Assimilation in the upper stratosphere and mesosphere: role of radiances

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High-Altitude Data Assimilation for NWP

Objective:

Improve the Navy's Numerical Weather Prediction (NWP) skill from surface to near-space by developing stratosphere and mesosphere assimilation capabilities for the Navy's new assimilation system, NAVDAS-AR

Approach:

- Extend Navy's new assimilation system, NAVDAS-AR, to 90 km altitude.
- Add middle atmosphere data from new operational and research satellite sensors such as SSMIS, SABER and MLS.

Payoff:

- Stratospheric and mesospheric wind & temperature analysis for middle atmosphere research.
- Improved long-range weather forecasting.
- Middle atmosphere weather forecasting for DoD systems

Outline

- Brief introduction to NAVGEM/NAVDAS-AR System
- Use of Microwave (MW) Sounders in Mesosphere
  - Zeeman Effect
  - Earth Geomagnetic Field
    - Strength
    - Angle Between Antenna Boresight and Geomagnetic Field
  - SSMIS Upper Atmosphere Sounder (UAS) Unified Pre-Processor (UPP)
  - Zeeman included in CRTM version 2.x forward, and RTTOV version 10 forward
  - Doppler shift of SSMIS UAS center frequency
- Experiments with Prototype Model and Sensors
  - Model top 0.005 hPa with 60-levels, horizontal ~0.75-degrees
  - Assimilation trials: SSMIS-UAS (all channels), Microwave Limb Sounder (MLS), SABER
- Experiments with Forthcoming Operational Model and Appropriate Sensors
  - Model top 0.04 hPa with 60-levels, horizontal (~0.28-degrees; ~31.25km)
  - SSMIS-UAS (assimilate 4 of 6 channels)

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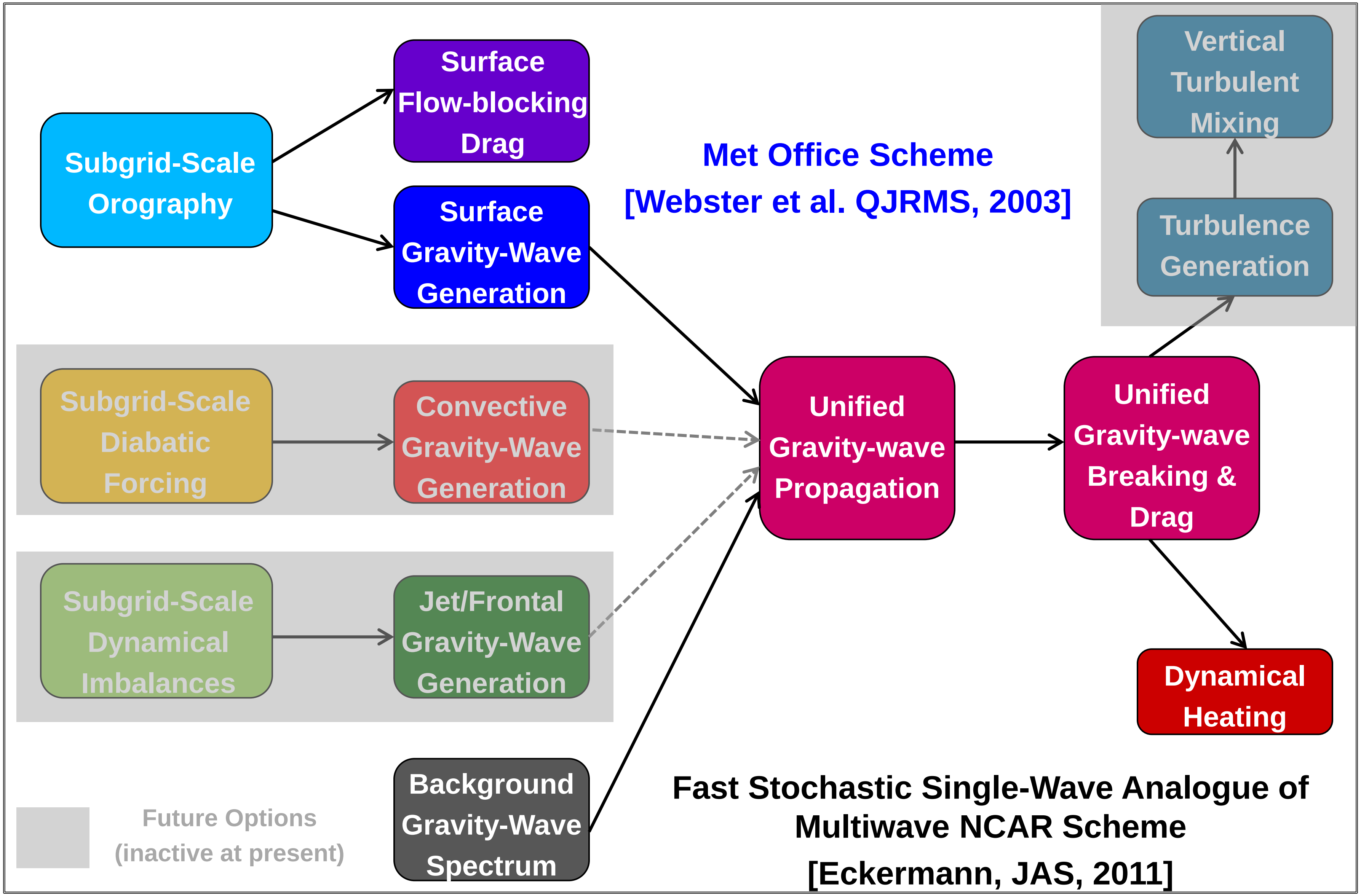
Recent Advances in NAVGEM/NAVDAS-AR NWP System

