Developing Space Weather Applications (SWA) of UFS in the Whole Atmosphere (WA) Modeling Framework

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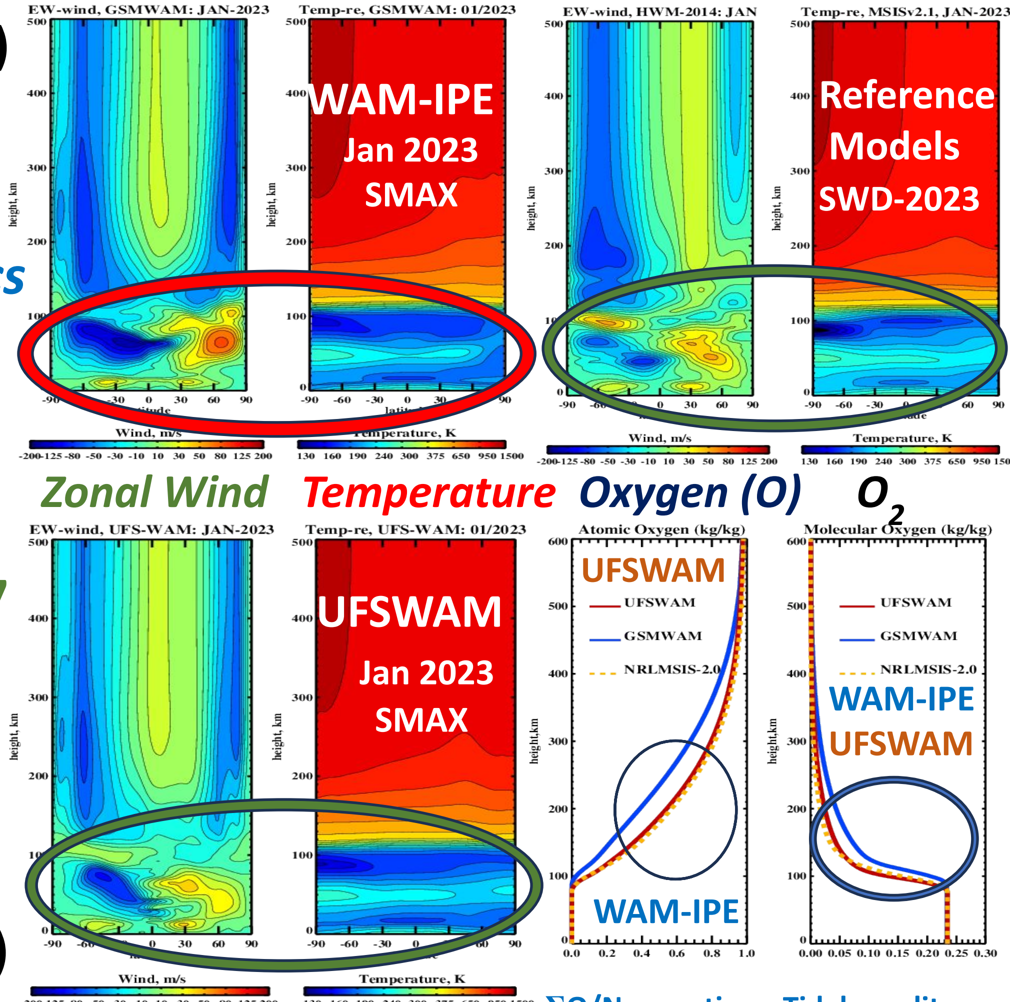
Operational SW Forecast System: WAM-IPE(GFSv13, 2016)

Data Assimilation: WAMDAS, 3DVAR-GSI (static B-errors)

Forecasts 0-80 km: *deviates from UFS/GFSv16-17 + Ref. Models*

Forecasts 80-600 km: *biases of neutral composition & dynamics*

(Deficiencies of WAM forecasts have been revealed-documented in R2O2R proposals).



$\Sigma O/N_2$ negative bias of WAM-IPE.

Tidal amplit. ~2 times larger

Oberheide et al., 2025

UFS – Unified Forecast System of Weather Community

Motivation: WA extension of UFSWM close to GFSv16-17

Current and Planned Activity:

- **2018-2020, FV3WAM-150L (EMC/CU/SWPC)**
- **2022-2025, FV3WAM-150L (EMC/CU/SWPC + CUA)**
- **2025-pres, UFSWAM-196L (+ NESDIS/SWO)**
- **current, UFSWAM-JEDI for OSSE (NESDIS/SWO+CUA)**

Proposal for UFSWAM-196L/JEDI as SWA in UFS.

(release of SWA-UFS for R2O2R and SWx Centers of NASA & NOAA in 2026/27)

Towards Space Weather Application (SWA) in UFS: UFSWAM

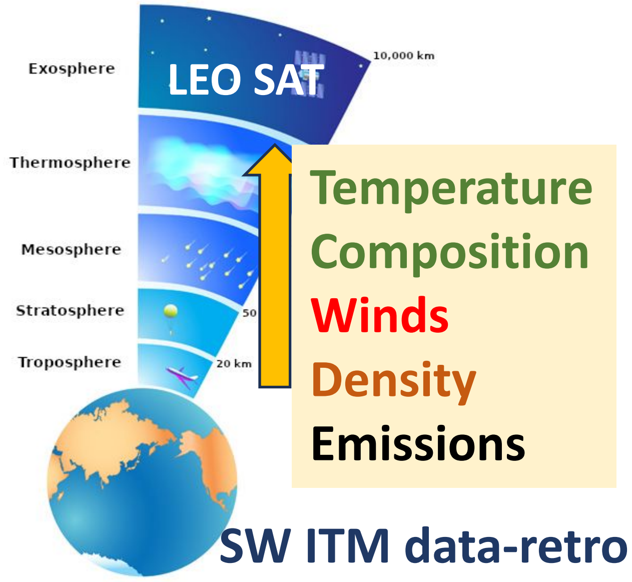
UFSWAM, as the next configuration of NOAA SW model:

Atmosphere Model: UFSWAM (GFS-v16/17, 2022-25, NH FV3 dynamics)

Data Assimilation : JEDI, 3DEnVar in the NOAA operational workflow

Forecasts 0-60 km: Match GFSv16-17 forecasts & MERRA2, ERA-5

Forecasts 60-600 km: Remove/suppress biases of WAM-IPE



Three Motivations to advance UFSWAM as SWA in UFS:

1. Develop the community OSSE in UFSWAM-JEDI (WP-2022)
for the next, current, and retrospective SW missions of NOAA and NASA;

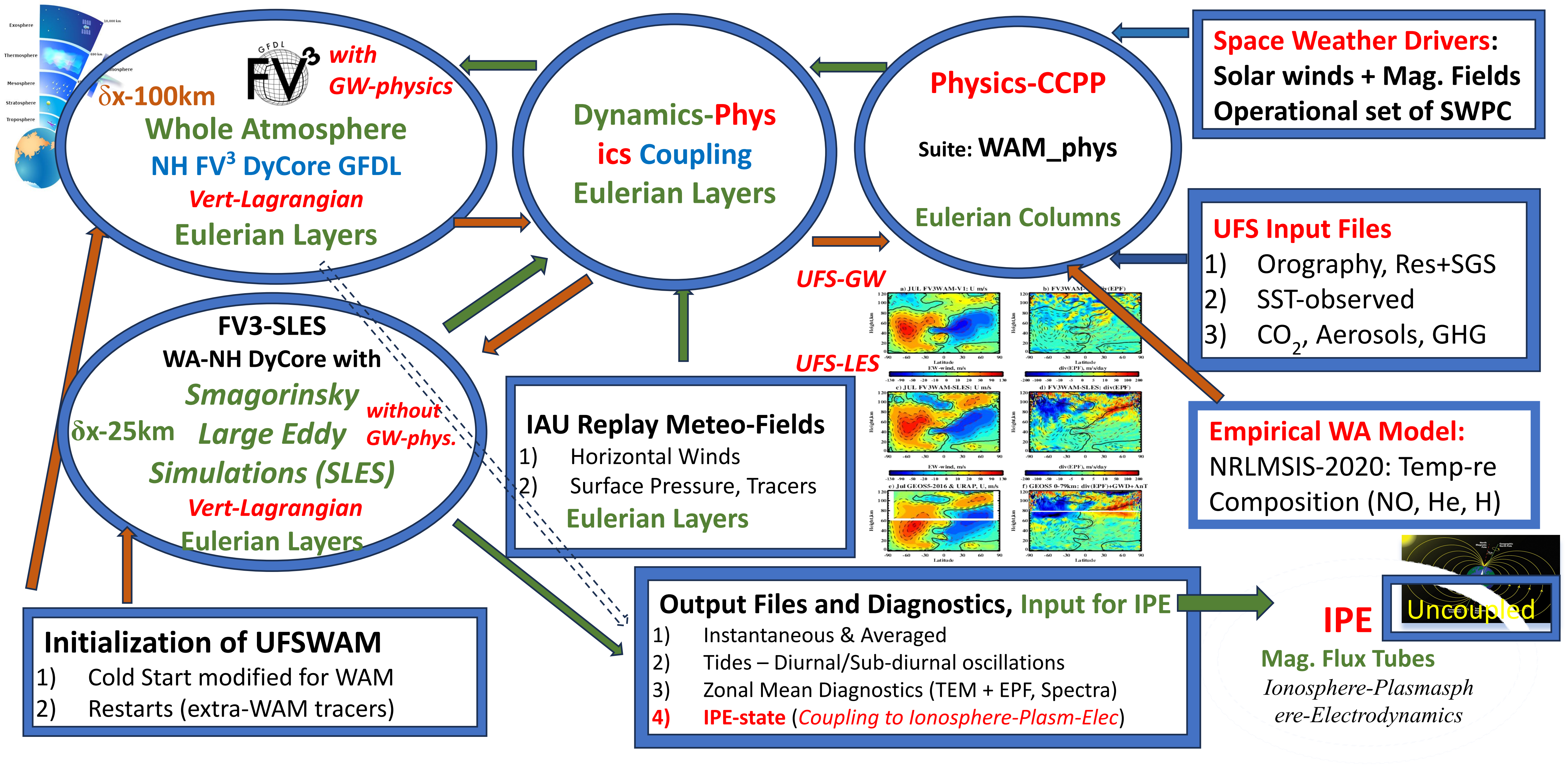
2. *Develop and test the SW Data Assimilation algorithms in UFSWAM , adapting JEDI for analysis of fast diurnal dynamics;*

3. *Make first steps for SW Reanalysis in UFSWAM* (2018-present, 40-600 km, combining observations of winds, density, temp-re & composition).

