Gravity Waves in the FV^3-based Models Extended into Mesosphere and Thermosphere

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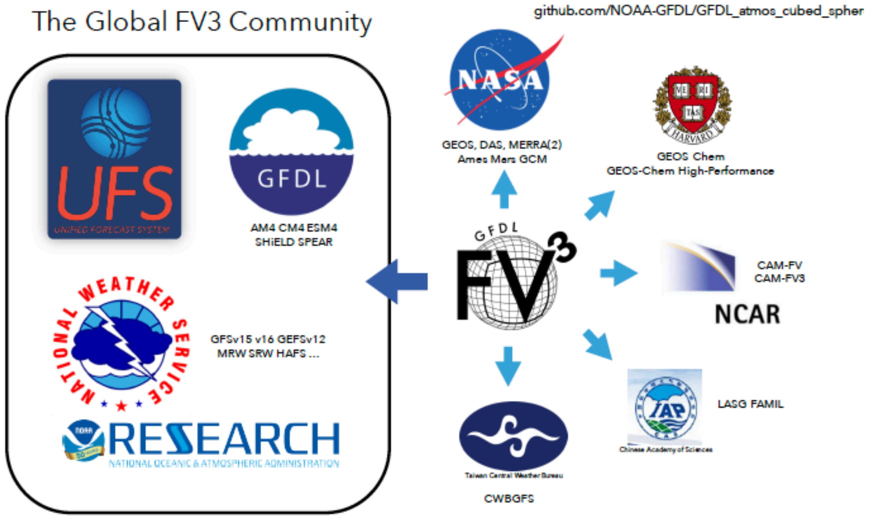
FV^3(FV3)-based operational and NRT models of NOAA and NASA

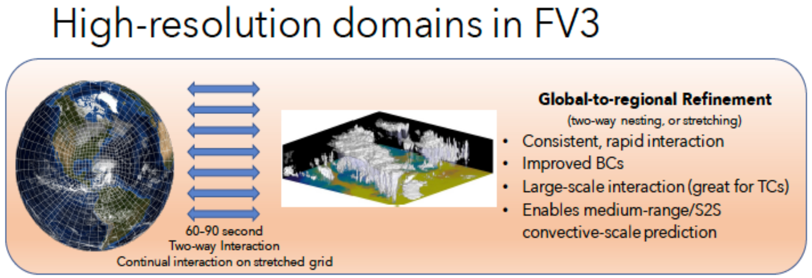
1) Role of GW dynamics and physics for Terrestrial and Space Weather Models

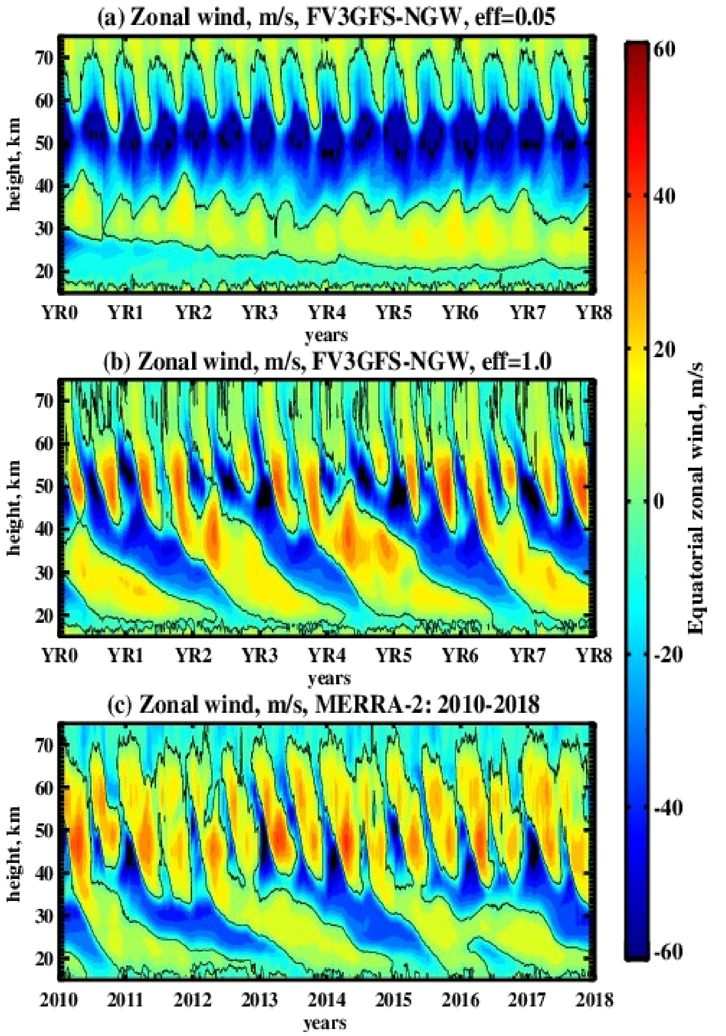
2) First retro-forecasts of UFS/GFS with revised GW phys. Role GWP in S2S and climate: QBO, SAO and AnnO of GFS-127 (80km)

3) Next GFS versions with upgrades of GWP: GFS-V17 and FV3WAM-V1 for NWP res-ns.

4) Concluding remarks







FV³-based Models at NOAA, NASA and NCAR:
UFS/NWS (GFS, WAM), GFDL(SHIELD/ESM4) , GMAO (GEOS/MERRA) and NCAR (CESM2-dycore) *https://www.gfdl.noaa.gov/fv3/fv3-applications*

GFSv16 AC Scores (NH 500-hPa Z at Day 5)

	GFSv15 (OPS)	GFSv16 (RET
Fall 2018	0.916	0.916
May 2019	0.880	0.897
ummer 2019	0.880	0.888
Fall 2019	0.897	0.901
ter/Spring 2020	0.909	0.913
l-Time Parallel	0.864	0.871

- **NOAA UFS FV3-model configurations are in NWS operations (V16), 03/2021**

  GFSv16*: FV3GFS -127L,* *TL~80km, doubled VR; δx ~12.5 km; NGW: UGWP-v0*

  WAM-IPE: SW-physics-based model, GSM-150L dycore, *TL~600 km (T254-70km)*

  FV3WAM-150L/196L- under development will replace GSM-WAM

  The short-term GFS forecasts are improved (*Yang et al*.,2021, 2024)

- **Sub-seasonal and climate runs of FV3GFS-v16 (100 km) and GSMWAM (200 km)**

  revealed shortcomings related to GW physics, and in 2020-2023 GWP-V1 was introduced to address:

in GFS-v16: *a) unrealistic QBO and SAO; b) weak extra-tropical circulation; and c) lack of the stratospheric teleconnections, QBO-Polar Vortex*

in WAM-IPE: *lack of realistic GW-MF-tidal interactions above ~50 km create inaccurate seasonal variations of prevailing circulation, tides and transport in the MLT.*

- ***Overview of recent improvements of GWP for GFS/UFS and GW-resolving simulations in FV3WAM with upgrades of FV³-dynamics and adding molecular and eddy dissipation to dycore.***

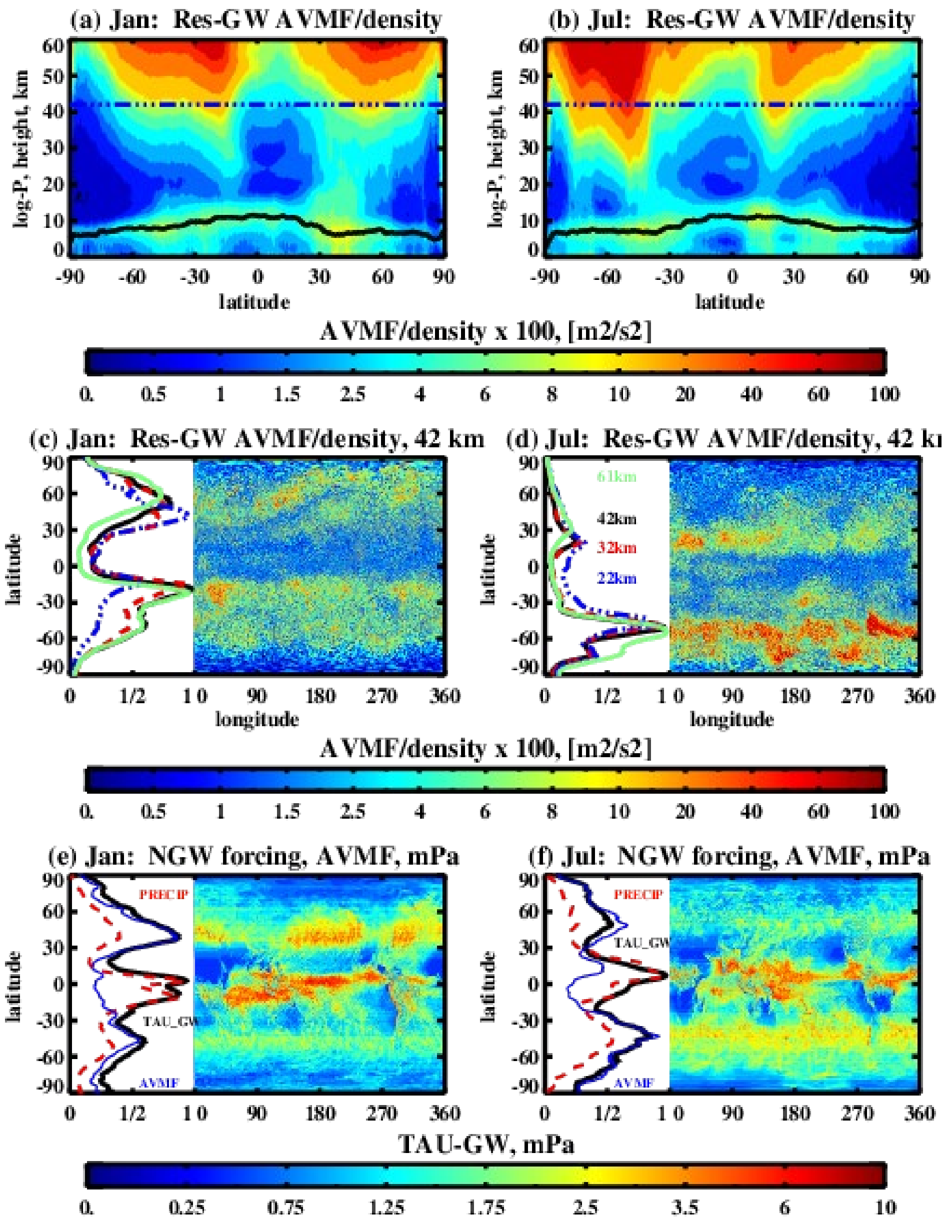
Upgrades of GW physics in GFS and WAM

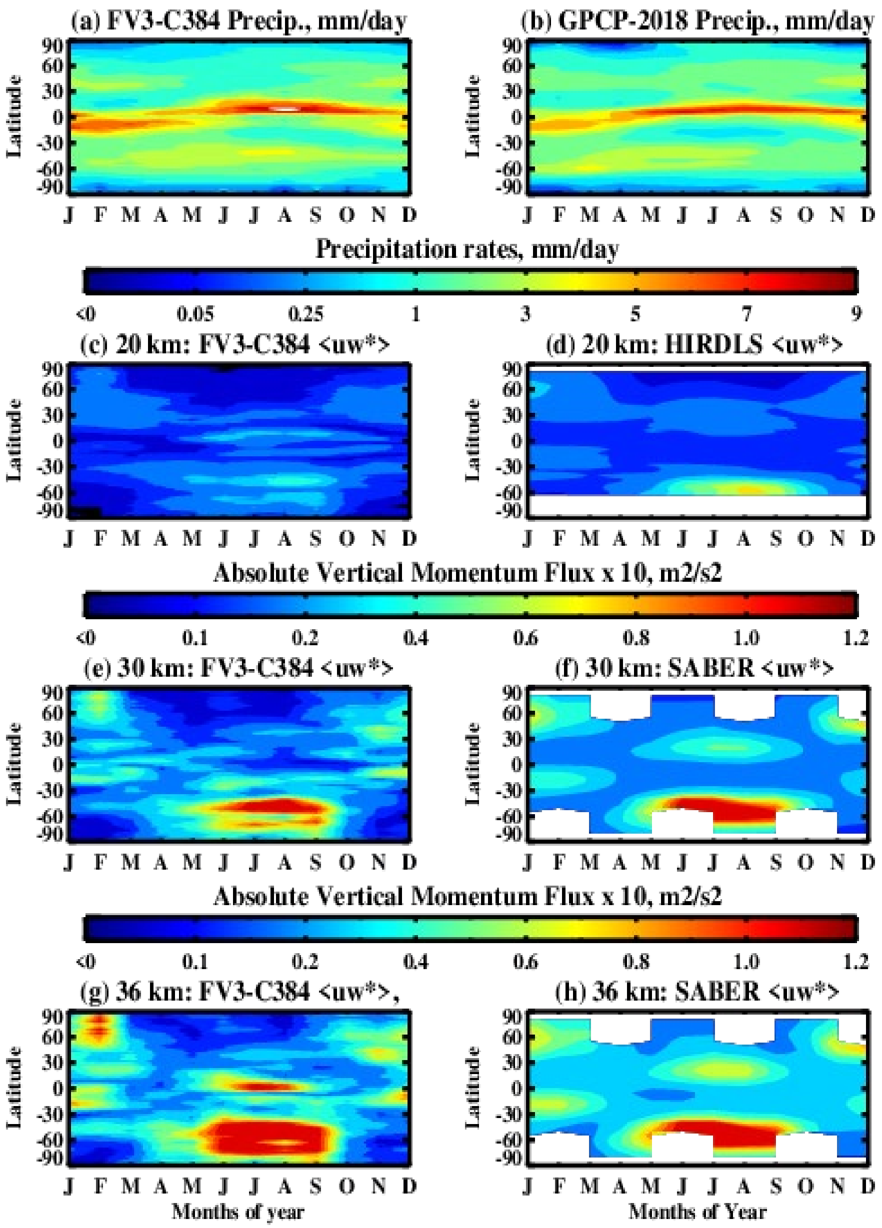
Major upgrade: Similar **specification of NGW sources and "solvers" for GFS-80 km & WAM-600 km;** Identical "solvers" for OGWs & NGWs.

