Constraining Upper Atmosphere Dynamics of WACCM(X)by met-analyses and MARS data

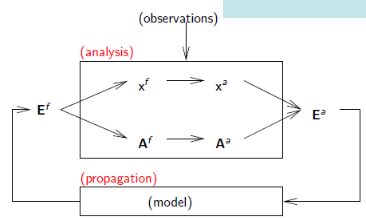
V. A. Yudin, H.-L. Liu, and B.V. Khattatov

Motivations

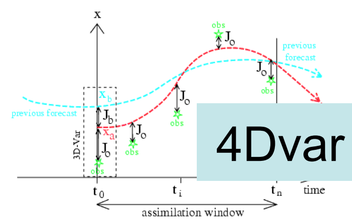
- **Constrain the low atmosphere** of WACCM by 6-hourly meteo-analyses (GEOS-5; MERRA, surf. to~ 40 km), **preserving fast/transient waves and tides.**
- **Perform trial assimilation of O_3 and temperature data** ***"on the fly"*** as additional chain in WACCM time step: **(Dynamical Core –> Physics –> Data assimilation).**
- **Demonstrate how assimilation can evaluate model errors by Middle Atmosphere Research Satellite (MARS data, *SABER and MLS*)**
- **Pin-point potential revisions in WACCM/CAM formulations** *initiated by diagnostics of persistent model-data differences.*
- **Demonstrate** how **'research'** DA schemes in WACCM can guide **in adaptation of 'Advanced' DA (ADA) algorithms** for fast/transient waves in the presence of large biases in the upper atmosphere.

EnKF: workflow

EnKF

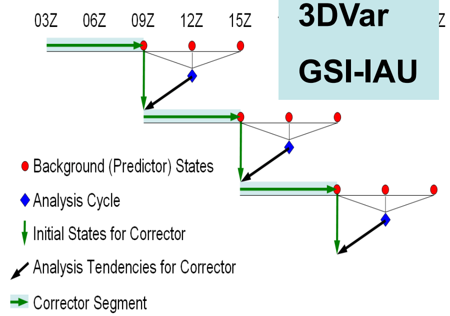


4Dvar



3DVar

GSI-IAU



ADA algorithms

"Some challenges of data assimilation in the middle-upper atmosphere"

- **Assimilation of the fast vertically-propagated wave signatures** from noisy observations (*ageostophic analysis increments with large diurnal oscillations, tides*).

- **Needs for the data with spatial resolutions that can 'correct' wave dynamics** of models (vertical resolution and horizontal resolution, ***amplitude and phases***)

- **Temporal resolution**: ideal case scenario: 24-hr LST coverage (~36 day fot UARS and ~60 for TIMED), but model physics has 'diurnal' dynamics, then

  model equations with analysis increments (tendencies) will 'advance' spatial wave structures creating 'adequate' LST oscillations **[*Space wave struc. -> Time Var.*].**

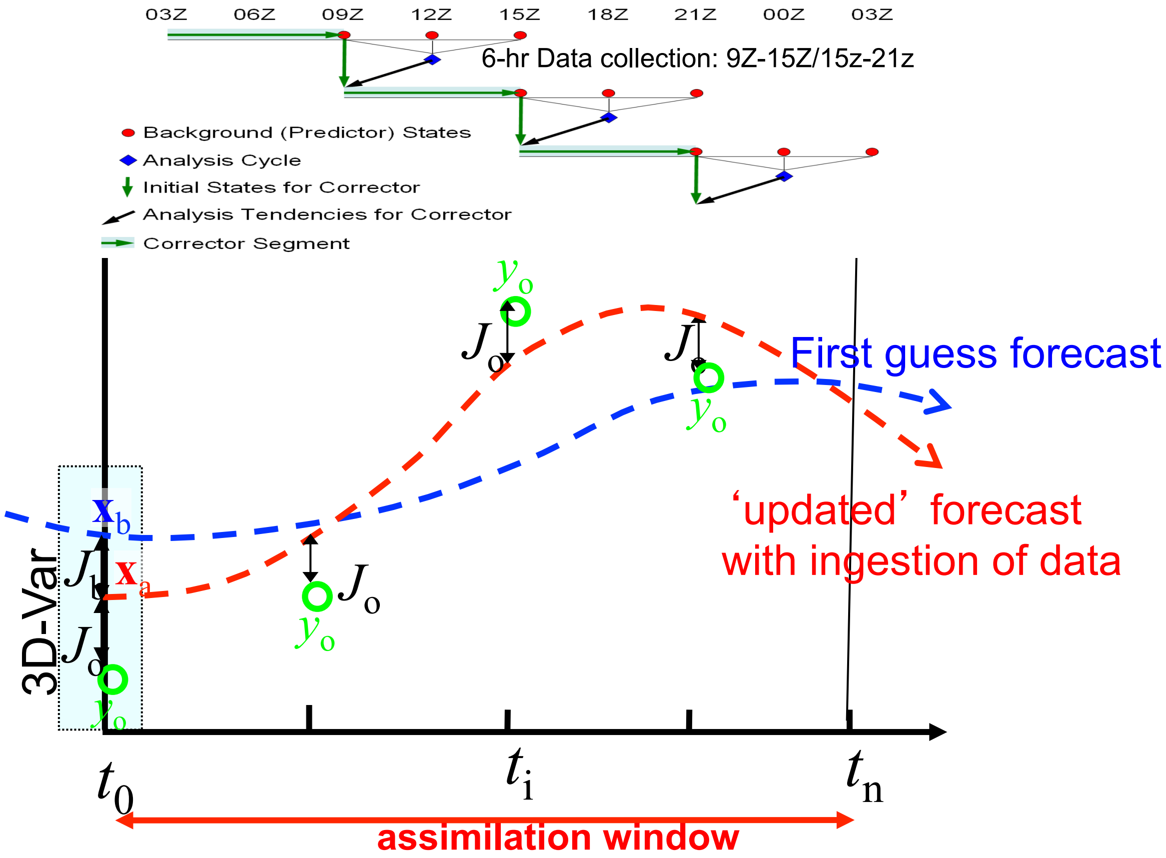
Analysis of 'fast' waves requires the short duration of analysis-forecast cycle

-*in incremental 3DVar* and *EnKF* (~1-hr, frequent time-consuming model restarts),

-*in 4DVar algorithms* with TL and ATL (wave equations with the data),

-or *assimilation on "the fly" every model time step (no restarts)*, observational tendencies similar to tendency due to sub-grid model physics

Advanced variational schemes: 3D-Var (GSI) and 4D-Var



24-hr 'moving' window for constraining tides

Time-evolving B-covariance, especially important.