- NAVGEM semi-Lagrangian forecast model high-altitude physics:
  - Non-orographic gravity wave drag
  - Linearized Water vapor photochemistry
  - Linearized Ozone photochemistry
  - Radiative transfer model, RRTMG
    - Only valid up to approximately 0.1hPa (65km)
    - Components missing for the middle atmosphere
      - SW O_2 heating terms, exothermic chemical heating, non-LTE CO_2 cooling, near IR heating
  - Hybrid-sigma vertical coordinate grid
- Recent modifications to NAVDAS-AR 4D-Var assimilation system
  - IASI water vapour, ATMS, GNSS-RO tropospheric error reduction
  - Tracer (variable number) assimilation added – tested with Ozone
  - MLS and SABER data assimilation added
  - Water vapor hybrid-pseudo relative humidity control variable developed to improve stratospheric water assimilation
  - SSMIS-UAS assimilation added

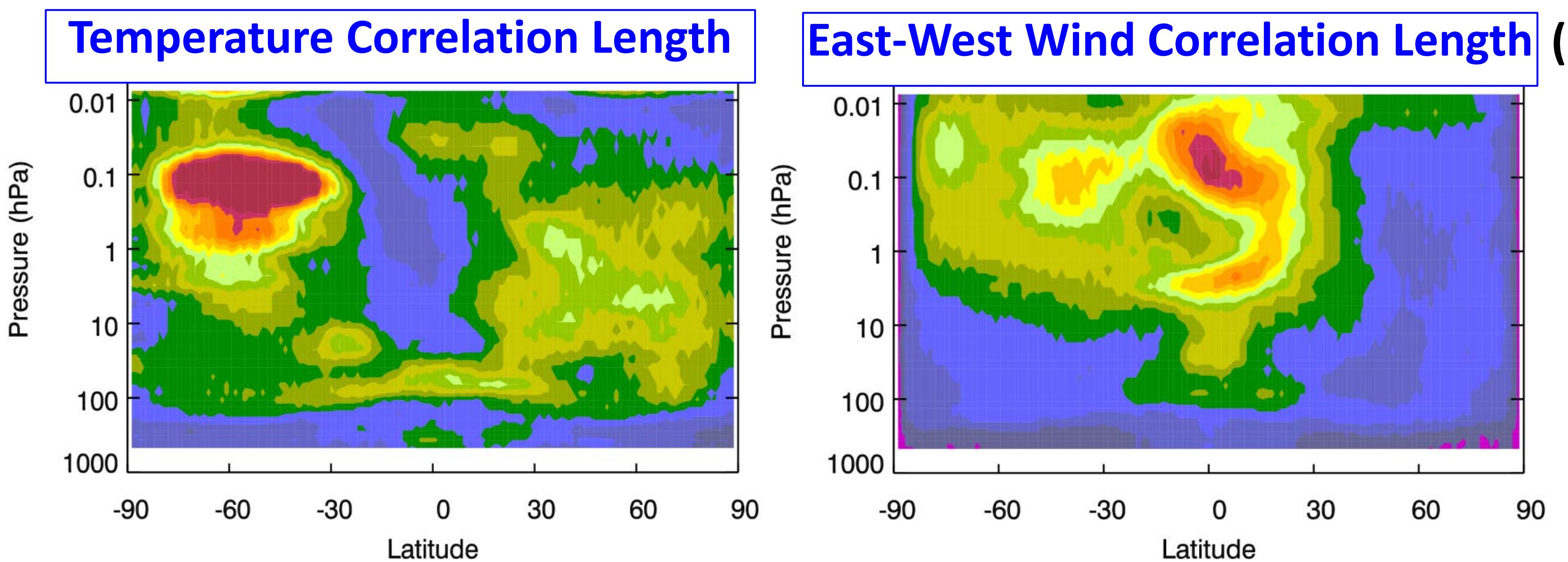
High-Altitude Data Assimilation for NWP:
NAVGEM Gravity-Wave Drag Parameterization

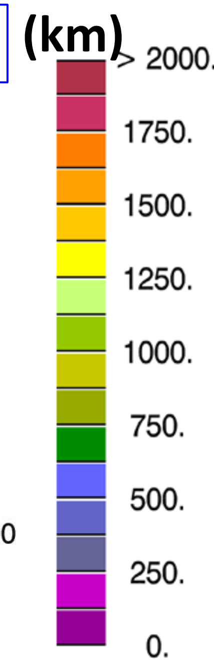


Revising Mesospheric Background Errors

Assigning a forecast error covariance is a key part of a data assimilation algorithm. We have been exploring the covariance at high altitudes in order to design improvements to the operational model which was developed primarily for the troposphere.