Dissipative damping and **corrections in GW-solver of the IFS (broad spectrum)** scheme; **Option to switch to and work with the Linear Saturation** of discrete GW modes (CESM/GEOS).

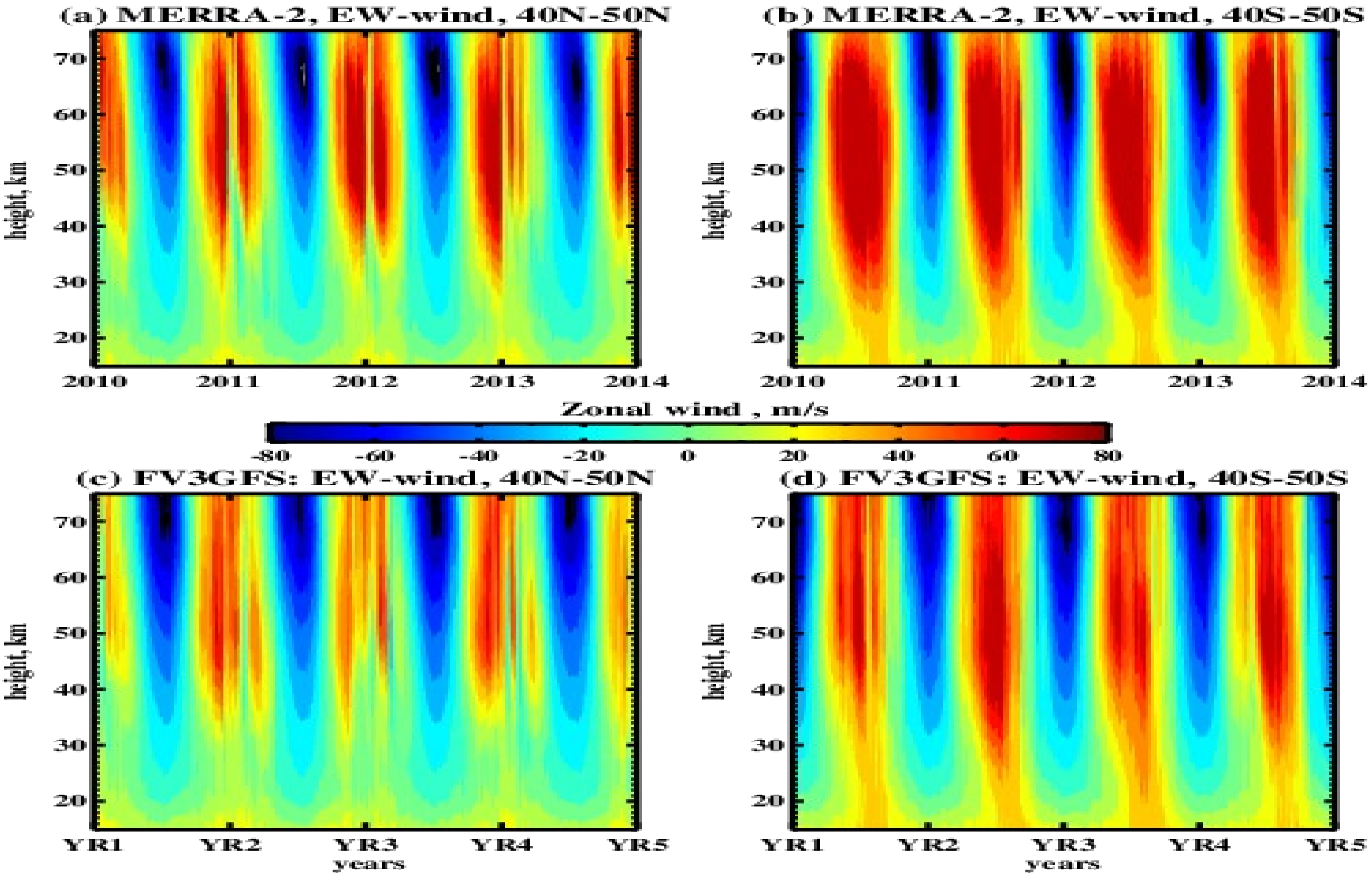
Non-local energy conservation in the vertical column.

GW-induced eddy diffusion.





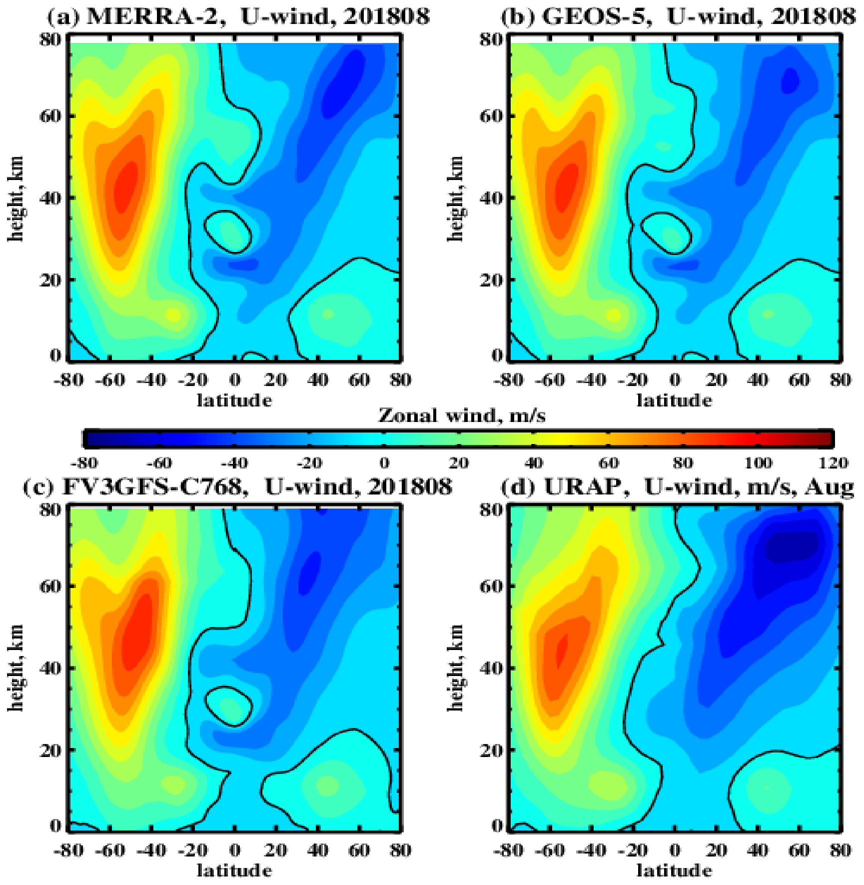
Zonal winds at mid-latitudes: MERRA-2 (top) & GFS/GW-v1 (bottom)



40N-50N

40S-50S

MERRA-2/GEOS-5, URAP and FV3GFS – Aug monthly mean

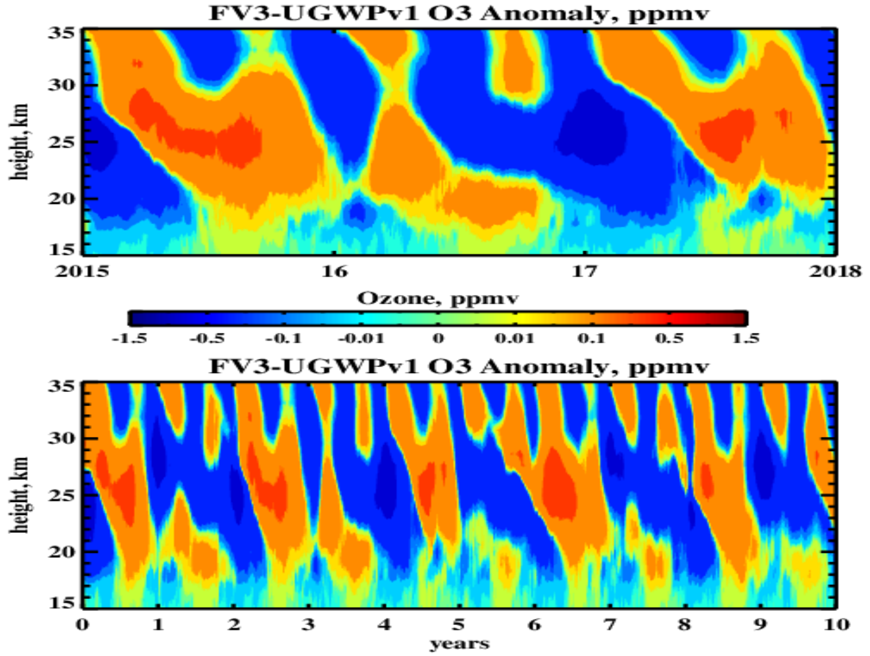


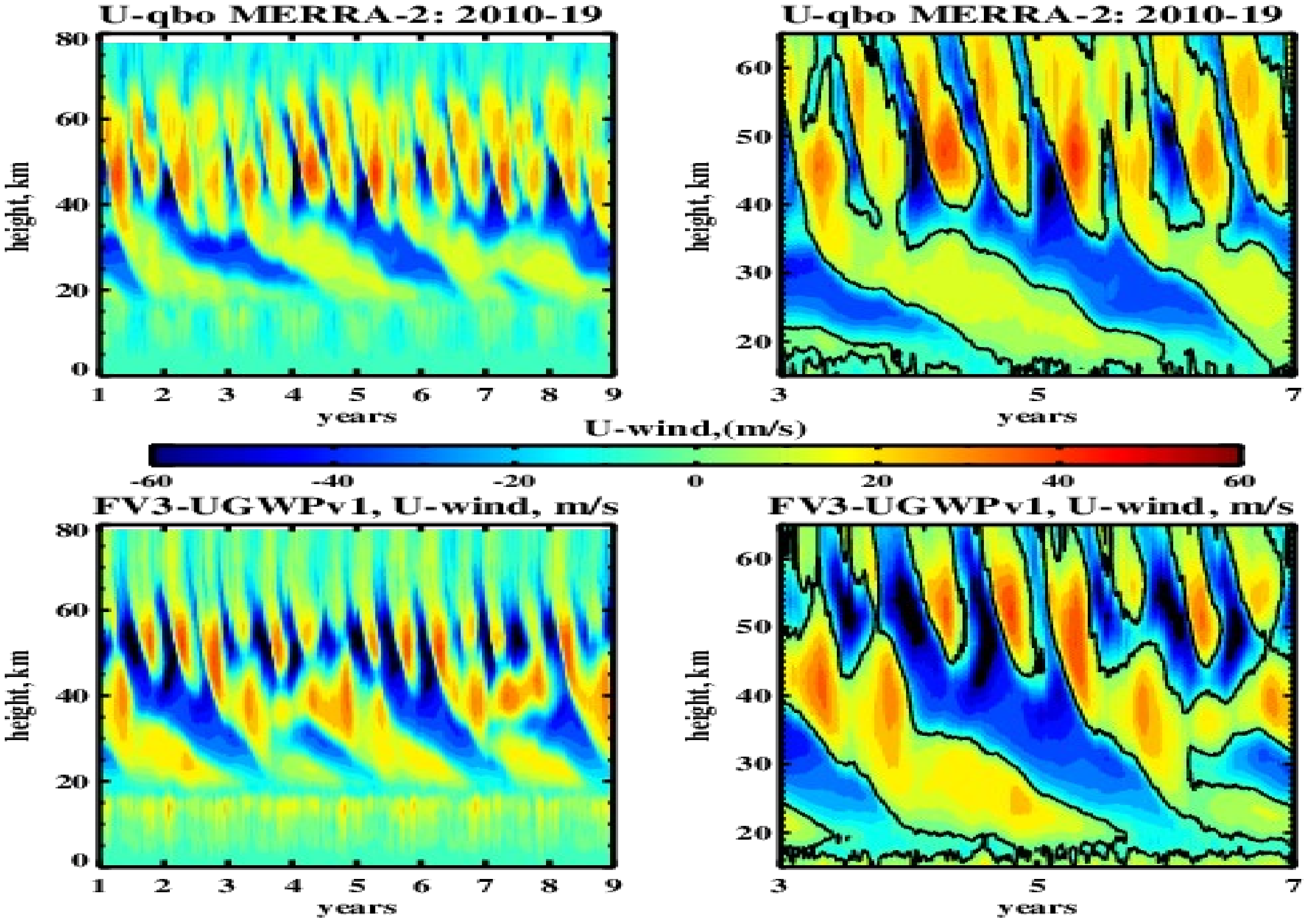
Equatorial QBO in MERRA-2 (top) and FV3GFS/UGWP-v1 (bottom)

10-years of FV3GFS-C96 (100 km) simulations
Comp with MERRA-2 (MLS-T and O3)
Molod et al -2015 QBO forcing/LinSat