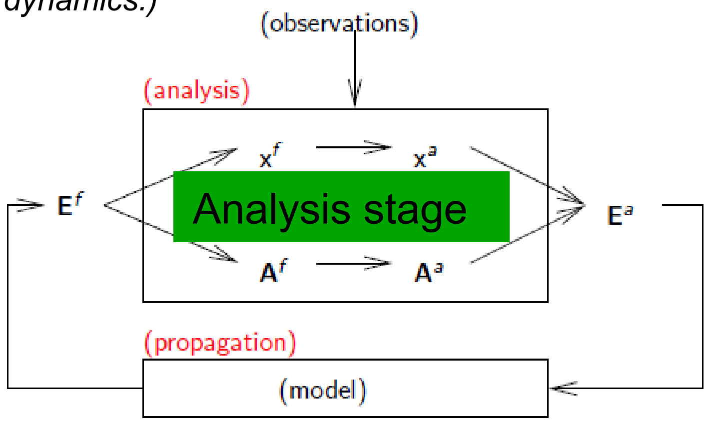
Chart from http://www.ecmwf.int/

1. 4D-Var assumes a perfect model *in the strong-constrained formulation w/o model errors*. It will give the same credence to "older data" as to 'fresh' observations;
2. 3DVar-shemes,operational algorithm *Derber, Wu* ..=> and GSI/NCEP, Community GSI-DTC, GSI-IAU GMAO
3. Background error covariance is 'static' in 3D-Var, but evolves with time in 4D-Var.
4. In 4D-Var, the adjoint model is required to compute ∇J.
5. Weak-constrained 4D-Var *DA-type of correction for model errors (biases)*

Sequential DA schemes: EnKF and sup-optimal Kalman Filters (Optimal Interpolation - OI and Optimal Nudging – ON, DAF)

EnKF: workflow

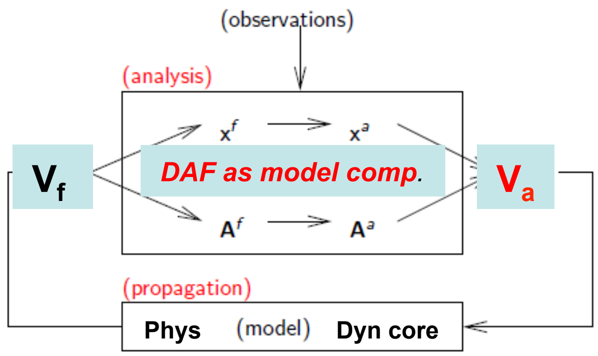
Frequency of com. between A – F stages: 3hr or 6 hr (1-hr for UA dynamics.)



Forecast stage: Ens. Model States ensemble spread …B-error

DA on 'the Fly' (DAF) workflow

A – F cycles every time step 15 min



Single model state, variance evolving schemes for B-errors

time step chain:

Dyn.core => Phys =>DAF

split: X-Y-Z Z-vcol split: Z-(XY)

DAF is oriented on MARS data, no needs to re-assimilate terabytes of data, can use Specified Meteorology option to constrain the LA-domain (< 40 km)

WACCM and WACCM-X with GMAO products in the LA, as a model configuration for data analysis in the MA and UA

- **GMAO analysis products:**

  GEOS-5 - Goddard Earth Observing System 72-lev (top lid ~77 km) & HR: 2/3x0.5.

  MERRA (1979-present)– Modern Era Retro analysis for Research and Applications

- **WACCM-GEOS5/MERRA (*Kinnison et al*.)** VR of GEOS5 + 16 levels. in 77-140 km;

- **WACCMX-GEOS5/MERRA** -116 levels from the surface to ~ 500 km (***Yudin et al.)***

- ***Coupling/Nudging in WACCM(X) and GEOS5/MERRA***

  (a) through tendency: for(*X=U, V, T*)

  dX/dt= (Xwac- Xgeos)/Tau

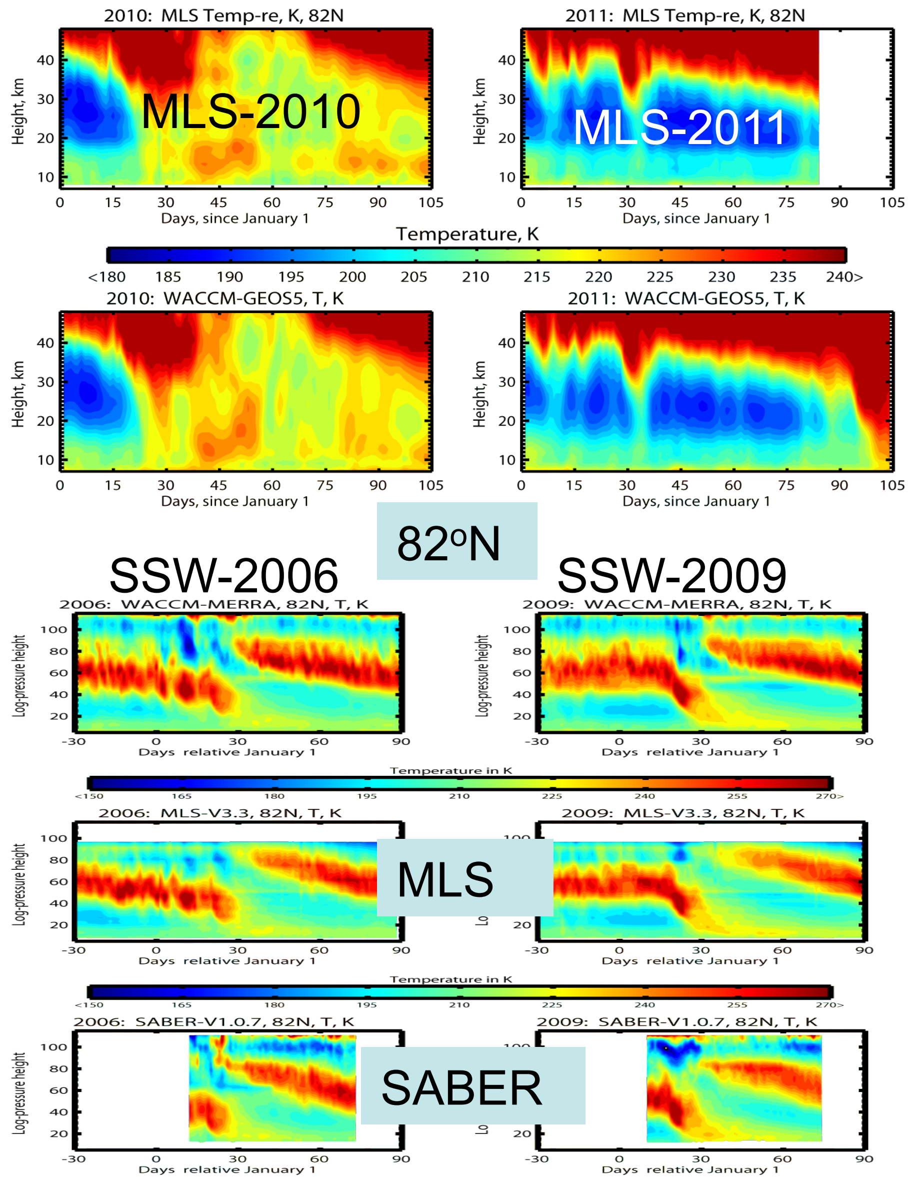
  [nudging domain, surface – ~40 km]

  dX/dt = 0, above 50 km;

  (b) n%-Nudging every time step (1%);

  SD-WACCM, **WACCM-X/NOGAPS-MERRA**(0-90)

Current configuration for DA of MARS data (SABER, MLS)is WACCM-X/GEOS5



Adapting operational assimilation schemes in the data analysis implemented in MA and WA models (current status)

- First implementation of 3DVar-IAU in **CMAM by *Saroja Polavarapu*** *and collaborators* (**Polavarapu, S**. et al.2005. (MLS and SABER, error growth with and w/o GWs).