SW ITM data-retro: 2000-2025

SABER
TIDI
ICON-T, ICON-Wind
GOLD
AWE
MLS
Radars
Lidars
GOCE, CHAMP, GRACE, GRACE-FO

UFSWAM: Two Configurations and Infrastructure for UFS-SWA



Why Explore Two Configurations of UFSWAM for UFS-SWA and DA?

δx=100 km

FV³

With SGS GW-physics

Whole Atmosphere

NH FV³ DyCore GFDL

Vert-Lagrangian

Eulerian Layers

$$\frac{\partial X}{\partial t} = Dyn(X) + Phys(X) + Anal(X)$$

1-st Pr.Eq. *Approx.* *Adj. to data*

$$\frac{\partial X}{\partial t} = \frac{F_{dyn}(X)}{\tau_d(z)} + \frac{F_{phys}(X)}{\tau_p(z)} + \frac{F_{DAS}(X)}{\tau_{das}}$$

FV3-SLES

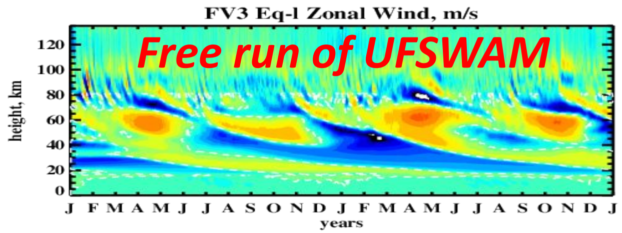
WA-NH DyCore with

Smagorinsky Large Eddy Simulations (SLES)

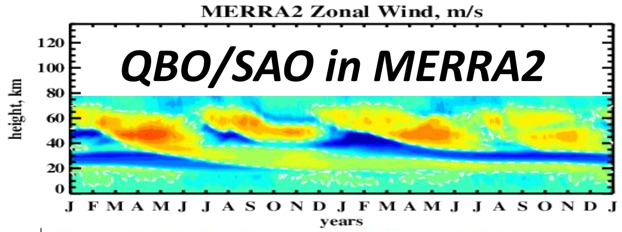
without GW-phys.

δx= 25km

Vert-Lagrangian Eulerian Layers



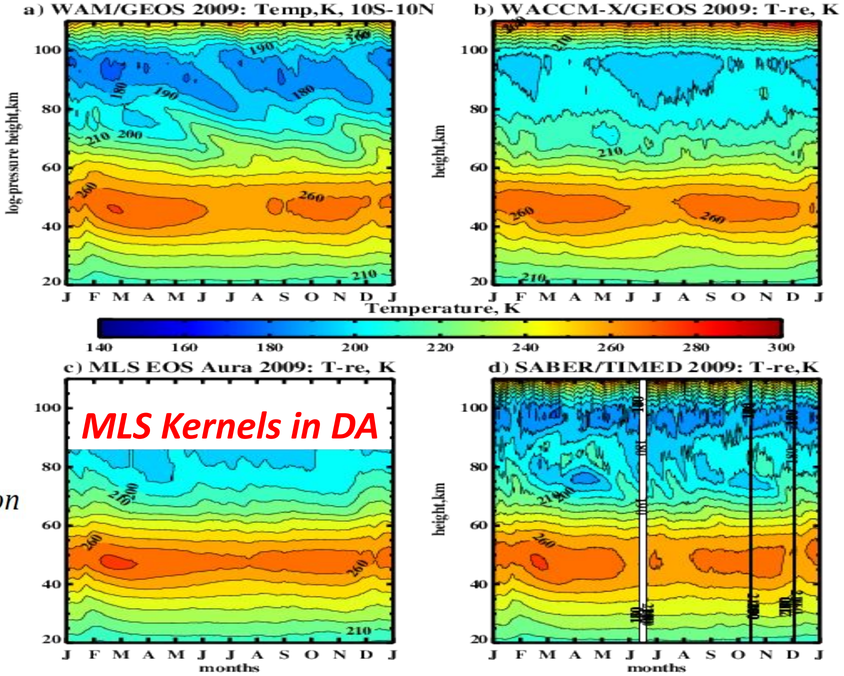
SGS-GWP supports QBO-SAO in zonal winds



$$X = [U,V]: -> Phys(X) = A_{GW} + A_{dif} + A_{ion}$$

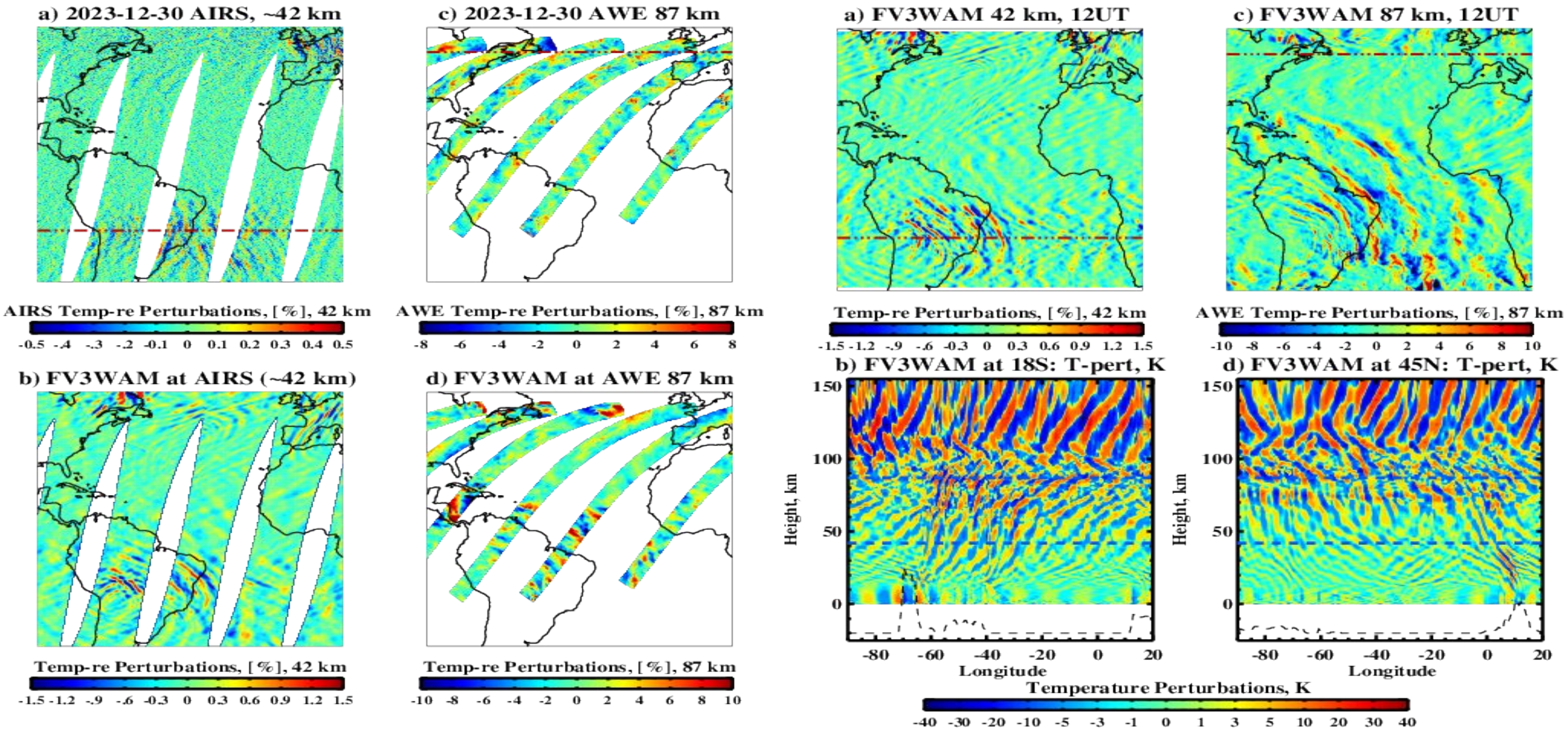
$$A_{GW} \approx -\frac{(c-U)^2}{H}\frac{\lambda_z}{\lambda_h} \approx -\frac{\delta U}{\tau_{gw}}$$

Annual Variations of Temp-re, Equator



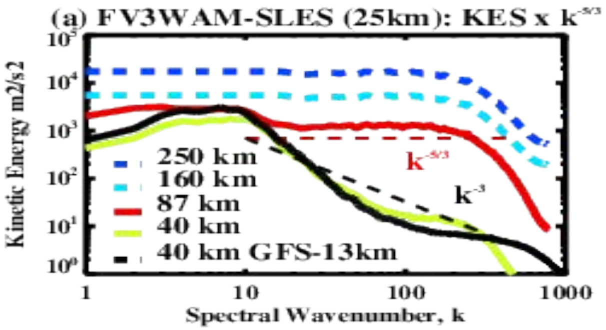
GW physics in the MLT (75-150 km) has *fastest* τ_{gw} ~0.5−2 hr; *GW wind tendencies can replace impacts of the SABER-T Analysis Increments for* τ_{das} *~1hr window under limited ~3000 prof/day.* **DA in GW-resolving models without the 'fast' uncertain GW physics is desirable.** ***Twin OSSE with SABER-T & ICON/TIDI winds using UFSWAM-SLES vs UFSWAM-GWP.***

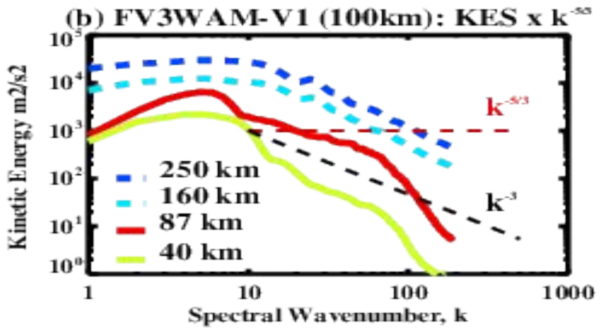
UFSWAM-SLES along AIRS (42 km) & AWE (87 km) swaths

