NGGPS Physics:

Integrating Unified Gravity Wave Physics into the Next Generation Global Prediction System:

First Year Results in the Global Forecast System and Whole Atmosphere Model of NEMS

Valery A. Yudin[1], T. J. Fuller-Rowell[1], J. C. Alpert[2] and R. A. Akmaev[3]

[1]Cooperative Institute for Research in Environmental Sciences, University of Colorado, NWS/SWPC , DSRC, Boulder, CO 80027
Valery.Yudin@noaa.gov

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Unified Gravity Wave Physics

- **Name and Organization:**

  Tim Fuller-Rowell and Valery Yudin (University of Colorado, CIRES)

  Collaborators: J. Alpert (NCEP/EMC) and R. Akmaev (NWS/SWPC)

- **Project Title:** **Integrating Unified Gravity Wave Physics into the Next Generation Global Prediction System**

- **Objectives:** **Development of the vertically extended configurations of NOAA atmosphere models across the stratopause** ***with realistic representations of sub-grid scale eddies by unified Gravity Waves (GW) schemes that improve the troposphere-stratosphere coupling, predictors of AO and NAO and propagation of atmospheric tides and planetary waves.***

- **Deliverable(s):** **A unified GW schemes in the vertically extended GFS and future NGGPS global atmosphere model configurations.**

- **Deliverables of Yr-1:** **The GFS-91L with GW physics were delivered to EMC GW group (J. C. Alpert); NEMS/WAM-150L simulations with GWs were used and evaluated by SWPC-WAM researchers (R. Akmaev and T.-W. Fang)**

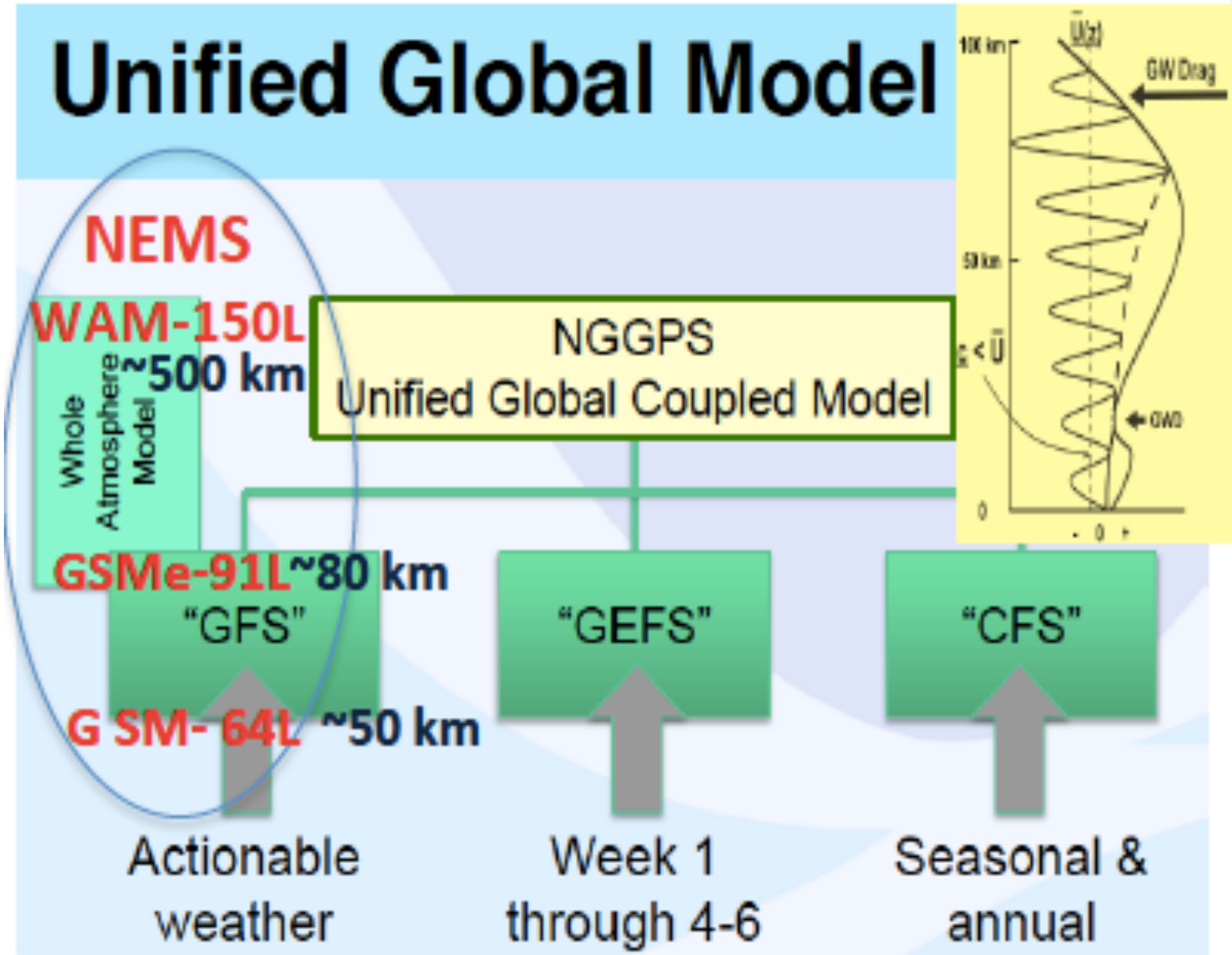
The Vertically Extended Global Atmosphere Models of NOAA Environmental Modeling System (NEMS)

The **R2O/NWS** transforms and upgrades the operational **GFS** into the Unified Global Model within **NEMS framework**.

The first vert. extended GFS (from the current 64L to 91L) promises to improve the stratospheric forecasts and the trop-stratosphere coupling.

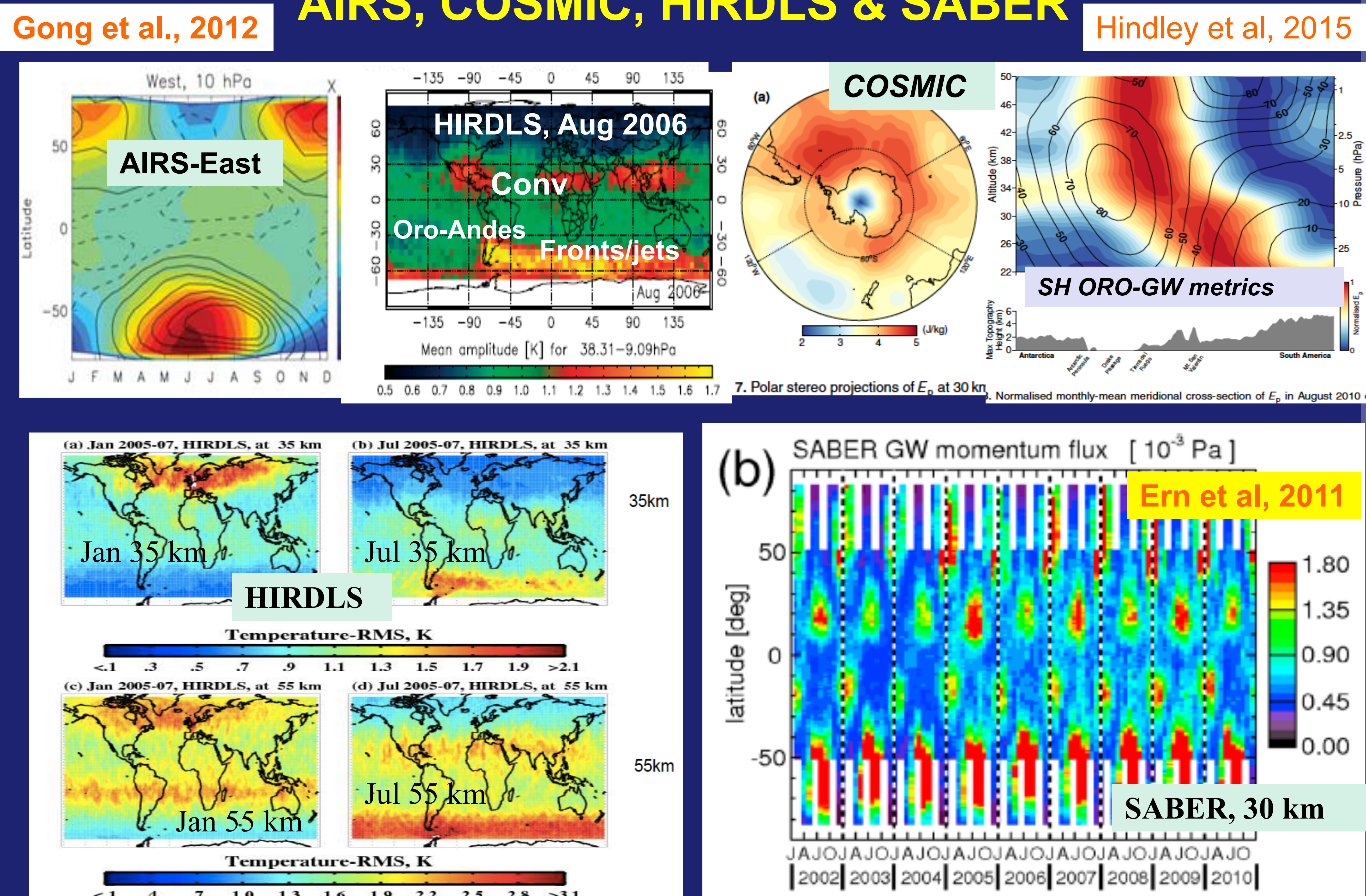
For *vertically extended* models, our current aim is to unify the **GFS-91L** (lid ~80km) and the 150L **Whole Atmosphere Model** (**WAM-150L,** ~500 km) under the *Global Spectral Model* (**GSMe**) of NEMS in 2016-17.

Unification and upgrades of GFS and WAM physics will streamline the interaction of analysis and forecast for terrestrial and space weather and climate predictions under NEMS/NGGPS framework



Dynamics and physics of resolved and sub-grid quasi-stationary *Orographic GWs* (OGWs) and *Non-stationary GWs* (NGWs) represent the major uncertainties for extended models of NEMS.
R2O/UGW project "unifies" GW physics.

Gravity Wave Hotspots/Sources from Satellites: AIRS, COSMIC, HIRDLS & SABER



Unified GW physics in the NCEP models: GFS, NEMS-GSM and NEMS-WAM

Specfic R2O Goals:

(1) Perform "orchestration" of the GW solvers for all types of wave sources (orography, convections, front, jets, and other imbalanced dynamics) ; same breaking criteria and dissipation.

(2) Create portable and adaptable to the type of parameterization "GW-unified" module with 3 stages: **Init - Advance - Diagnose.**

(3) Allow both stochastic and deterministic performance of GW schemes (sources, spectra, and triggers).

(4) Explore novel observational GW metrics/ constraints for "resolved" and sub-grid GWs

(5) Introduce GW effects (drag, heat & eddies) **in the self-consistent, energy-balanced and resolution-aware formulations;** *orchestrate strengths of GW-drag, eddies and Rayleigh friction and "spectral" damping.*

Unified GW Physics Module

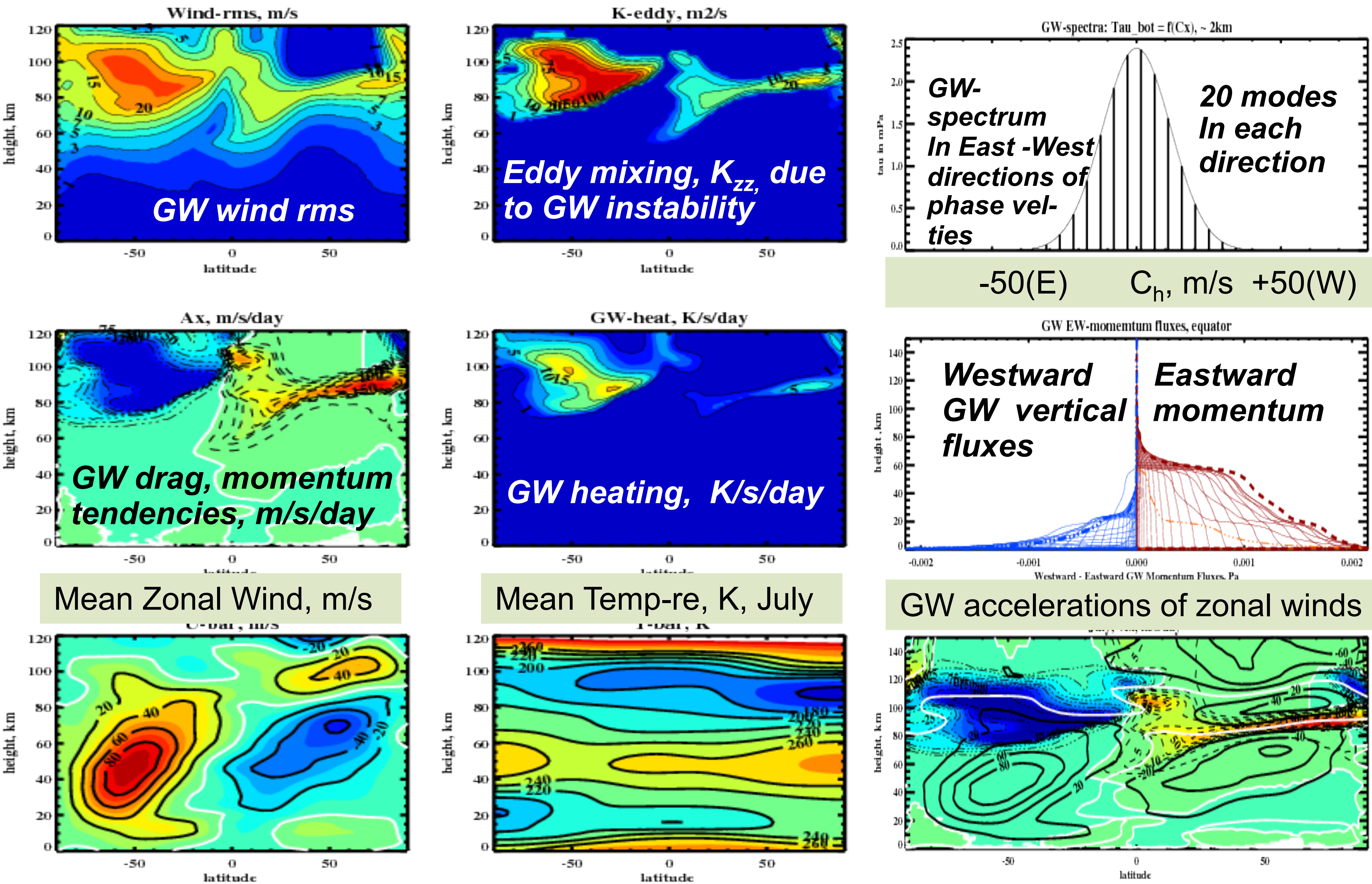
INIT: GW_NML, choice of GW sources and solvers