- **NRL NOGAPS-ALPHA, NAVGEM-3DVar FGAT**. *Hoppel* et al. and *Eckermann et al.* [2008]. (MLS and SABER, T and O3, H2O)

- **NOAA/CIRES and SWPC, GSI-IAU (3DVar) in WAM** (*Wang et al*. 2012) SSW-2009 (*Fuller-Rowell et al*., 2013, GSI data in WAM)

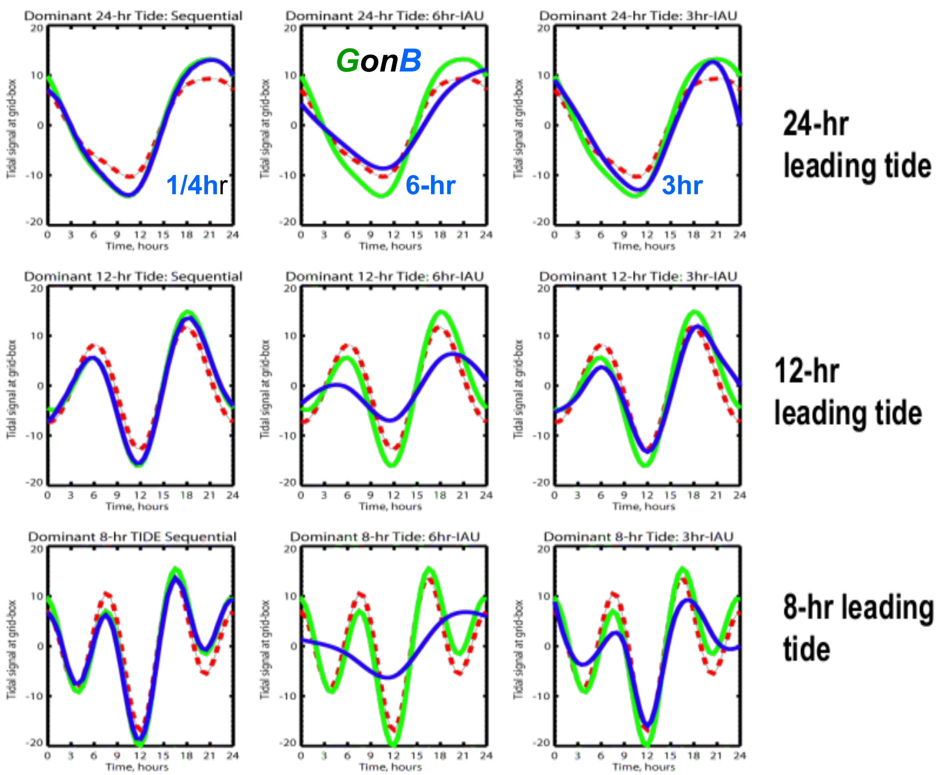
- *All 3DVar-schemes used multi-hour analysis-forecast update* cycles (3-hr or 6-hr); it is only a reasonable approximation for 'weak' diurnal and sub-diurnal oscillations.

Constraining tides in models by SM and DA

- **Task-1:** Prevent tidal signatures simulated by models during DA. They can be degraded by multi-hour analysis update cycles, or/and nadir data with the restricted vertical resolutions, AMSU-A radiances near the stratopuase).
- **Task-2**: When data contain tidal signals, update the DA algorithms of NWP centers to assimilate properly tidal observations (temporal/vertical resolutions).
- **Task-3:** Demonstrate using OSSE studies what kind of the temporal and spatial data coverage in the UA-region is needed to advance the Space Weather applications influenced by tides.

Green-true; Blue-DA; Red-Forecast

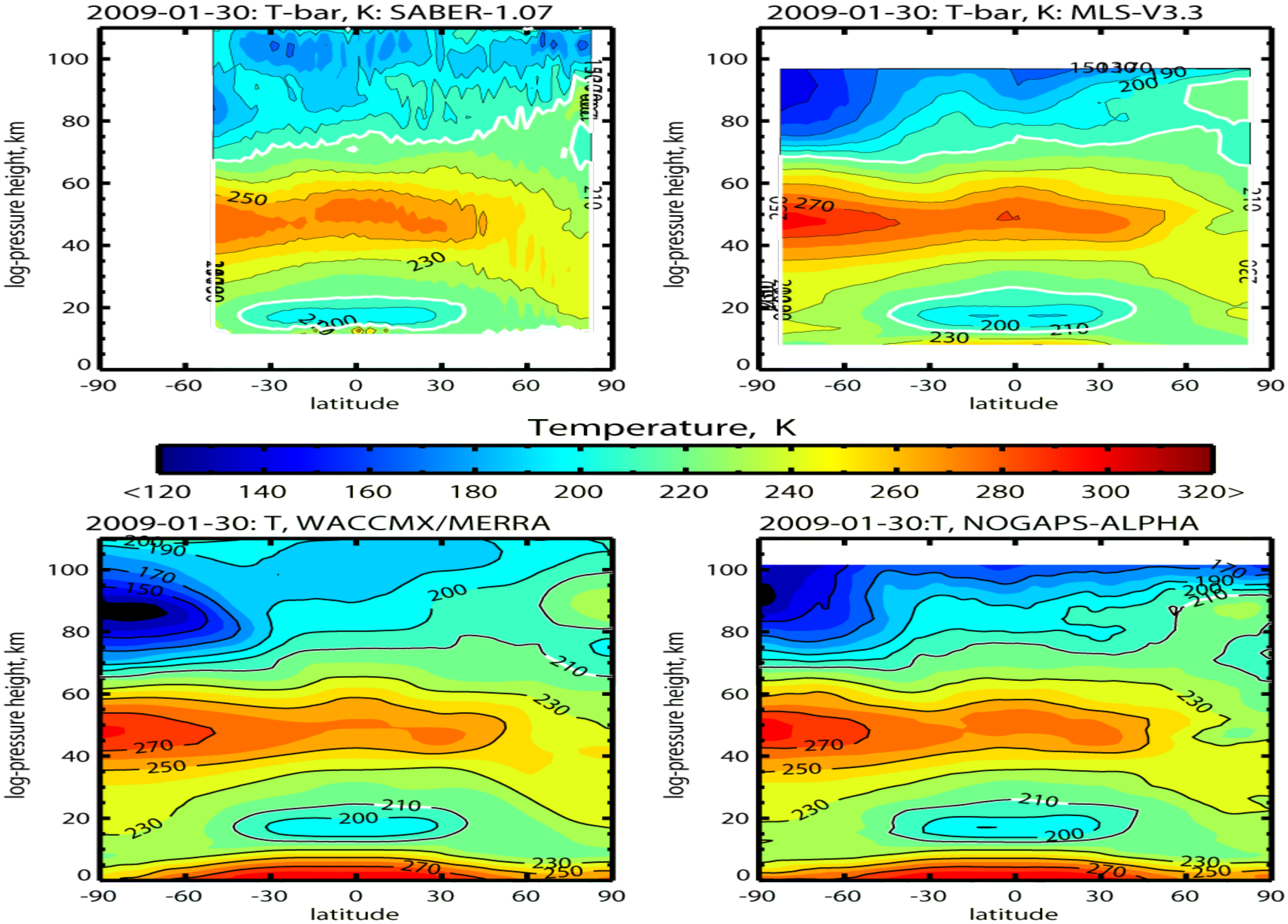
DA for tides in the toy-model (decreasing DA-windows)