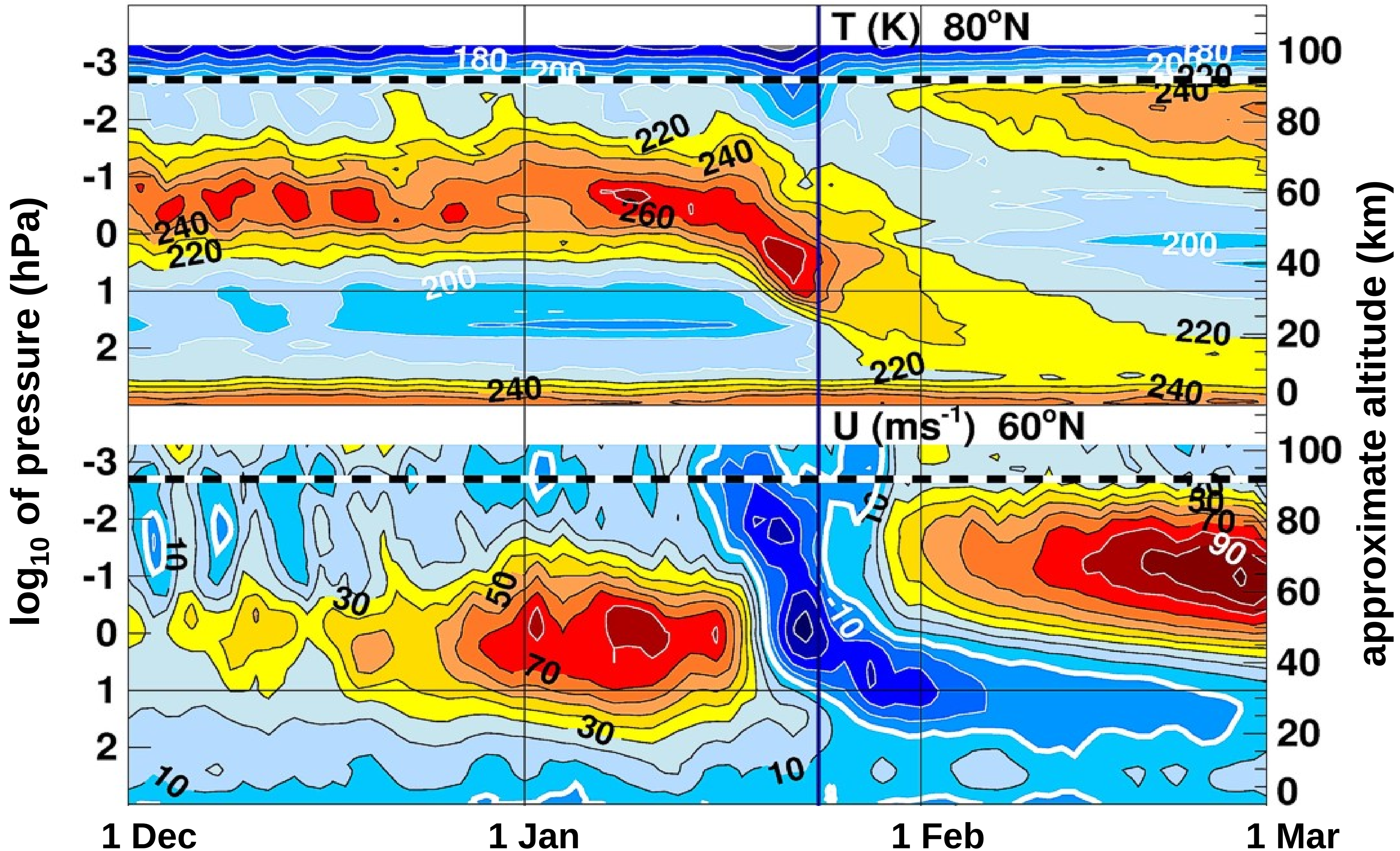
- **Below are new calculations of the horizontal correlation length.**
- **Above the tropopause (above 100 hPa), length scales are larger and more variable.**
- **Operational covariance needs to be upgraded to reflect true correlations.**





Calculated from a set of 24 & 48 hour forecasts during Nov-Dec 2011

Descending NAM Anomalies During January 2009



[Coy et al., *JAMES* 2011]

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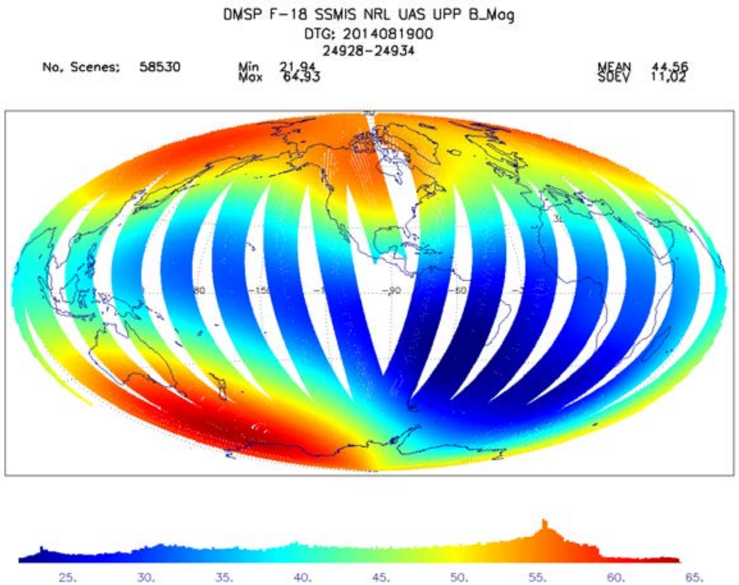
Zeeman Effect

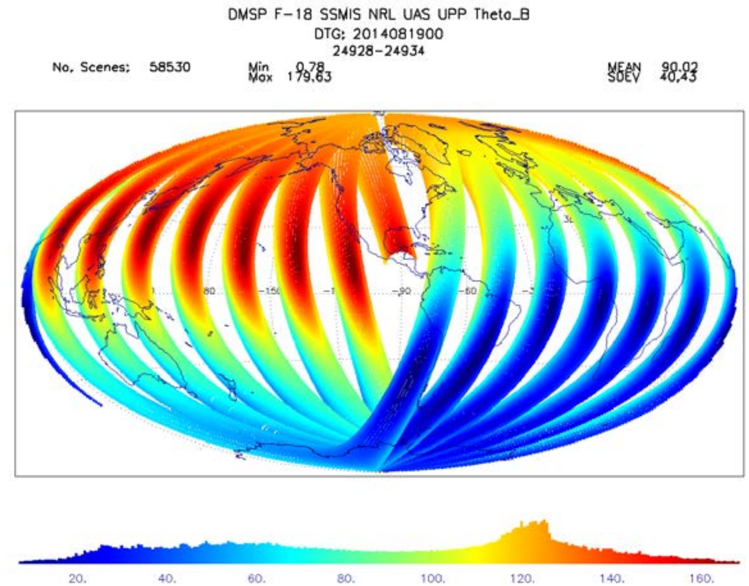
- **Microwave (MW) sounders which use narrow spectral bands near the O_2 magnetic dipole transitions (60GHz) must account for Zeeman splitting of the absorption lines by the Earth's magnetic field.**