GFS-v16/UGWP-v1 new forcing and spectral GW-scheme w/o eff-factors.
QBO periods in MERRA-2: *26-30 mo*. (28.3)
GFS-v16: ~ *24-28 mo (27)*

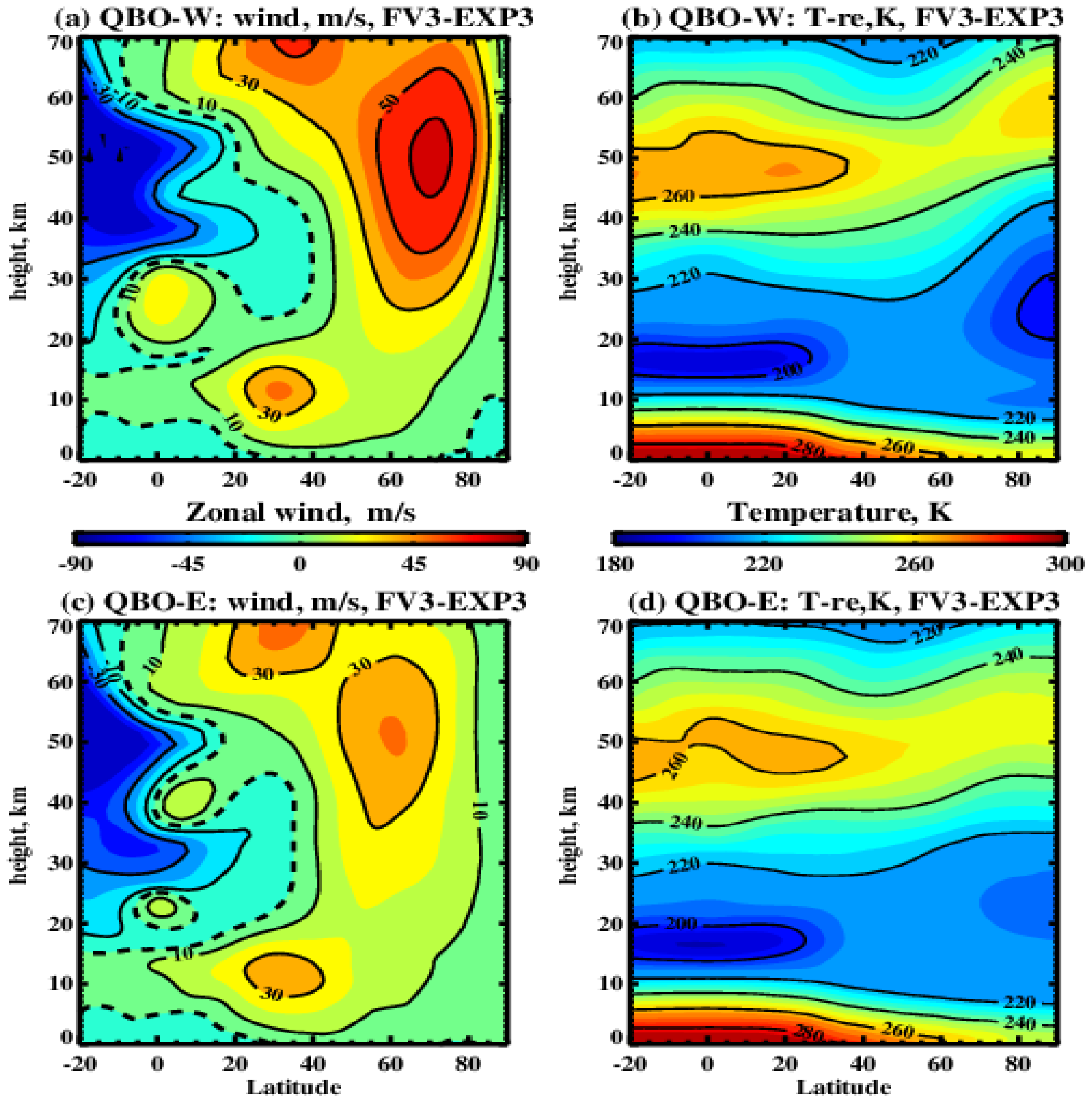
stronger W-ly winds; reasonable SAO in winds



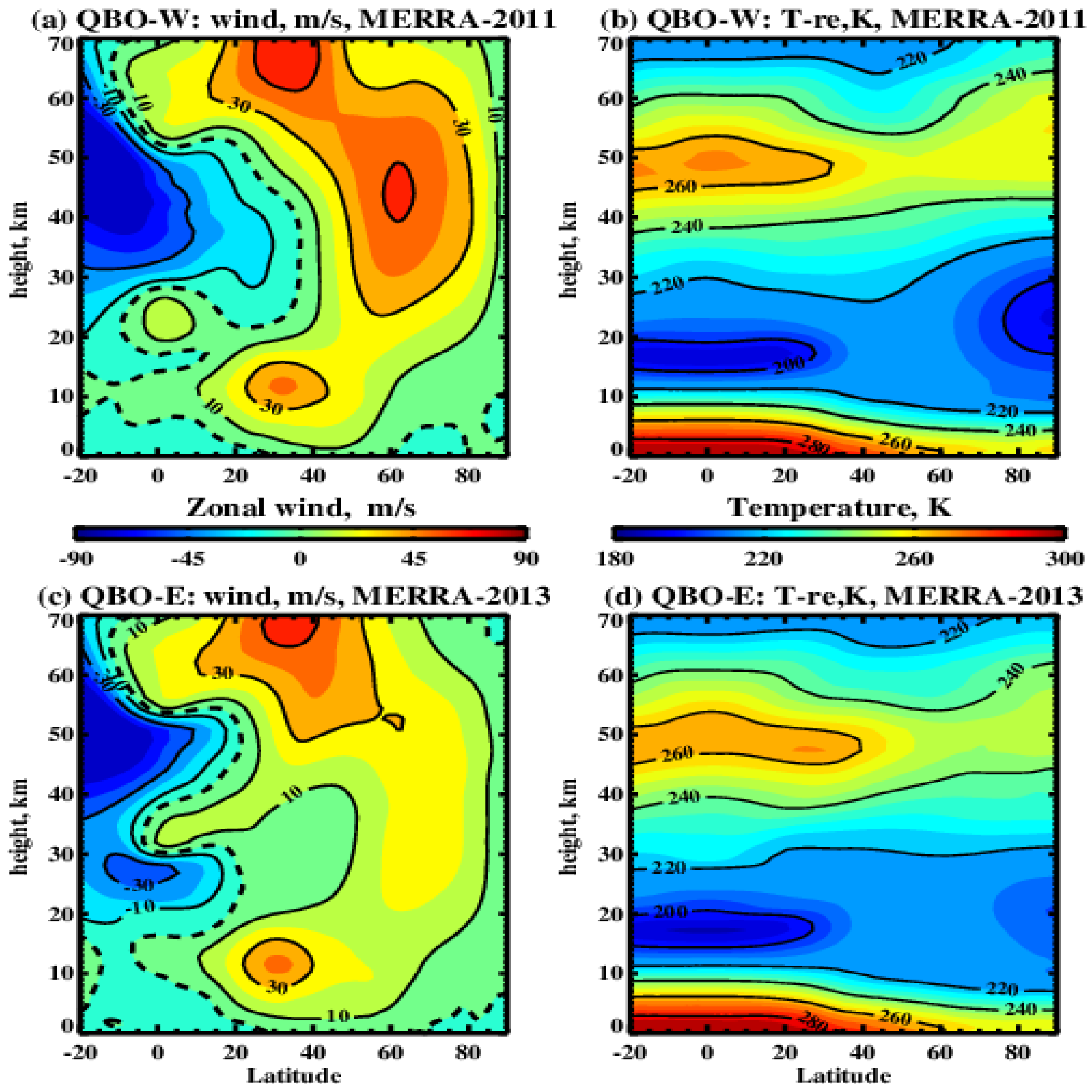


Additional work and tune-up: Optimization and diagnostics of equatorial PWs : RGW and KW, that drive the lower QBO domain;
"Key factors": wave damping (dycore) and vert. res-n; PW forcing by convection

FV3GFS-GWP: S2S capability for Arctic "climate" teleconnection: Phase of Eq-l QBO ⇔ Strength/Spread of the Arctic Vortex below 35 km