ADVANCE: Drag, Heat, K_{eddy} every time-step or 1-hr cadence

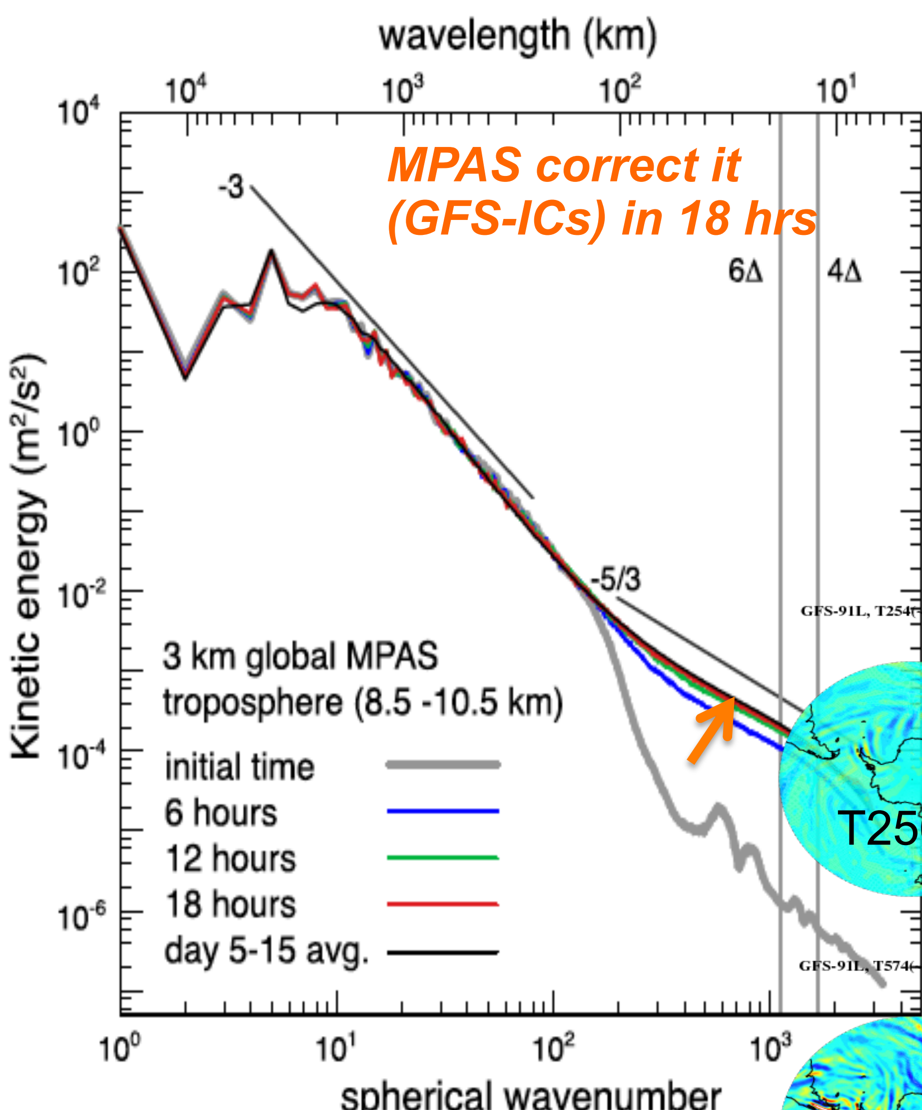
Data-driven Diagnostics: dominant wavelengths, energy, momentum and heat fluxes.

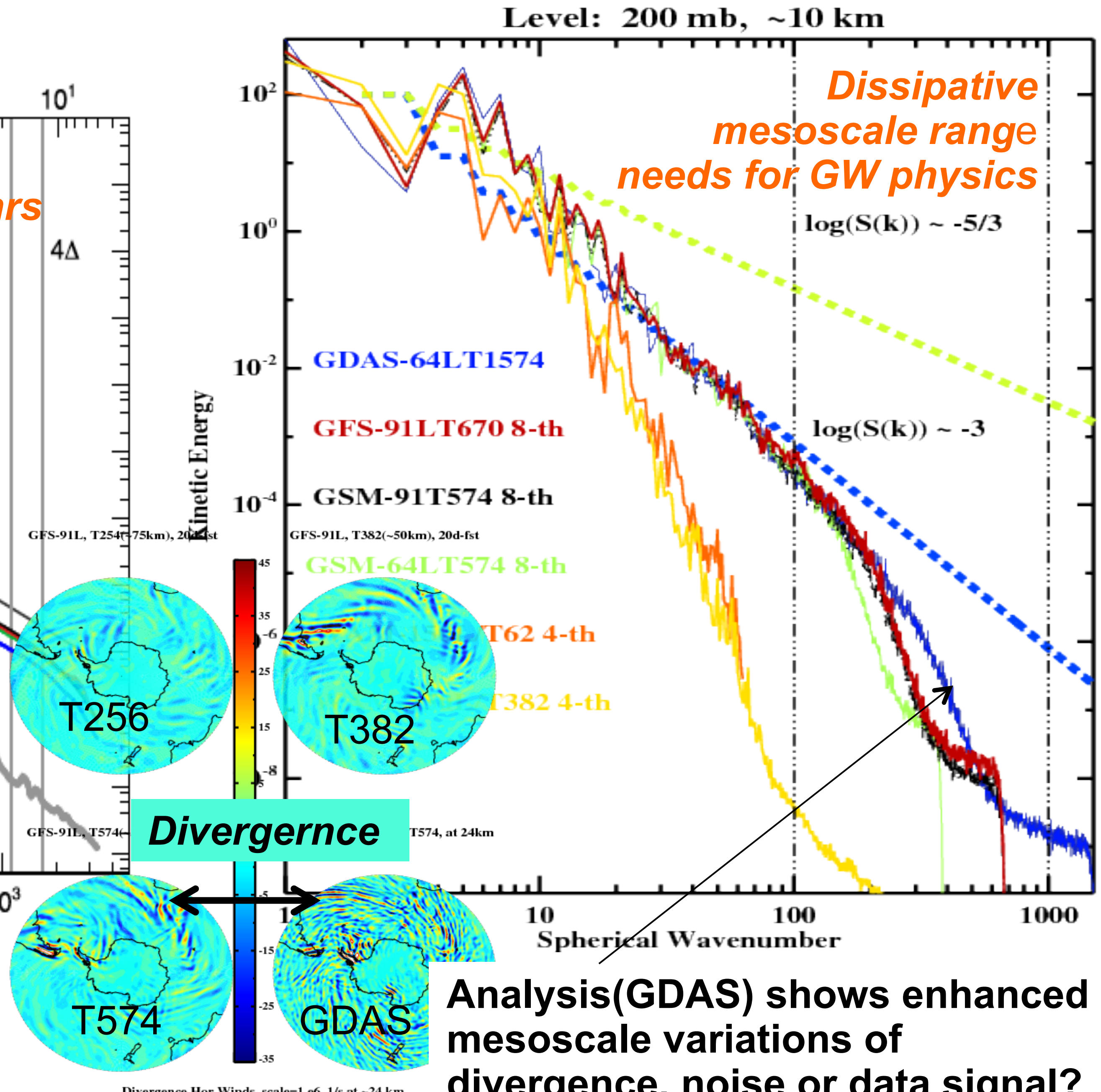
GW-sources: *NRL, GMAO, ECMWF, NCEP and NCAR;*
GW-solvers : *operational weather and climate schemes with adapts for:*
(a) energy-balanced formulations:
(b) eddy diffusion and mass fluxes and self-cons. heat-drag-K;
(c) resolution-sensitive specifications of parameters.

Diagnostics of GW-forcing: non-stationary GWs in July
NOAA-CIRES scheme, implemented in WAM-NEMS



Resolving "GW-mesoscale" by Dycores: Kinetic Energy Spectra (KES) from Skamarock et al. (2014), MPAS with GFS-ICs, and KES from NOAA forecasts & analysis

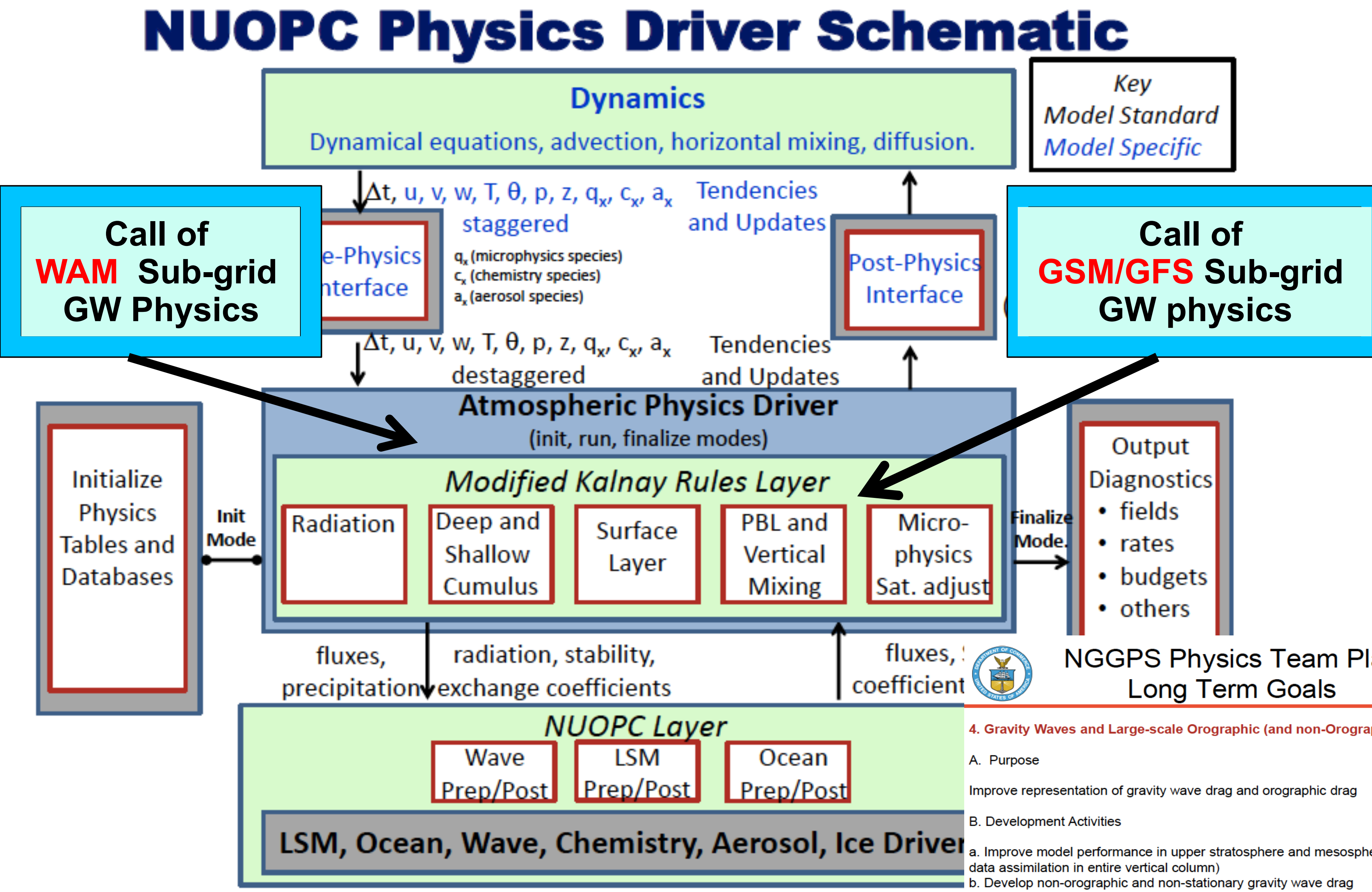




MPAS and FV3 are two dycores selected for NGGPS and final decision …in Aug of 2016.

Analysis(GDAS) shows enhanced mesoscale variations of divergence, noise or data signal?