- **Required information to include this effect in a fast radiative transfer model are the Earth's Geomagnetic Field strength (|B|) and the angle (Θ_B) between antenna boresight and the vector of the geomagnetic field.**

|B| - Magnetic Field Strength (µT)



Θ_B- Angle between antenna view and magnetic field (degrees)



SSMIS UAS UPP

- Co-developed by NRL and the MetOffice (UK). An extension of the SSMIS-UPP which is used for the lower atmospheric channels (LAS).
- Processes channels SSMIS 19-24 with a Gaussian averaging footprint of 75km.
- Includes estimates of |B|, Bx, By, Bz from the International Geomagnetic Reference Field (IGRF) model which has an estimated uncertainty 5%.
- UAS UPP computes propagation vector used to derive Θ_B

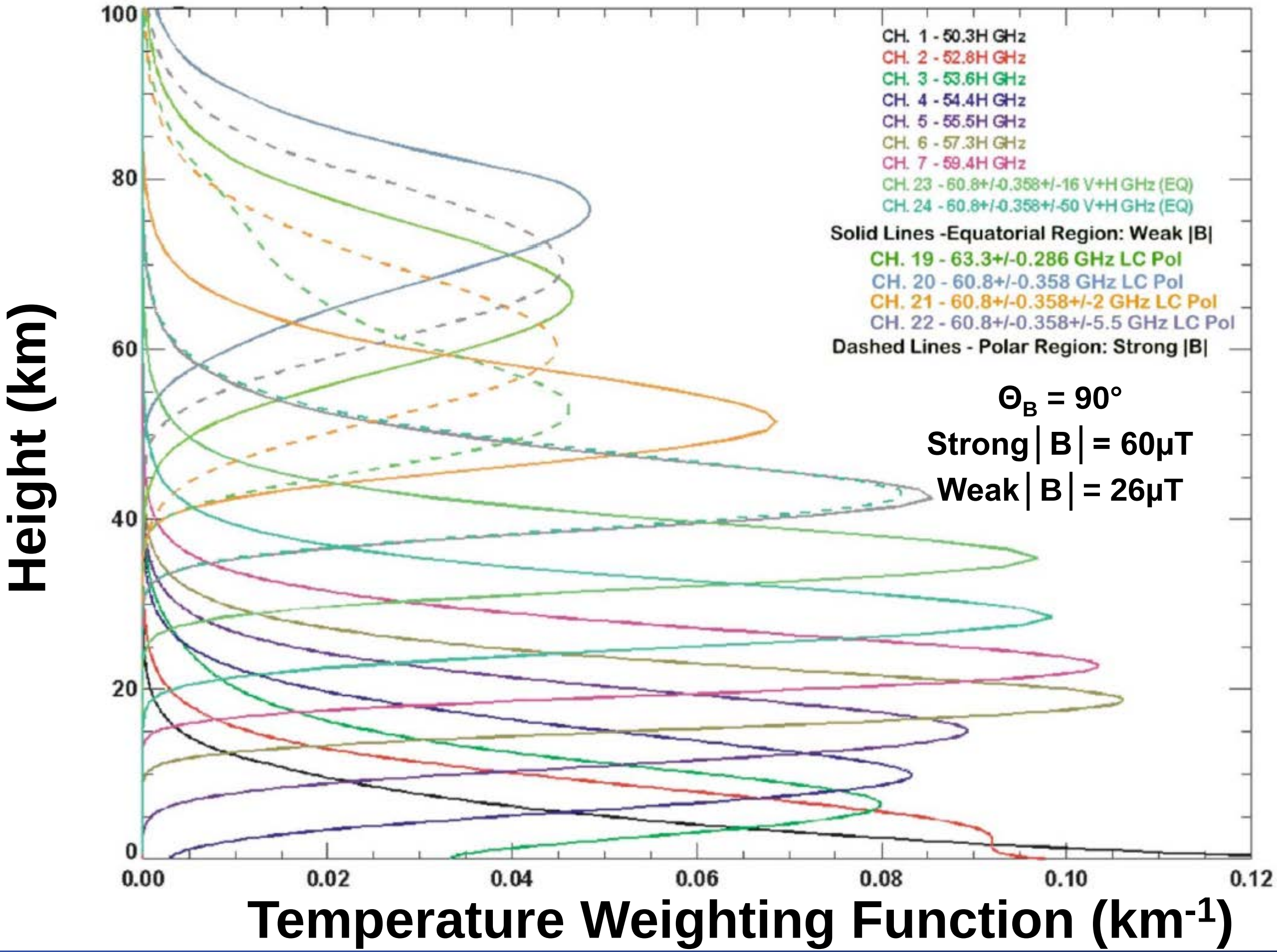
SSMIS UAS CHANNEL CHARACTERISTICS

SSMIS UAS Channel	Center Frequency (GHz)	3-db Width (MHz)	Frequency Stability (MHz)	NEΔT (K)	Sampling Interval (km)
19	63.283248 ±0.285271	1.35(2)	0.08	2.7	75
20	60.792668 ±0.357892	1.35(2)	0.08	2.7	75
21	60.792668 ±0.357892 ±0.002	1.3(4)	0.08	1.9	75
22	60.792668 ±0.357892 ±0.0055	2.6(4)	0.12	1.3	75
23	60.792668 ±0.357892 ±0.016	7.35(4)	0.34	0.8	75
24	60.792668 ±0.357892 ±0.050	26.5(4)	0.84	0.9	37.5