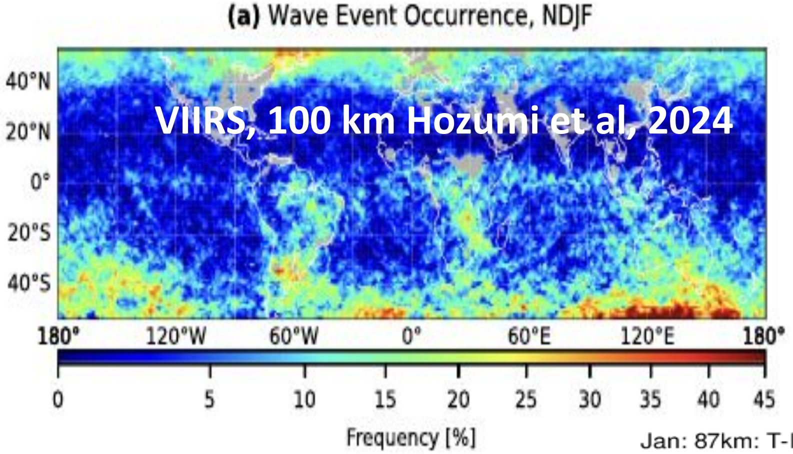


Diagnostics of Resolved GWs: Energy Spectra, Wave Energy, RMS of observed fields, Momentum Fluxes and EPF for different L_h-bands

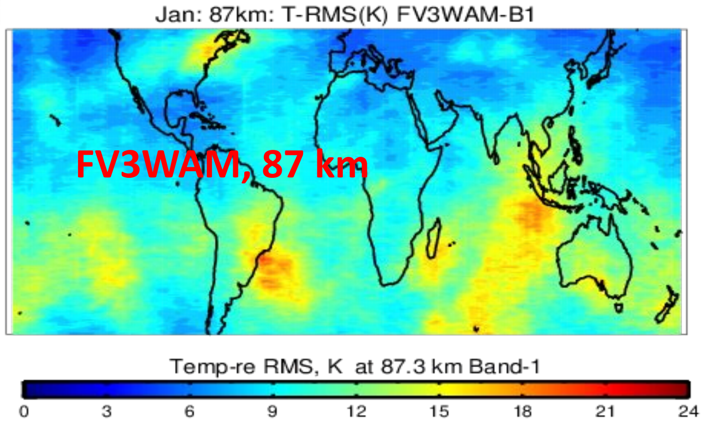
FV3-based models reproduce the mesoscale GW patterns observed from the troposphere to upper thermosphere. **FV3WAM-25 km** displays seasonal migration of GW hotspots at ~30-40 km observed by **HIRDLS EOS Aura and SABER/TIMED;** At 80 km-100 km **GW diagnostics 'fit'** locations of GW events seen by **VIIRS** radiances at ~100 km (Nov-DJ-Feb).





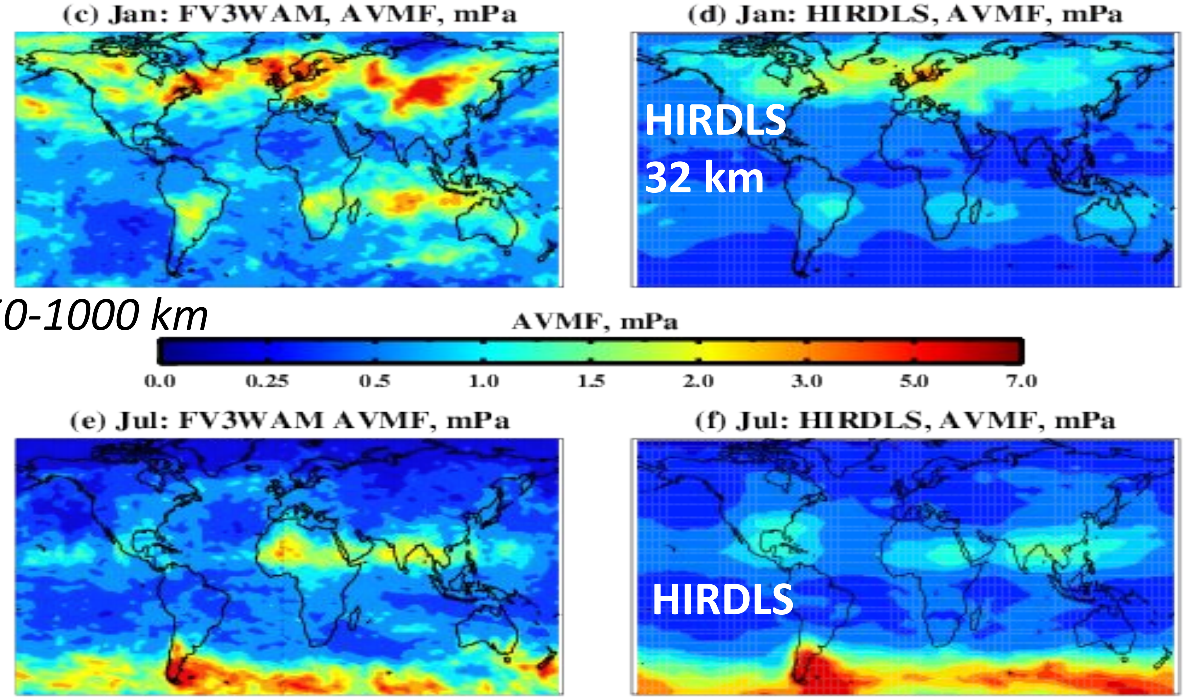


L_h: 150-650 km



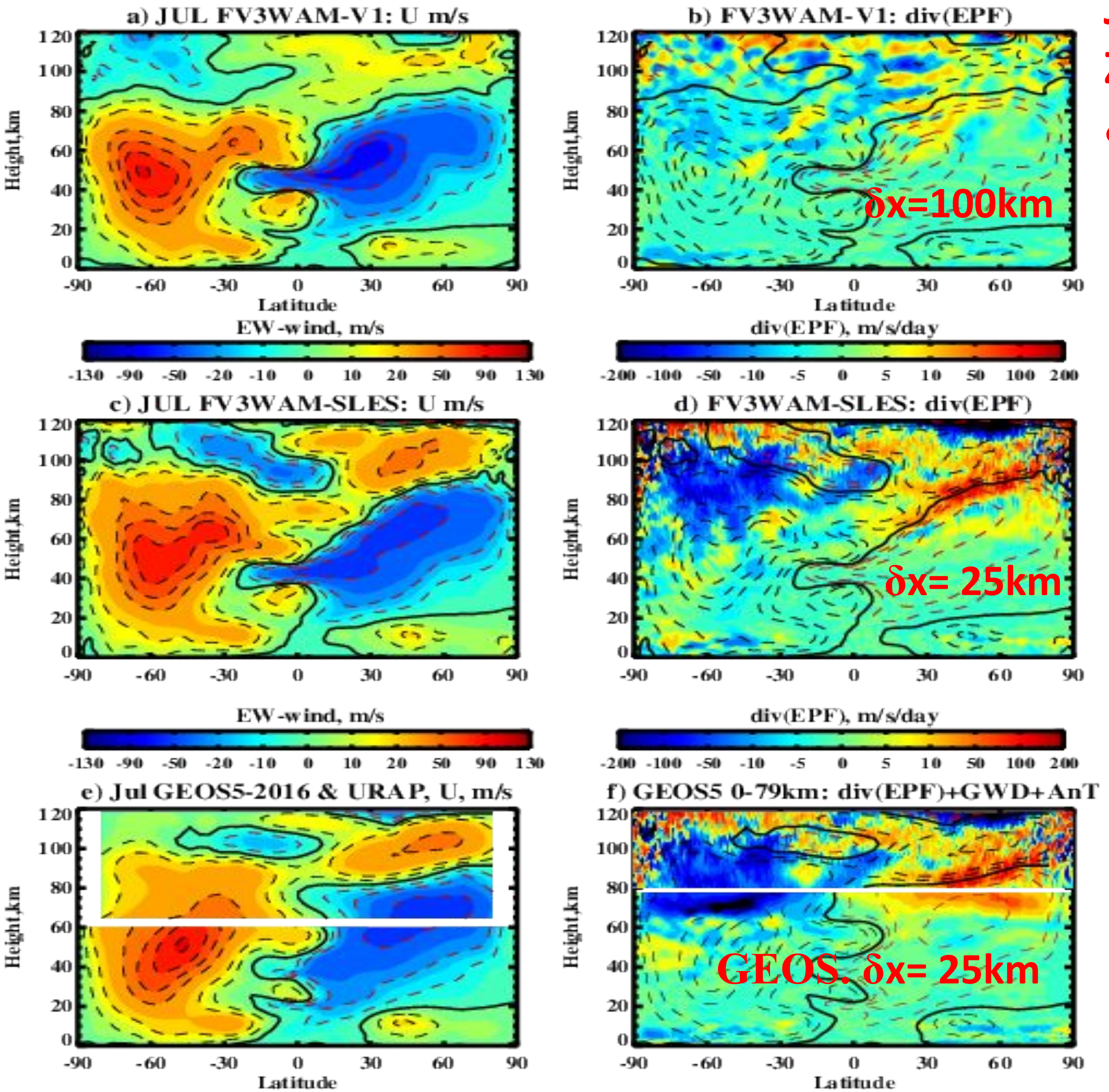
UFSWAM, *Yudin et al.* (2025) **GW climate** *Ern et al.*, 2018

