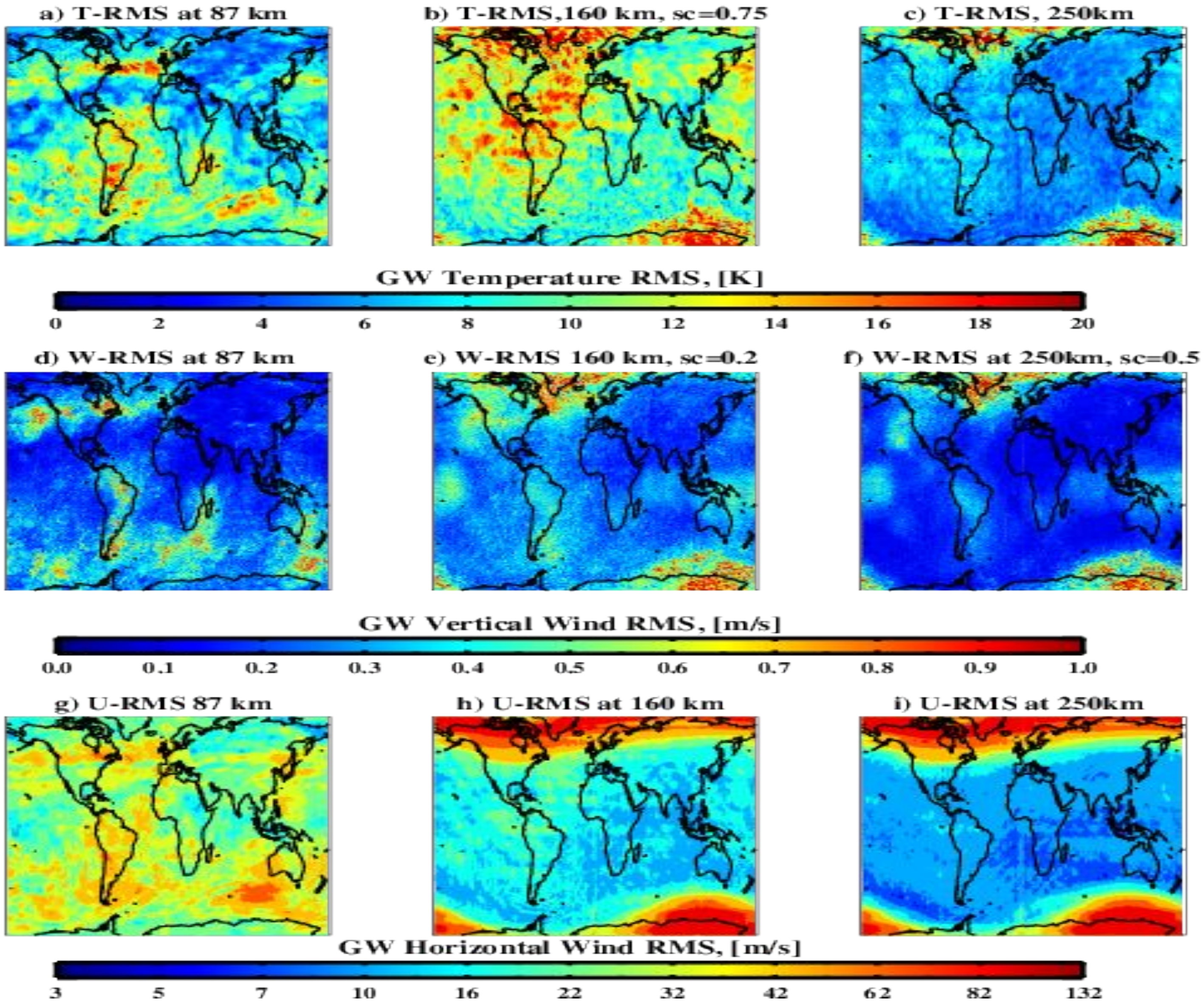


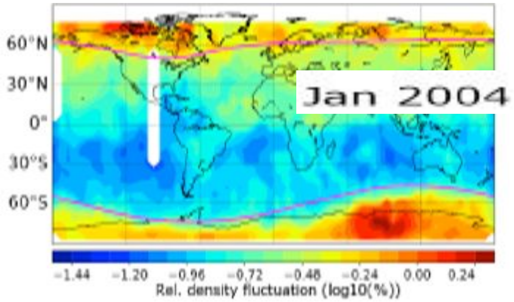
January FV3WAM-SLES GW Regional Activity in 3 Layers
AWE (87km) , GOLD (160 km) & GOCE (250 km) /Data Analysis/