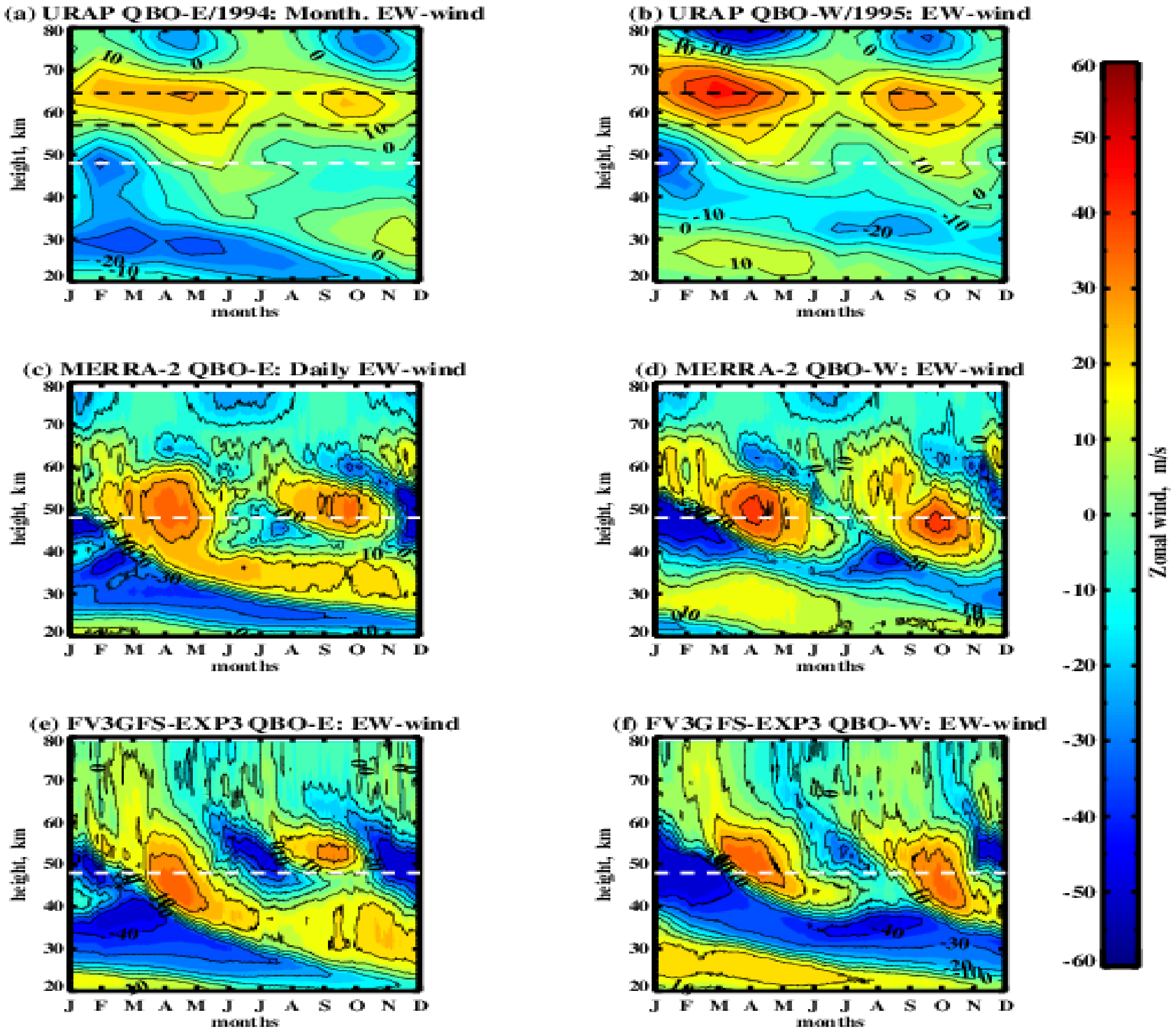


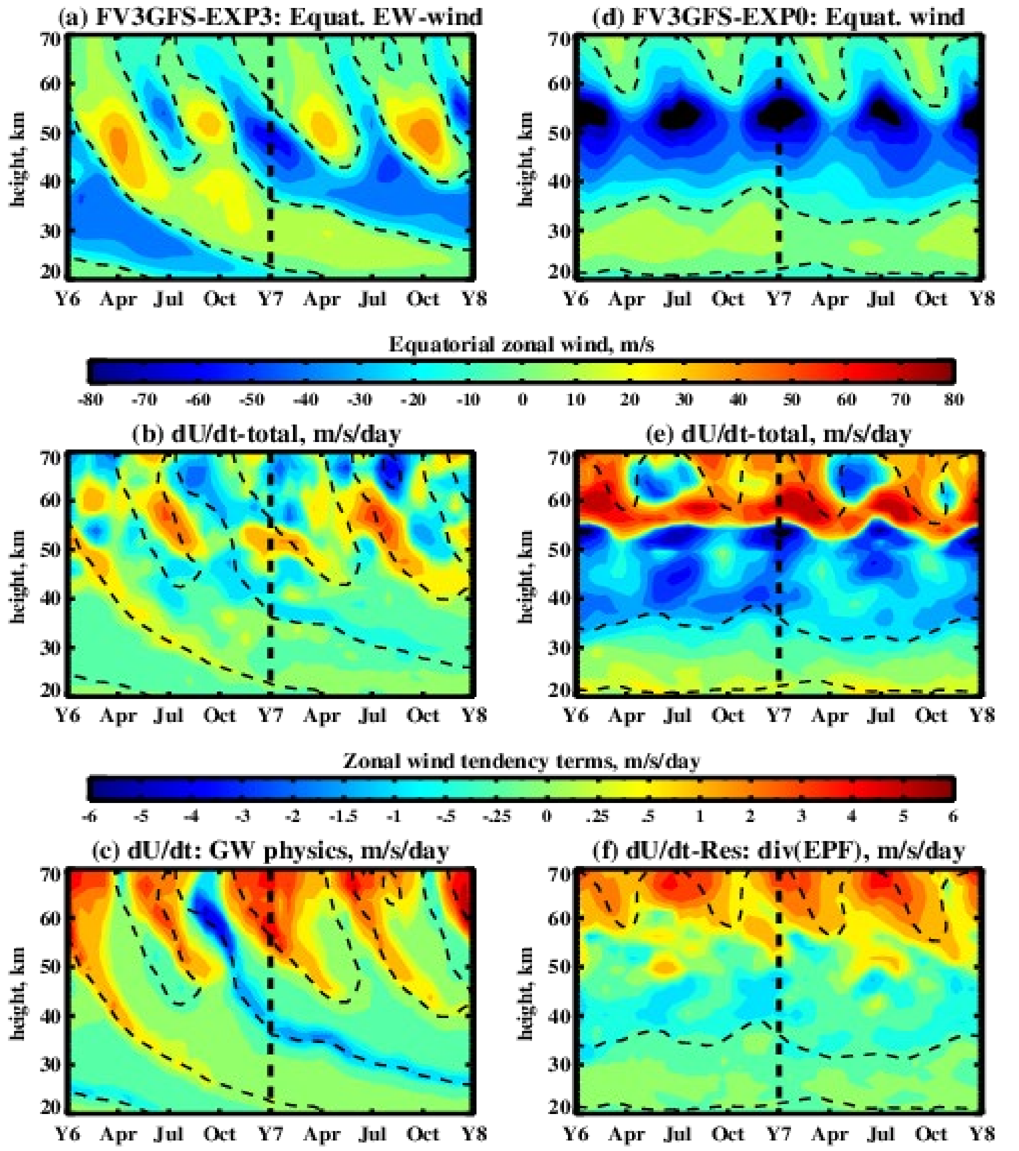
FV3GFS-C96 (10-YR run)



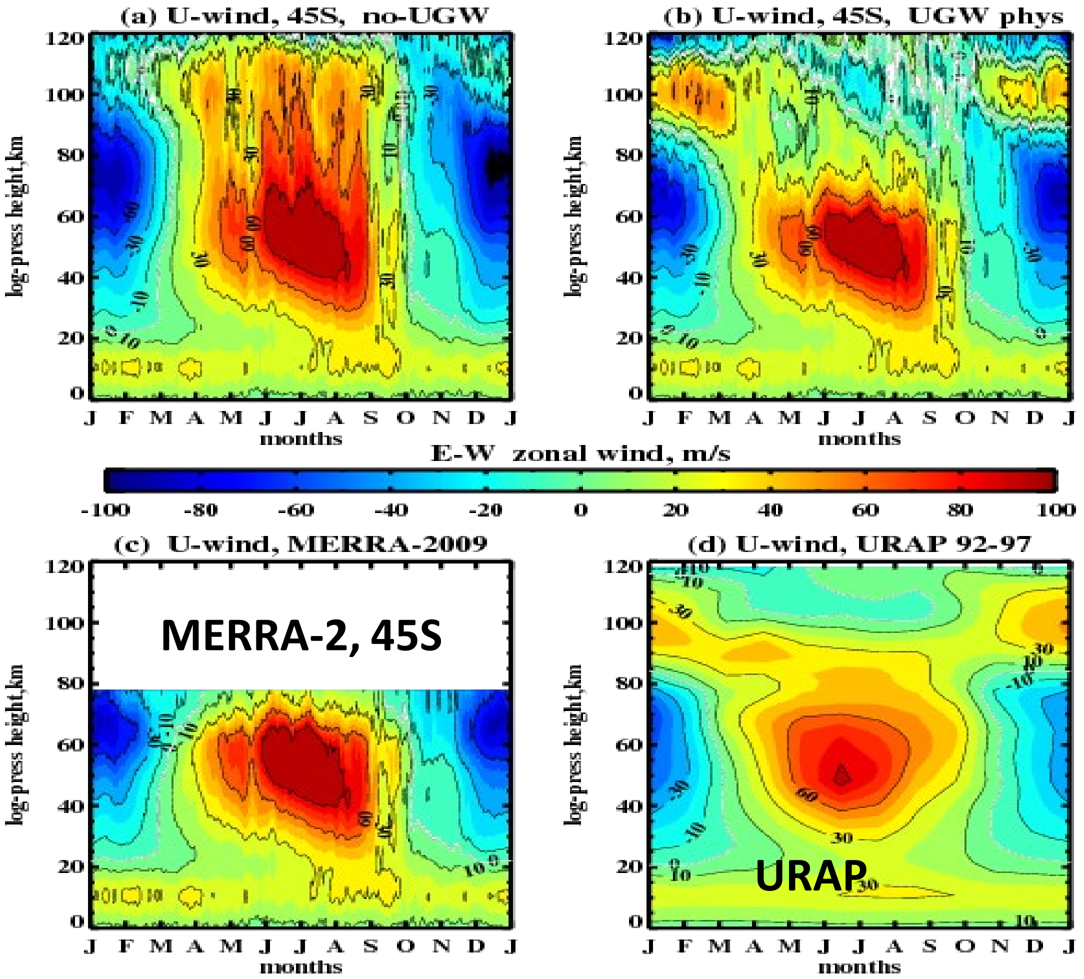
MERRA-2 QBO-W (2011, top) and QBO-E (2013, bottom)

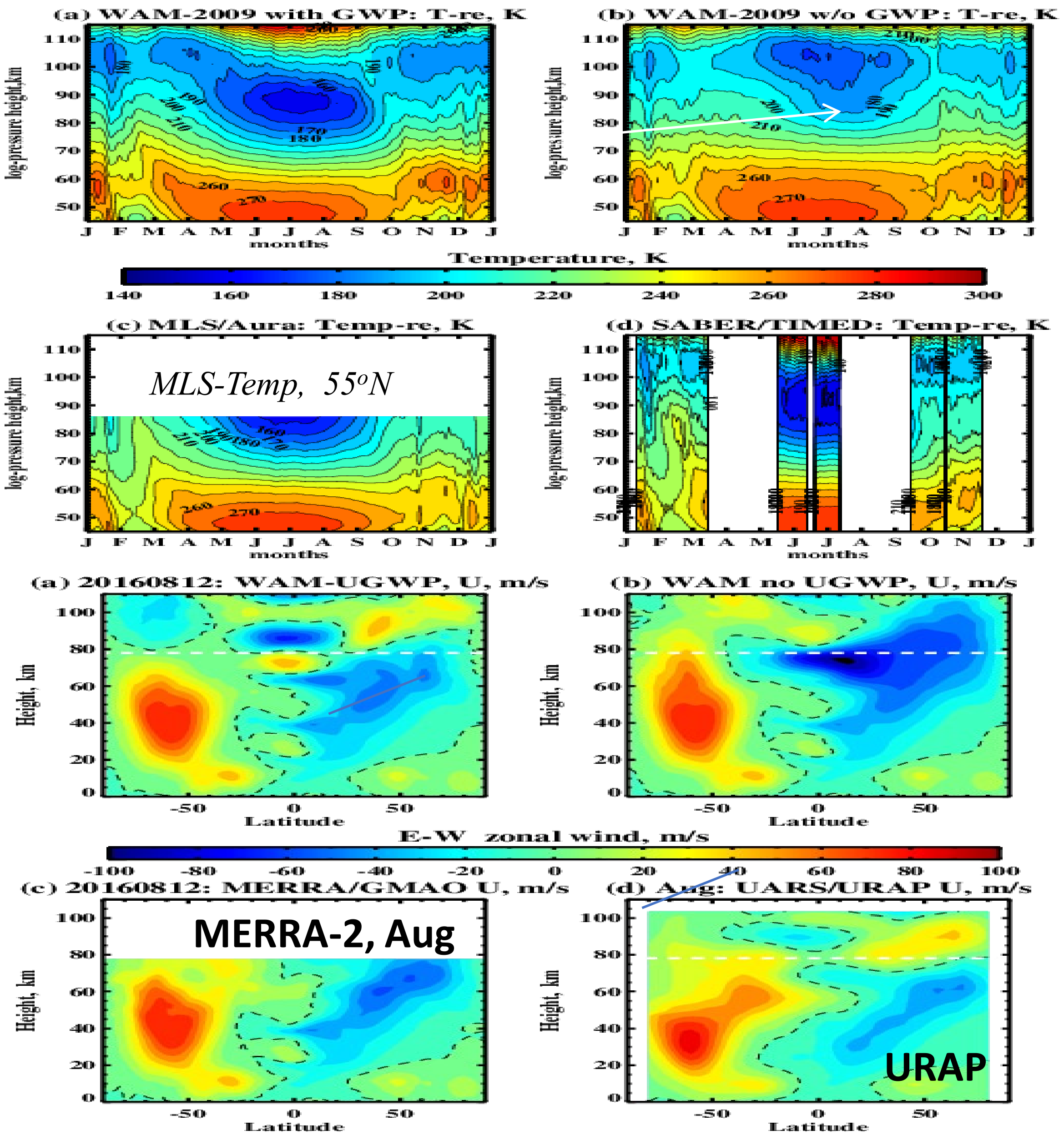
Equatorial SAO: URAP, MERRA-2, FV3GFS with and w/o GWP





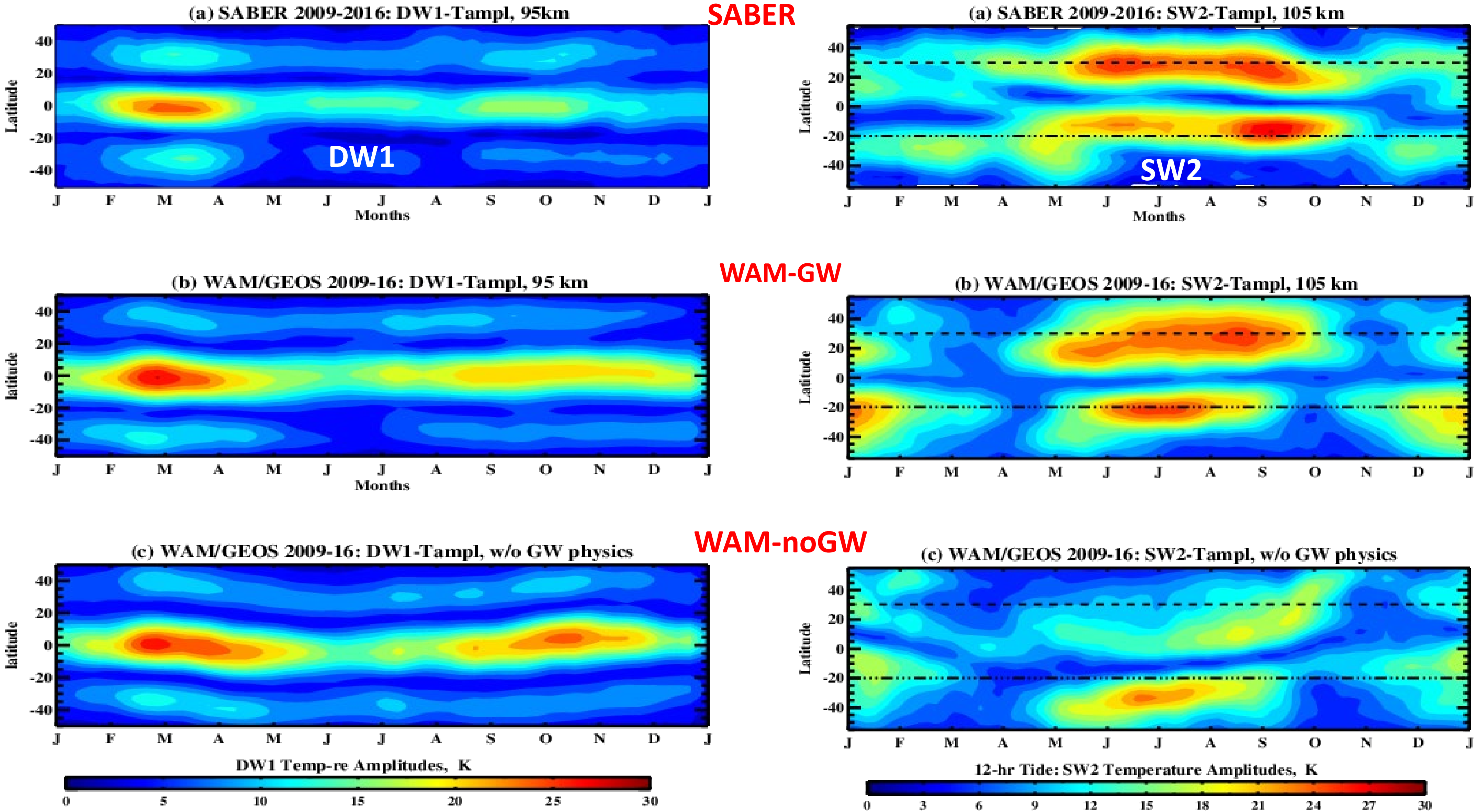
WAM: Differences between MLT Zonal Winds and Temp-res in GSMWAM due to impact of GWP-v1 (Annual cycle and Aug zonal winds); WAM – nudged below 40 km to MERRA-2





WAM-IPE errors in the MLT winds due to "current" absence of NGWs :elevated mesopause (~100km in 'polar summers'), unrealistic tidal dynamics and transport of major species.