"Placing" non-st. GW schemes in the chain of NEMS (NUOPC) physics of Global Atmosphere Models (WAM & GSM)



NGGPS Physics Team Plan
Long Term Goals

4. Gravity Waves and Large-scale Orographic (and non-Orographic) Drag

A. Purpose

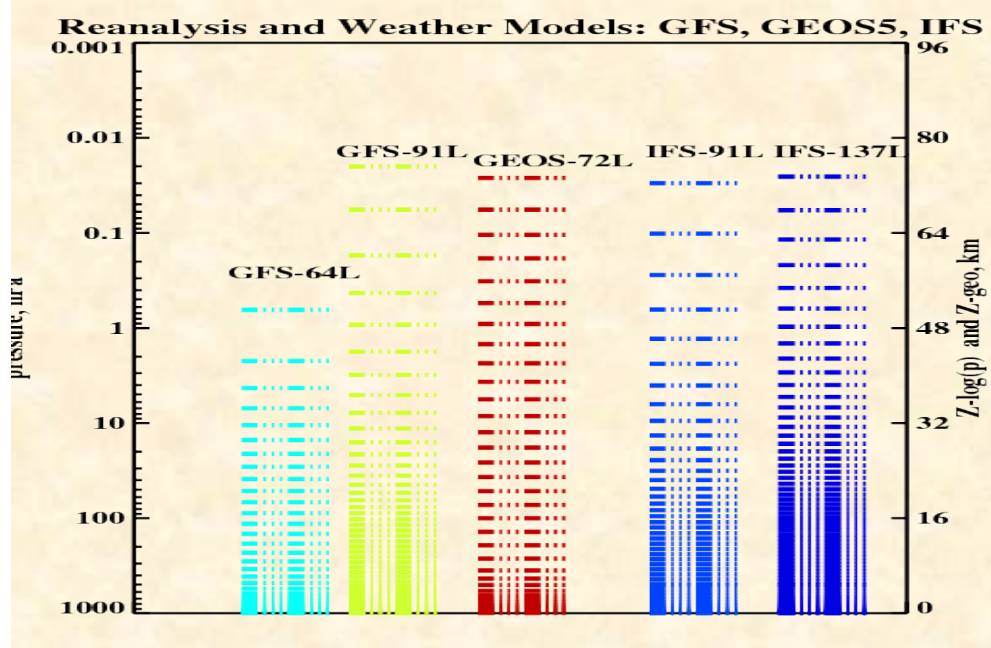
Improve representation of gravity wave drag and orographic drag

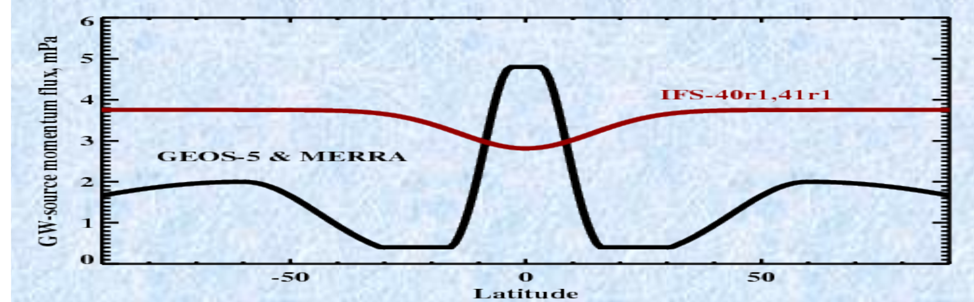
B. Development Activities

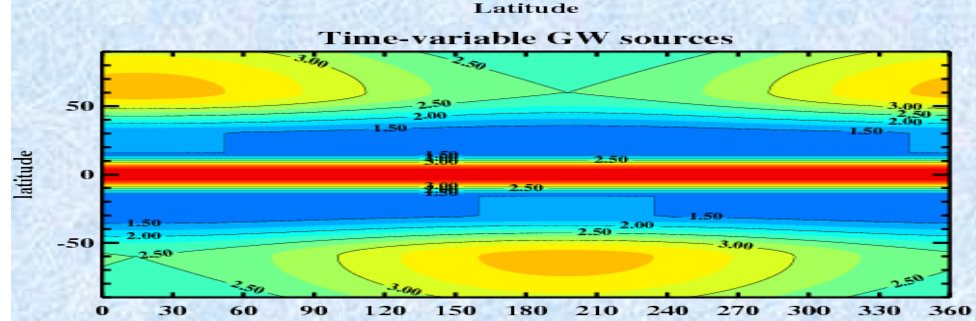
a. Improve model performance in upper stratosphere and mesosphere (will also improve data assimilation in entire vertical column)
b. Develop non-orographic and non-stationary gravity wave drag
c. Scale-aware orographic drag formulation
d. Gravity wave physics that is adaptable to variable horizontal and vertical resolutions

Specifics of Vertically Extended Configuration of NEMS, GFS/GSM-91L: GW Physics in the Strato-Mesosphere

- **Vertical levels of GFS/GSM-91L** follow IFS-91L of ECMWF and resemble GEOS-5 (72L) of GMAO (TL ~80 km);
  Decreased (~3-times) **Rayleigh friction above ~70 km with inv. scale 15 days.**
- **Previous (**IFS, NOGAPS, GMAO) **choices for GW intensity at ~ 700 hPa** (or at ~500 hPa) *to replicate latitudinal and seasonal GW activity from data.*
- **Adapted GW solvers:** (a) Linear saturation with dis-n; (b) IFS-2000 with dis-n; (c) DSP-Hines' with dis-n and nonlinear saturation; (d) Alexander & Dunkerton-99 with dissipation.
- **GW physics acts every time-step**: four azimuths and tested for **T62 ..->..T670**
- **In progress**: online diagnostics and eddy mixing; other GW "candidates"; adding non-LTE radiation of WAM for GSM; tests for oper. res-n at T1574 (~ 13km)







Non-stationary sub-grid Gravity Wave (NGW) Physics in Climate and Weather Models

Model Climate/ Weather	Levels & Top Lid	GW-NST scheme	GW sources	GW-drag	GW-heat	GW-eddy
WACCM & WACCM-X NCAR	68 L (88L) ~140 km (500km)	Lin. Saturation (65 x 2 modes)	Physics-based triggers	Y	Y?	Y
NAVGEM/ NOGAPS-NRL	L70, 0.04 hPa , 70km; (0.001 hPa ~100 km)	Lin. Sat . with stochastic triiggers (~1-4)	Lat-time depend.	Y	Y	Y?
IFS-40R1/ ECMWF	91L (137L), 0.01hPa , 80 km.	Univer. Lin. Sat. (25 x4 modes)	Lat-depend.	Y	Y?	No
GEOS-5/GMAO/ GSFC	72L, 0.01 hPa, ~80 km	NCAR scheme with reduced # of GW modes.	Lat-depend.	Y	Y	No
GFS/NCEP-91L	91L, 0.01 hPa, ~80 km	Lin. Sat (25 x4 modes)	Lat-depend.	Y	Y	No
WAM/NCEP-CU	150L (T62) ~500 km	Lin. Sat (25 x4 modes)	Lat-depend.	Y	Y	Y

June 2014: GFS-forecast in 64L & 91L models with Rayleigh Frictions (RF) and physics of NGWs

Role of RF (wind damping), it attempts to resolve 2 issues:

(1) The top lid model effects, sponge layer to suppress resolved wave reflections; (GFS-64L); extra-heating;

(2) The winter-summer zonal wind drag in the strato-mesosphere.

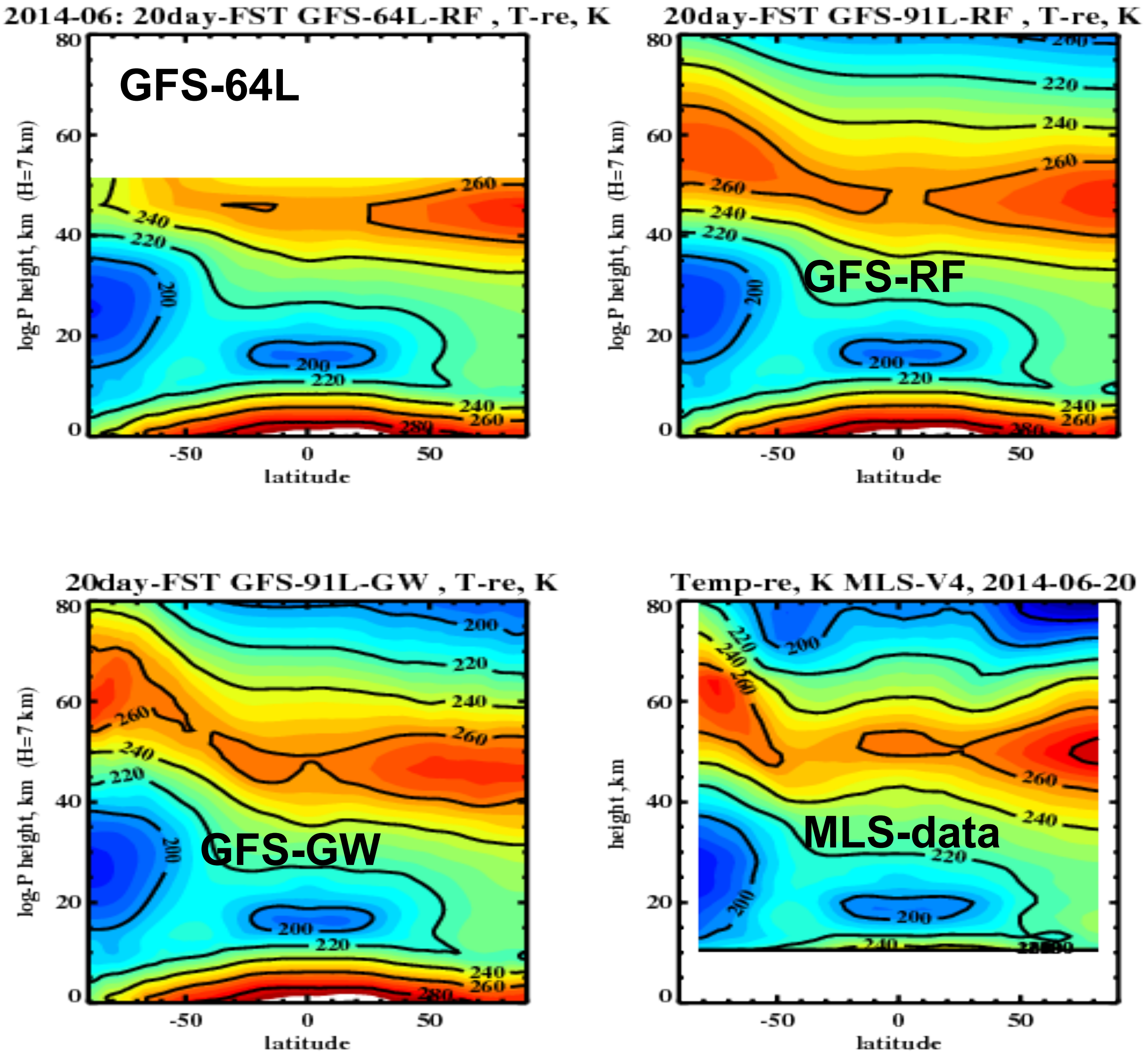
Issues with RF-schemes:

- erroneous reflections of PWs;

-absence of the U-wind reversals above ~70-80 km;

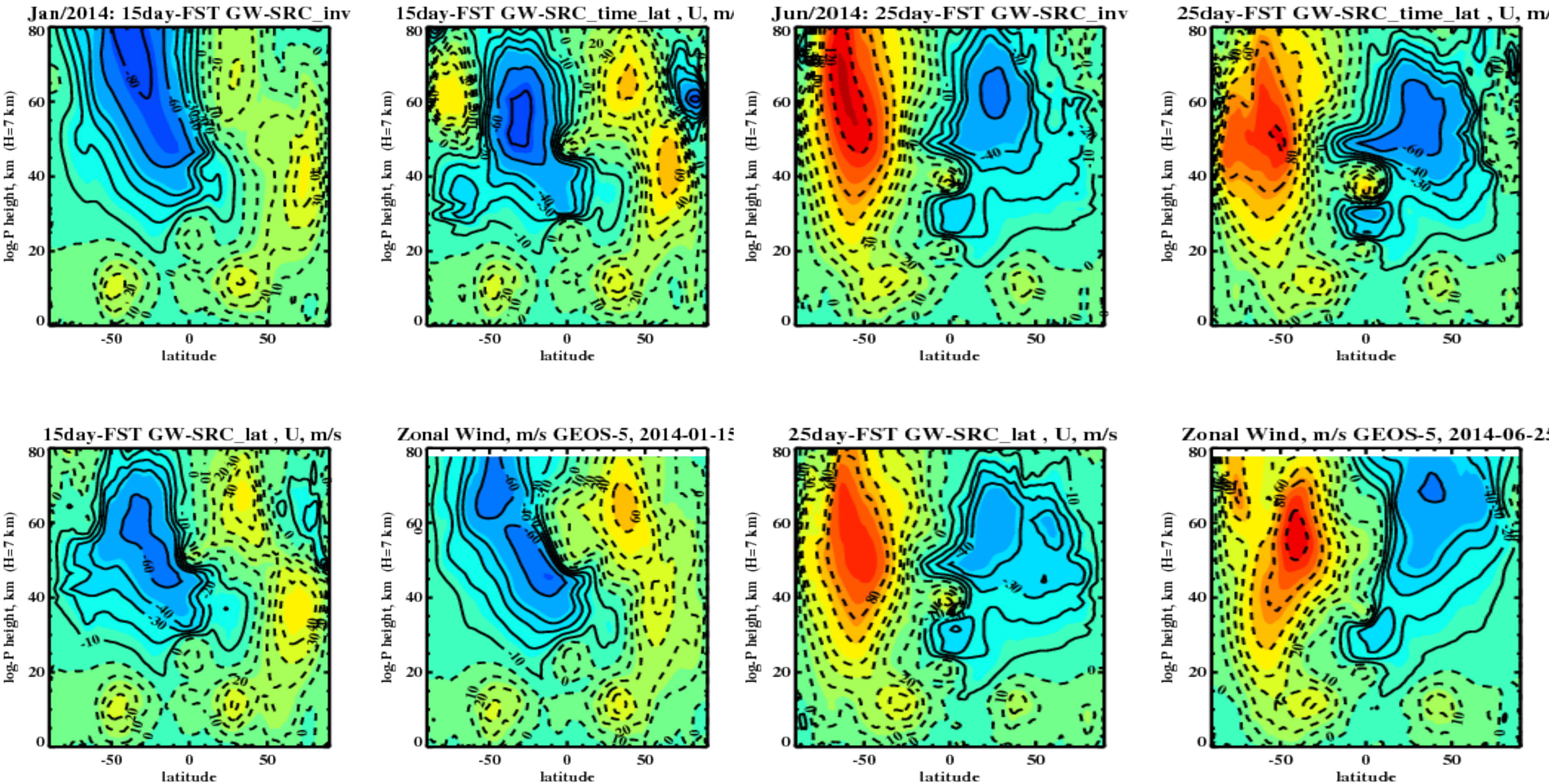
-warm mesosphere relative to EOS-Aura MLS and TIMED-SABER multi-year observations.

Advantage of GW-physics: handle "above-listed" GFS-biases; consistency with the data.