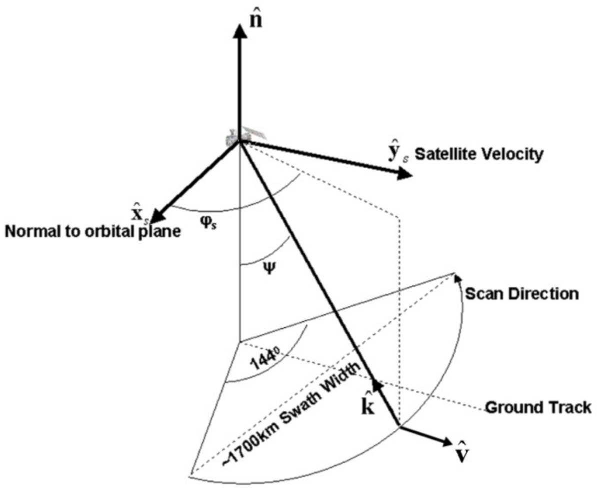
Notes:
1. Sampling interval refers to along scan direction based on 833 km spacecraft altitude.
2. NEΔT for instrument temperature 273.15 K and calibration target 260 K with integration times 12.6 msec for channel 24 and 25.2 msec for channels 19-23.
3. Number of symmetric passbands is indicated by (n) next to individual 3-db width.
4. All SSMIS UAS channels are Circular Polarized.

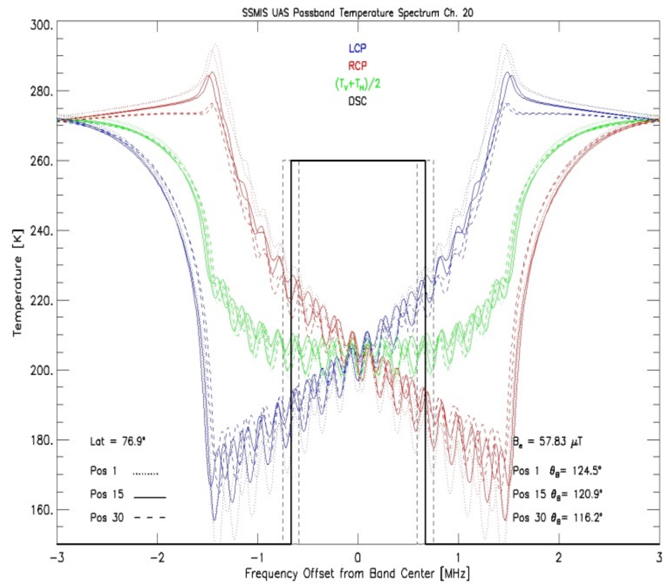
CRTM Zeeman

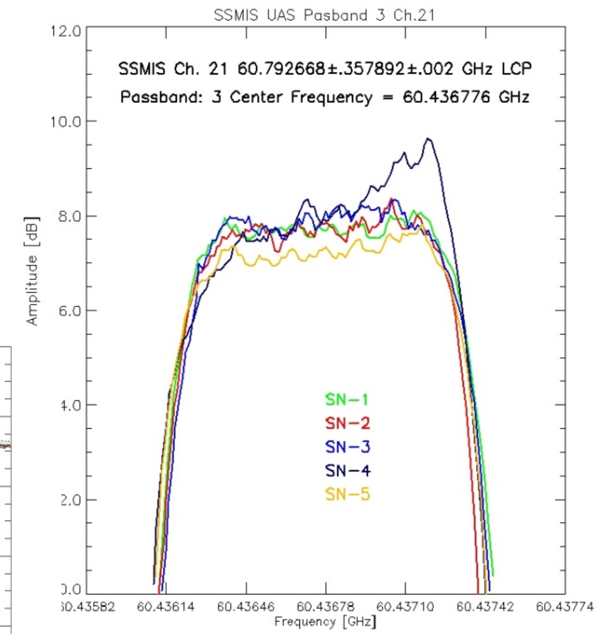
- **Verified against NRL MW line-by-line model which includes the Zeeman Propagation Model (ZPM) [Liebe and Hufford, 1989; and Liebe et al., 1993] and was tested with the MAS payload on the NASA space shuttle ATLAS missions.**



SSMIS UAS Doppler Shift







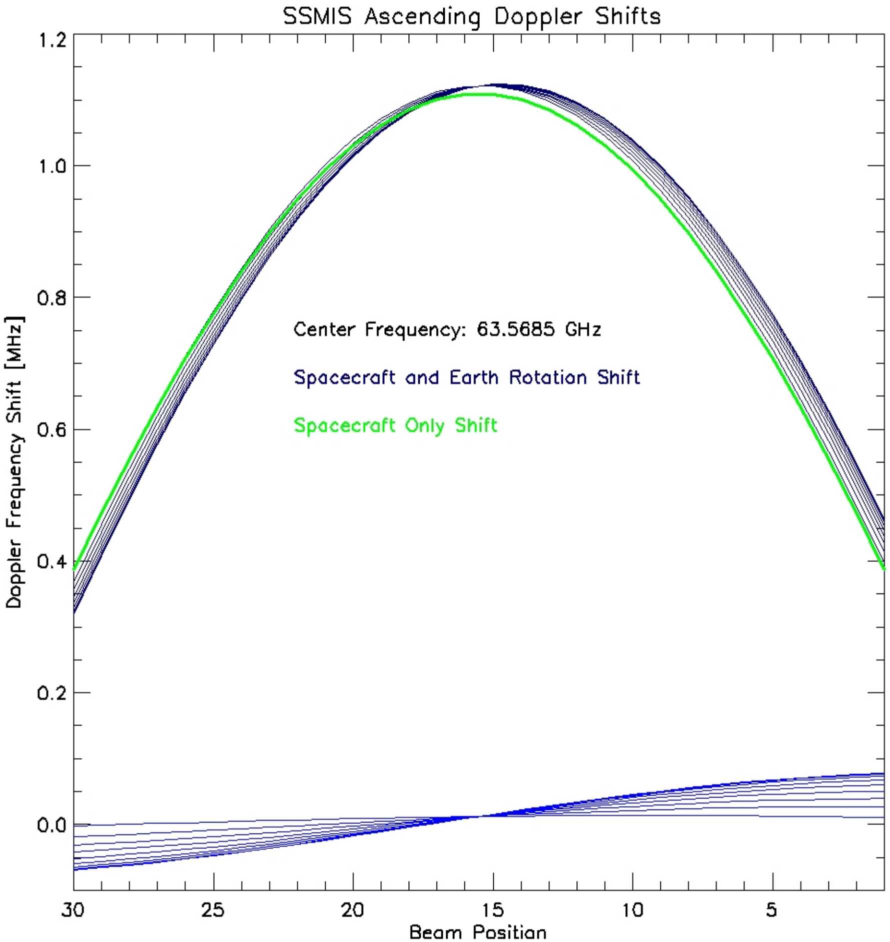
$$\Delta f_{Total} = \Delta f_{s/c} + \Delta f_{erot} = \left(\frac{f_0 \overline{v}_{s/c}}{c}\right)\sin\psi \sin\varphi_s + \frac{f_0}{c}\Omega R_{sat}\sin\psi\left[\sin\varphi_s \cos i_{orb} \mp \cos\varphi\sqrt{\sin^2 i_{orb} + \sin^2\lambda}\right]$$