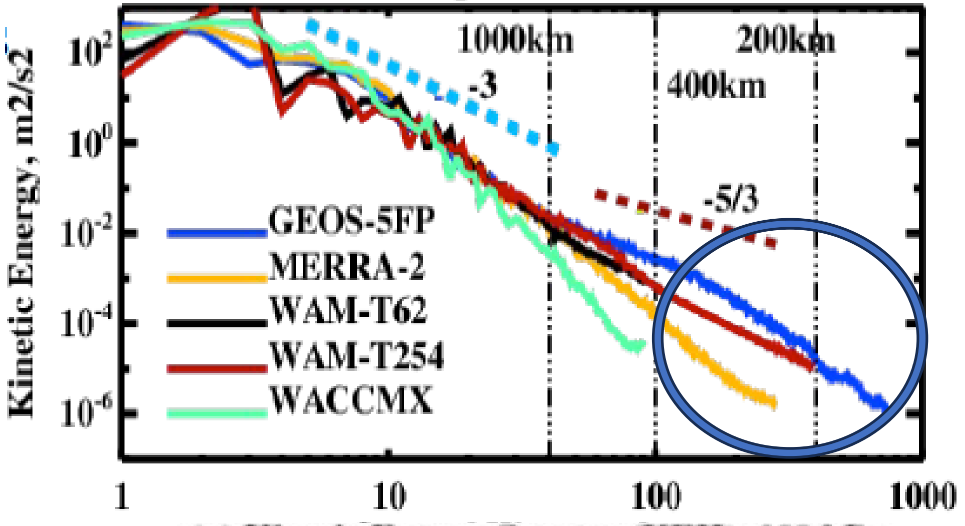
Tidal Dynamics in SABER and WAM: 24-hr T-amplitudes (DW1, 95 km) & 12-hr (SW2, 110 km); without GWP WAM fails to reproduce observed Seasonal Cycles of tides.



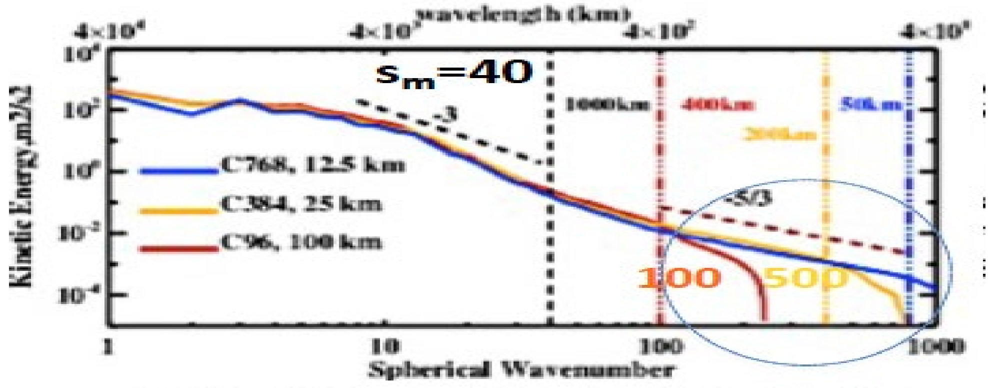
Working on WA modeling and DA to "resolve" GWs by enhancing HR of simulations

1) **WAM-T254 (~50 km)** ***in operations; Fall 2023***
2) ***Malhorta et al.*** (2024); **Resolved GWs from WAM-T254 run (thermosphere).**
3) **WAM with FV3-dycore and UGWP-V1 (100 & 50 km)**
4) **Enhanced (25 & 12.5 km) res-ns of FV3WAM** to **support** ***GW-oriented missions*** *by operational models.*
5) **Challenge to simulate GWs (s > 100): WAM stability at enhanced resolutions** ***above 80 km***