20-day GFS forecasts from June 1 of 2014 vs MLS-Aura 2014-06-30 (mean temperatures)

2014 GFS-T574 forecasts in 91L model with GW sources: Jan (15 day, right) and Jun (25 day, left)



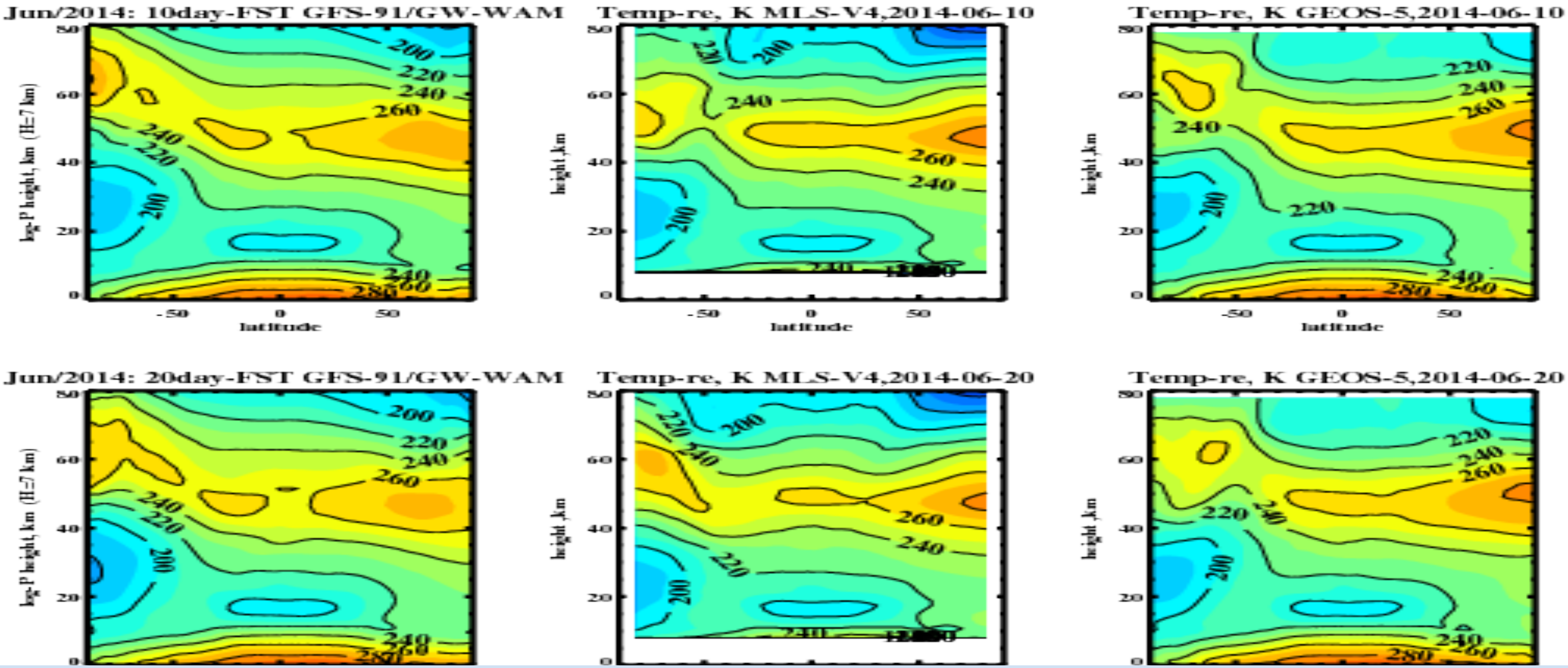
GFS-91L with GW physics and GEOS-5 analysis

Sensitivity of GFS-91L runs to specification of GW-sources: *constant, time-lat dependentt & latitude-only dep-nt*

GFS-91L (T670) 10-20-30 day forecasts vs MLS-Aura and GEOS-5

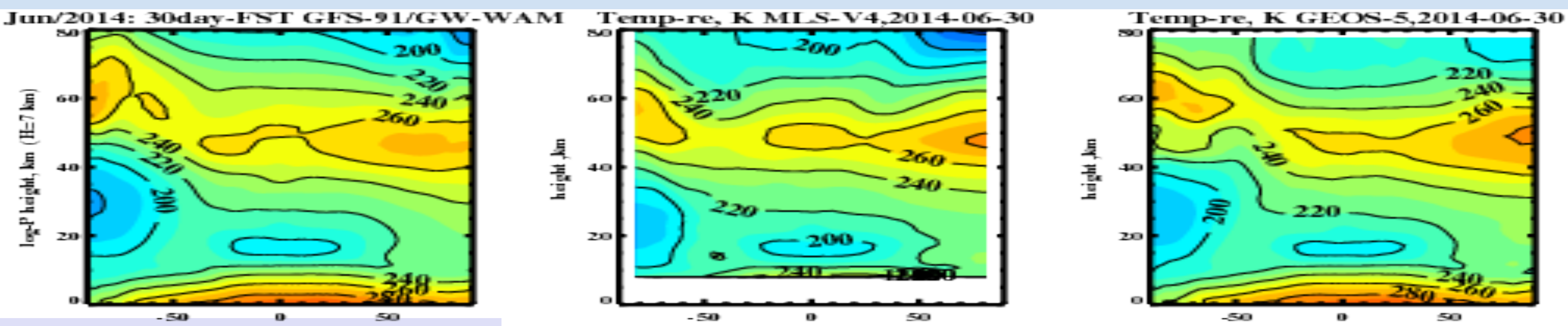
10-day

20-day



GFS-91L forecasts after 30 days continue to match MLS data and GEOS-5 analysis

30-day

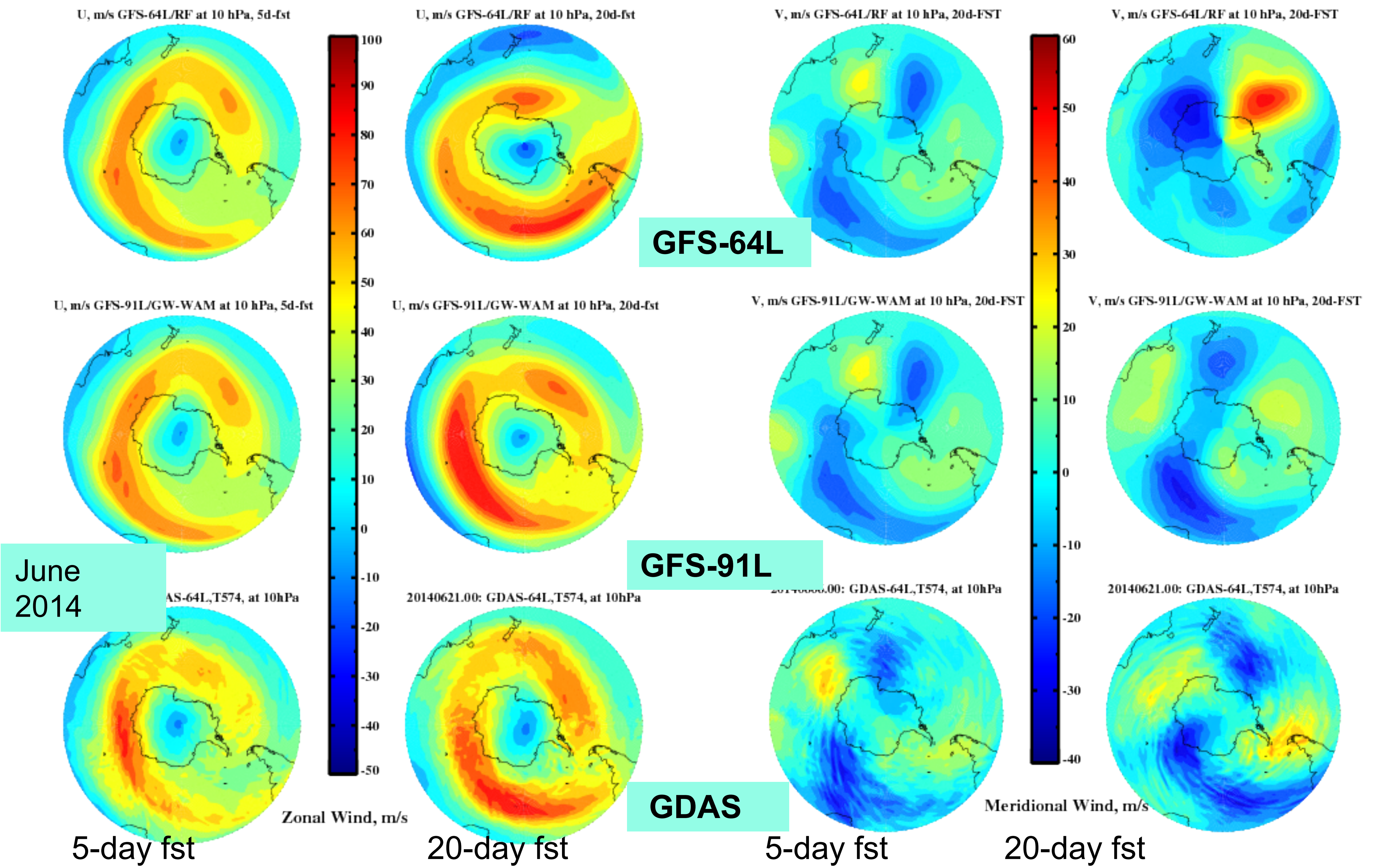


GFS-91L 800-hr forecast
WT: 4 hr 48 min RF
WT: 5 hr 57 min GW-40

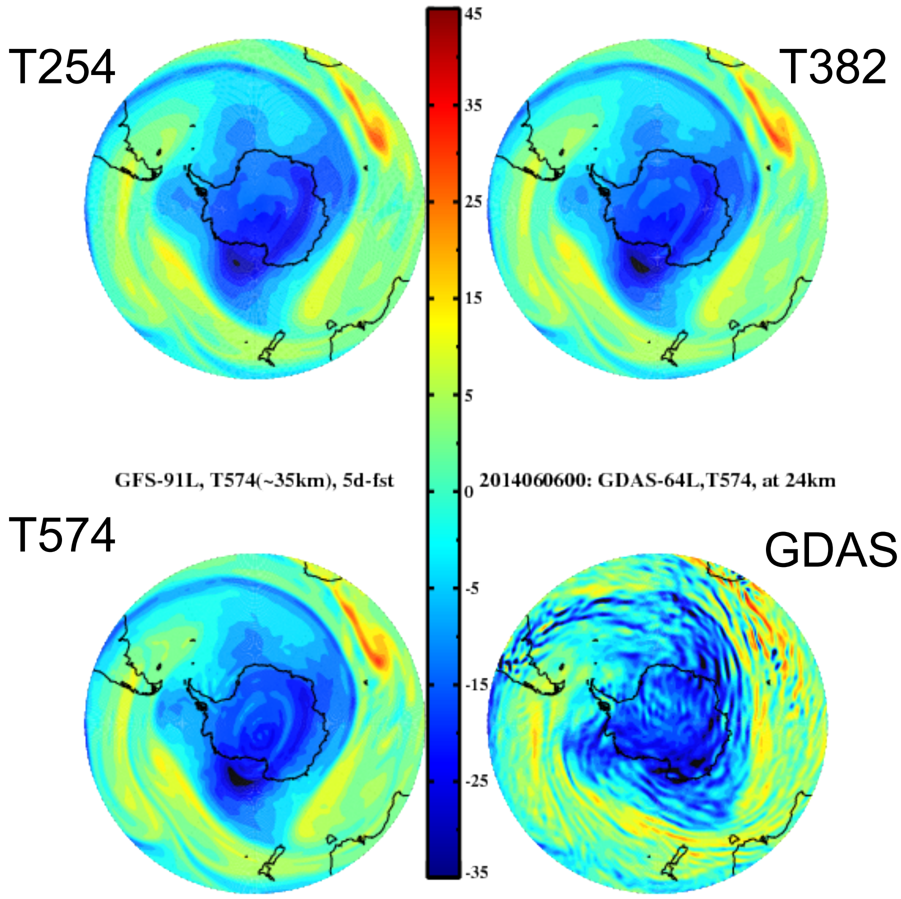
EOS-Aura MLS-V4.3
June 2014

GEOS-5 Analysis,
June 2014

The 10 hPa (~30 km) Forecasts of the South Ocean Winds by GFS-64L, GFS-91L and GDAS-analysis, June 2014

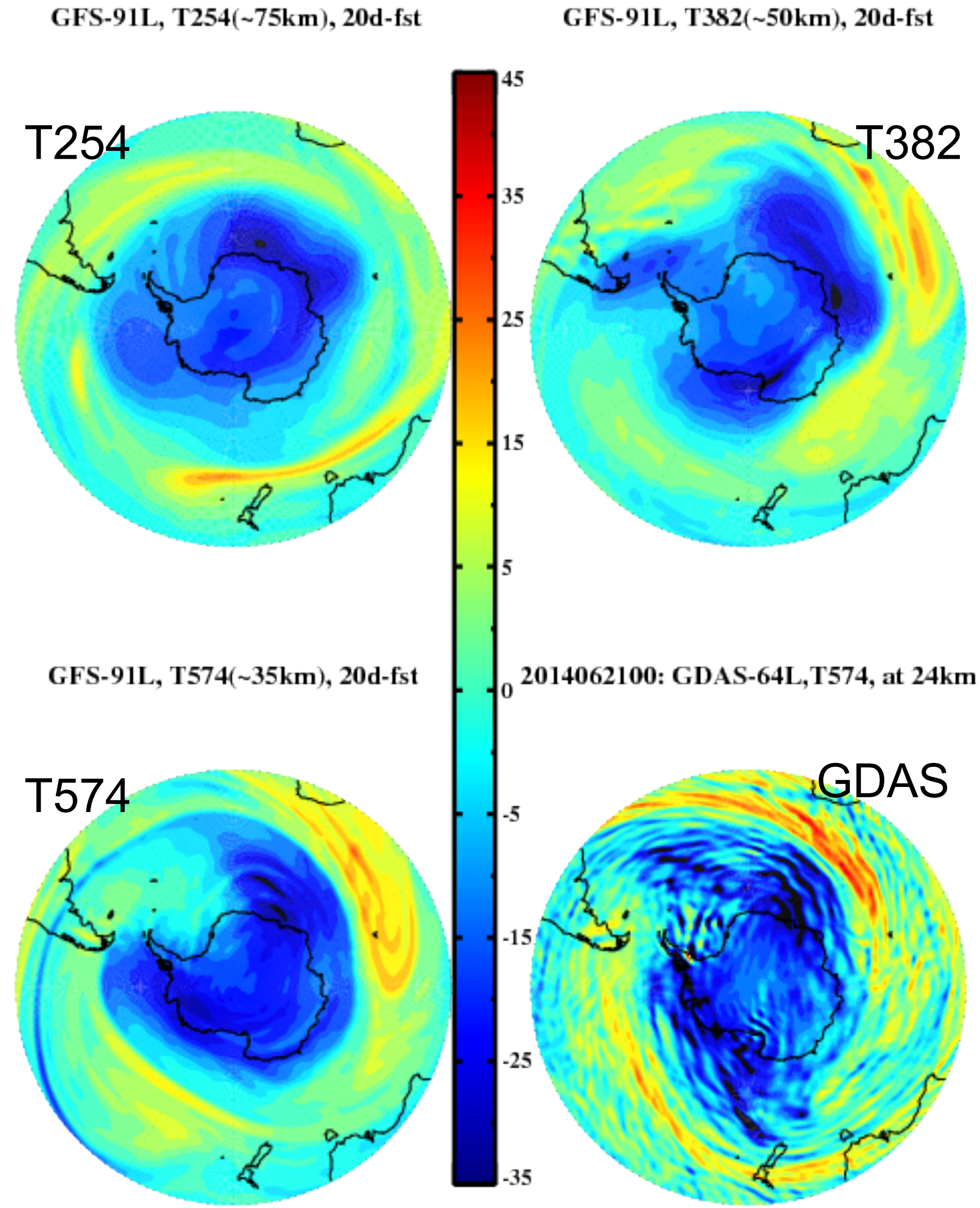


Enhanced resolution of GFS-91L (75 km => 34 km) may better fit GDAS Vorticity and the filament shapes after 20-days over the South Ocean and Antarctica at ~24 km (50 hPa)