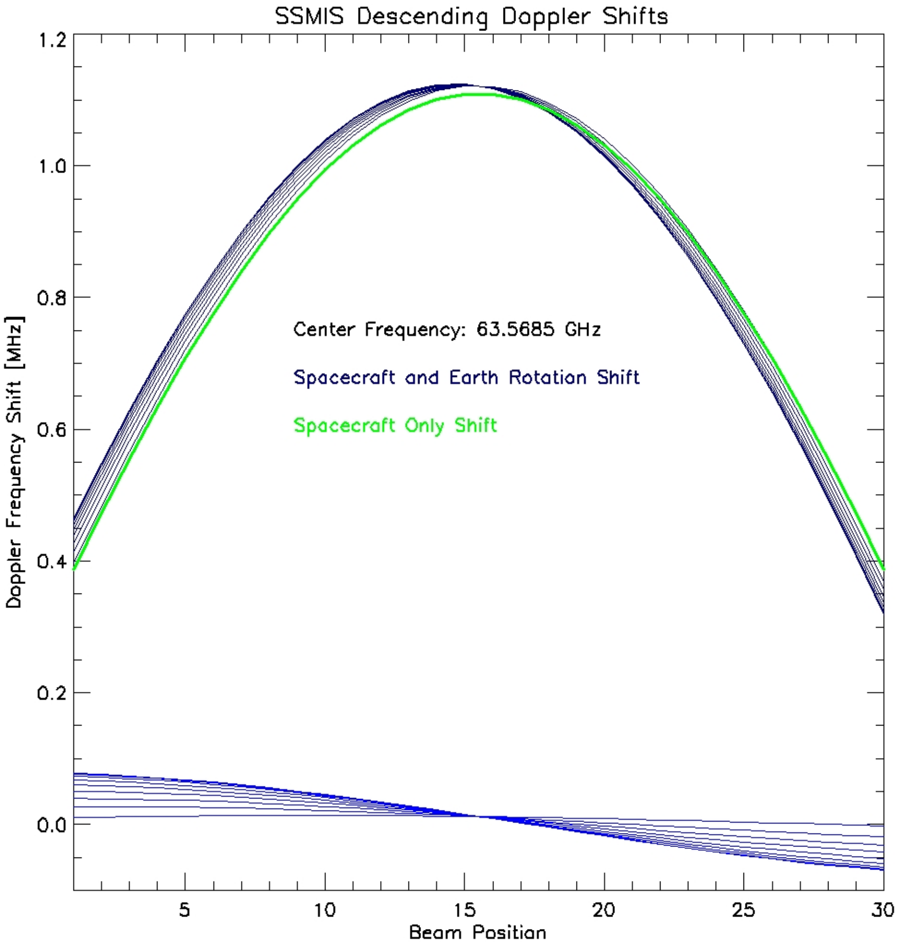
$\Delta f_{s/c}$ compensated for in software on spacecraft

Δf_{erot} compensated for in radiative transfer

SSMIS UAS Doppler Shift

$$\Delta f_{Total} = \Delta f_{s/c} + \Delta f_{erot} = \left(\frac{f_0 \overline{v}_{s/c}}{c}\right) \sin\psi \sin\varphi_s + \frac{f_0}{c} \Omega R_{sat} \sin\psi \left[\sin\varphi_s \cos i_{orb} \mp \cos\varphi \sqrt{\sin^2 i_{orb} + \sin^2 \lambda}\right]$$