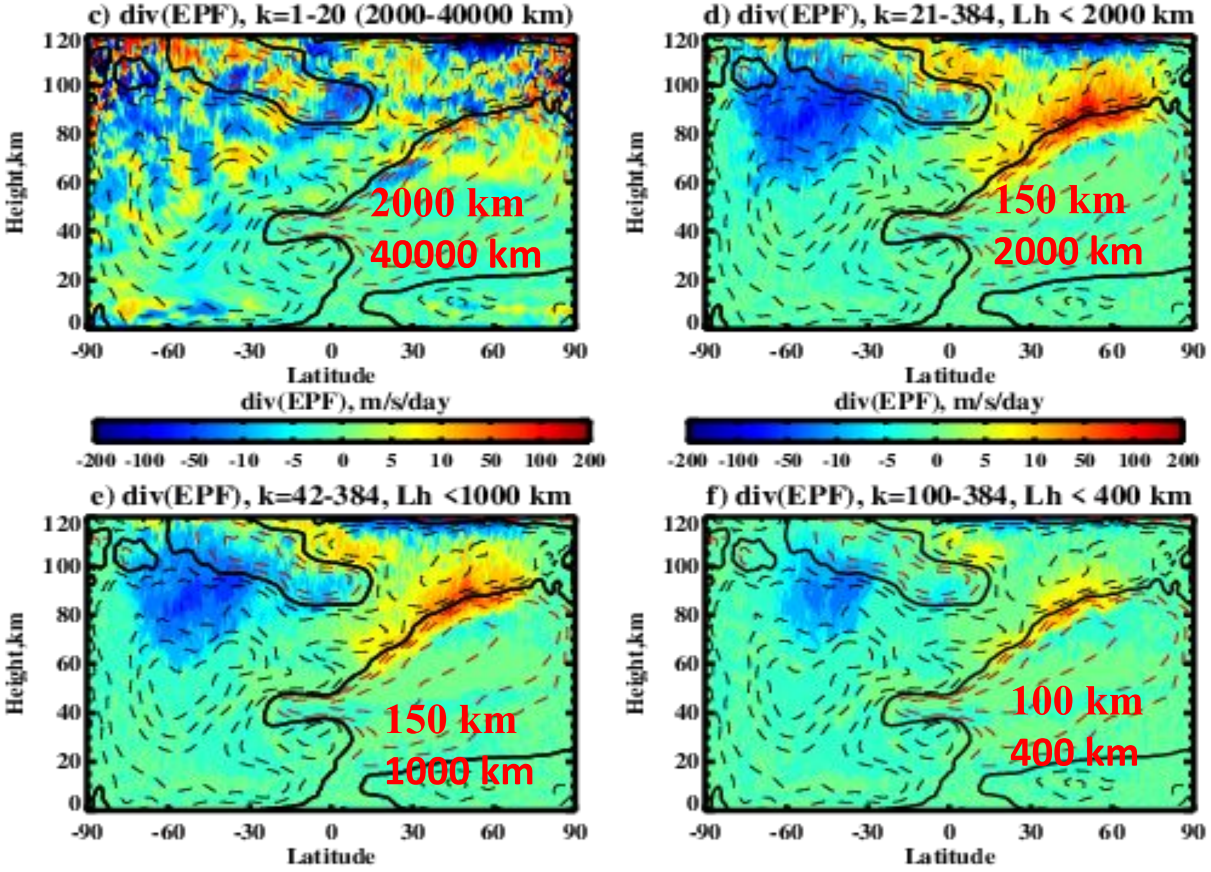
L_h: 150-1000 km



UFSWAM-SLES (C384): Effects of Mesoscale GWs Resolved by Dycore

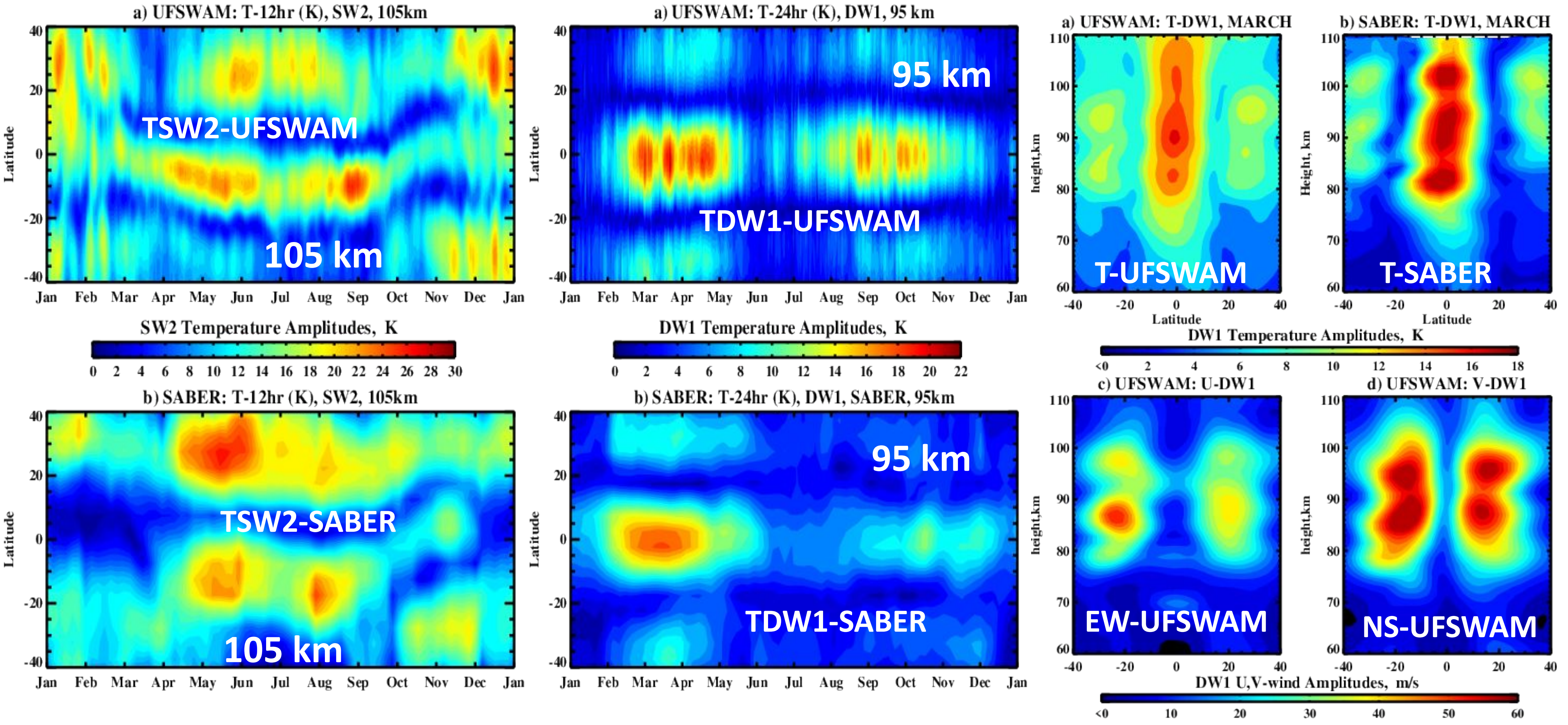
July Sim. *UFSWAM-C96* (*100 km) with NGWs (top)*
Zonal Wind *UFSWAM-SLES (25 km) w/0 NGWs (middle)*
& div(EPF) *GEOS5/2016 25 km) with GWs + URAP (bottom)*





Divergence of the Elliassen-Palm Fluxes, div(EPF), (resolved forcing) and its spectral distributions

UFSWAM & SABER: Migrating Tide Amplitudes (SW2 and DW1)



Needs for the Vertical Profile Data like SABER-Temp to Verify GW-tidal interactions in the MLT

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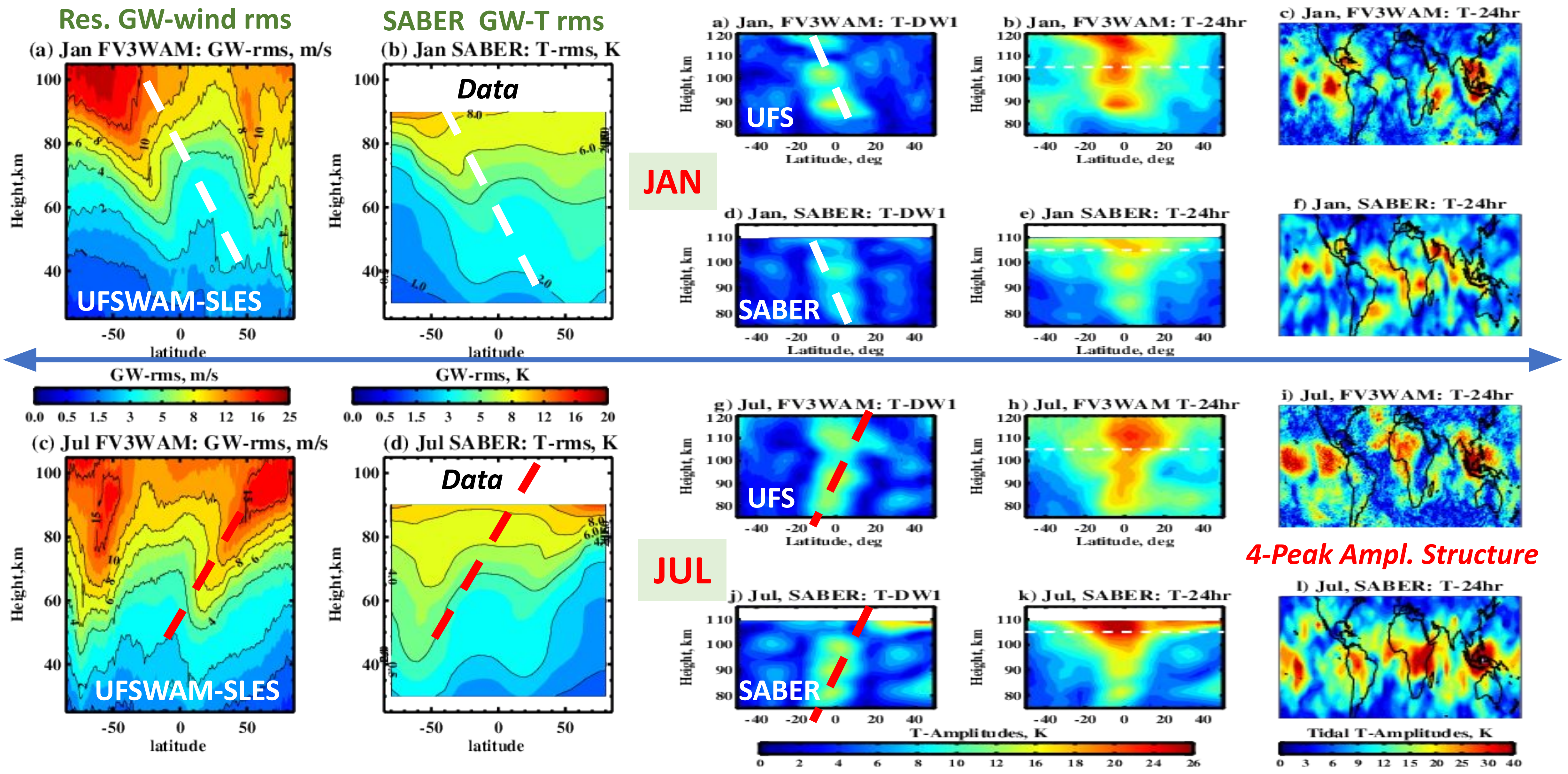
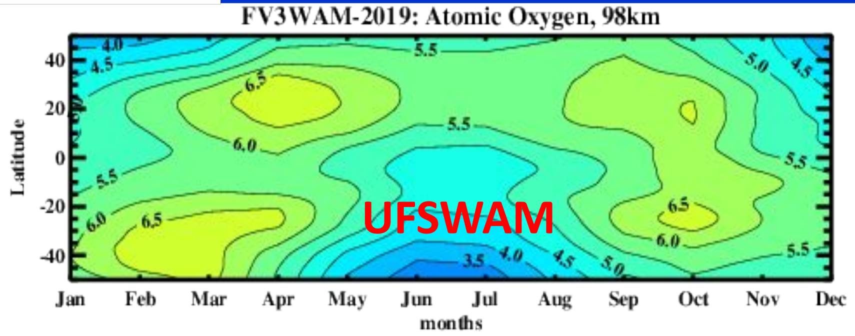
Jan-Jul: Resolved GW-activity and Diurnal Tide