Temp-re

Vertical wind

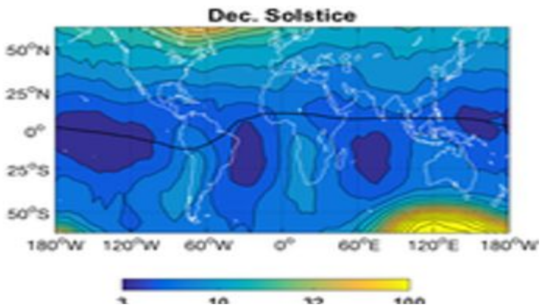
Horizontal winds

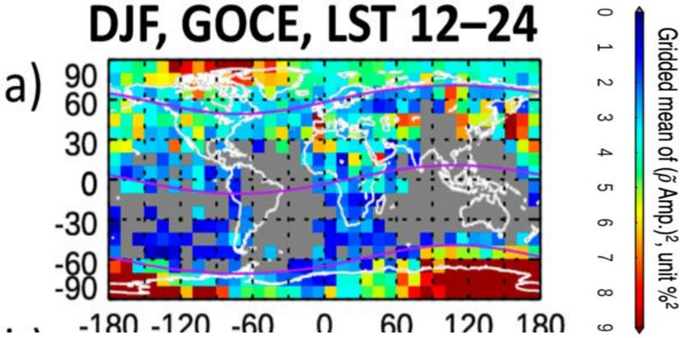