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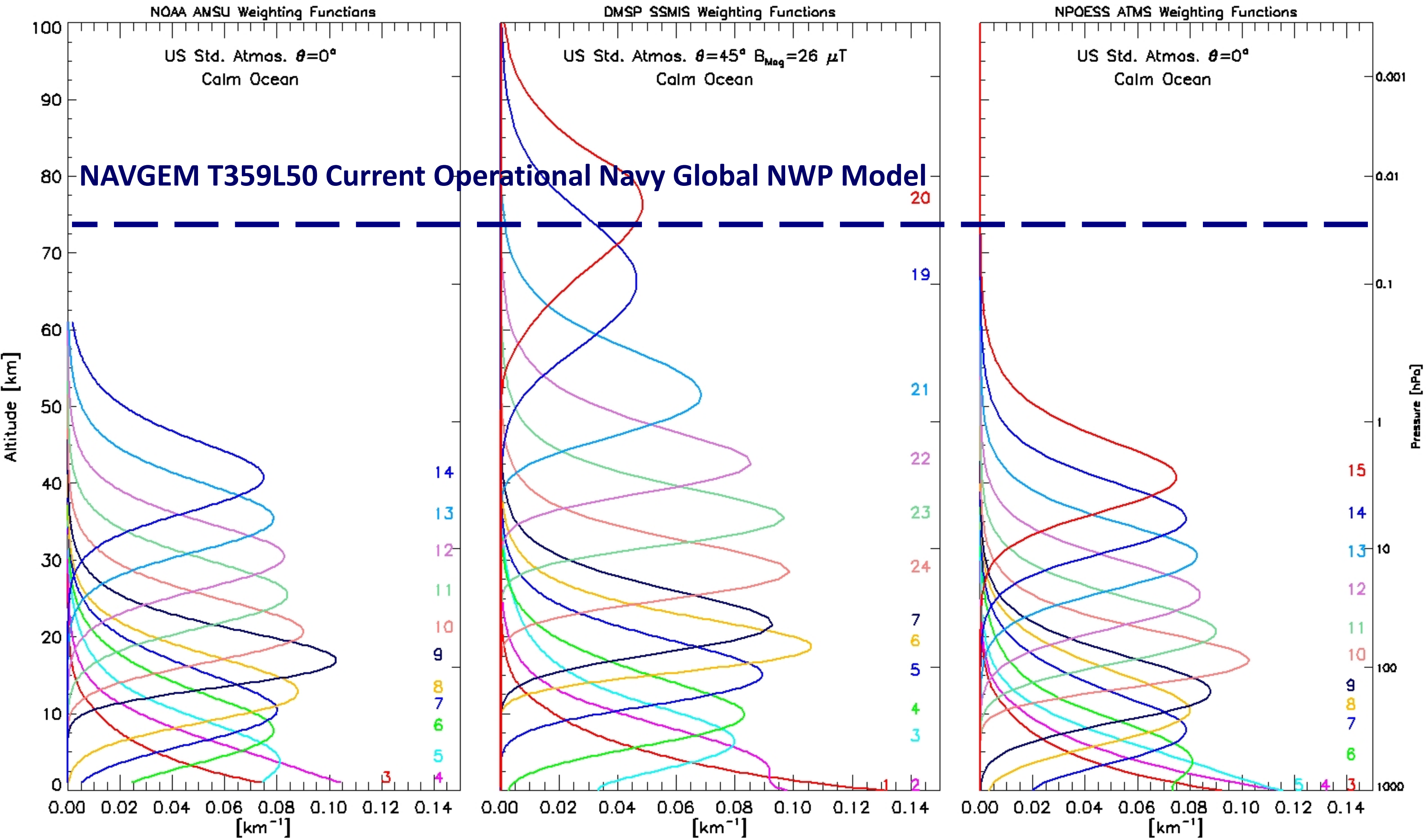
Currently SSMIS-UAS are the only radiances sensitive at altitudes from 60-100km

Swadley, S., G. Poe, W. Bell, Y. Hong, D. B. Kunkee, I. S. McDermid, and T. Leblanc, 2008. Analysis and Characterization of the SSMIS Upper Atmosphere Sounding Channel Measurements. *IEEE Trans. Geosci. Remote Sens.*, **46** (4), pp. 962-983, doi:10.1109/TGRS.2008.916980.

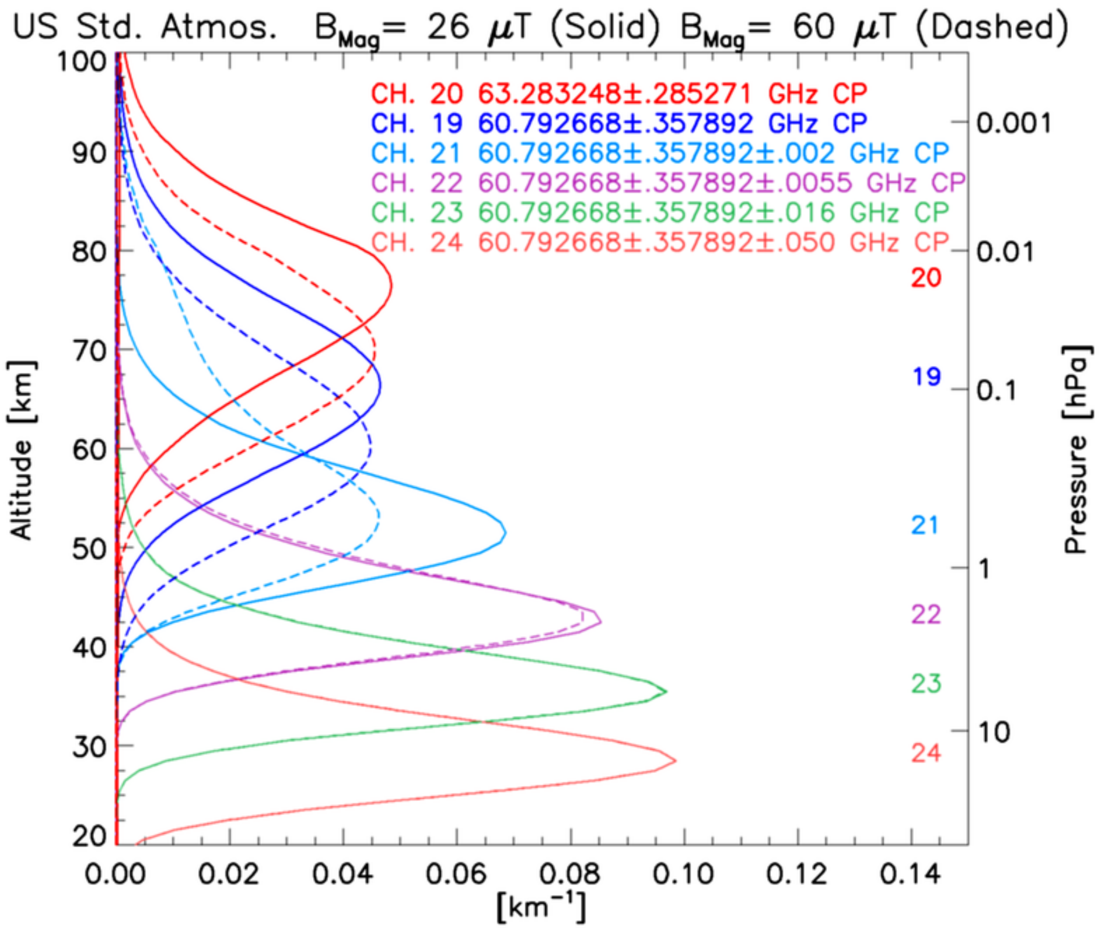
Karl W. Hoppel, Stephen D. Eckermann, Lawrence Coy, Gerald E. Nedoluha, Douglas R. Allen, Steven D. Swadley, and Nancy L. Baker, 2013. Evaluation of SSMIS Upper Atmosphere Sounding Channels for High-Altitude Data Assimilation. *Monthly Weather Review*, **141**, 2013. DOI: 10.1175/MWR-D-13-00003.1