(UFSWAM-SLES versus SABER/TIMED-2023)

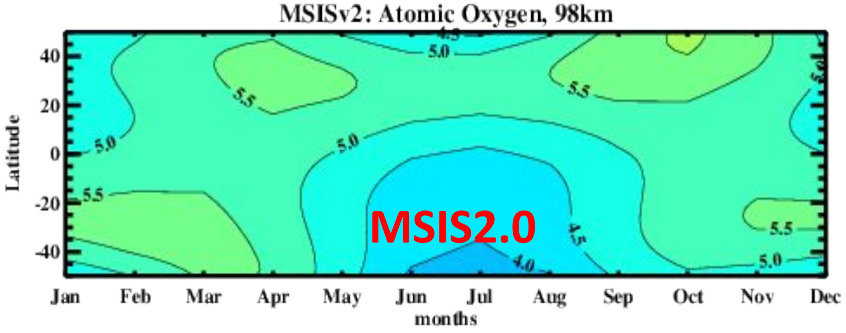


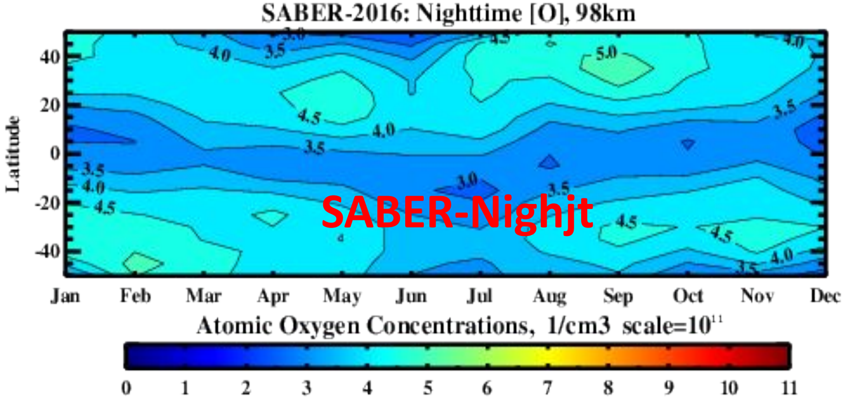
Thermosphere Composition (O and $\Sigma O/N_2$, 2019 SMIN) with SWD & subset of SWD: [F10.7/K_p -only]