Vorticity of Hor.Winds, scale=5.e5, 1/s at ~24 km

5-day FSTs & Analysis

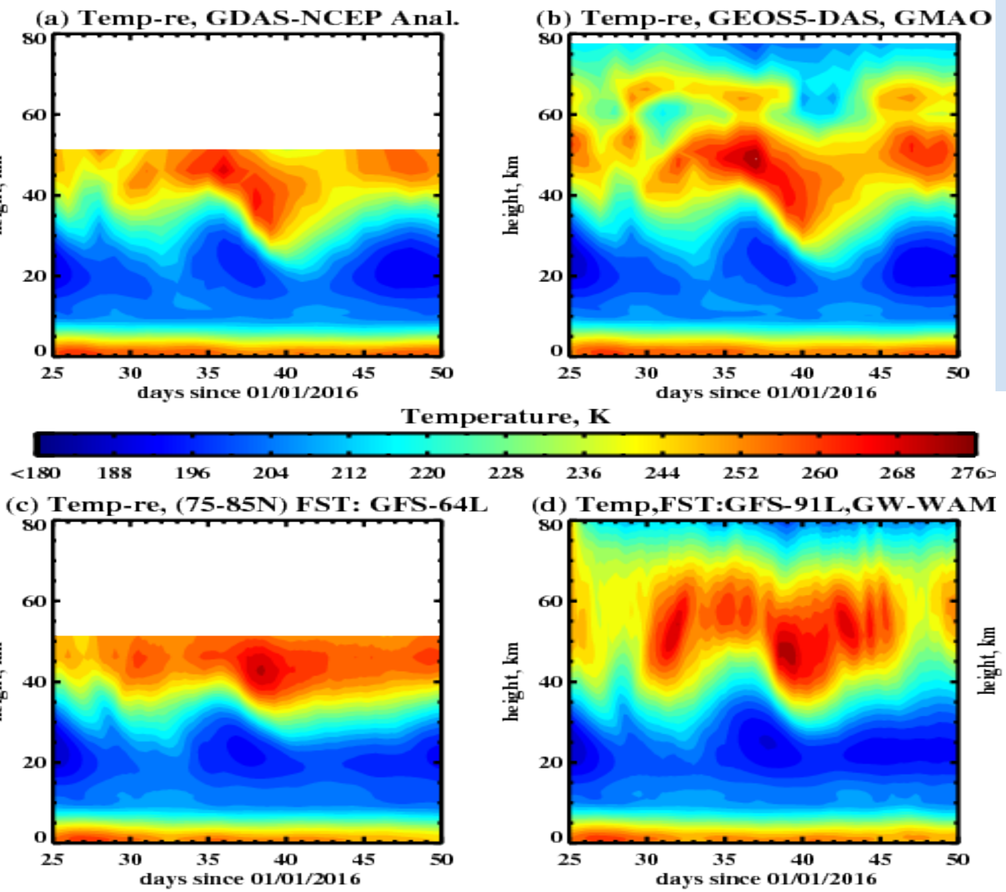


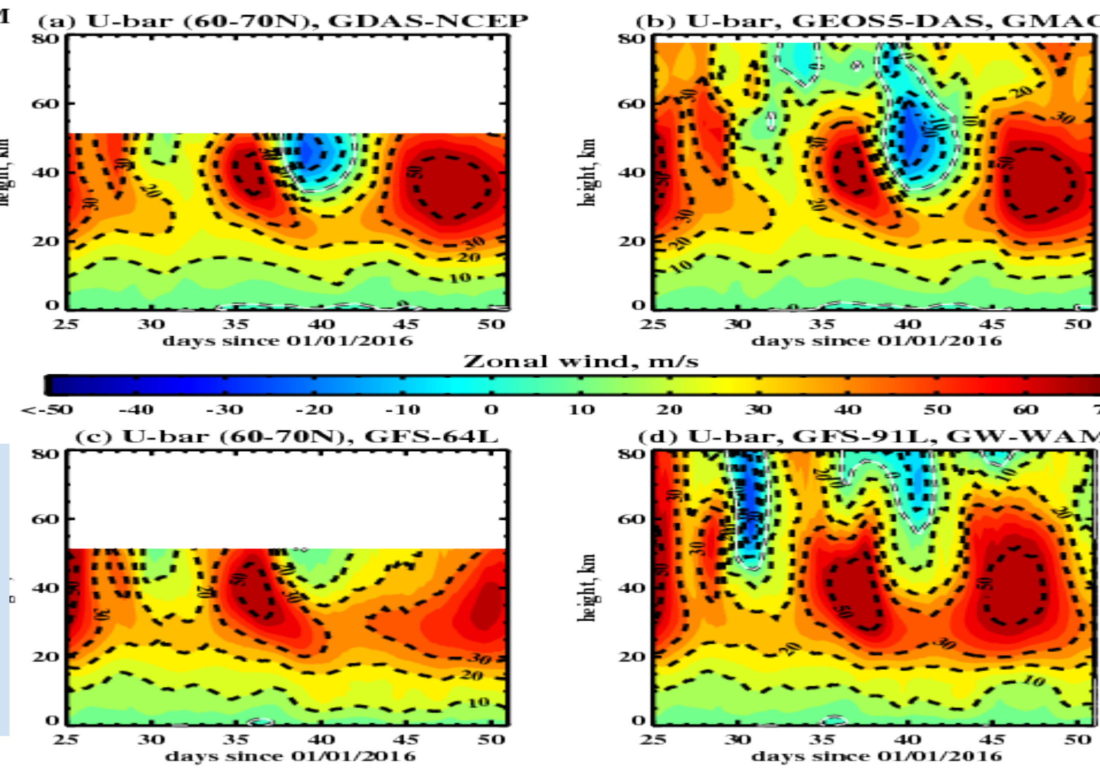
20-day FSTs & Analysis

PV-filaments, desirable feature for forecasts of the ozone transport and polar stratospheric chemistry

NEMS-GSM, 64L & 91L during SSW pulsations of 2016 (01/25 –02/20) vs GDAS-NCEP & GEOS-5/GMAO analyses

The 6-hr separated polar (75-85N) zonal mean temperatures and the high latitude (55-65N) zonal mean winds during the minor Sudden Stratospheric Warming (SSW) pulsations, Feb 2; GFS-91L with GWP tends to predict the wind reversals in upper layers and temperature-wind variations.





The top rows (a-b) display temporal variations deduced from GDAS (64L, T1534) and GEOS-5 (72L, 1/8 deg);
The bottom (c-d): GSM/GFS forecasts at T670 with 64L (c) and 91L (d).

Integrating Unified Gravity Wave Physics into the Next Generation Global Prediction System

- ***Summary of the 1-year results***

GW physics in NEMS-WAM improved zonal mean flows, planetary waves and tides.

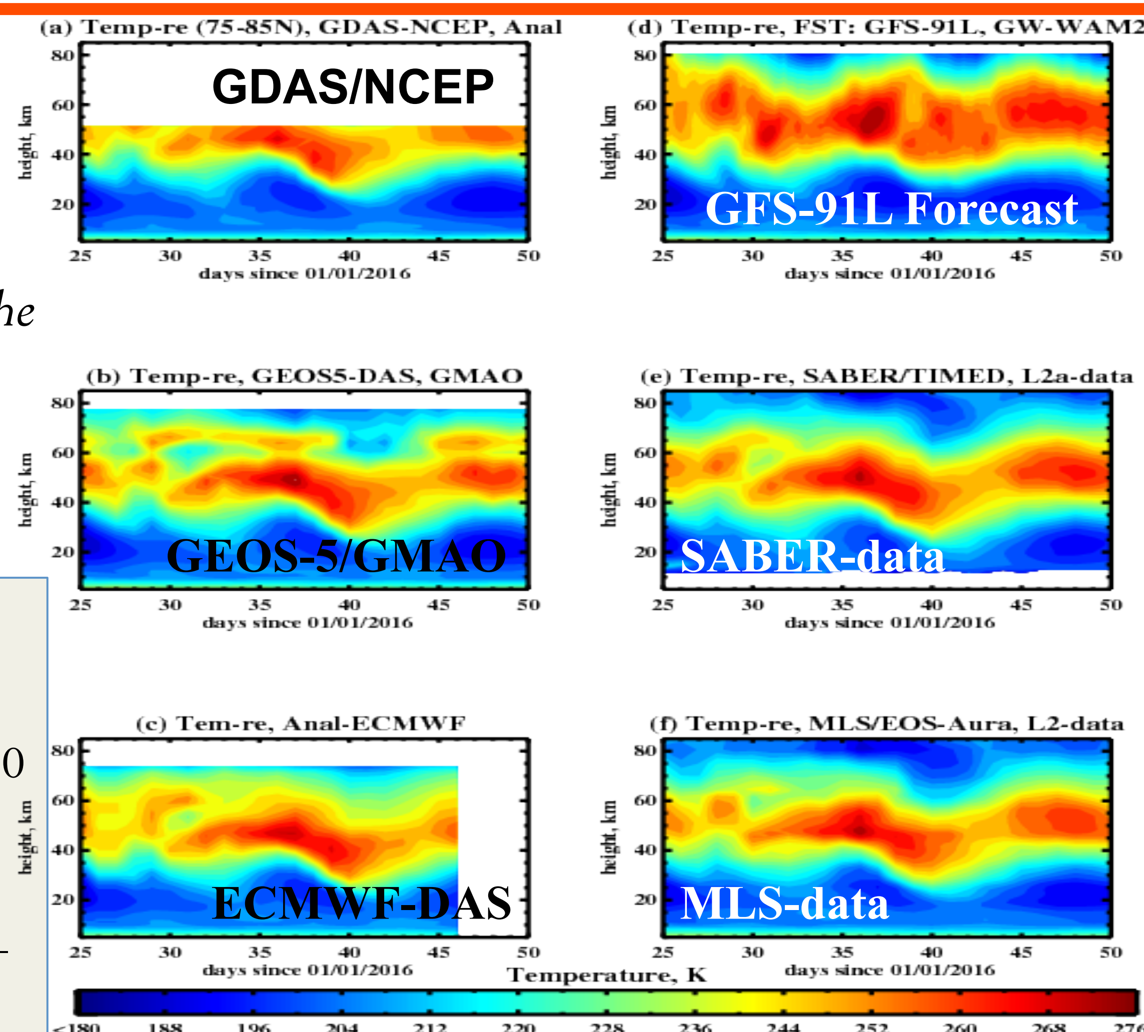
GW physics in GFS-91L brought a realism in the stratospheric dynamics during winters and winter-to-spring transitions comparing to the Rayleigh Friction simulations.

Transition to NOAA operations, climate tests, and future plans

a) ***Analysis-Forecast Cycling with GFS-90L*** (~80 km top) with "parallel" operational scripts; tests during SSW events (2009, 2013, & 2016).

b) ***NEMS-WAM multi-year climate runs*** for self-generated equatorial oscillations (QBO and SAO).

c) ***New related projects: Assimilation of middle atmosphere O_3, H_2O and T-re profiles*** (MLS & SABER) to properly initialize NGGPS forecasts.



Jan-Feb 2016: GFS-91L 25-day polar temperature forecasts (d), SABER (e) & MLS (f) data (left), and NWP analyses (right column) : GDAS-NCEP (a), GEOS5-GMAO (b) and IFS-ECMWF(c).

WAM-trunk, no NGW Physics in the Strato-Mesosphere and Thermosphere, vs NOGAPS, UARS and MERRA

WAM Trunk Run: WAM-NEMS, January (left, top) no NGW physics

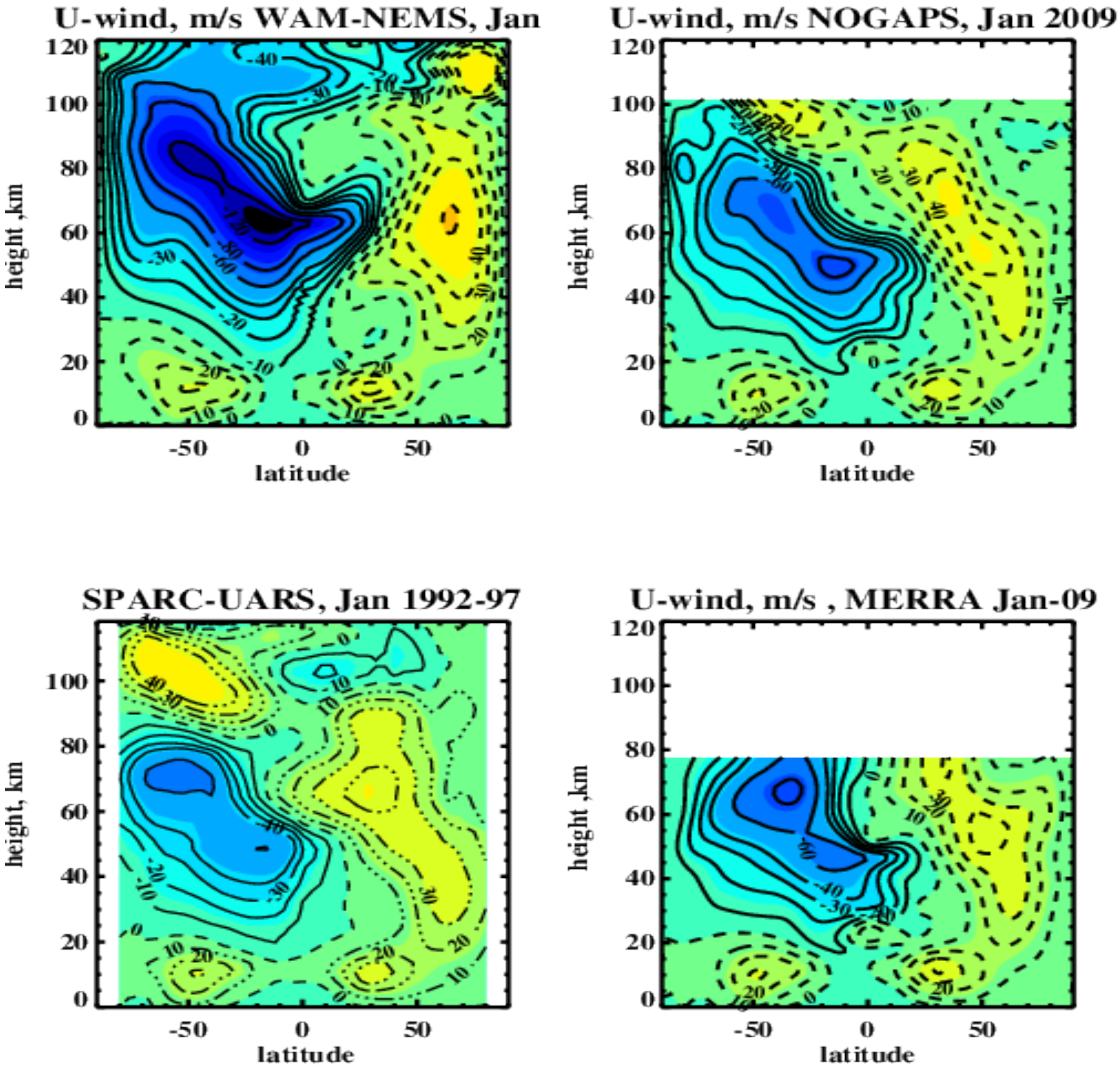
NOGAPS-Alpha, Jan 2009 with DA of SABER and MLS (right, top)

UARS-SPARC wind climatology (1992-97) (HRDI-WINDII) +UKMO

MERRA-V1/GMAO Jan 2009 (right, bottom).