Seq. DA, every model step | IAU, 6 hours | IAU, 3 hours

On-the-fly | **With model restarts**

Model evaluation by data and meteo-analyses



Typical model-data differences, diagnosed by the DAF in WACCM

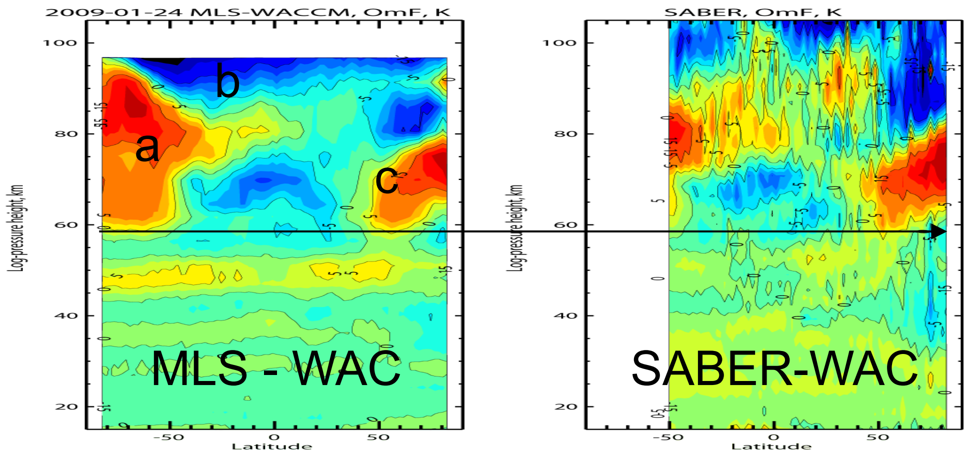
MLS &SABER vs **WACCMX/MERRA Temperature biases**

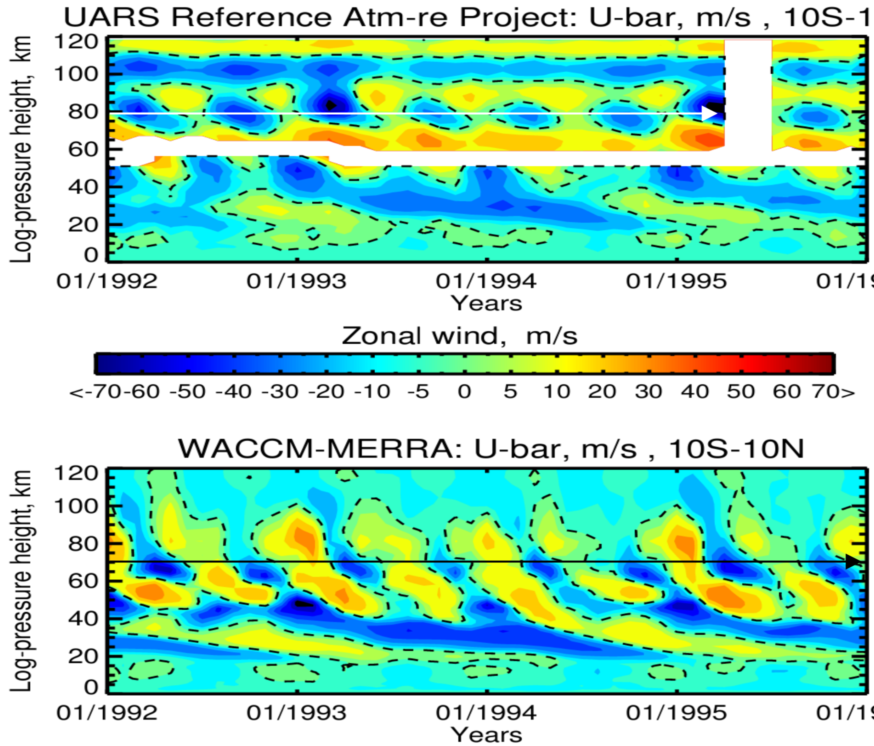
a) polar SH MLT; very cold
b) warmer 90-110 km band;
c) polar night NH above 60km
d) elevated winter stratopause

Winds, WACCM vs UARS and radars

a) strong tropical E-ward winds above 80 km;
b) strong wind reversal in extra-tropics of MLT
c) weak amplitudes of tides (~50% less).