CHAMP Trinh et al., 2018

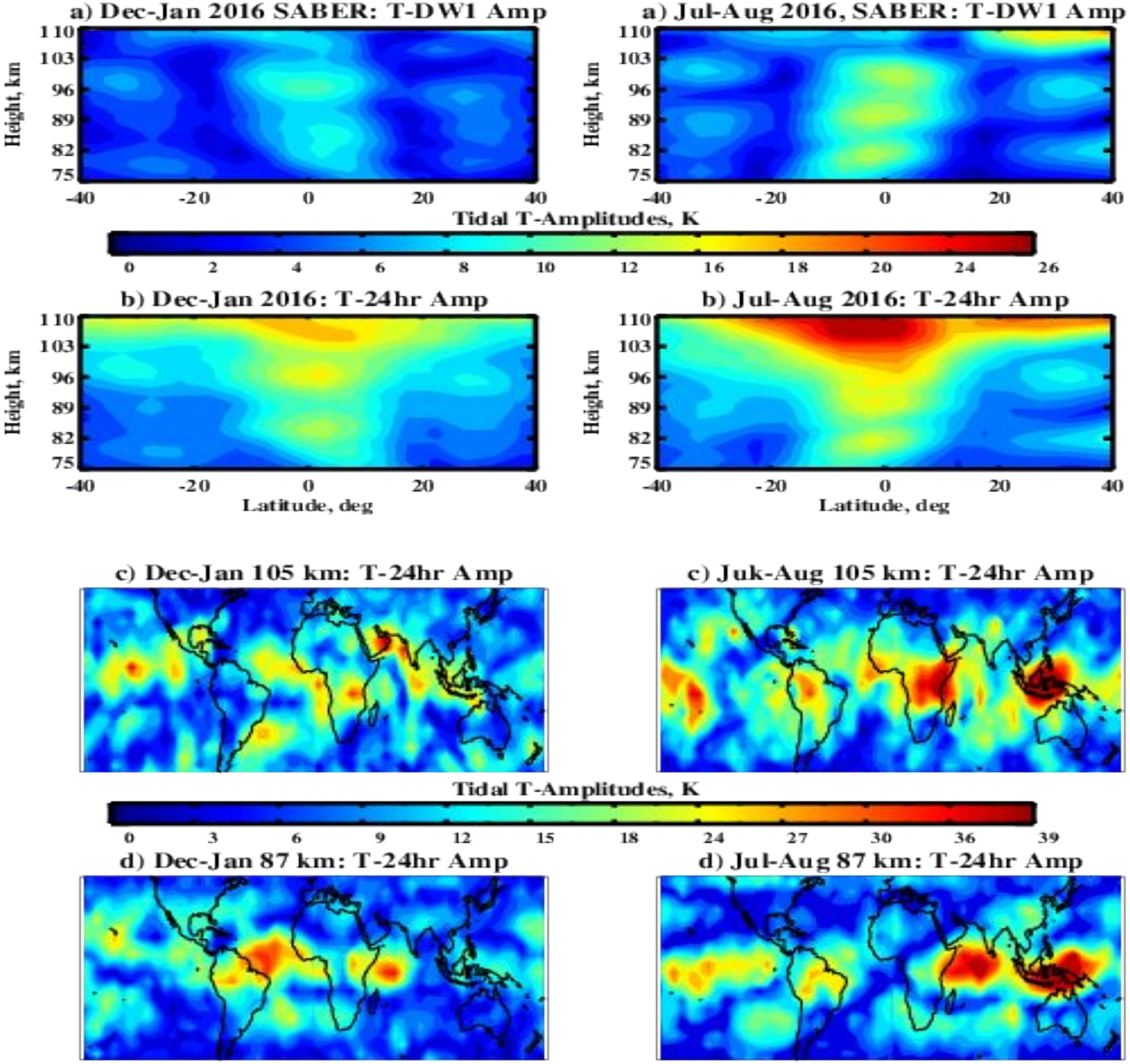
GOCE: Huixin Liu et al. 2017



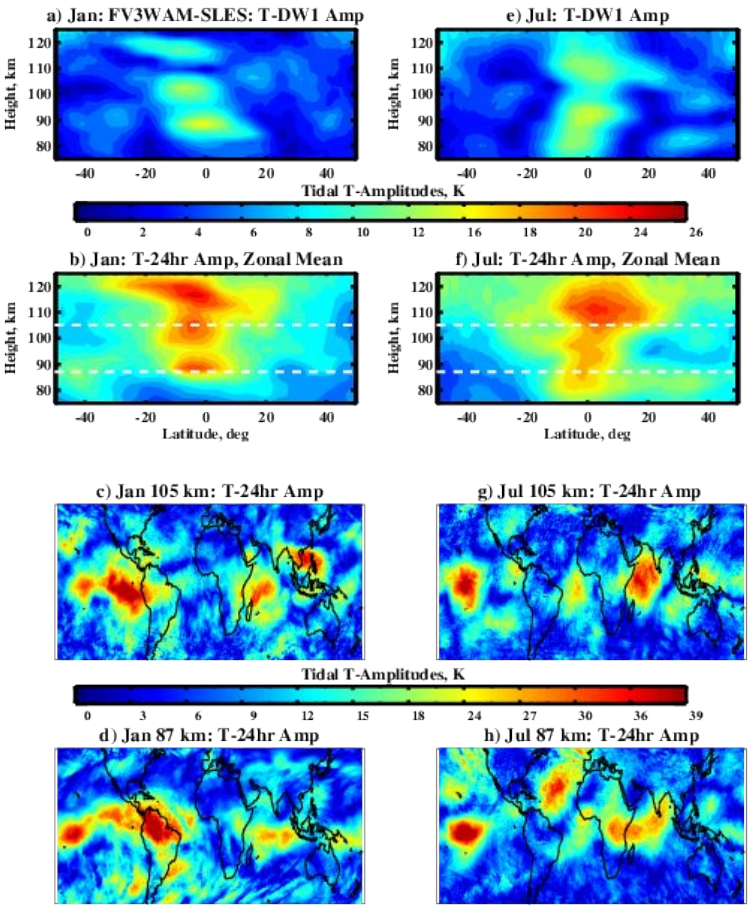