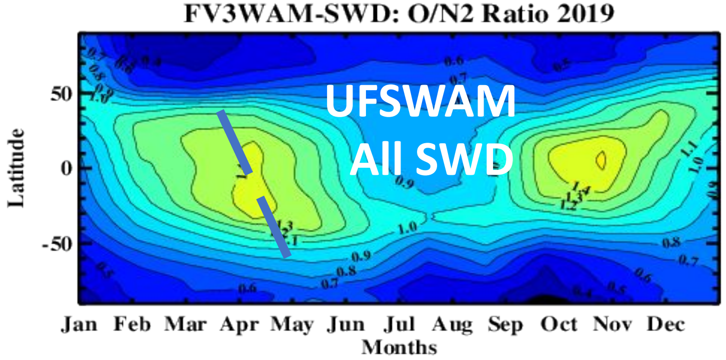
THE CATHOLIC UNIVERSITY OF AMERICA



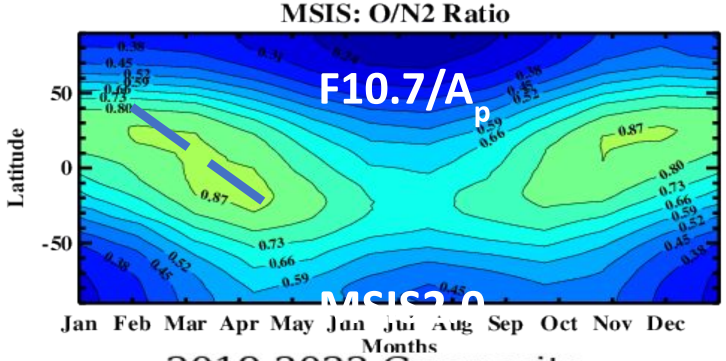
Atomic Oxygen at 98 km

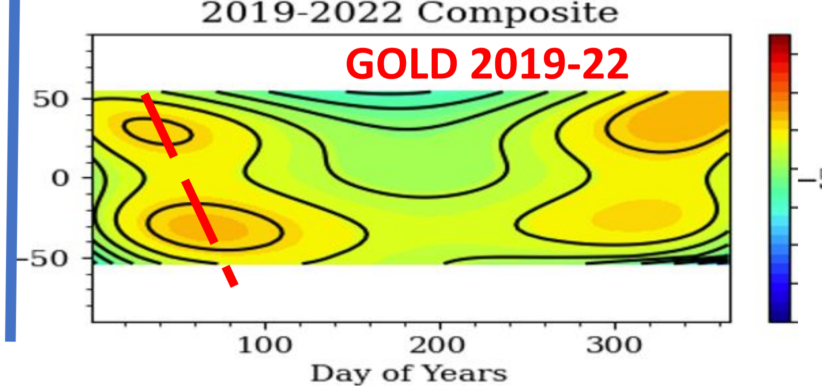


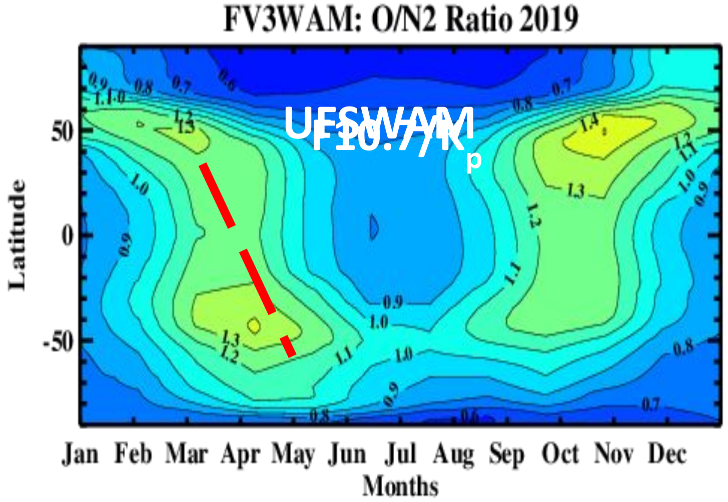




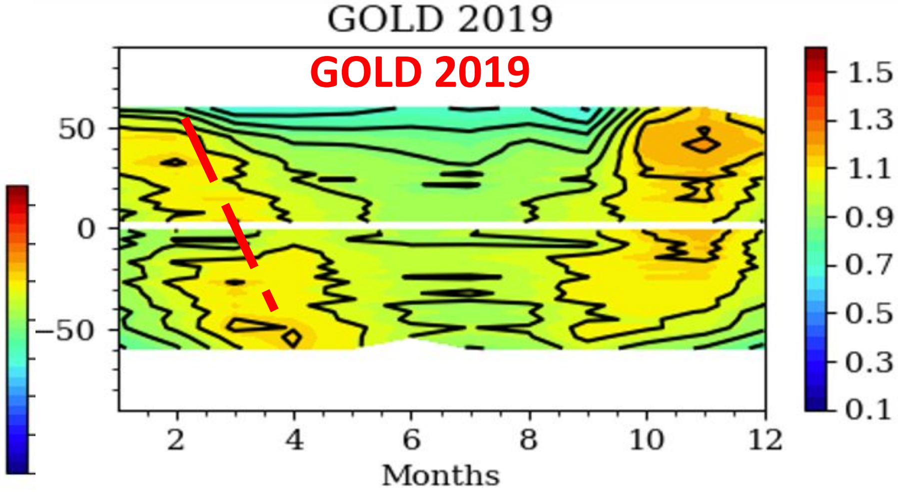
Column Ratios: $\Sigma O/N_2$





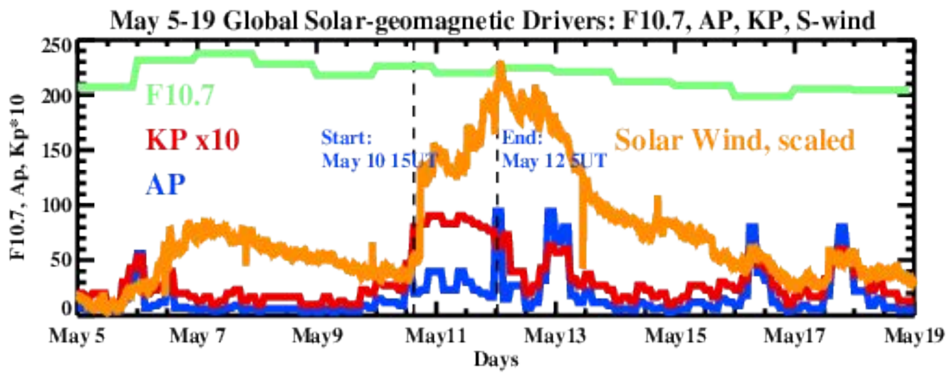


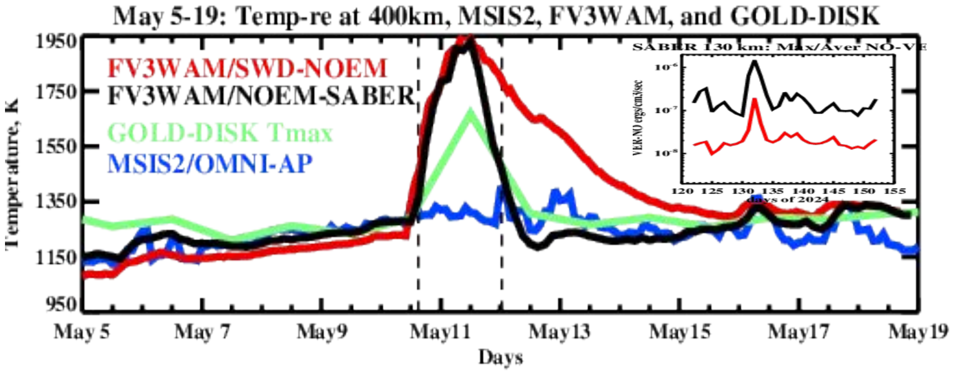
FV3WAM "quantitatively matches NASA/GOLD with **SWD= [Kp, F10.7],**

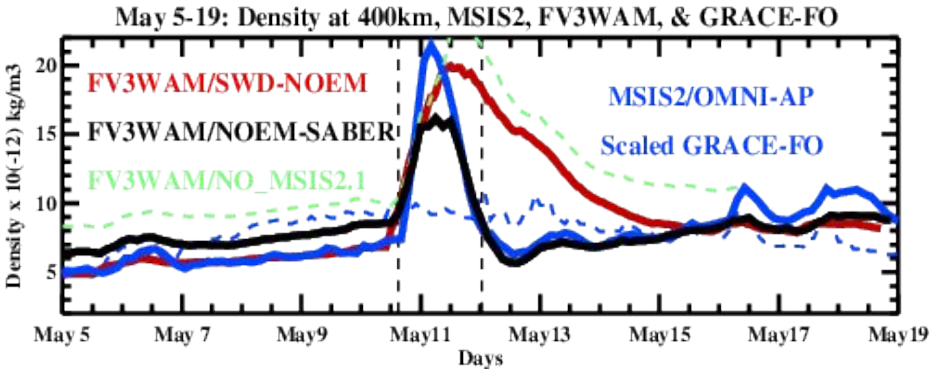


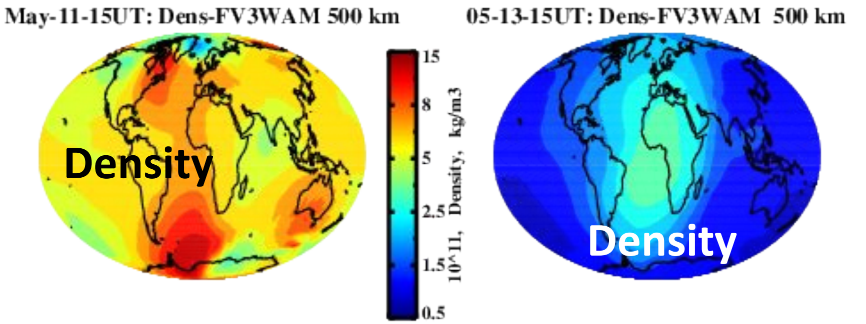
Fazlul Laskar et al, 2025

UFSWAM: Retrospective Simulations of G5-Storm (May 10-13, 2024)

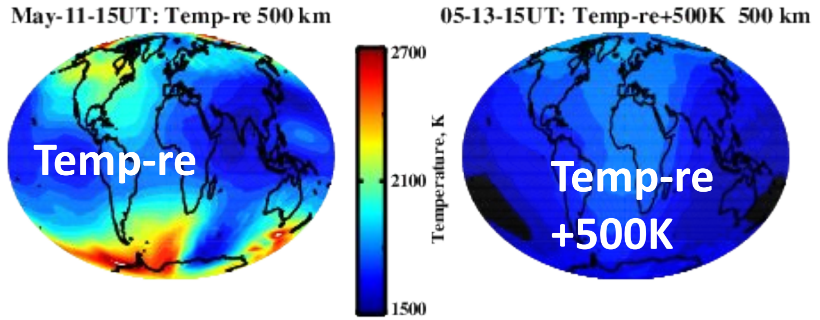


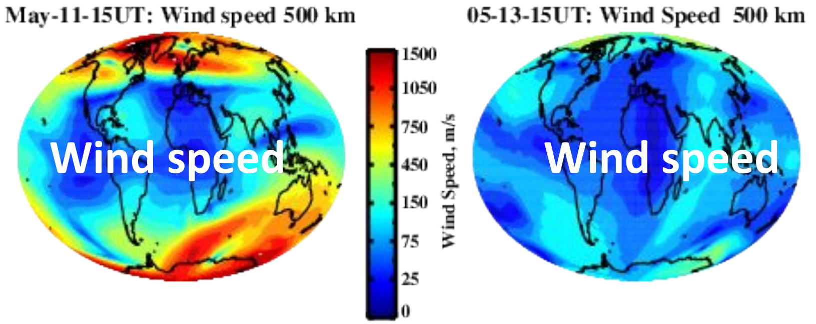






UFSWAM Hindcasts at 500 km

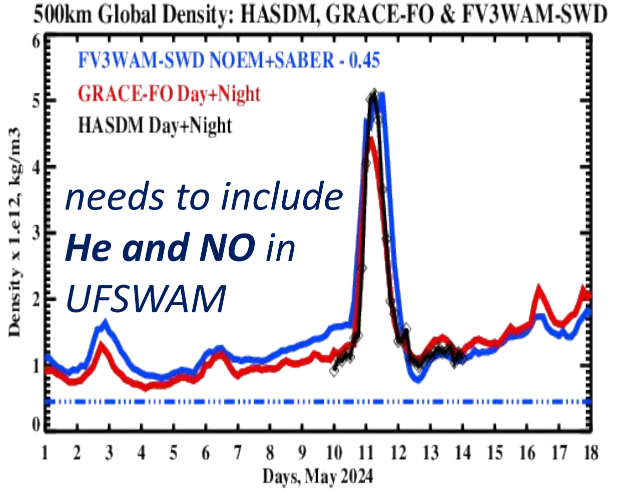




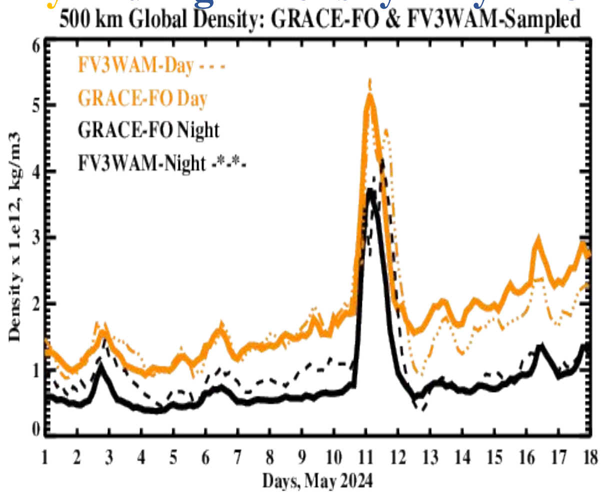
Storm Peak and 2-days later

$T_{max} > 2500$ K, $U_{max} > 1500$ m/s

Density at 500 km May 1-18
GRACE-FO, HASDM
UFSWAM (+30% bias removed)