Tracers: *Strong eddy mixing in coldest regions of MLT*



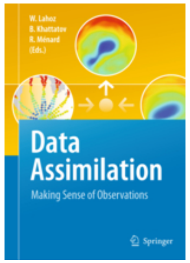


80km

70km

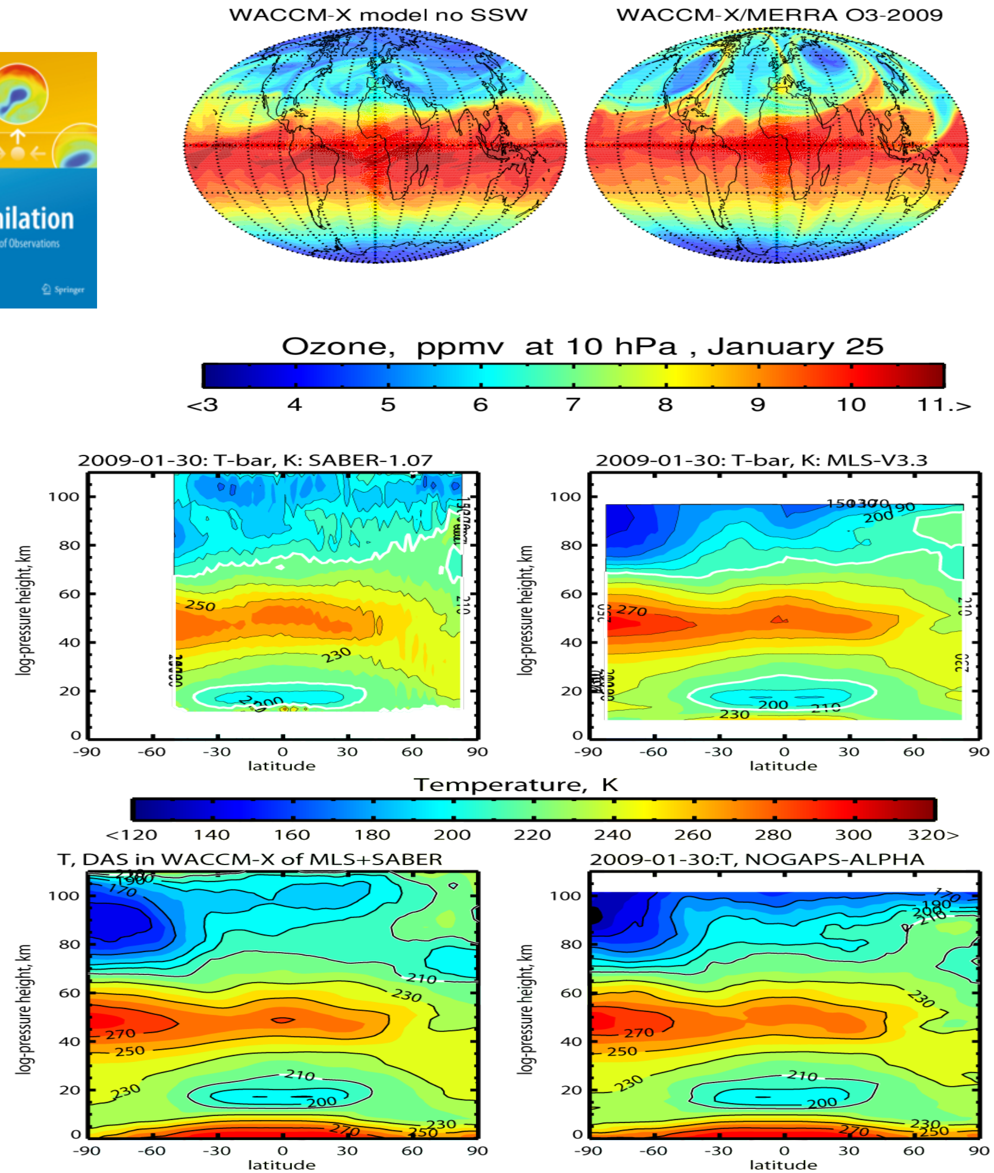
Data Assimilation (DA on the ‘Fly’) of Temperature and Ozone in WACCM

Chemical Data Assimilation, Chapter 4, 2010: *Atmospheric Chemistry and Constituent Transport .Representation and Modelling of Uncertainties in Chemistry and Transport Models, Khattatov and Yudin.*



Application of sequential filters on-the-fly in WACCM: *the resolution-sensitive filter-split algorithms for analysis of the space-borne chemical constituents and temperature.*

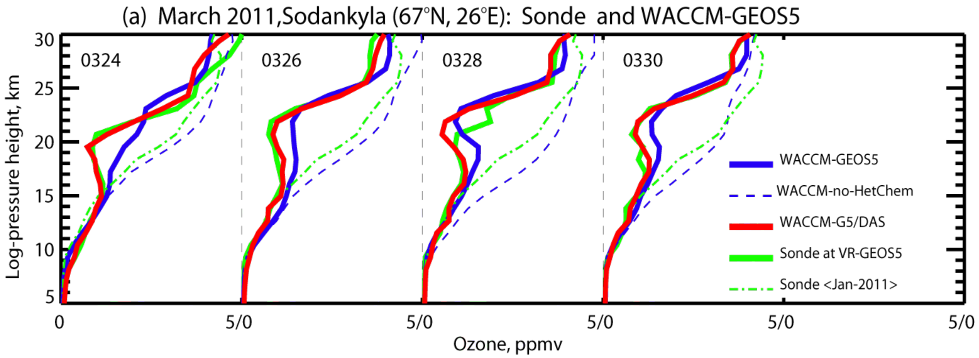
For assimilation of tides: *frequent and “gentle” data constraining at every time-step*

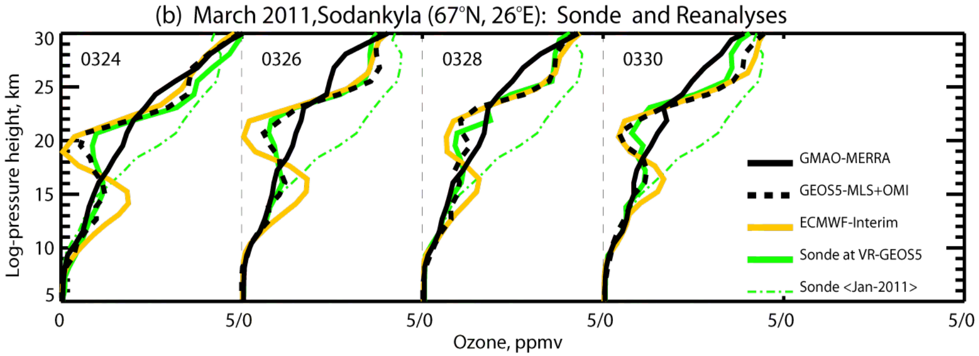


Severe record-high Arctic Ozone depletion in March 2011:

WACCM-DA with MLS data

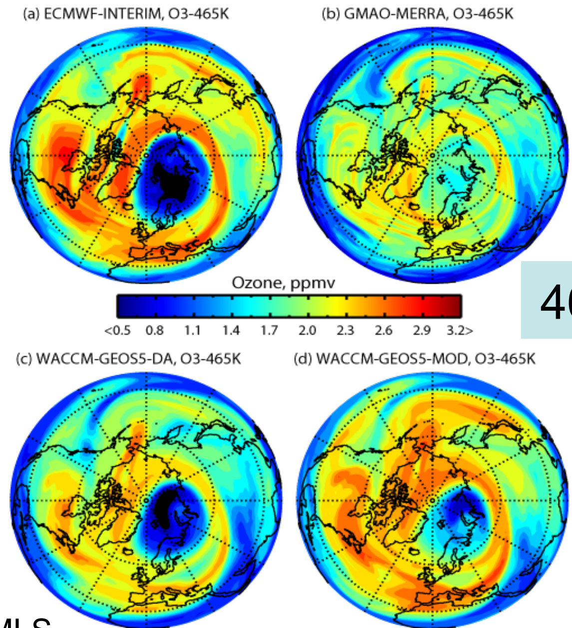
MERRA with SBUV2 data





ERA

MERRA



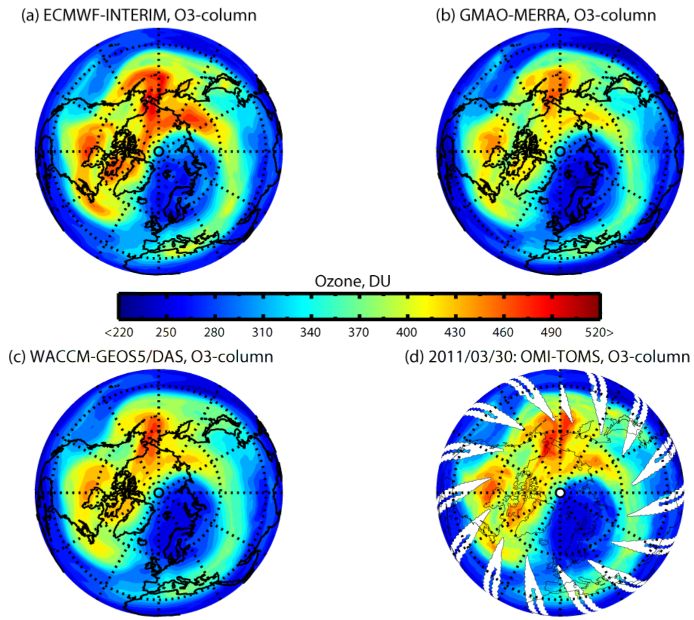
465K PT

WACCM-MLS

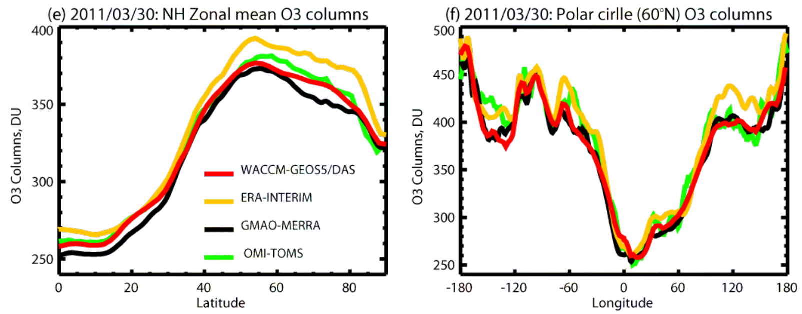
WACCM

ERA-Int, TO3

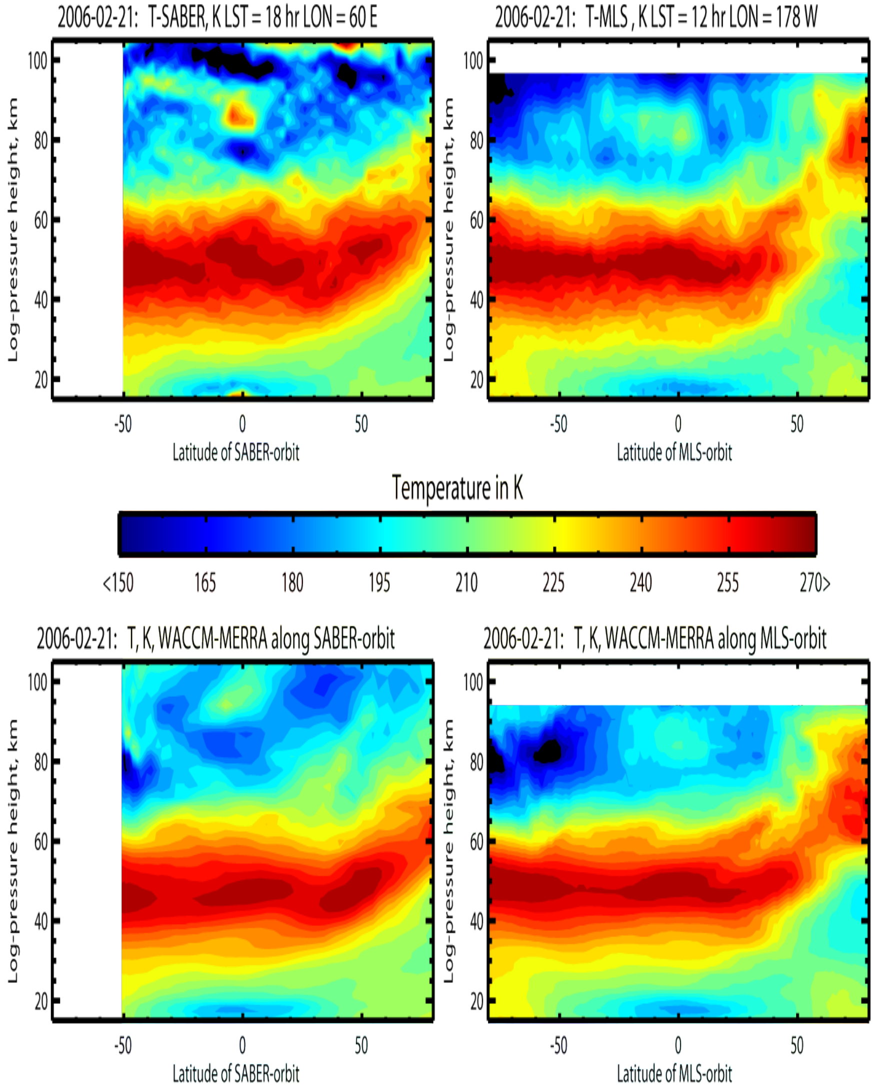
MERRA



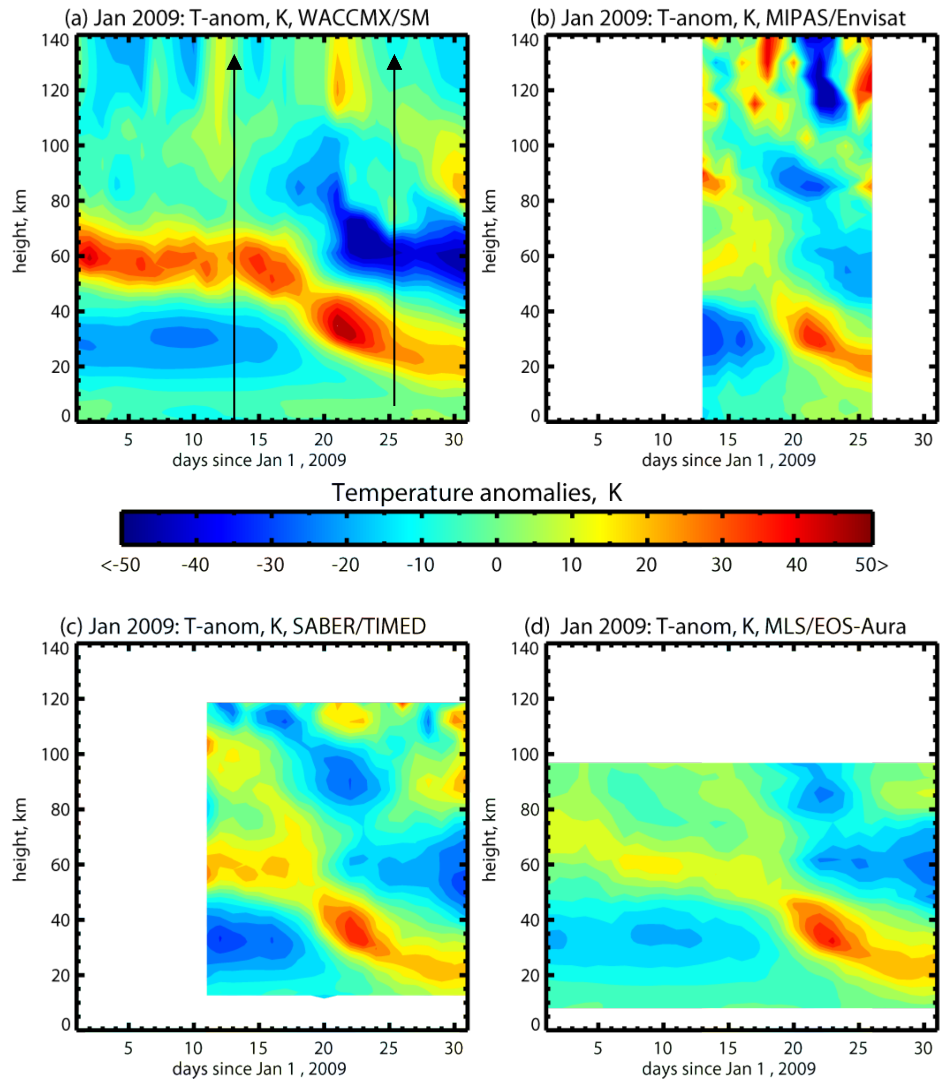
WACCM-MLS



Joint O_3-T analysis of MLS in WACCM with MERRA: signatures of vertically-propagated waves and polar coupling



Single orbit T-structures



Zonal averaged 75-85 N T-anomalies

Lessons from constraining model by MERRA and MARS data: list of potential model updates