Xu et al., 2024

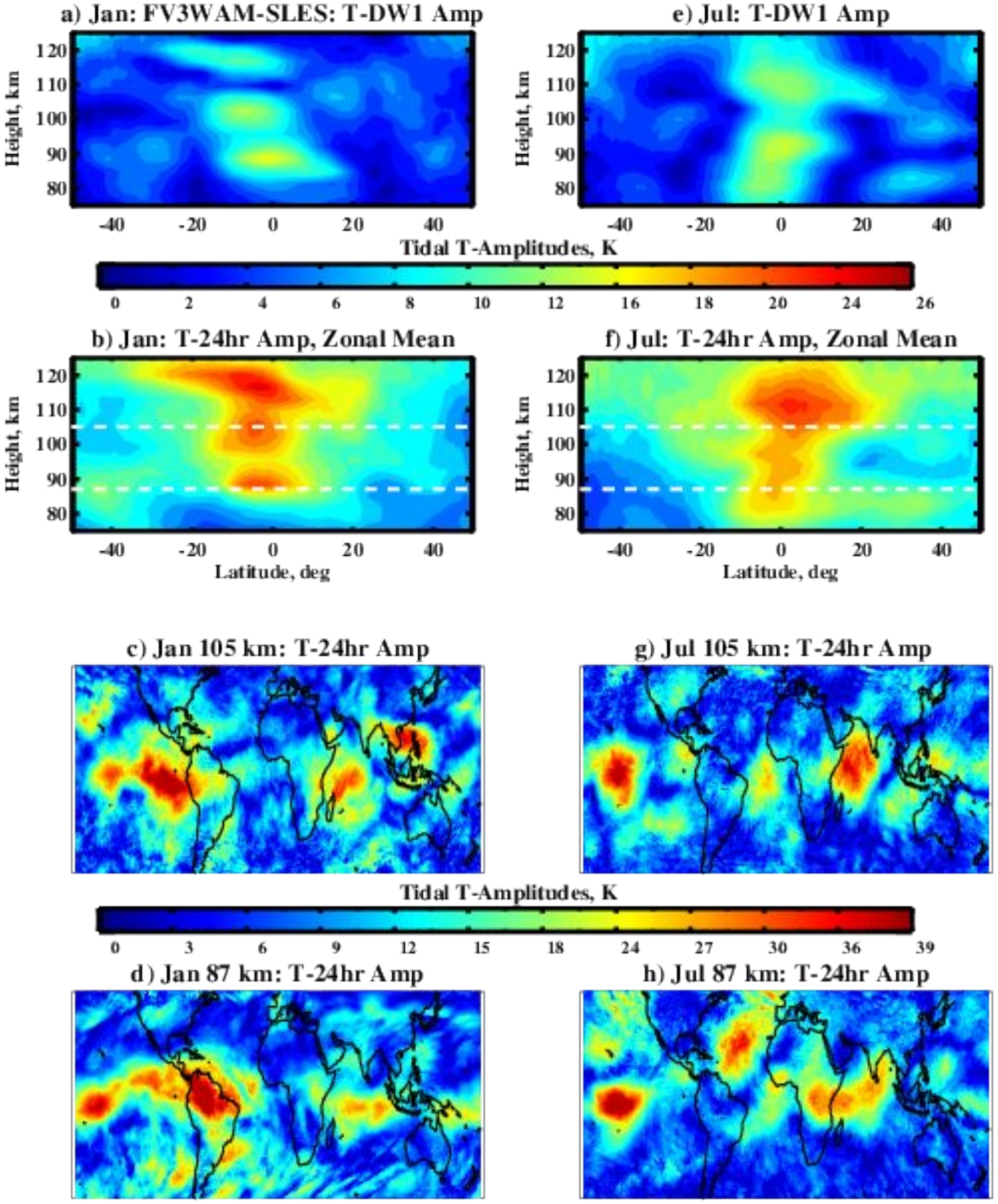
SABER/TIMED: Seasonal Variability of Diurnal Tide in MLT