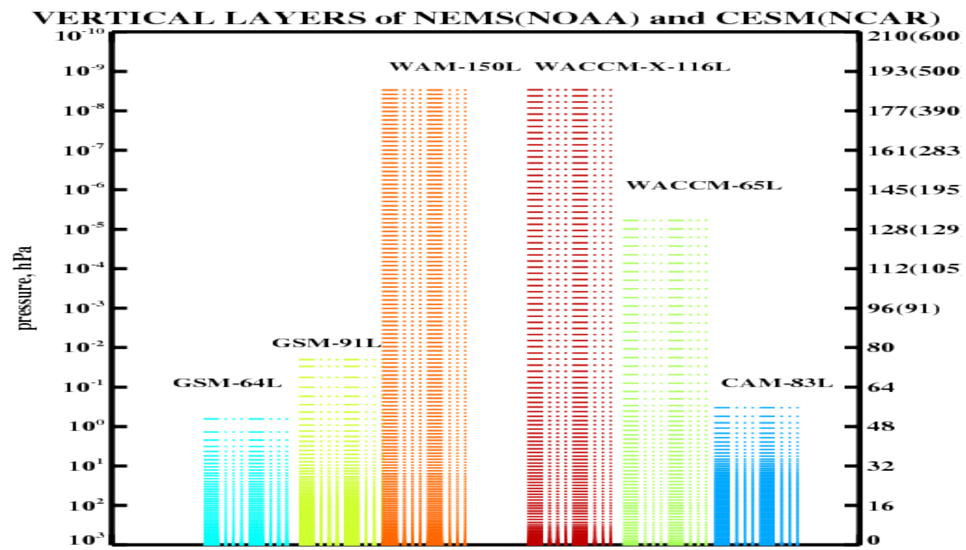
Biases above 40 km:

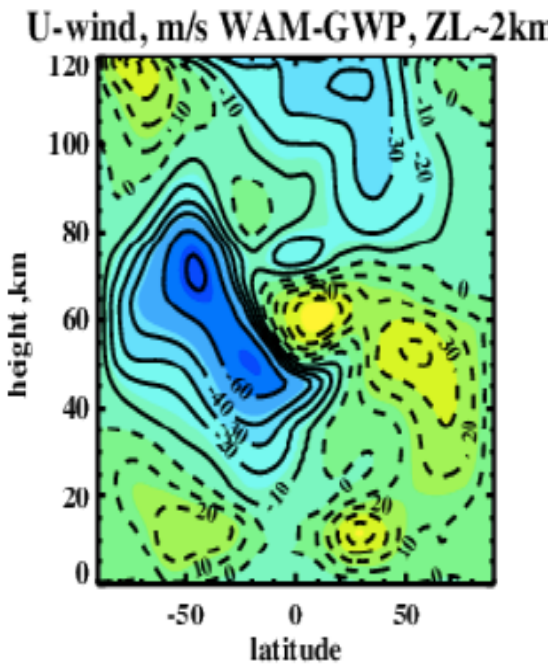
- *No MLT wind reversals*
- *Cold T-bias at 90-110 km.*
- *Strong strato-meso winds.*
- *Errors in PWs and Tides.*

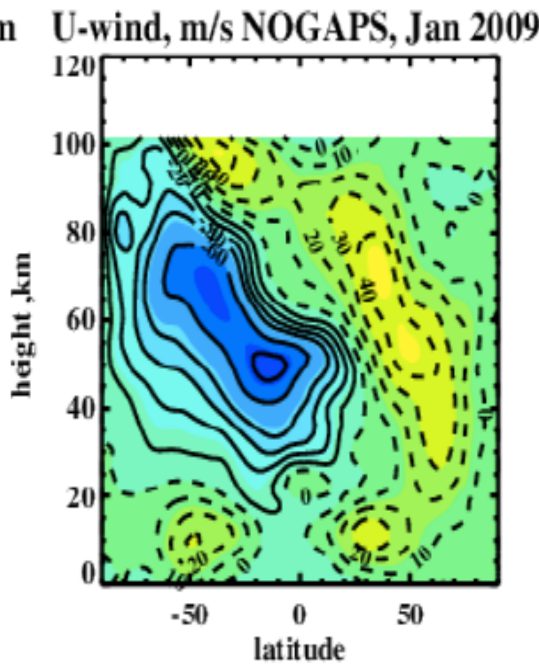


WAM-150L as Vertically Extended Atm-re Model of NEMS: specifics of Physics in the Mesosphere and Thermosphere

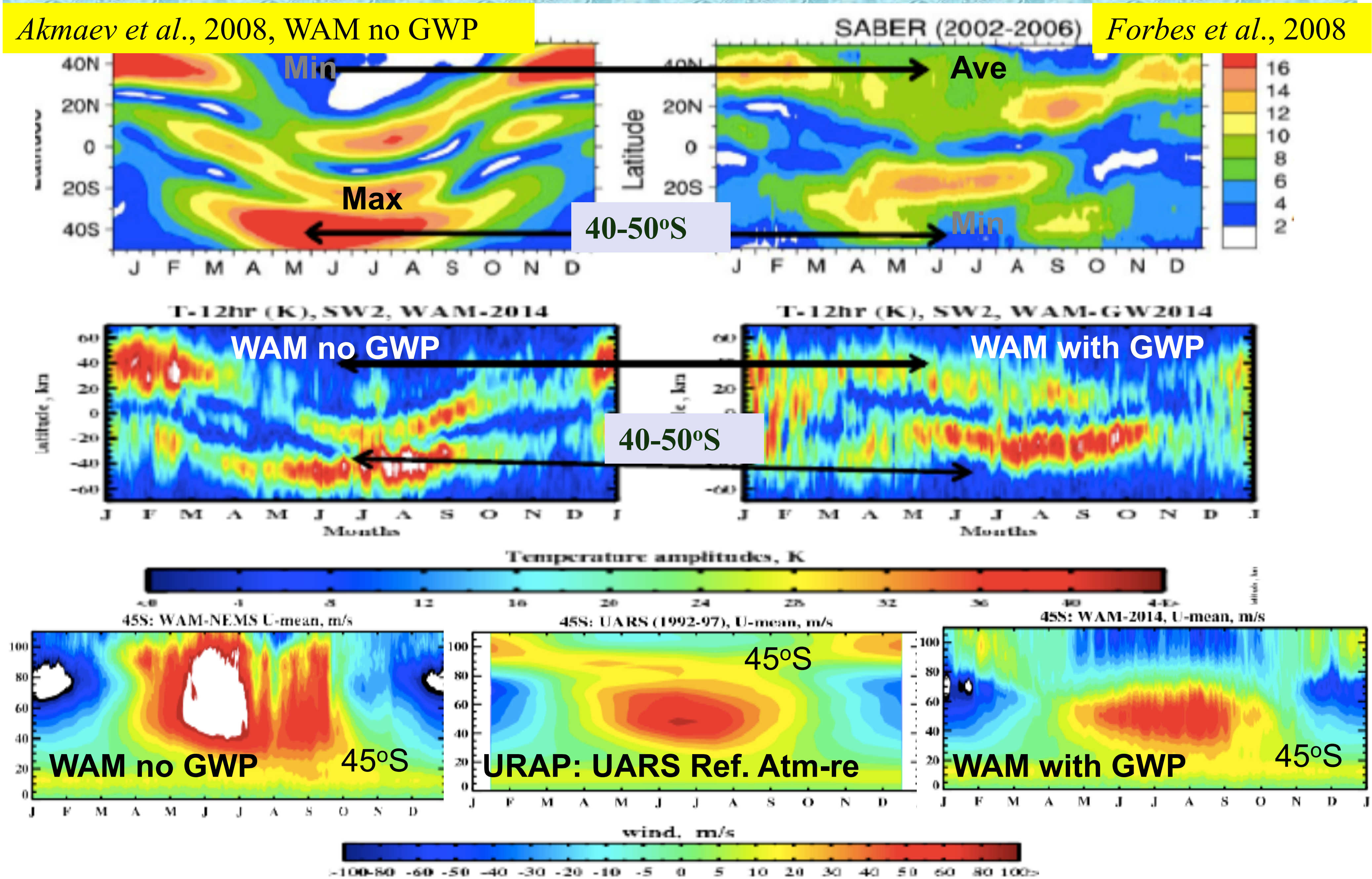
- **WAM, 150 vertical levels with top lid at ~500-600 km; “Zero” Rayleigh damping with molecular visc./cond and 4-th order spectral diffusion.**
- **EUV and non-LTE radiation, ion drag, Joule heating, molecular processes, major tracer (O-O_2N_2) transport-diffusion-chem, & variable “g-C_p-R” (enthalpy).**
- **WAM-T62 as development runs with Eulerian dynamical core enhanced res-ns T254,T382; uniform NGW triggers,~700 hPa.**
- **GW solvers with molecular dis-n: GW drag, heat & mixing**: *4-8 azimuths; stochastic (random draw of single wave) and deterministic spectra (10-20 modes per azimuth) for the linear saturation schemes.*





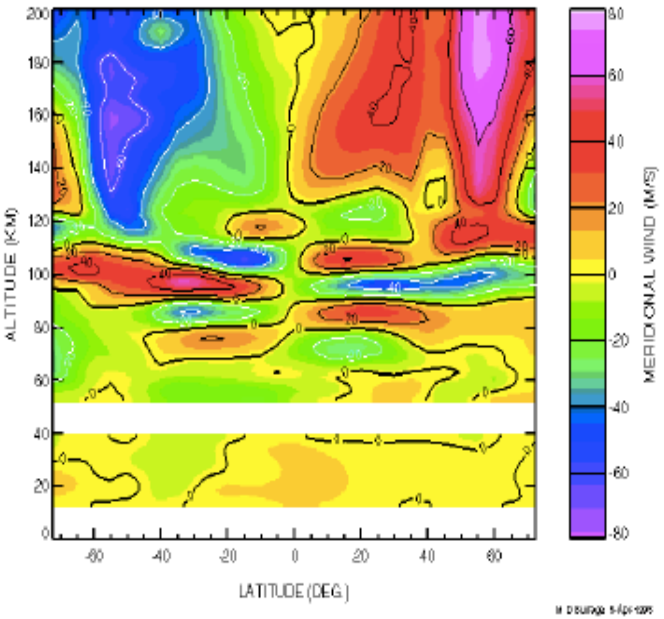


Role of Realistic Zonal Mean Flows in SW2 Tidal Predictions for "JJA" by NEMS-WAM with GW Physics (GWP)

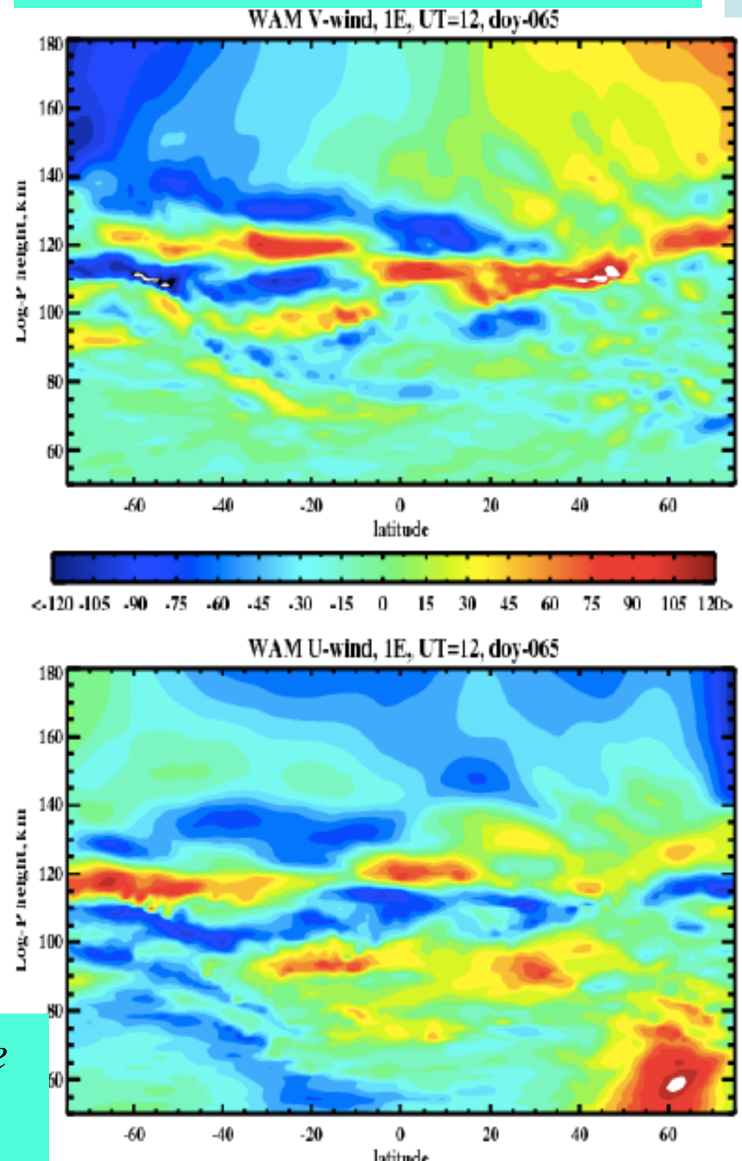


Towards Assimilation of the Space-Borne MLT winds: Outlook for Analysis of WINDII/UARS Data in NEMS-WAM