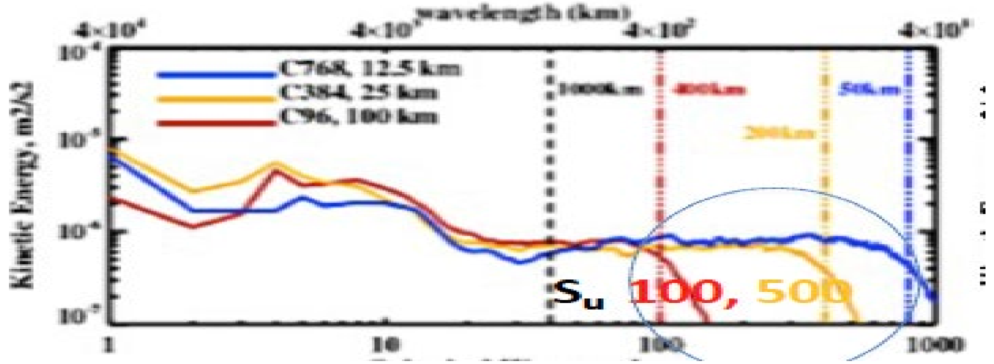
(b) KE spectra at 65 km

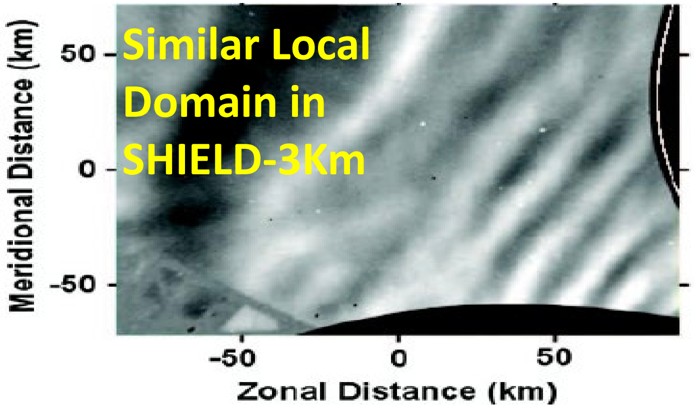


(a) Kinetic Energy Spectra (KEH), 100 hPa

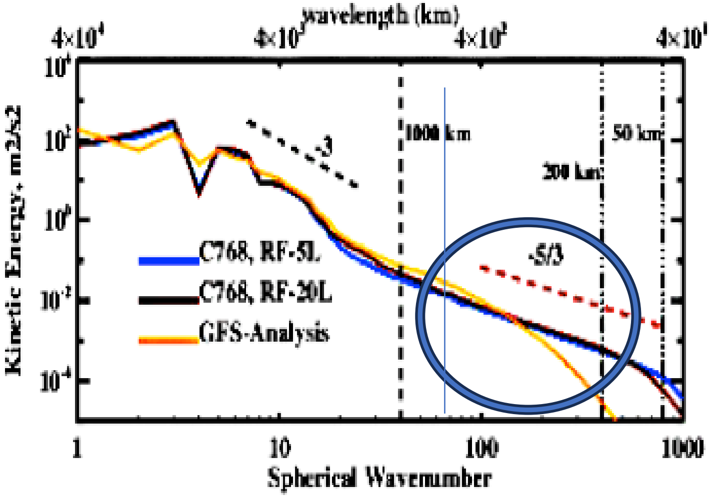


(c) Kinetic Energy-W Spectra (KEW), 100 hPa

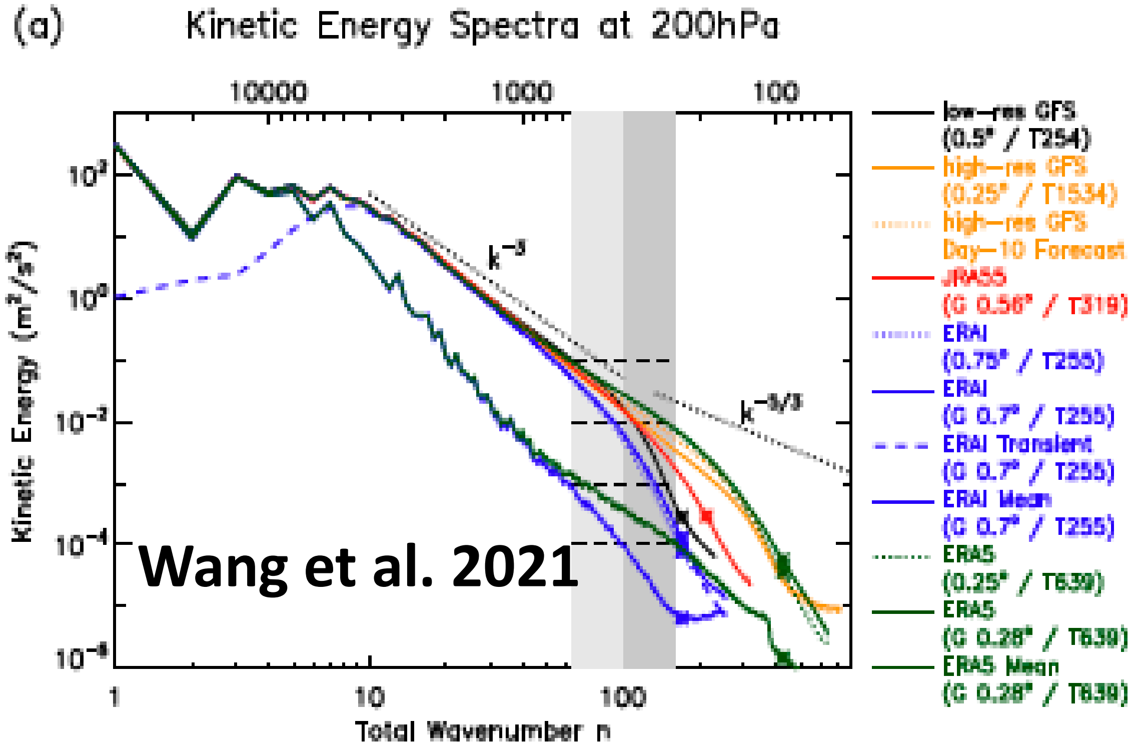


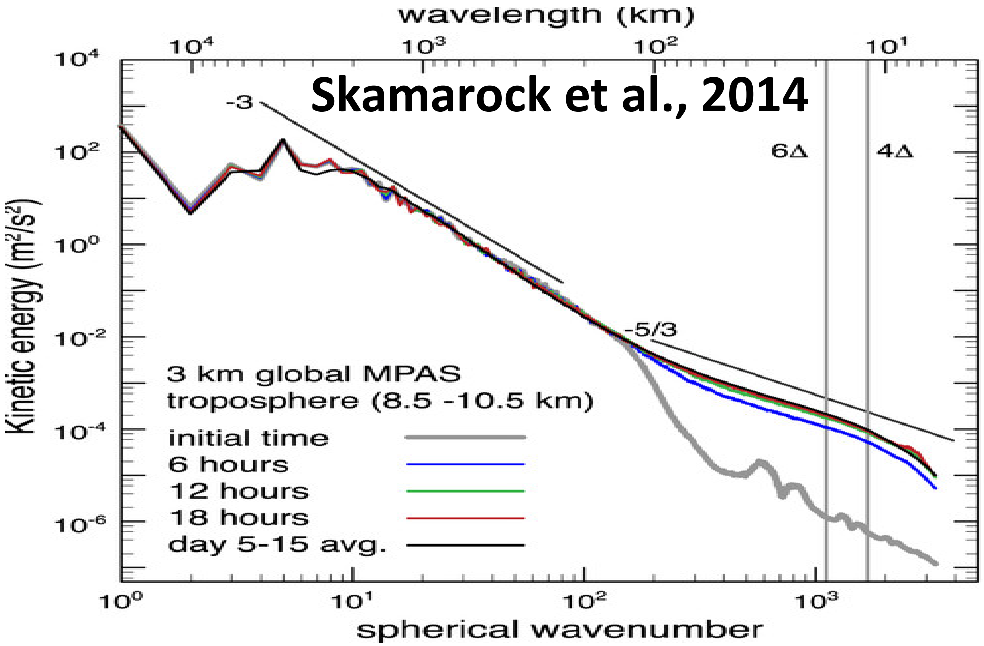


(a) Kinetic Energy-H Spectra (KEH), 100 hPa



Regional GW events in MLT, adapting SHIELD-nesting for FV3WAM

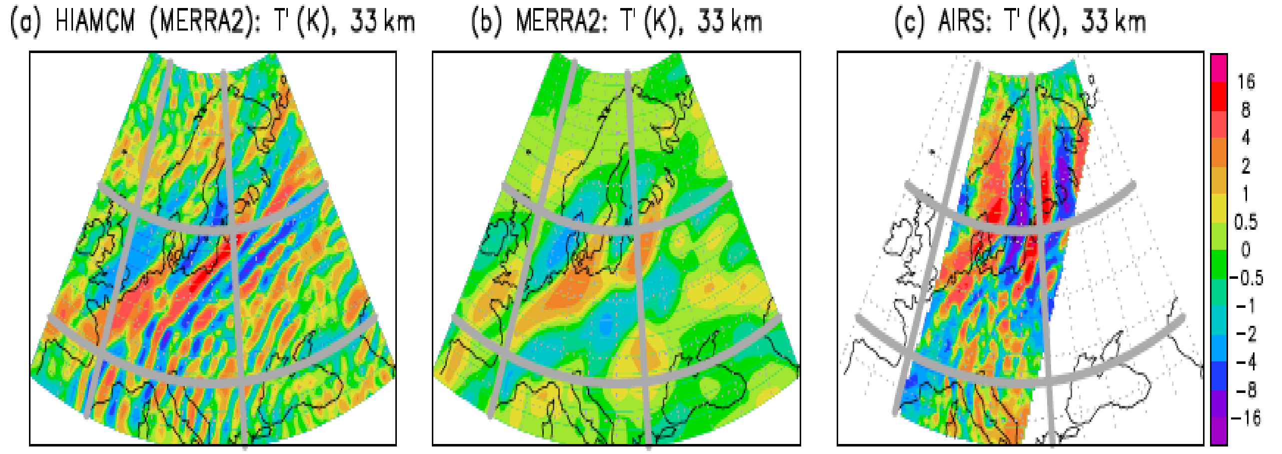




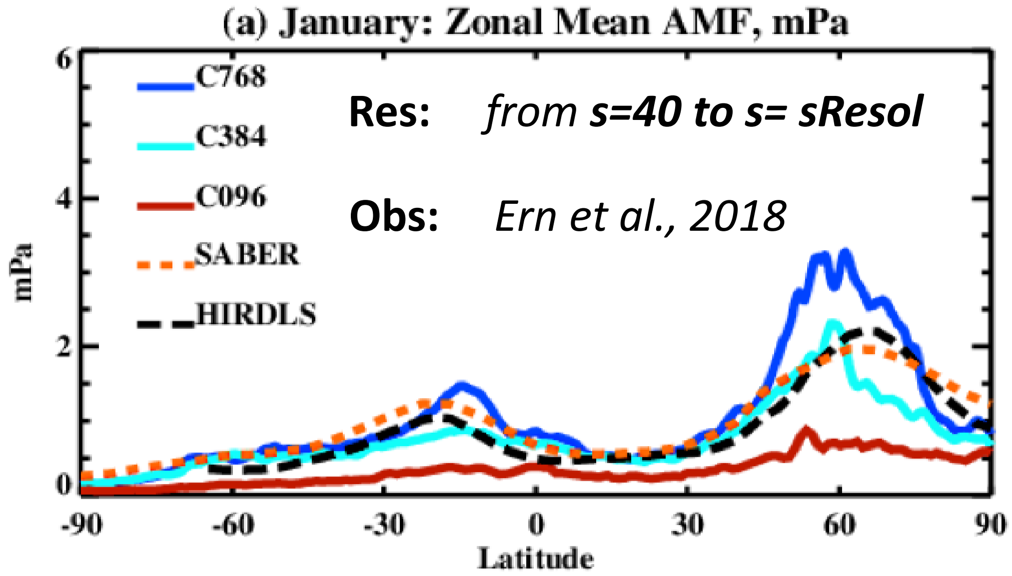
Credibility of the Modern Reanalyses and DA **to resolve mesoscale wave dynamics**, that can be ”accurately” reproduced by the “free”-running HR models; Models initialized from analyses with damped Mesoscale Kinetic Energy Spectra (MKES) can “restore” MKES in 6-12 hours;

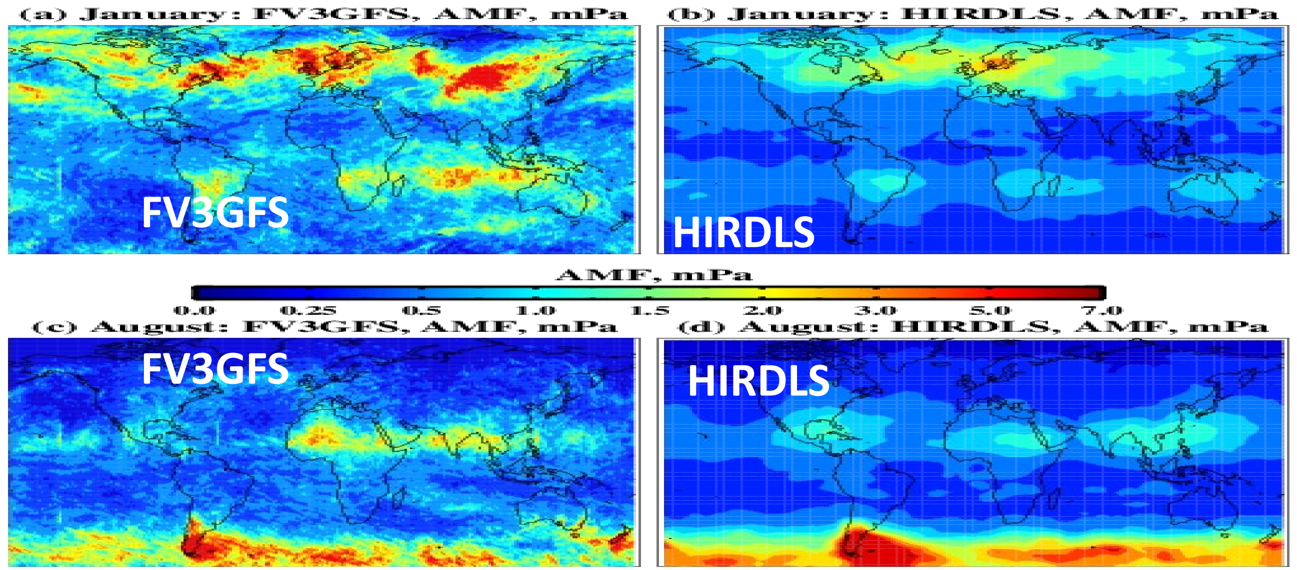
BECKER ET AL.: NUDGED GCM WITH RESOLVED GWS

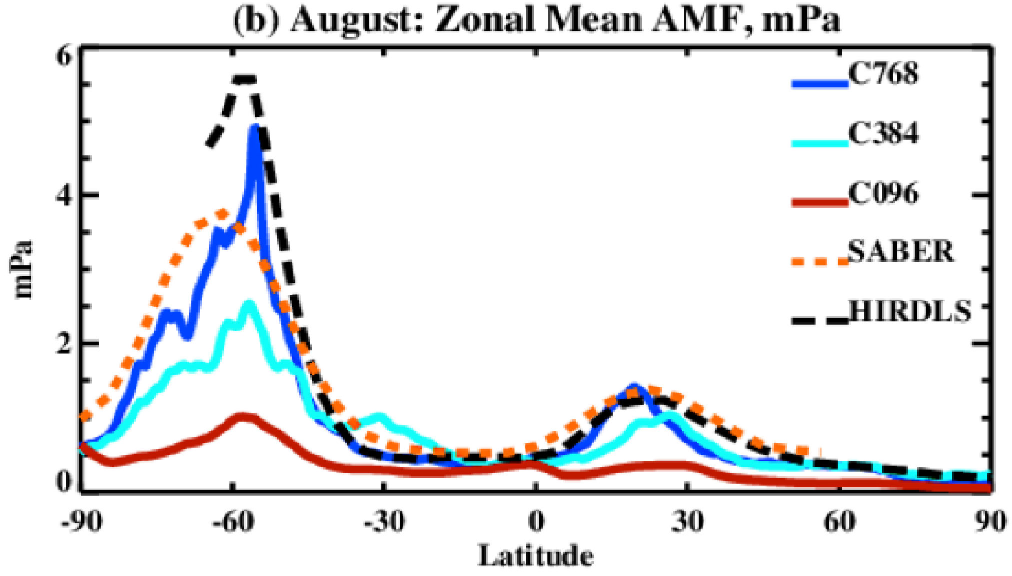
HIAMCM/MERRA2 **MERRA-2** **AIRS**

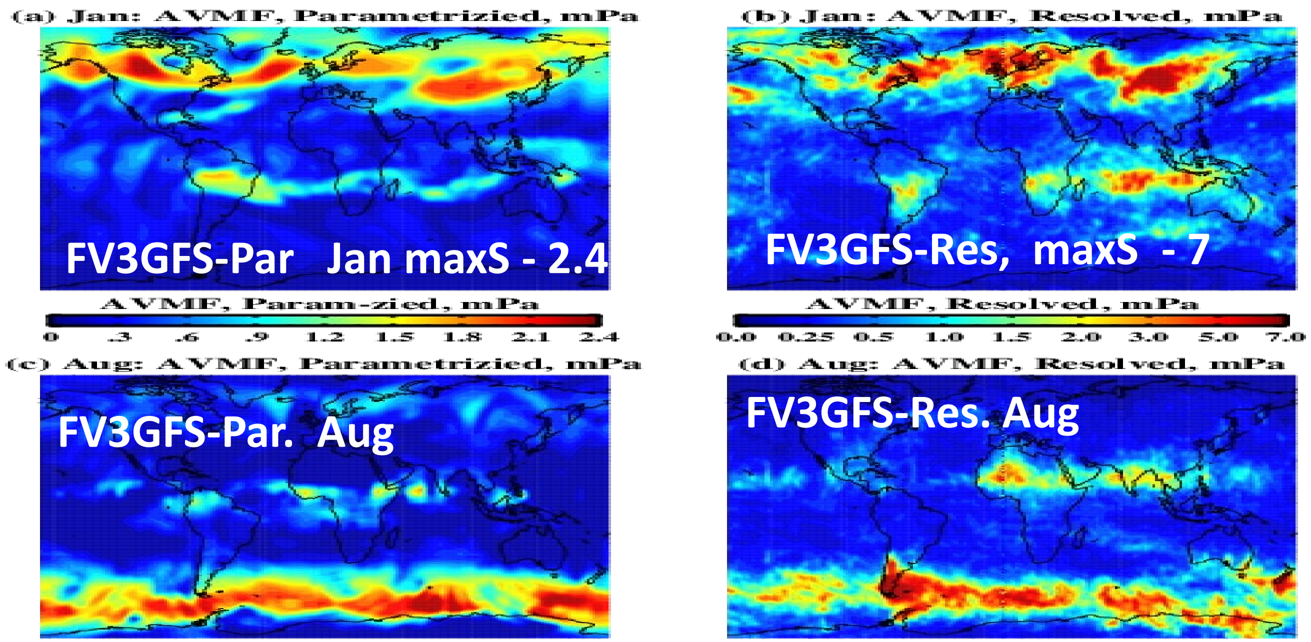


Mesoscale GW fluxes: Observed, Resolved and Parameterized, 10 hPa





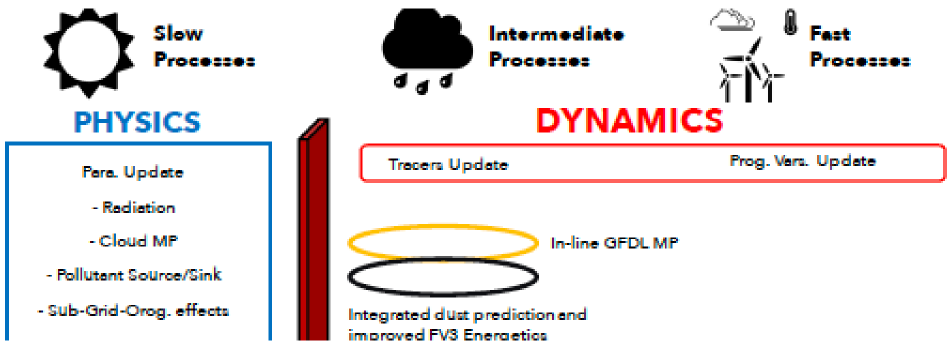




GFDL Strategy on DYNAMICS-PHYSICS COUPLING

Rethinking Physics-Dynamics Coupling

- Moving modeling forward requires breaking the strict separation of physics and dynamics.
- Partially-resolved and fast processes can be integrated directly into FV3 for better dynamical consistency, energy conservation, and efficiency

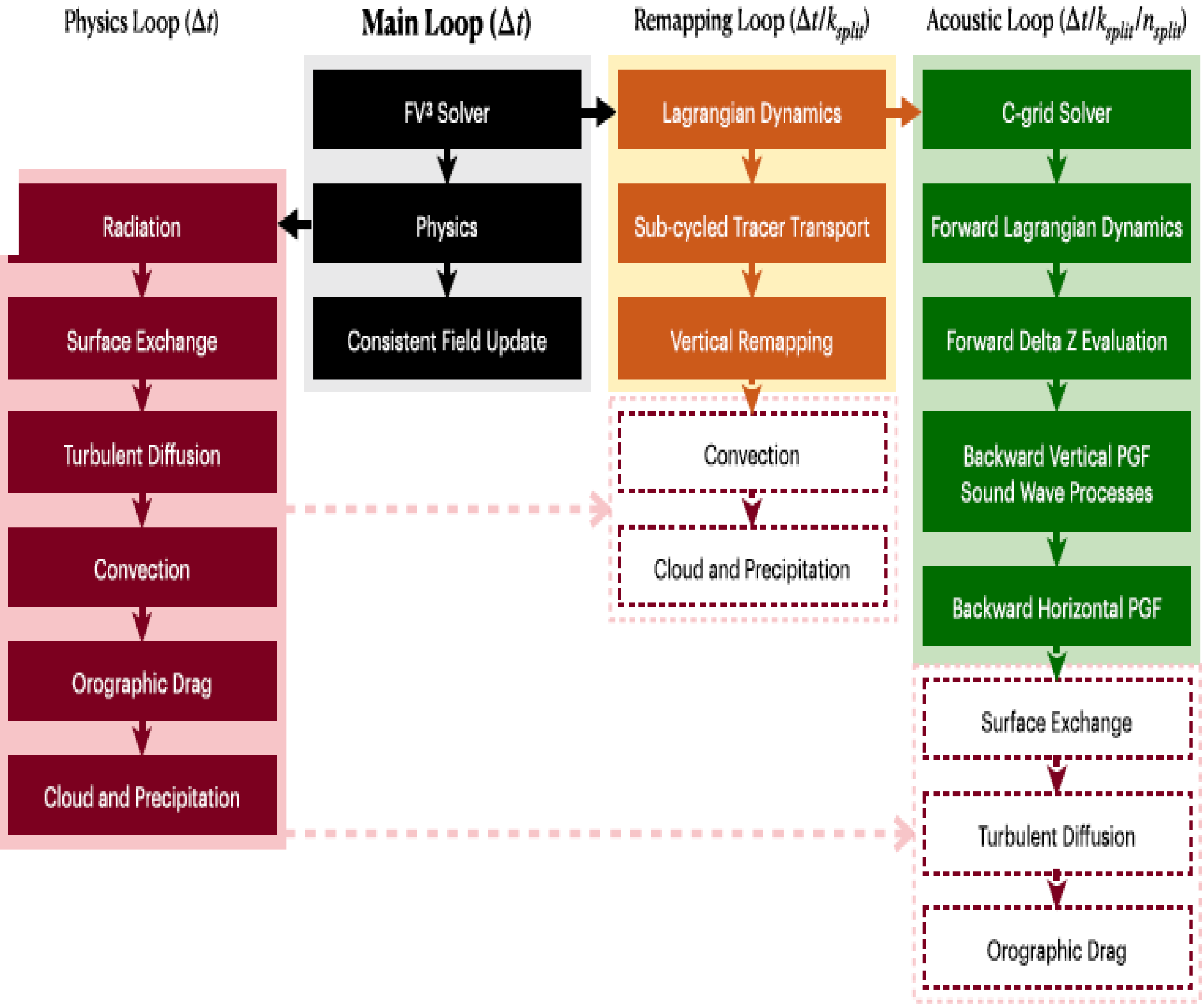


Harris et al., 2020

GFDL: Physics inside FV3-dycore on Pressure-Eulerian layers or/and Vertically Lagrangian (VL) surfaces