- Disassemble dry static energy as a model state variable during physics and update eddy diffusion operators.
  (solves in part cold MLT polar T-bias; and eliminate T-dependence of eddy heat conductivity/viscosity/diffusion).

- Consistent mass and energy conservation for physics and dynamical cores *(accurate physics tendencies between parameterizations and d-p coupling)*

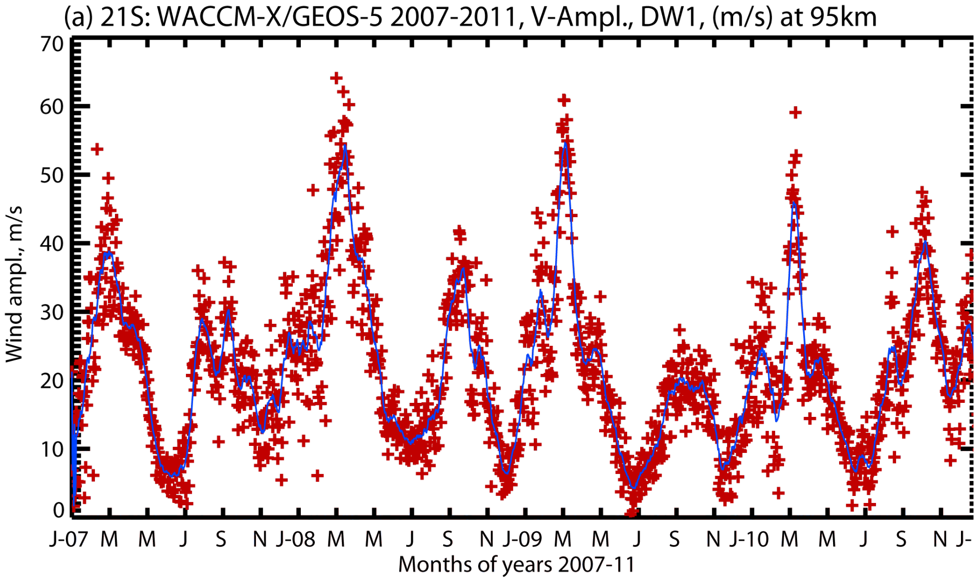
- Scale-aware parameterization schemes for GWs with:

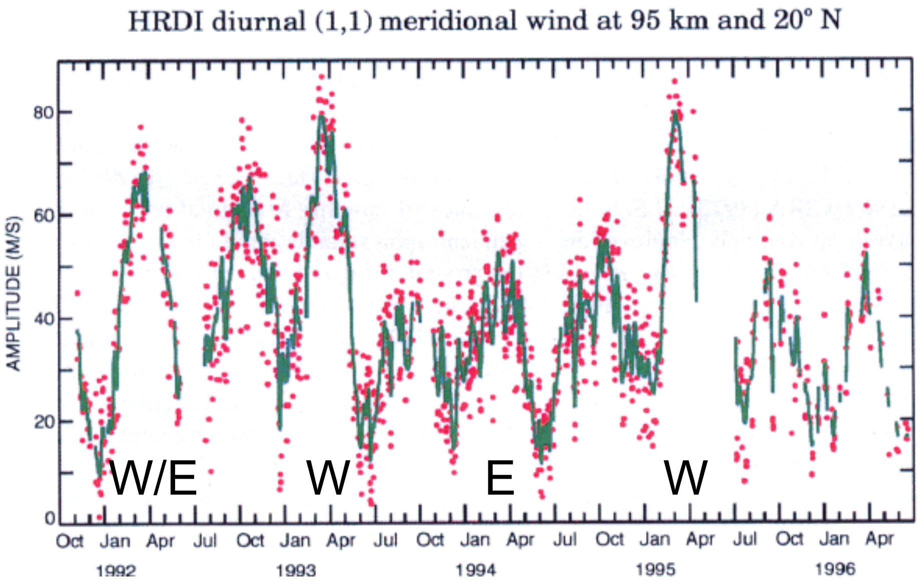
  (a) new GW-MF closure, mean flow (reverse) and tidal (ampl) calibration;