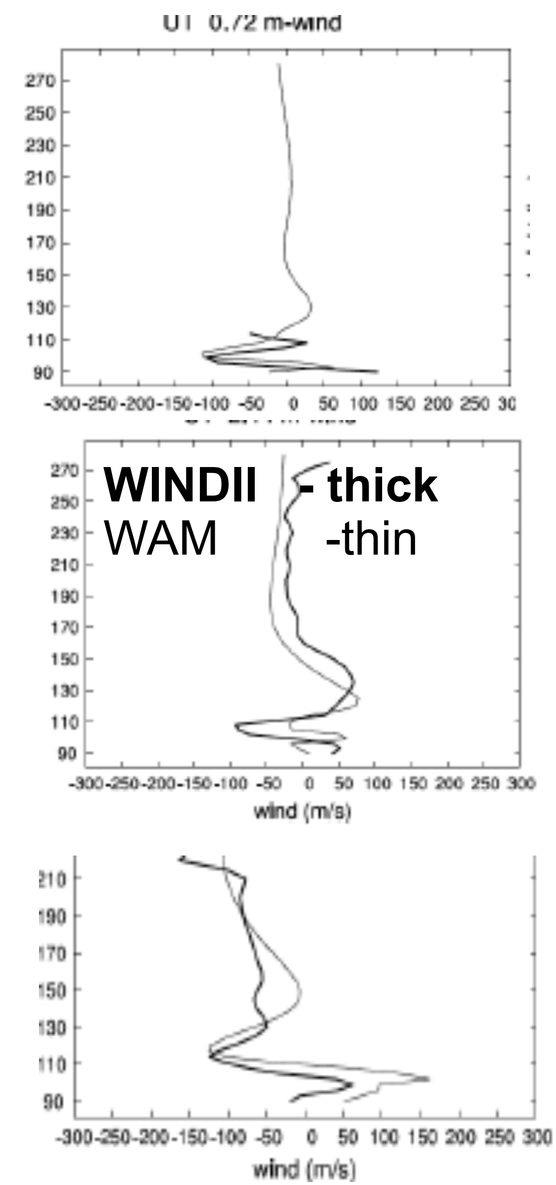
UARS, V-wind, 1993-94



NEMS-WAM, T254, Mar 8



individual profiles



WINDII/HRDI Meridional Wind composite (Feb-Apr)1993-94, 12 LT

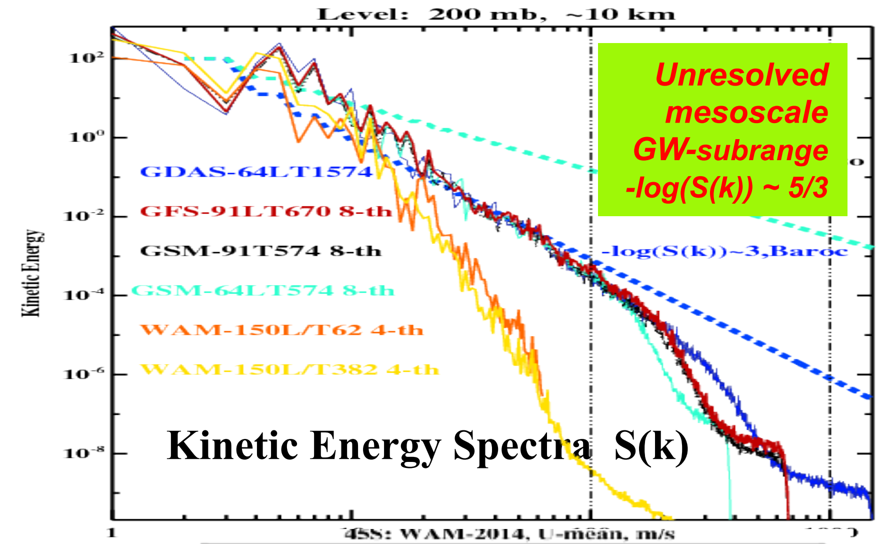
The 12 UT WAM zonal & meridional Winds (DOY 65, March 6) along Greenvich meridian (1deg E)

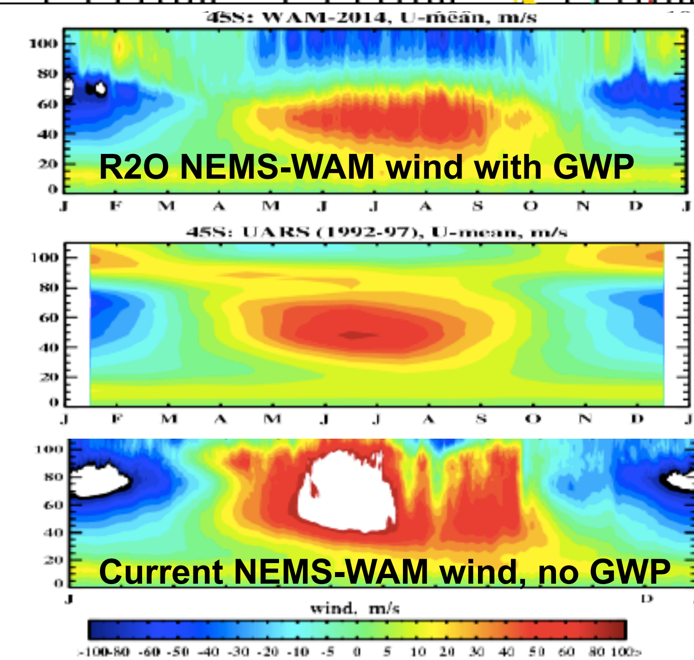
Dominant structures of the 24-hr tide in the tropical MLT, l_z ~25 km seen in UARS data and WAM.

Integrating Unified Gravity Wave Physics into the Next Generation Global Prediction System

Timothy Fuller-Rowell and Valery Yudin, CU-CIRES

- **As R2O NGGPS effort,** this project implemented the non-stationary Gravity Wave (GW) schemes in NOAA weather and climate predictions system, GFS and NEMS to extend them above ~50 km and improve vertical atmosphere coupling, annual and sub-seasonal variations.
- **Expected outcome:** improvement of forecast skills from the surface to the thermosphere for time windows from ~2 weeks to ~1mth by adding physics of GWs for unresolved momentum, heat and energy depositions. **Deliverables:** GFS-91L, WAM-150L with GW physics

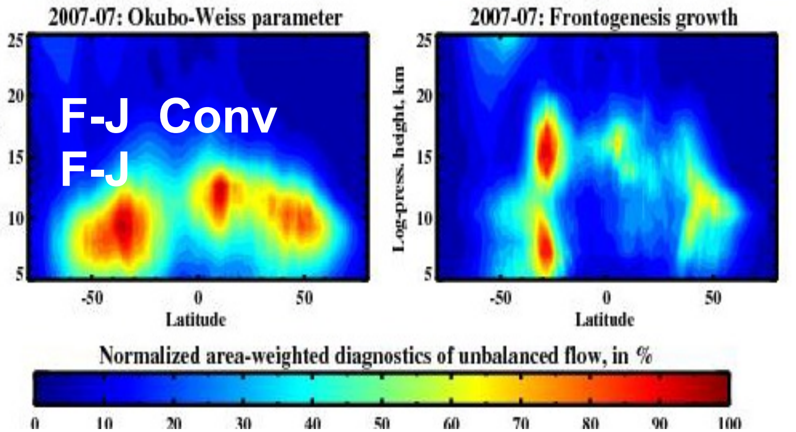




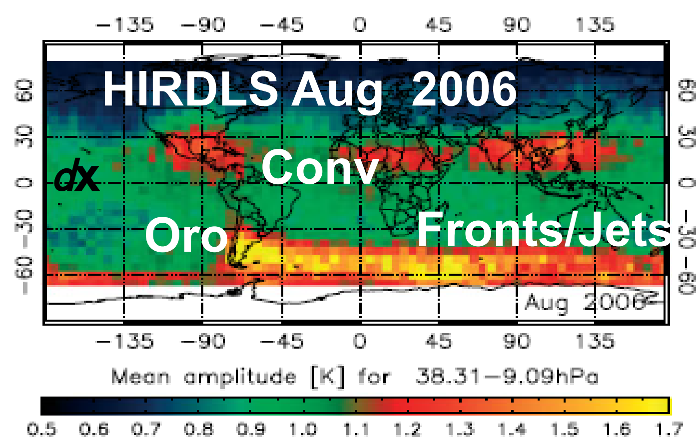
- **Connection to NGGPS:** Development and implementation of **Unified Sub-Grid scale Gravity Wave (GW) physics in the vertically extended global atmosphere models of NGGPS** that resolve upper stratosphere and mesosphere for the terrestrial weather and climate predictions **(NEMS-GFS/GSM 90 level, ~80 km lid)** and space weather predictions **(NEMS-WAM, 150 levels, ~500 km top lid**).

Key future elements of Unified GW physics in the extended atmosphere NOAA models: GFS/GSM-91L and WAM-150L

1. ***GW Sources:*** Stochastic and physics-based mechanisms for GW-excitations in the lower atmosphere, calibrated by the high-res runs analyses, and observations (***3 types of GW sources: orography, convection, fronts/jets***).



2. ***GW Propagation:*** Unified solver for "propagation, dissipation and breaking" of waves excited from all type of GW sources.
3. ***GW Effects:*** Unified representation GW impacts on the 'resolved-scale' flow for all types of GWs (energy-balanced parameterizations of momentum, heat, depositions and eddy mixing).



4. ***Resolution-awareness of sub-grid GW schemes*** in all aspects of wave physics (sources, propagation, dissipation, effects on the resolved-scale flow).

GW Momentum Flux:

$F_{uw} = \langle U'W' \rangle = -L_z \langle U'^2 \rangle / L_x$

$L_x \sim (1\text{-}3)\, dx$

dx – typical size of the H-grid

$F_{uw} \sim 1/dx$, $F_{uw}(T62) < F_{uw}(T670)$

But… $\langle U'^2(T62) \rangle \ll \langle U'^2(T670) \rangle$

Summary and what will be next in 2016-17 and… beyond

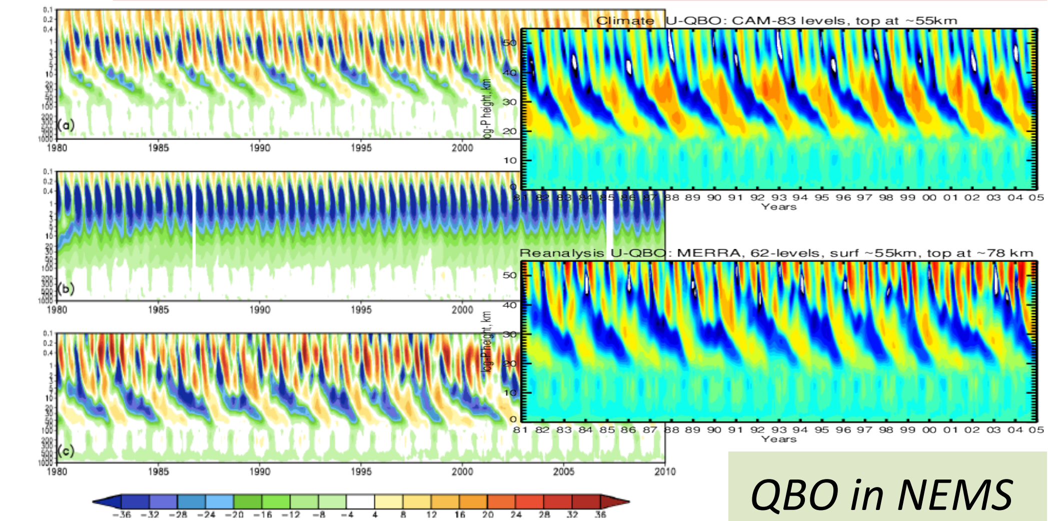
The unified GW physics package (*momentum/ drag, energy/heat, and mixing*) for OGW and NGW **was developed**. Its implementations in **GFS-91L show better skills in the service windows 6-10 days and 2-4 weeks in the stratosphere**. As expected, extended models may improve winter predictions of SSW, NAO and AO patterns.

For "dissipative" atmosphere four candidates for GW solvers are now adapted and evaluated in WAM. **WAM-GW simulations display improved dynamics above 40 km: *MF, PWs and Tides.***

Next, **select "primary" NGW scheme for NEMS/GSM-91L, commit it in Sep/Oct 2016** with GW physics extended for WAM-150L.

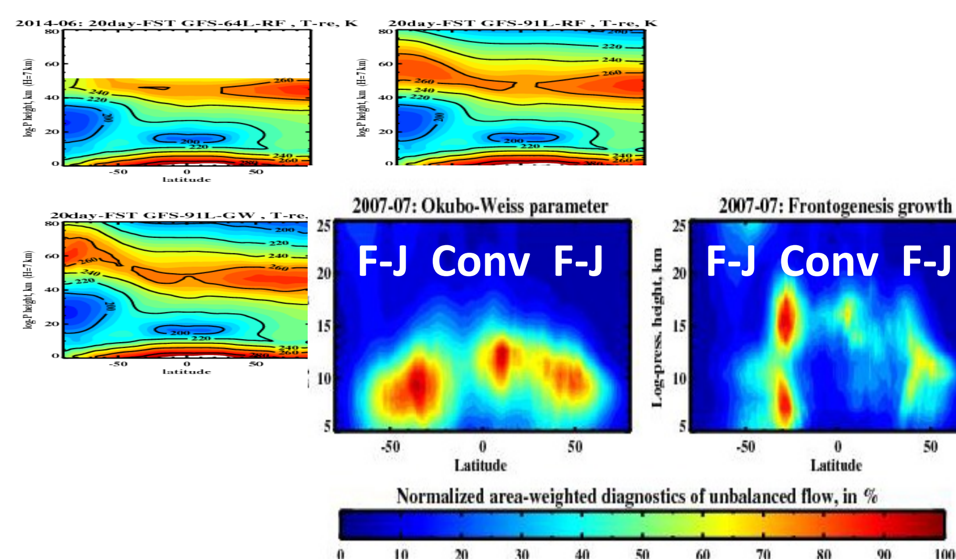
Test GW physics package in the Research-2-Operation NOAA Global Models (GFS-T1574, GSM-T1574 …) between Sep/16- Apr/2017.