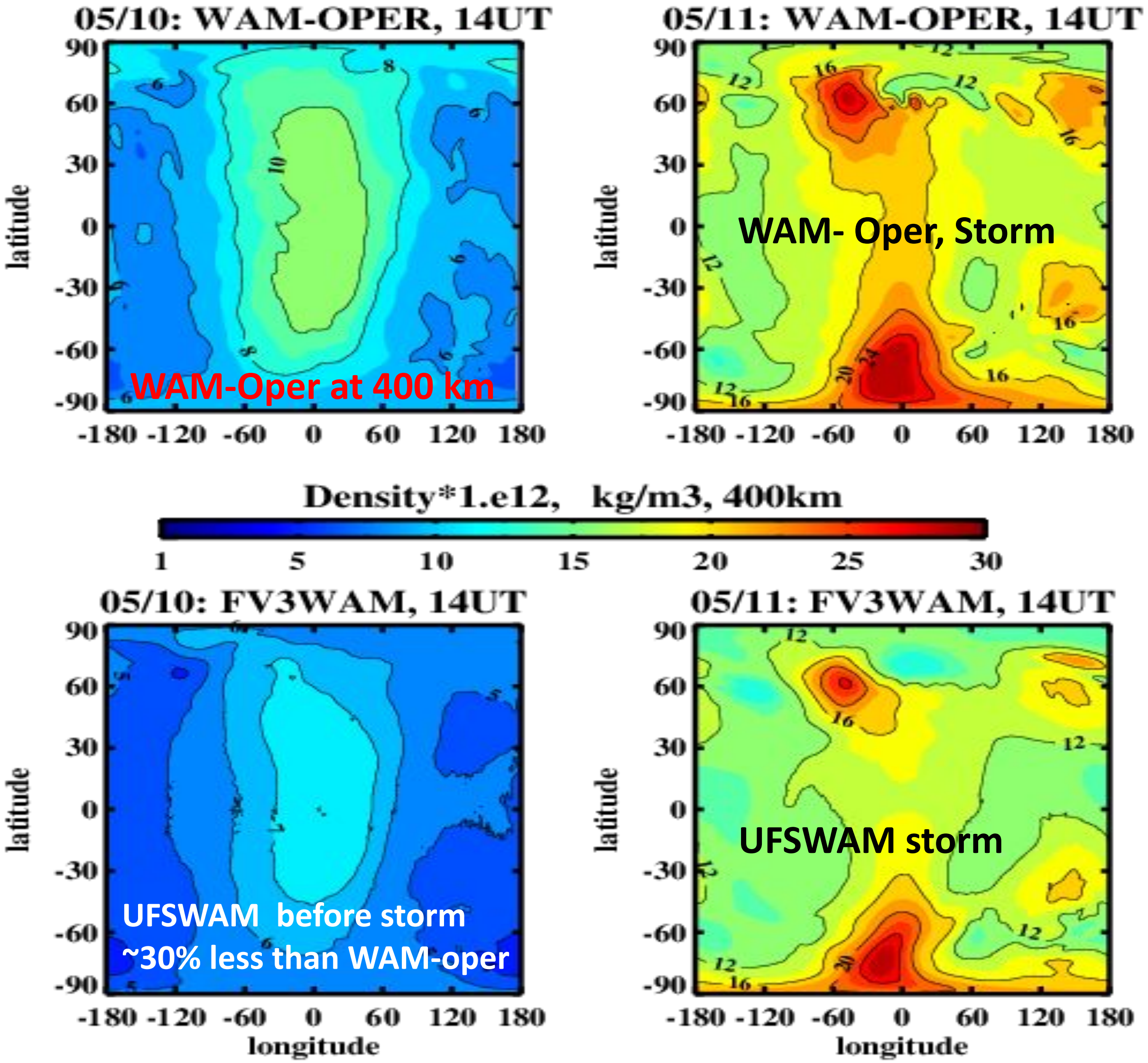


Day and night Density May 1-18

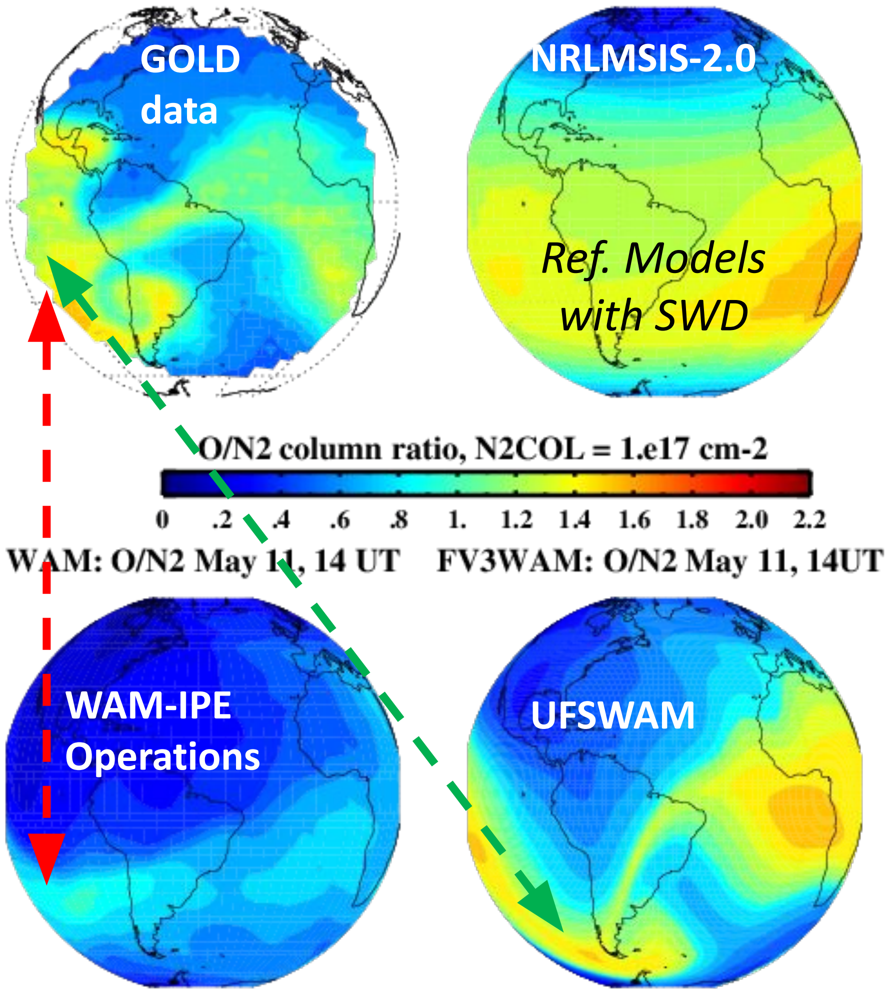


May 2024 Storm: WAM-IPE/NWS vs FV3WAM-UFS (Density & $\Sigma O/N_2$)

Density: PRE-STORM 400 km STORM (14UT, as in GOLD view)



ΣO/N2: Storm May 11, 14 UT



WAM-IPE has "negative" bias vs Data $\Sigma O/N_2$ (GOLD);
UFSWAM (same SW drivers) can match GOLD $\Sigma O/N_2$ patterns

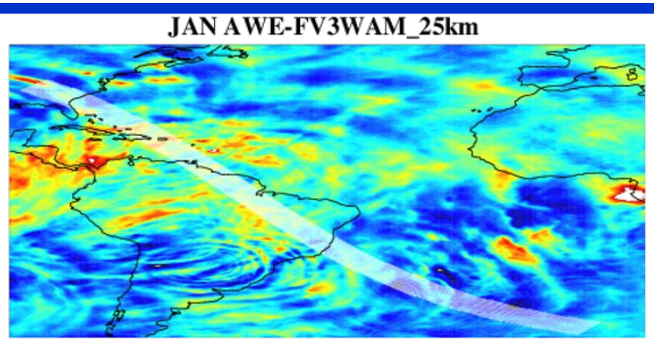
Summary and Next Steps for Space Weather Applications in UFS

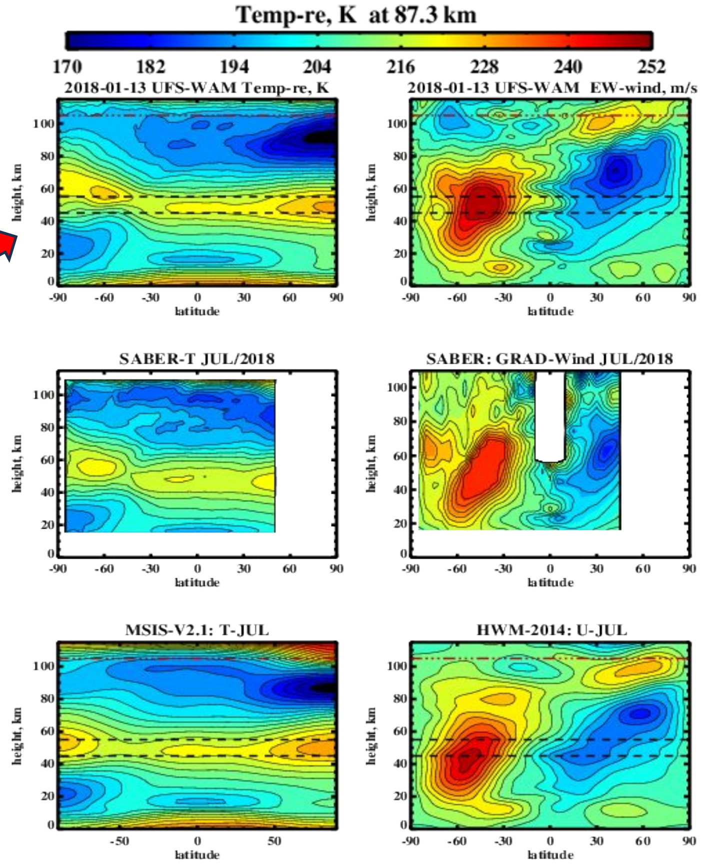
1. Two WA configurations of UFS, *UFSWAM and UFSWAM-SLES*, were developed as extensions of GFSv16/17.

2. UFSWAM (100km) & UFSWAM-SLES (25 km) reproduce seasonal variations & variability of MF, tides, & GWs.
3. UFSWAMs addressed major “deficiencies” of WAM-IPE operational forecasts, *except the 350-500 km density (GRACE-FO).*

4. Current work: UFSWAM-SLES (25 km) constrained by GEOS meteorology for GW case studies (AWE, AIRS & SABER).
5. Next: Annual runs of UFSWAM-SLES will be assessed and suggested as NR for the Twin-OSSE to support SW missions.