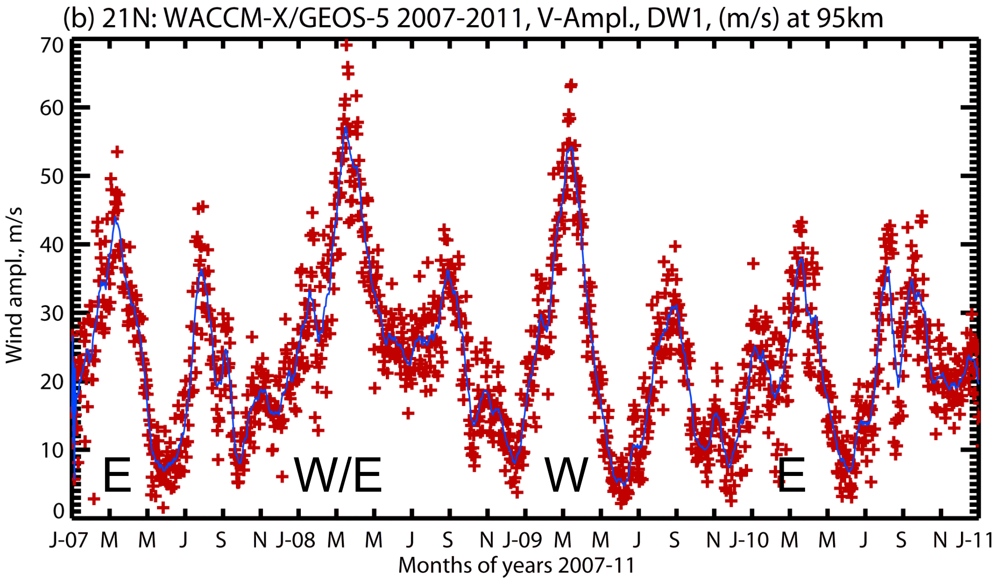
  (b) dual eddy viscosity (conductivity) and momentum (heat) depositions;

  (c) orchestrating oro-GWs and TMS, multi-directional waves, CAT.

WACCM-X/GEOS-5: Tides after calibration of GW-schemes



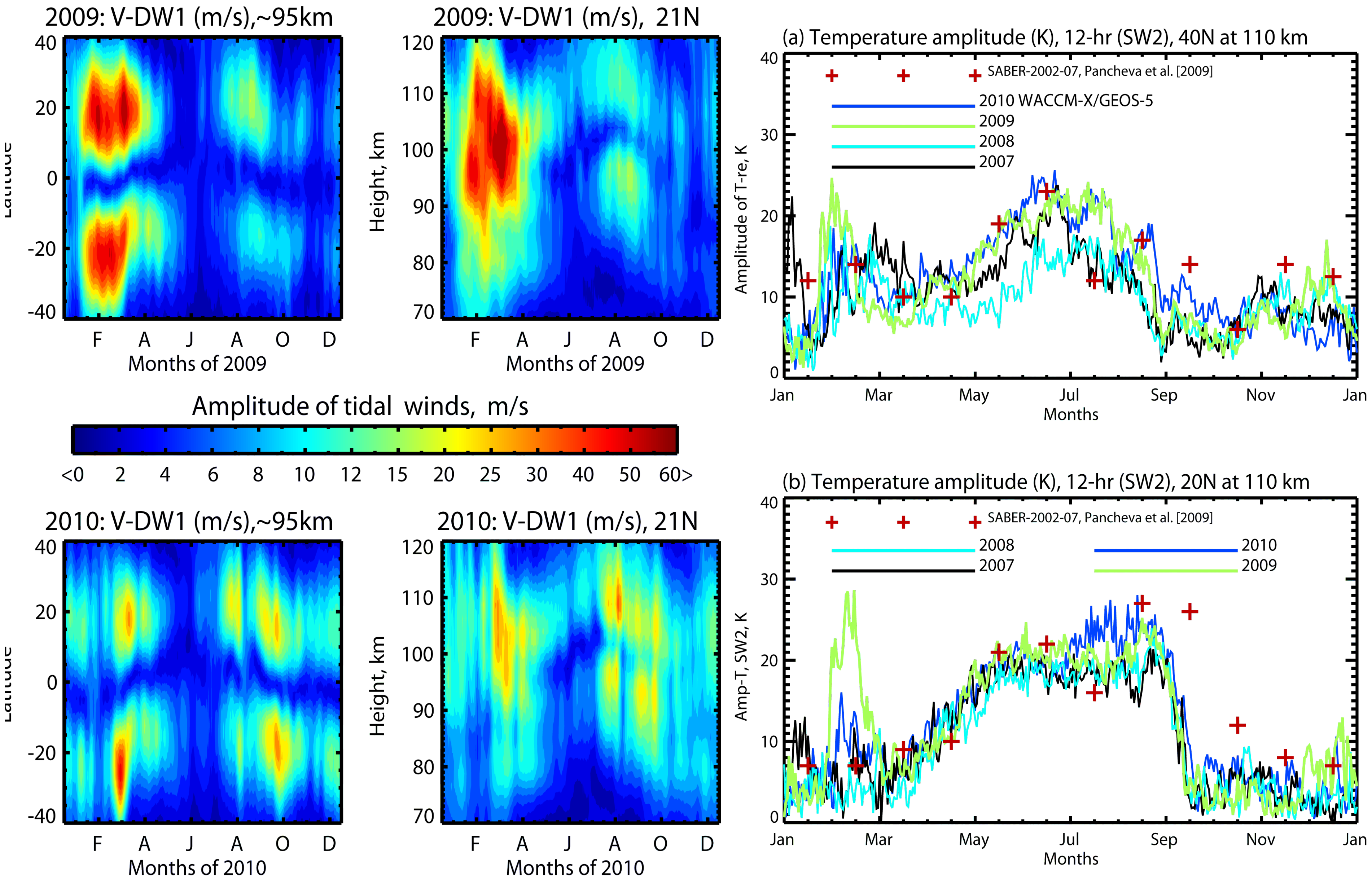




Similar day-to-day variations of DW1 and (1,1) Hough mode from HRDI

Easterly => Weak DW1 and H(1,1)

Westerly and W/E => larger (~x 2) DW1 and H(1,1)



Year-to-year variability of migrating tides (DW1 and SW2)

Concluding remarks

Specified Meteorology below 40 km and assimilation of MARS data 'on-the-fly' in WACCM provide direct 'model-data' comparisons allowing to address and highlight the following aspects:

- **Case studies of wave dynamics with realistic weather patterns** during SSW events; revision of GW schemes, reasonable MF and tides (more work is needed)…
- **New topic:** how to assimilate MARS data (**ozone, temp. and winds**) and constrain fast-varying waves with efficient adaptation of ADA of NWP centers.
- **Information on model biases**: GW-schemes, diffusion operators, and energy conservation in Physics of WACCM.
- **First WACCM-X/TIME-GCM** *one-way ionosphere-atmosphere coupling during latest warming events (2006, 2009, 2012).*