Integrated Dynamics-Physics Coupling for Weather to Climate Models: GFDL SHiELD With In-Line Microphysics

Linjiong Zhou[1] and Lucas Harris[2]



FV3WAM:
Fast UA Physics inside dycore on the Eulerian pressure layers

fv_dynamics + diffusion
Extension of FV3 solver

fv_update_phys
PNH-tendency

3D Eddy mixing:
Horizontal eddy viscosity
Vertical eddy viscosity/heat
following Becker et al. (2018, 2022)

Current considerations to add the sub-grid horizontal divergence of <u'u'>, <u'v'> =>
1D-GWP to 3D-GWP

dyn_core,
VL FV-dynamics

fv_tracer2d, horizontal advection for each Layer

Vertical Remapping

Sub-grid scale GW physics and eddy mixing

3D molecular and eddy momentum, heat, and tracer transport; Ion drag

C_SW, C-grid solver

D_SW, Forward Lag-dynamics

update_dz_d, dz-evaluation hydrostatic pressure/density

riem_solvers for NH-corrections of fast AGWs and V-PGF

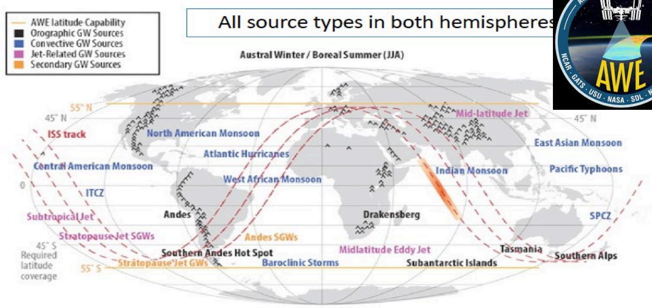
Backward H-PGF

k-split mapping, sub-grid GWP diffusion (90s 2 x 5)

k-split "AGW"- loop with upgrades of NH-corrections

Next Configurations of FV3WAM for Support of GW-oriented missions: AWE, EZIE, MATS and DYNAGLO

AWE-NASA (USU) will monitor GW a ctivity at ~ 87 km, the peak of OH(3-1)

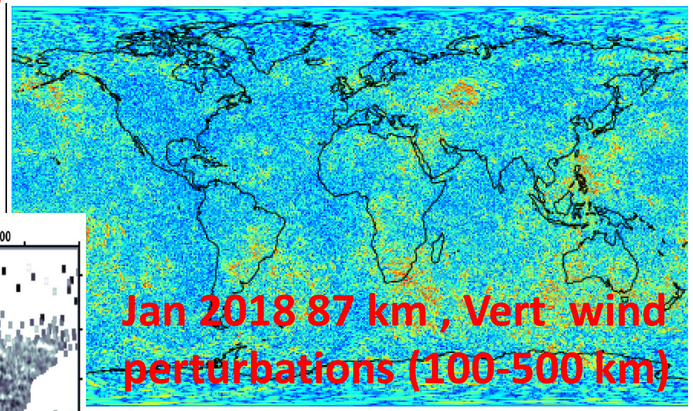


Major Target: *How does tropospheric weather and LA dynamics influence SW and ITM?*

Major Goal: *Investigate global GW dynamics, its impacts on the ITM.*

New challenge for WA models: **Resolve GWs with lengths from ~30 km to 300 km**

01/2018, W-awe [m/s], ~87 km HR= 000



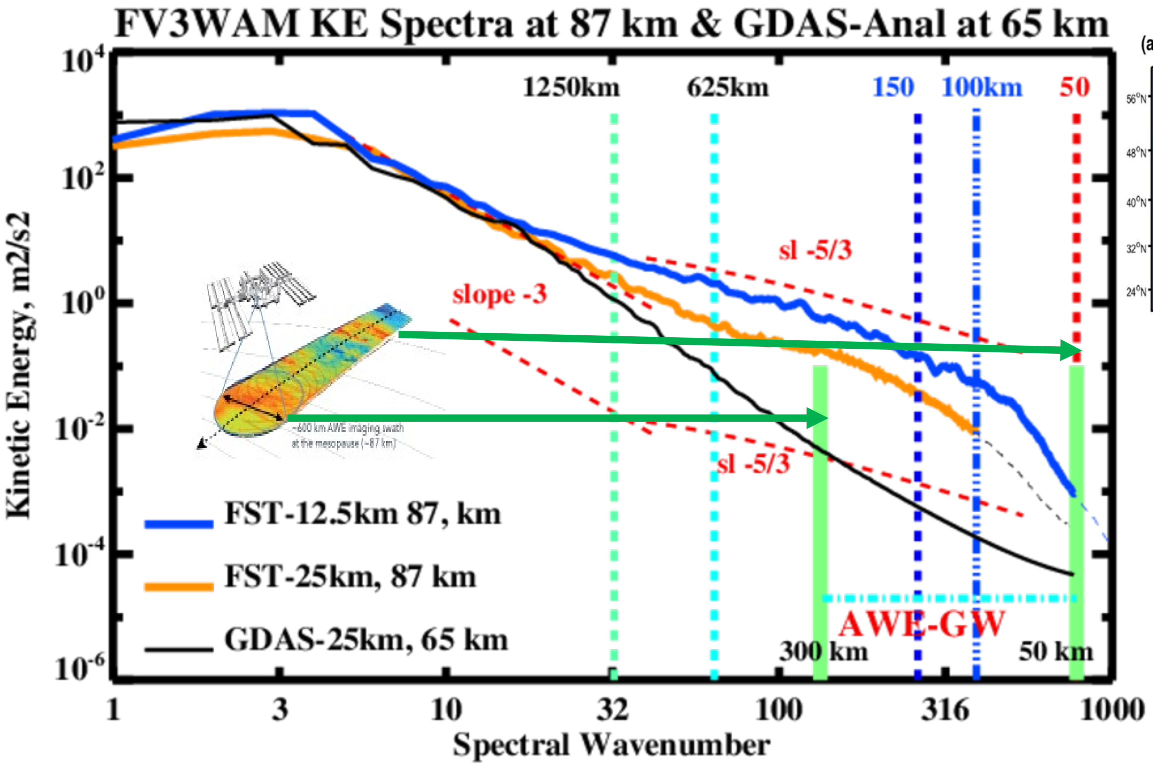
Enhanced Resolution WAM simulations with the NH FV^3 dycore and nesting domains (~3 km) may resolve the mesoscale GW spectra observed by AWE (30-300 km).