6. As SWA, the UFSWAM performance will be advanced by JEDI adapted for analysis of SW retro-observations & OSSEs.





THANK YOU

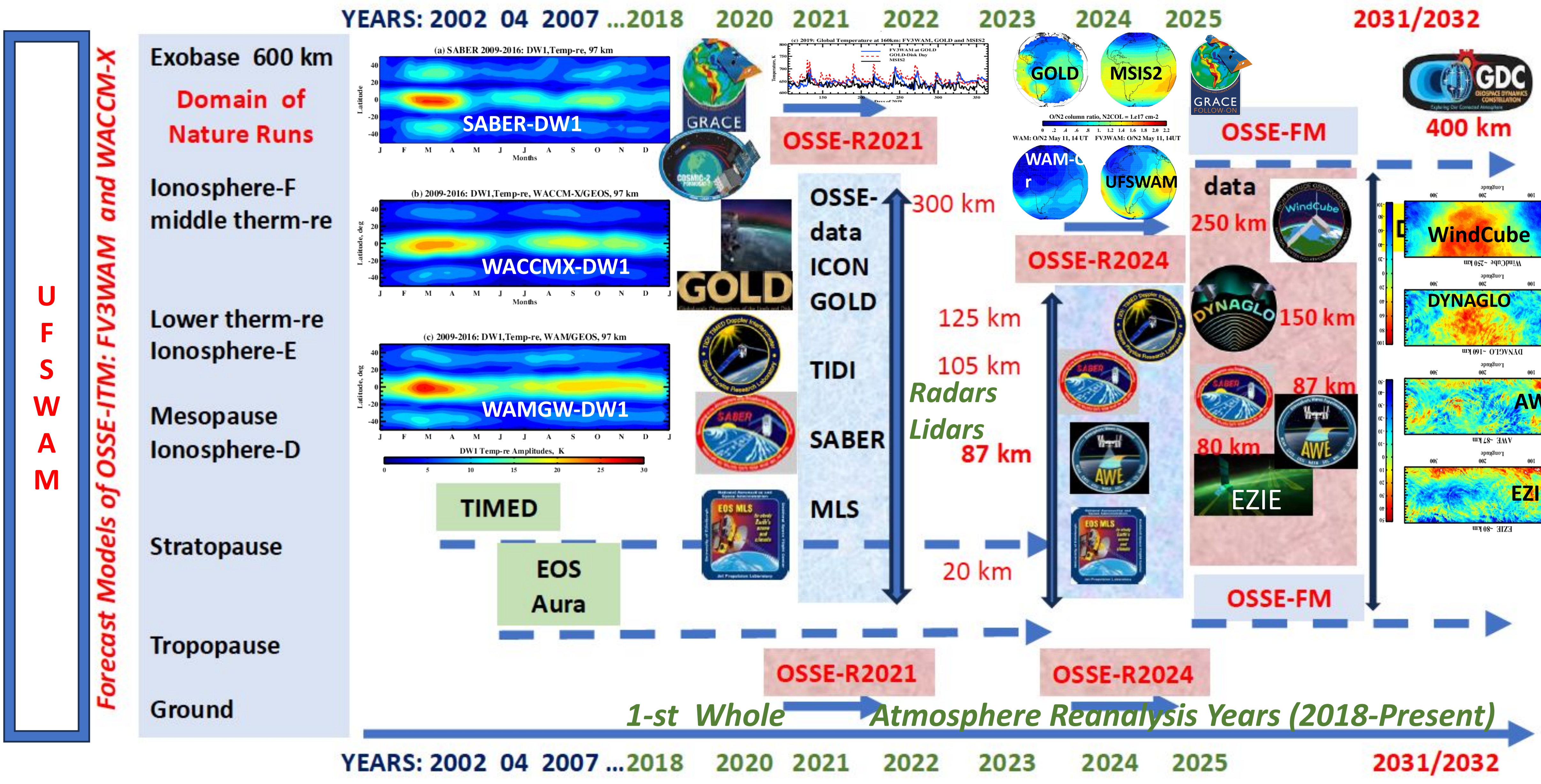
Acknowledgements to Drs. Rashid Akmaev and Henry Juang

First Developers of WAM Framework at NOAA/NWS

***The FV3WAM-150L (2022-25) are managed by NOAA/SWPC/EMC, T.-W. Fang & F. Yang*.**
The 2025 work on UFSWAM-196L is supported by NOAA/SWO (Irfan Azeem) & NASA/GSFC (Antti Pulkkinen) through the CUA/PHASER (R. Robinson and J. Brosius).

Twin OSSE in Whole Atmosphere Models (*UFSWAM-WACCMX*):

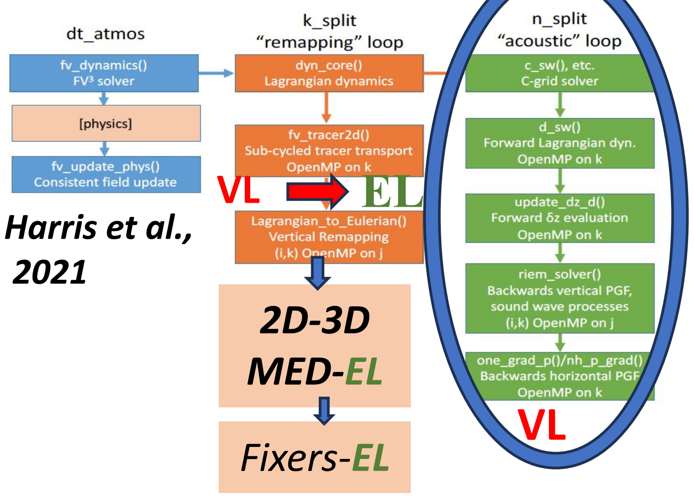
Adapt and Test DA Algorithms for SWA and Support of Novel SW Missions



UFSWAM: Whole Atmosphere Extension of FV^3 dycore into the Mesosphere-Thermosphere

Whole Atmosphere
NH FV^3 Dycore GFDL
Vertically-Lagrangian
Eulerian Layers

UFSWAM
Smagorinsky Large Eddy Simulations
SLES



Harris et al., 2021

Five Upgrades of of FV^3 Dycore

1) **Variable Molec. Weight** (μ: 29ae => 16ae) (μ, C_p, C_v, R/μ)
2) **Gravity** ($9.81\ m/s^2$ => $8.2\ m/s^2$);
3) **New Tracers** (O, O_2, $k=R/C_p$);
4) **MED-operators** (viscosity, heat conduction, & diffusion);
5) **No Rayleigh Friction/Sponge**

UFSWAM:
Whole Atmosphere Ext-FV^3: Step 3

FV3 dycore on Eulerian (EL, 3 Steps) & Vertically Lagrangian (VL) layers

S1) **NH dycore** ("acoustic" loop on **VL**)

S2) **Remap from VL to EL layers**

S3) ***2D Molec-Eddy Diffusion*** (***MED***, **EL**)

S4) **Fixers** (energy, mass, tracers) **on EL**

Dynamics-Physics Coupling (EL)

EL Column Physics: 3 steps (p-based)

1) **Radiation** of GFS/UFS
2) ***WAM_phys*** *with Mol/Eddy processes*
3) **Standard UFS/GFS** *with UGWP-WAM*

UFSWAM-SLES:
Mesoscale Large Eddy Simulations

FV3 dycore on Eulerian (EL, 3 Steps) & Vertically Lagrangian (VL) layers

S1) **NH dycore** ("acoustic" loop on **VL**)

S2) **Remap from VL to EL layers**

S3) ***3D Molecular-Eddy/LES Diffusion*** (**EL**)

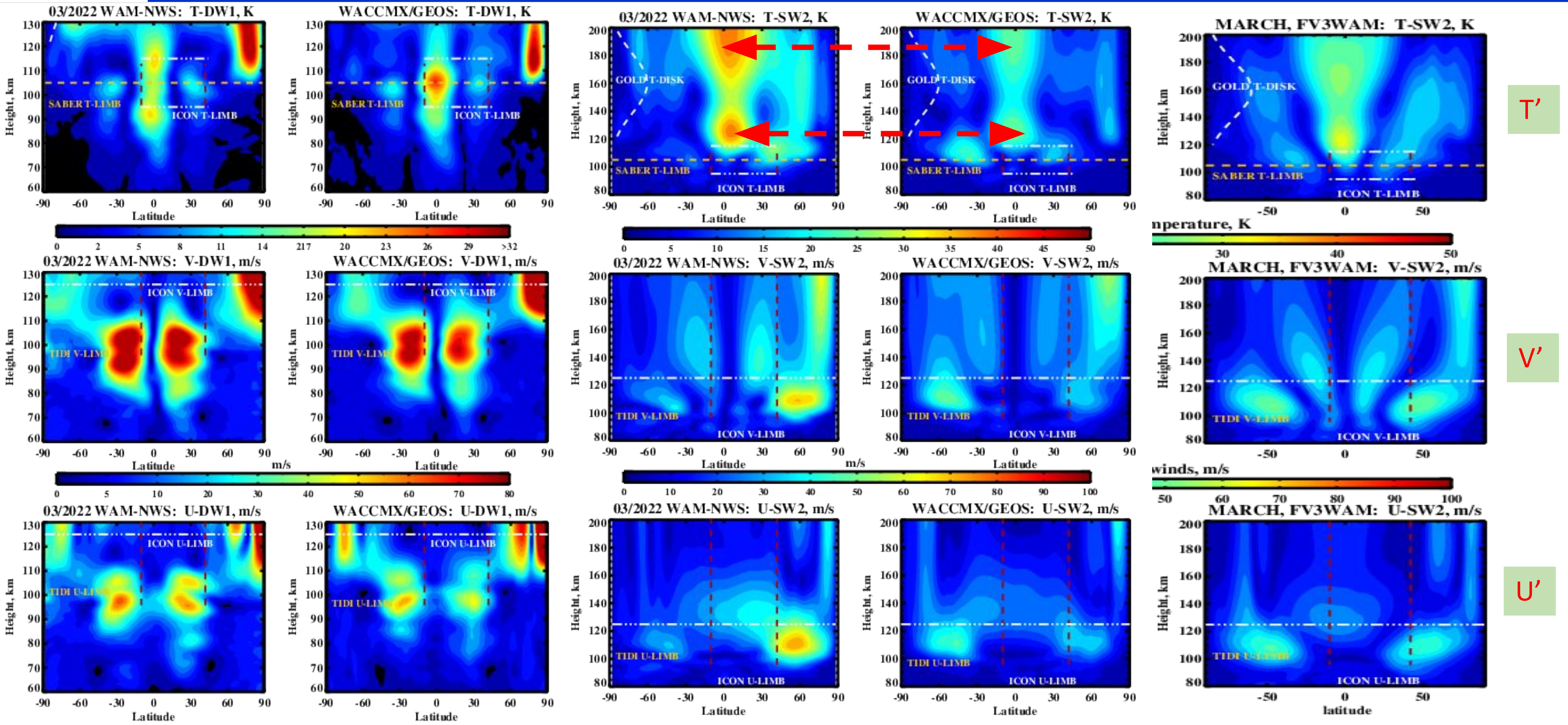
S4) **Fixers** (energy, mass, tracers) **on EL**

Dynamics-Physics Coupling (EL)

EL Column Physics: 3 steps

1) **Radiation** of GFS/UFS
2) ***WAM_phys*** *without Mol/Eddy processes*
3) **Standard UFS/GFS** *without UGWP-NGW*

March: ‘Consensus’ between WAM-DAS and WACCM-X/GEOS (surf-50 km) for migrating Tides and SW2 by FV3WAM-UFS (unconstrained)



WAM/DAS 24-hr WACCM-X/GEOS WAM/DAS 12-hr WACCM-X/GEOS 12-hr FV3WAM