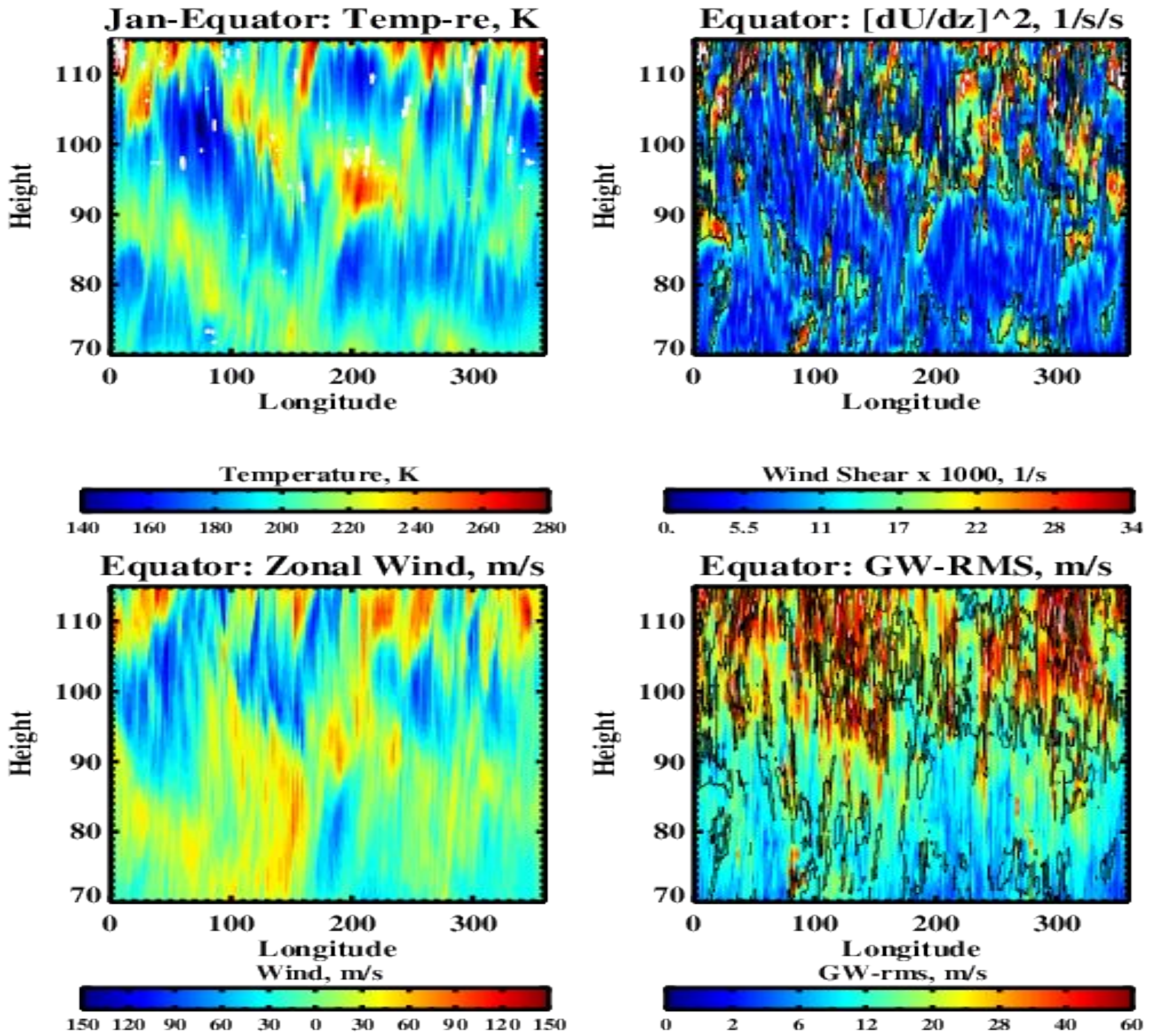
FV3WAM-SLES, Diurnal Tide



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

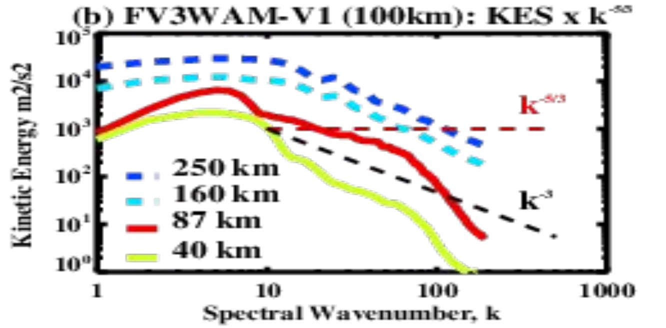
1. **Two configurations of FV3WAM as the Space Weather Application of UFS were designed and assessed.**

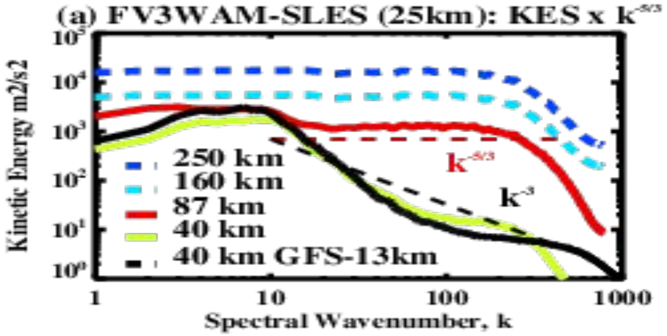
2. **FV3WAM-v1 (100 km) will be in the next UFS community release.**

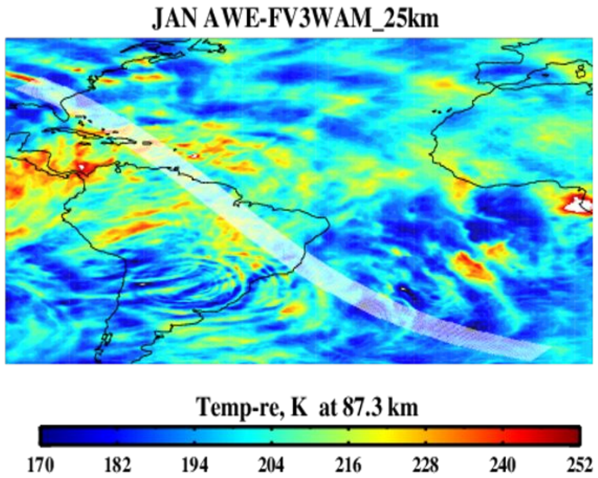
3. **Combination of two FV3WAM-v1 resolutions (100 km and 50 km) are planned for the JEDI data assimilation with the 1-hour analysis-forecast cycling with retrospective ITM observations.**