Long-Term plans for NGGPS GW physics

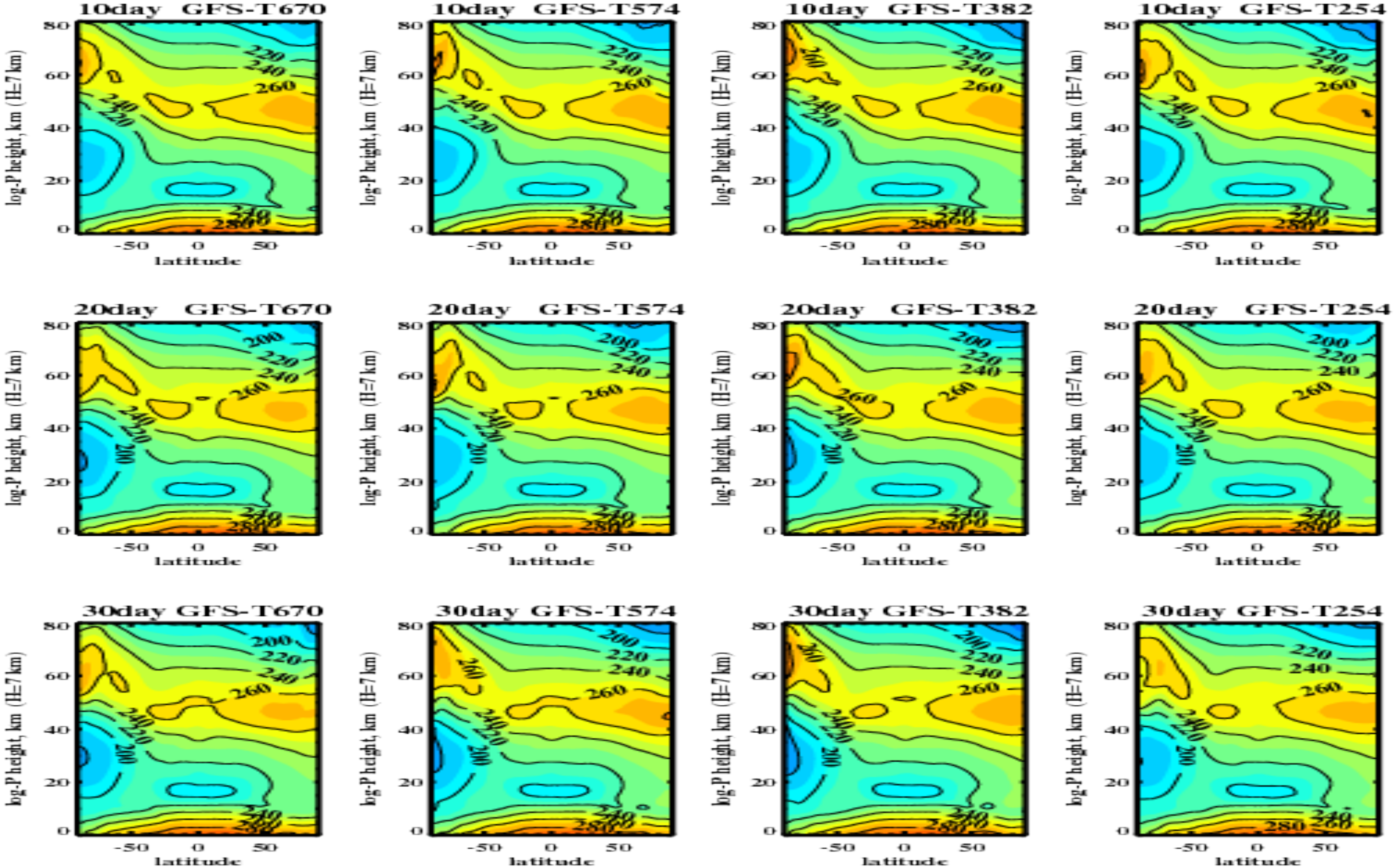


Spatial average of zonal wind in m s^{-1} from 10° S to 10° N latitude as a function of pressure level in millibars ;

Stochastic GW physics and wave triggers: role in the ensemble spread & bias corrections in the upper layers for temperature and winds.

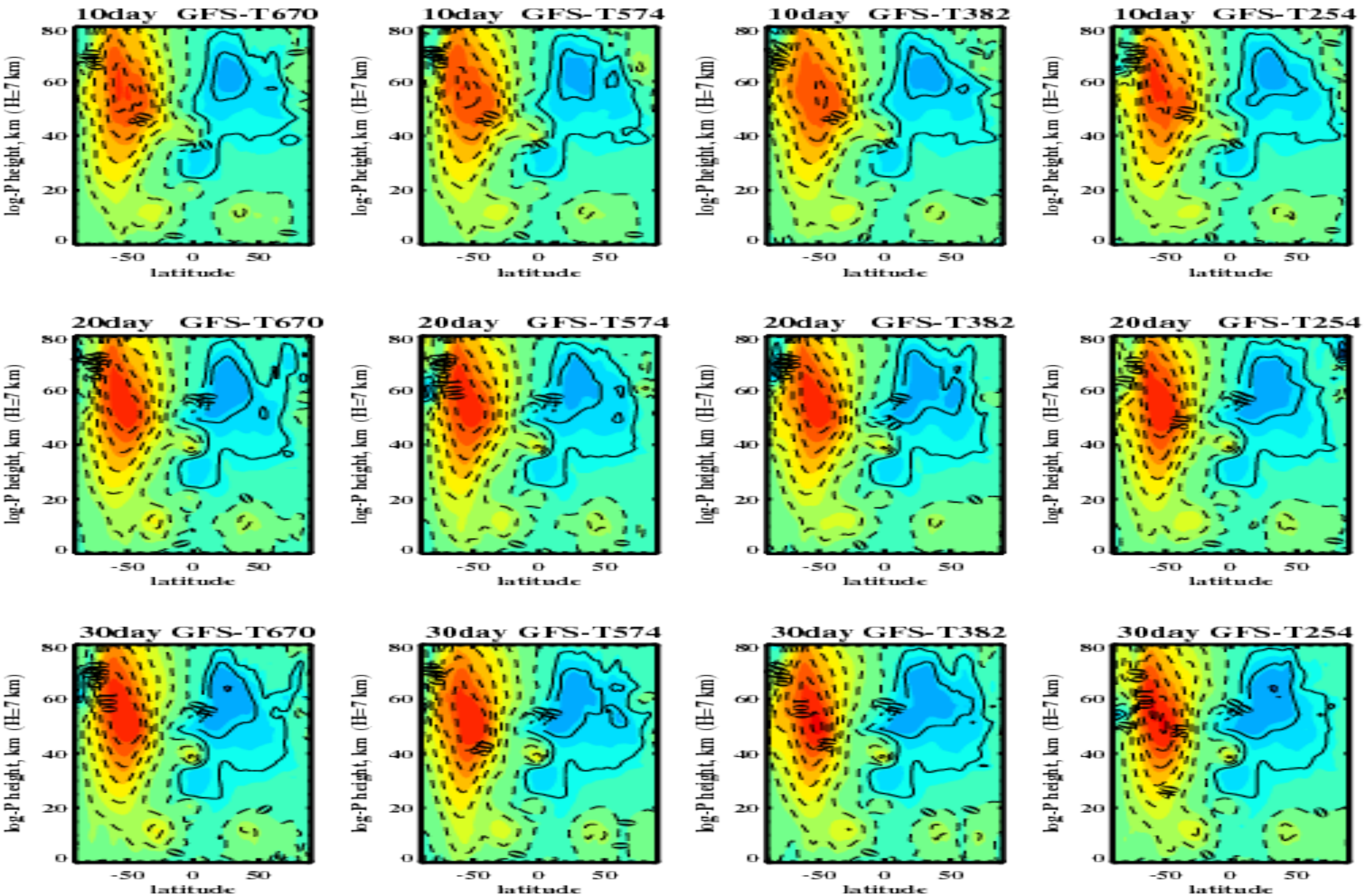


Sensitivity GFS-91GW to horizontal resolutions



T670 (30km) T574 (35km) T382 (50km) T254(75km)

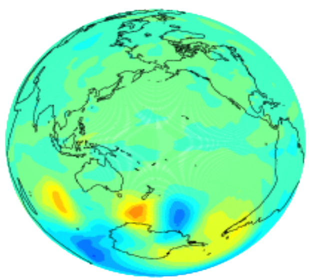
Sensitivity U-winds GFS-91l/GW to horizontal resolutions



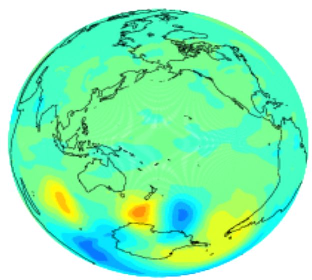
T670 (30km) T574 (35km) T382 (50km) T254(75km)

Merid. winds: 5- and 20-day GFS forecasts and analysis

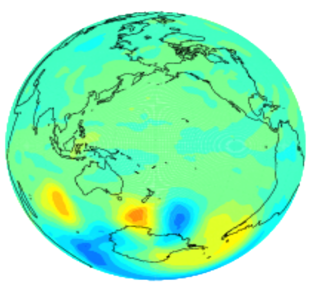
V, m/s T574-RF91 at 32 km, 5d-fst



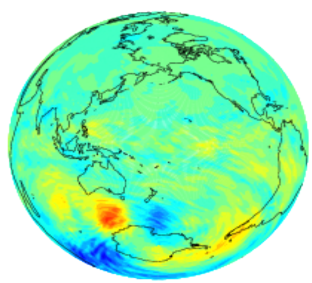
V, m/s T574-RF64 at 32 km, 5d-fst



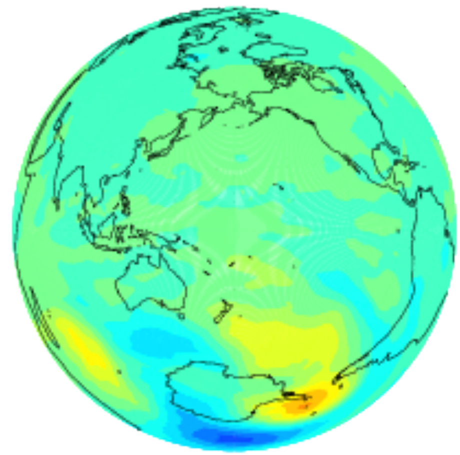
V, m/s T574-GW91 at 32 km, 5d-fst



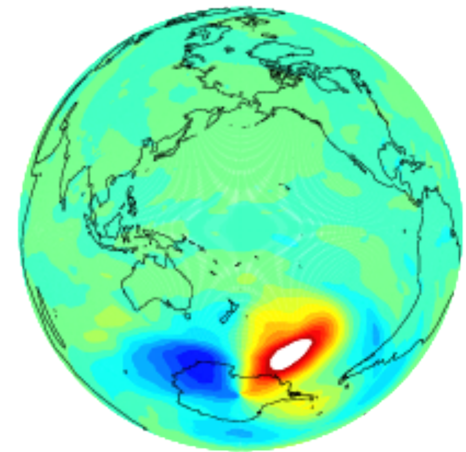
20140606: GDAS-64L,T574, at 32km



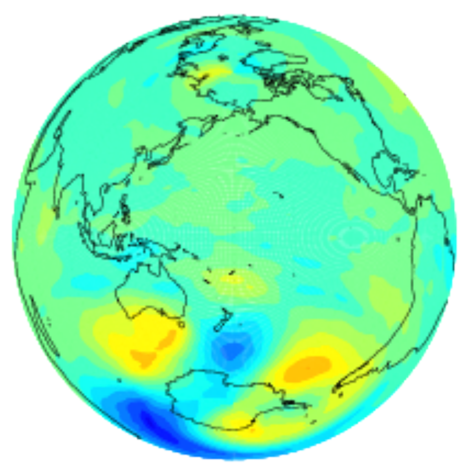
V, m/s T574-RF91 at 32 km, 20d-fst



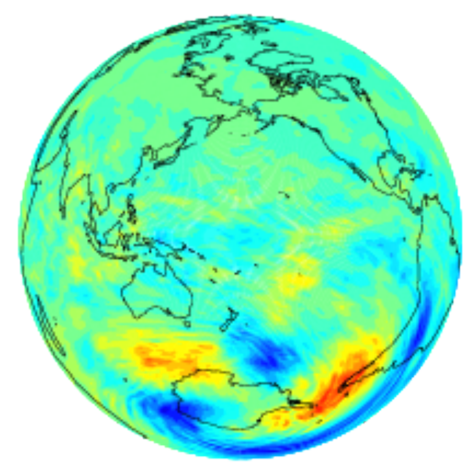
V, m/s T574-RF64 at 32 km, 20d-fst



V, m/s T574-GW91 at 32 km, 20d-fst



20140621: GDAS-64L,T574, at 32km



Goals and Objectives of R2O for GW physics

CU-CIRES collaborative research with NOAA/NWS is to support upgrades and improvements of GW physics in the NEMS global atmosphere models, CFS, GFS and WAM. The planned improvements for the NEMS models are:

1) Calibration of model physics for higher vertical and horizontal resolution and an extended (from ~50 km to ~100 & 500 km) top lids of simulations;
2) Upgrades to GW schemes, including the turbulent heating and eddy mixing due wave dissipation and breaking, and
3) Tests of GW physics and understanding its role on weather dynamics (SSW, season-to-season transitions) and seasonal/climate oscillations (QBO, SAO, NAO, AO) with emphasis on impacts of non-orographic GWs.

Development and evaluation timeline

Year 2015/16: Porting and testing unified suite in the vertically extended models NEMS-WAM and GFS-90L to demonstrate role of GW physics of non-stationary and orographic waves (performed)

Year 2016/17: Evaluations of GW physics in updated atmosphere models: sub-seasonal predictability; experiments with NEMS GFS/GSM operational versions to quantify skill in the service windows 6-10 days and 2-4 weeks verifying with NAO-AO patterns; experiments with WAM multi-year runs (QBO and SAO) and WAM-IPE with space weather forecast indices (ongoing).