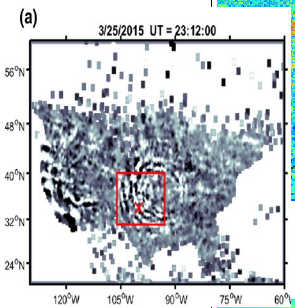
NASA/JHU-APL, 2024

NASA/USU, 2023

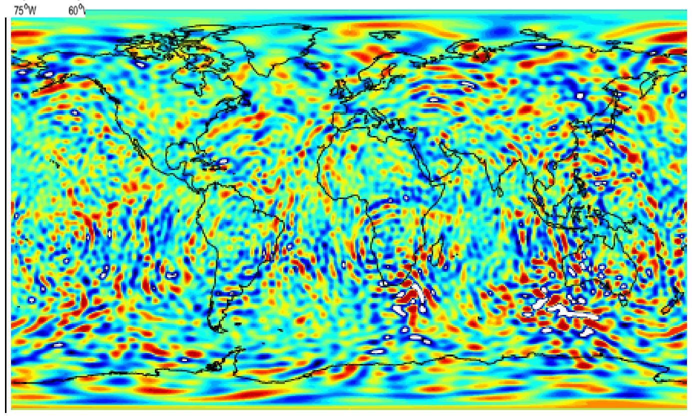
SSA, 2022

NASA/LASP, 2025

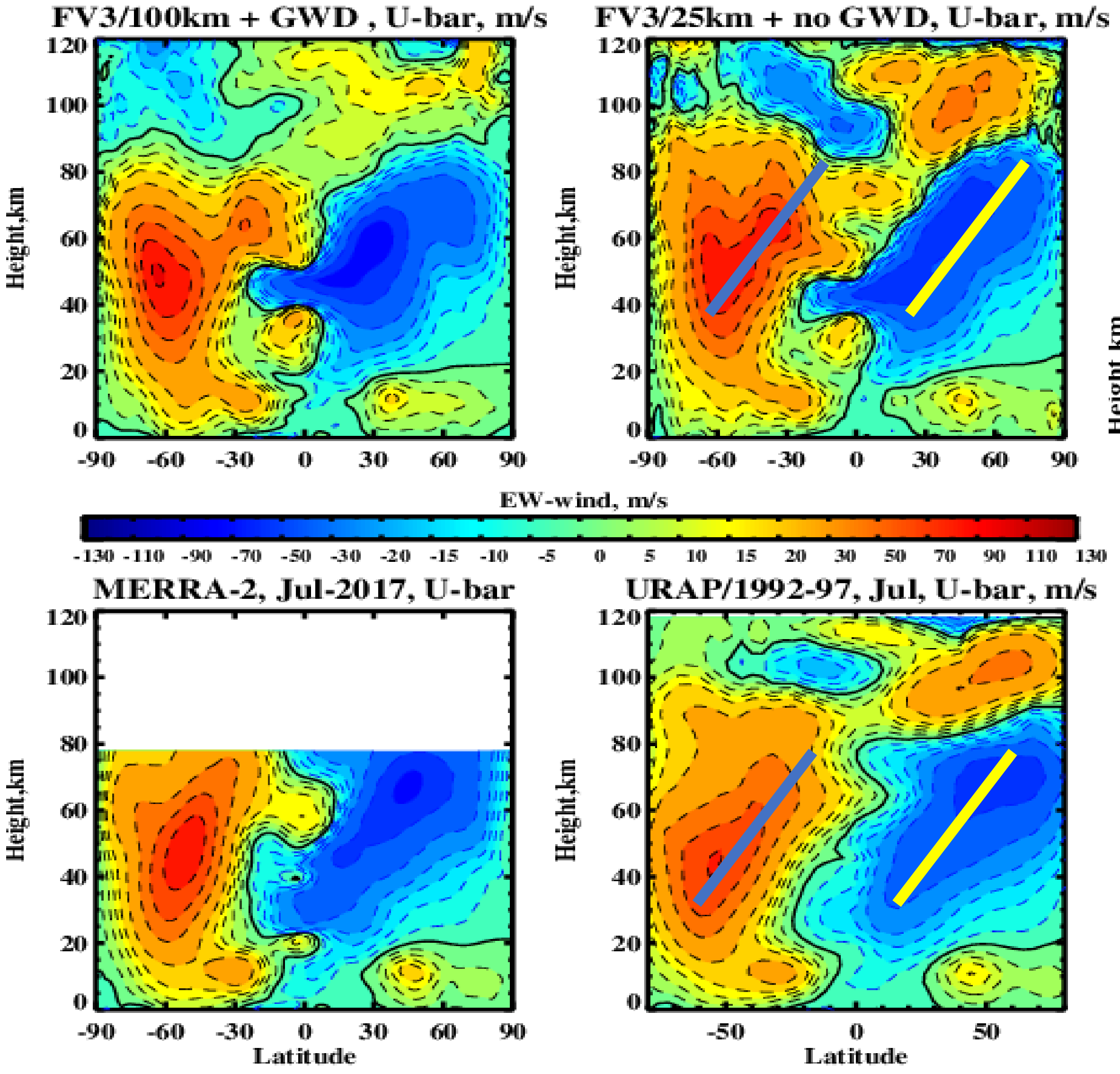


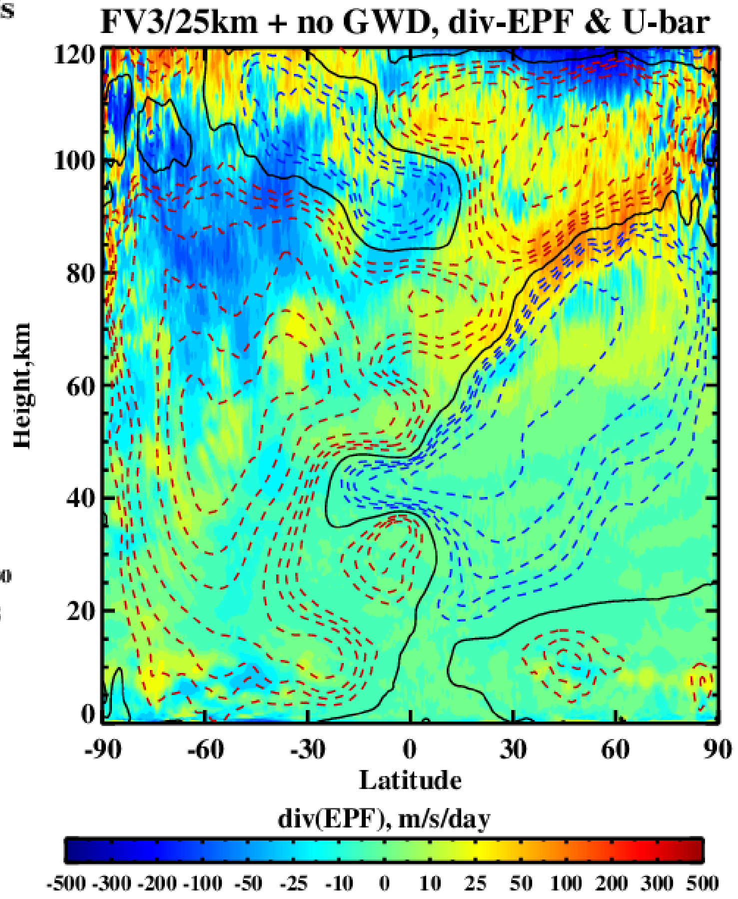


01/2018, W-ls [m/s], ~87 km HR= 000



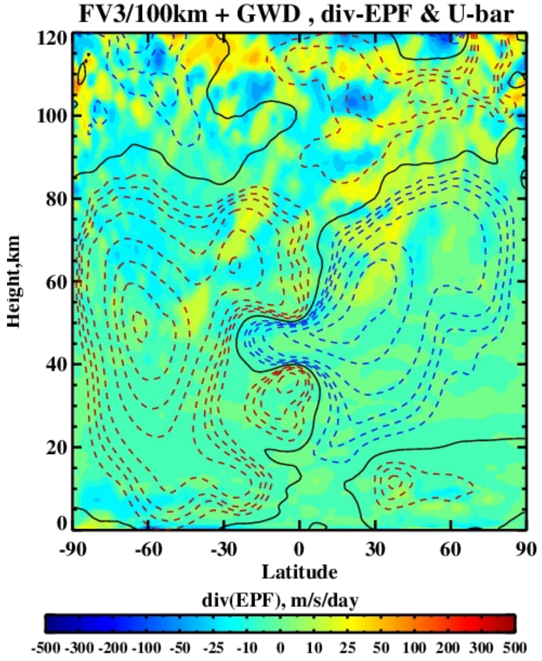
AUG: FV3WAM-100 km vs FV3WAM-25 km





FV3-25 km
Res-wave forcing

FV3-100 km
Res-wave forcing



Next steps detailed diagnostics of GW-tidal interactions, and AWE-portion of GW spectra (30-300 km)

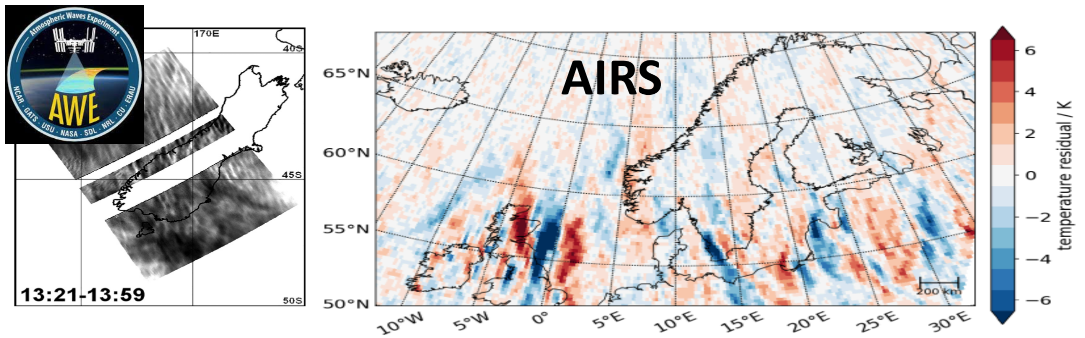
Concluding remarks on GW dynamics/physics, specifics for WA models

- **NWP models** at grids of ~10 km to 25 km **can resolve substantial portion of GW-activity, but they still use OGW and NGW to address model biases** (*SAO, QBO, strato-mesopheric jets, and MLT reversals*).

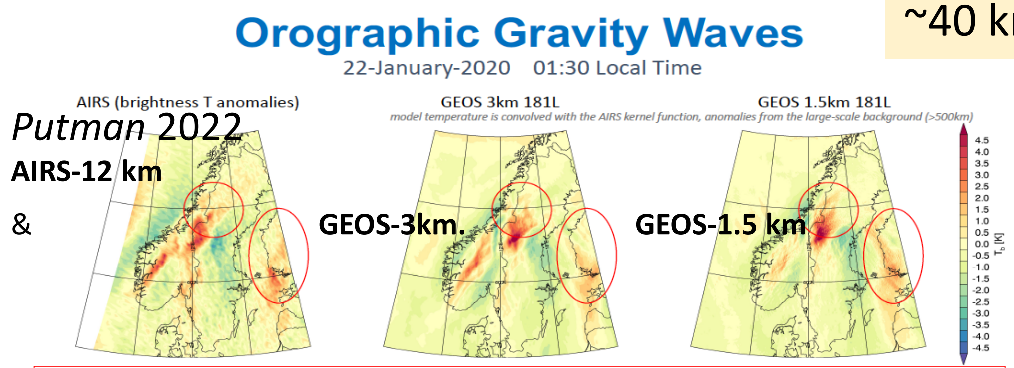
- **Starting from analyses the ~10-km resolution global NWS/GFS forecasts cannot accurately predict wave dynamics with L_h < 600-400 km (s > 80-100). Free-running FV3-based models can simulate MKES.**

- ***To support the novel GW-oriented missions in the MLT and mid-thermosphere:*** (a) advance dycores of WA models; (b) design the resolution-aware DA schemes that properly constrain scales observed by instruments.

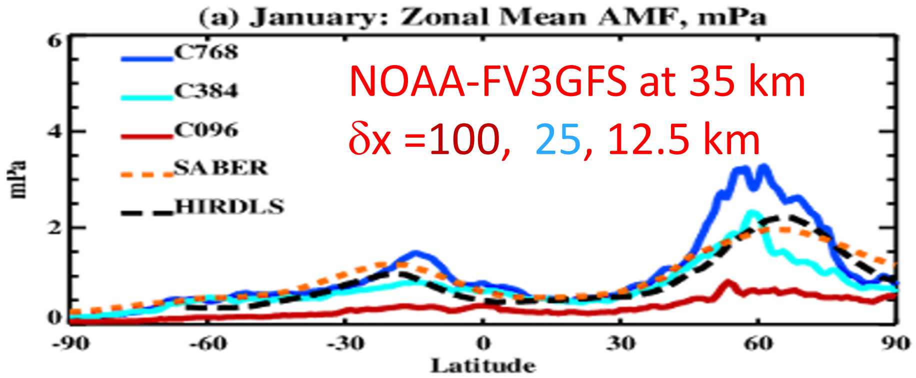
- **Initiate work to "retire" the vertical column GW physics in global models** shifting to the 3D scale-aware sub-grid fluxes (ML + GW schemes).



~40 km



Global mesoscale dynamics of GEOS NASA/GMAO



Predicting GW (L_h ~500-100 km) activity by WAM-FV^3 dynamics (25-km, 196L)

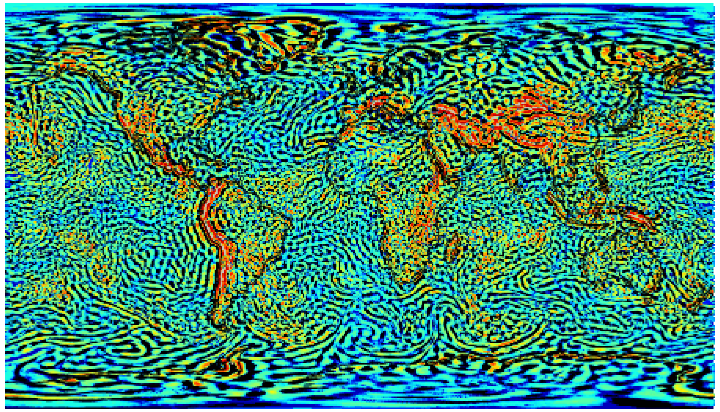
Troposphere

MLT

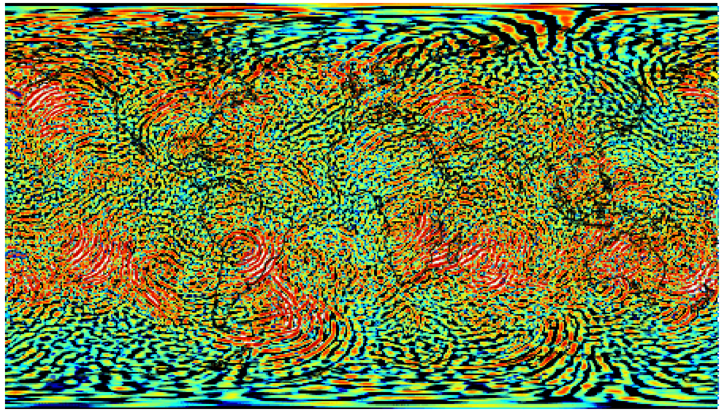
Mid-Thermosphere

Temp-re Perturbations

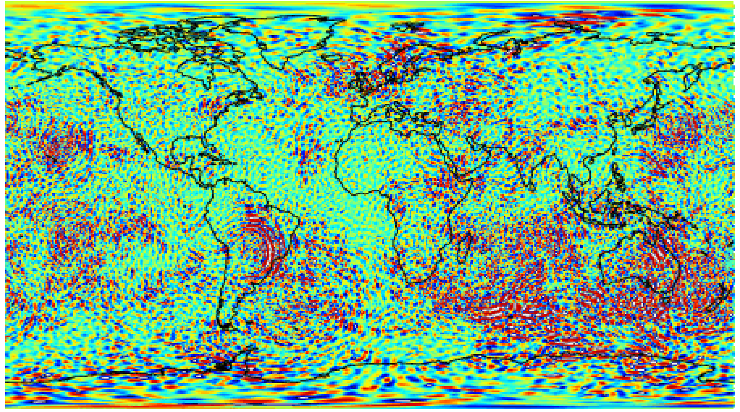
01/2018, T-ptb [K], ~360 hPa



01/2018, T-ptb [K], ~60 km

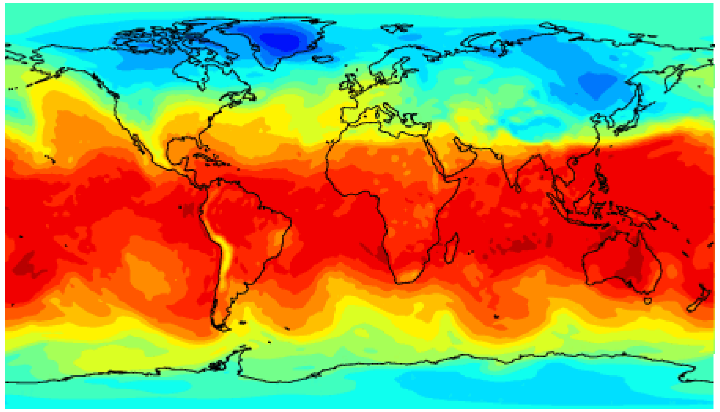


01/2018, T-AWE [K], ~160 km

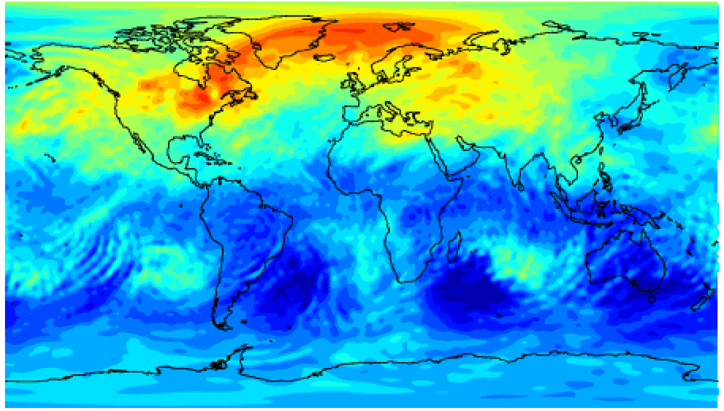


Temp-re Background

01/2018, T-bkg [K], ~360 hPa



01/2018, T-bkg [K], ~60 km



01/2018, T-bkg [K], ~160 km