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







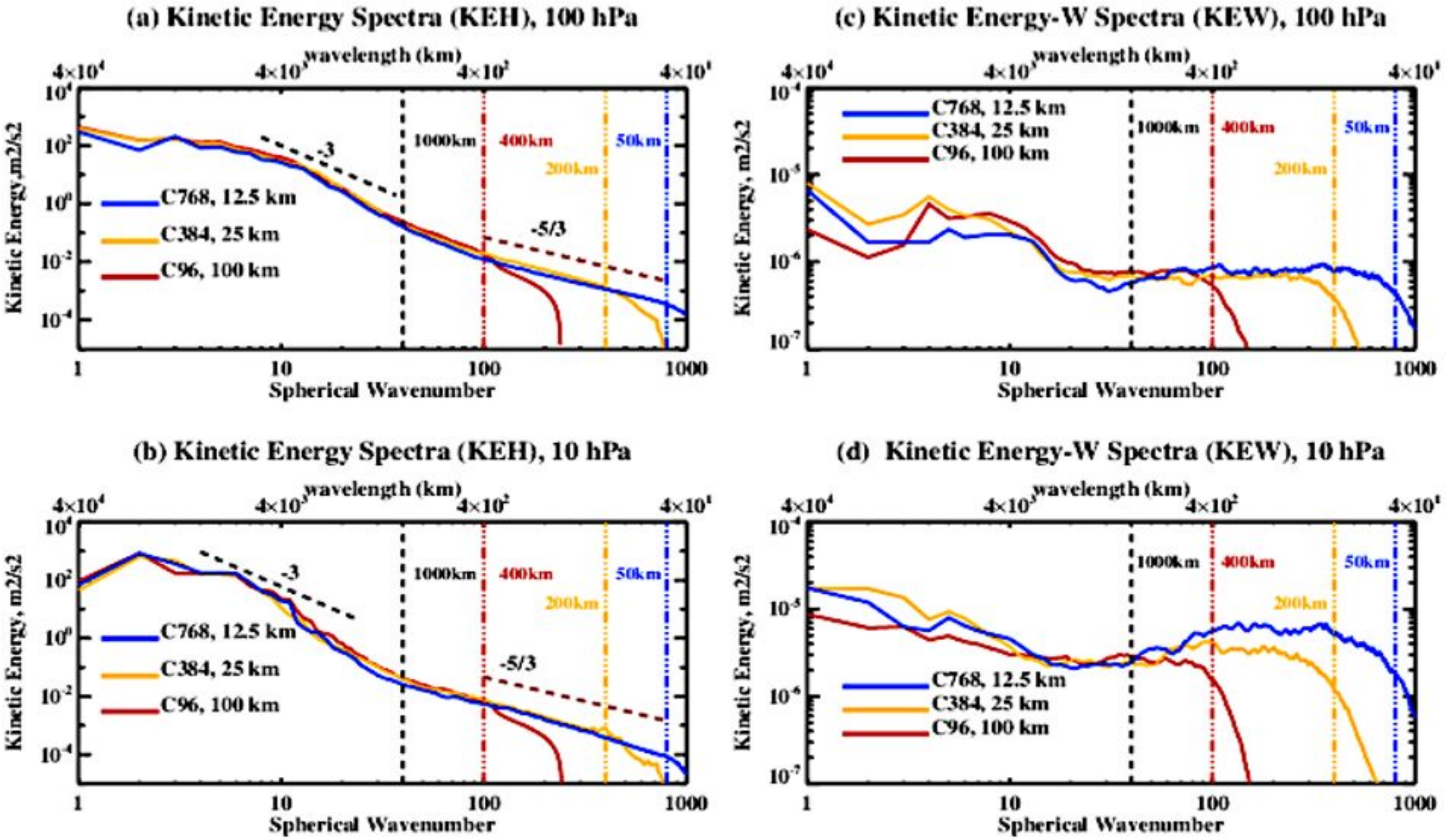
FV3WAM: Kinetic Energy Spectra and Scale-Aware GW Physics

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.*



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

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