Han, Y., P. van Delst, and F. Weng, 2010. An improved fast radiative transfer model for special sensor microwave imager/sounder upper atmosphere sounding channels. *J. Geophys. Res.*, **115**, D15109, doi:10.1029/2010JD013878.

SSMIS Upper Atmosphere Sounding Radiances



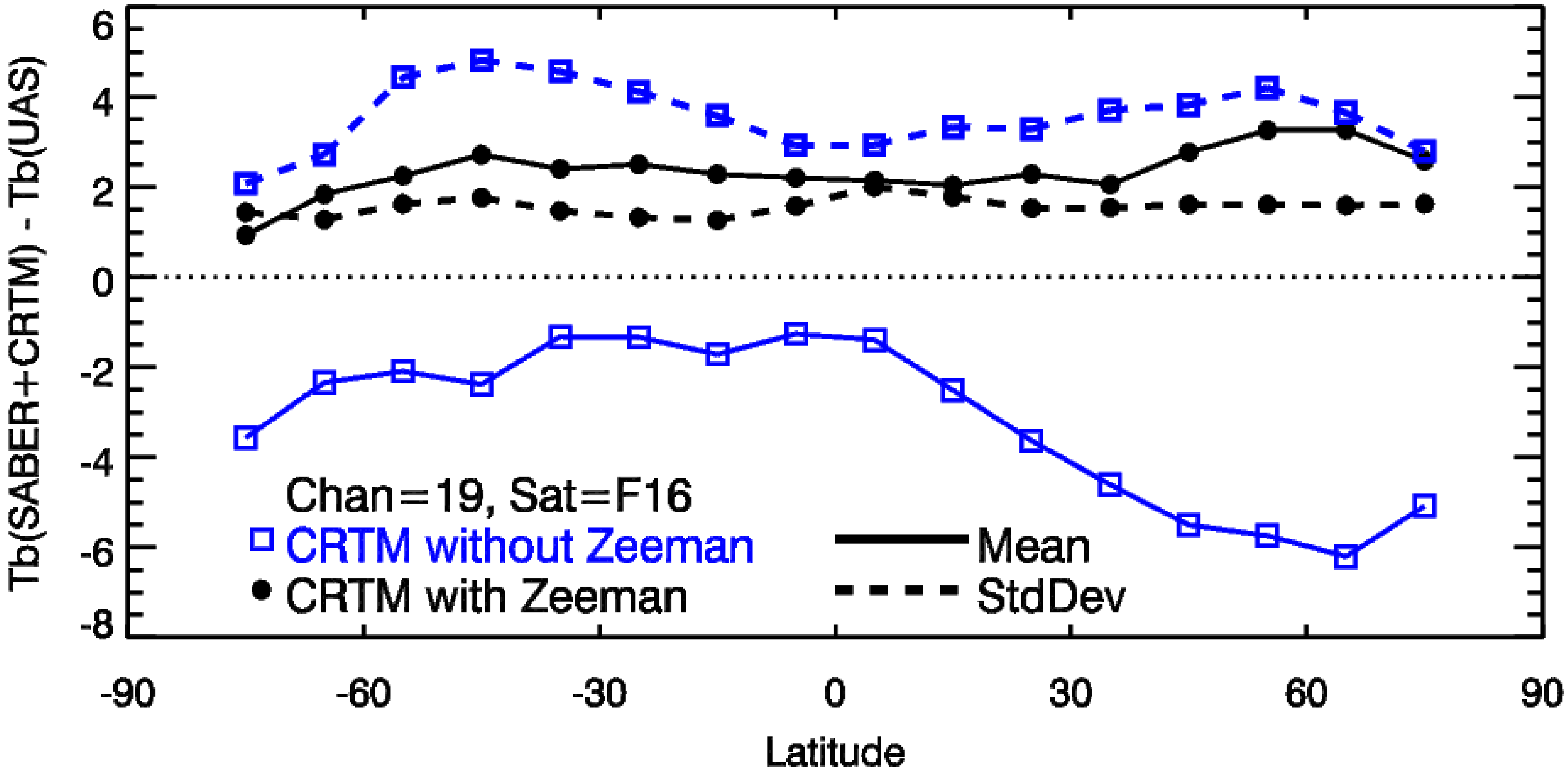
SSMIS UAS channels w/ Zeeman effects: 19, 20, 21



SSMIS weighting functions for a weak geomagnetic field (26 μT) typical of equatorial regions (solid curves) and for a strong magnetic field (60 μT) typical of polar regions (dashed curves).

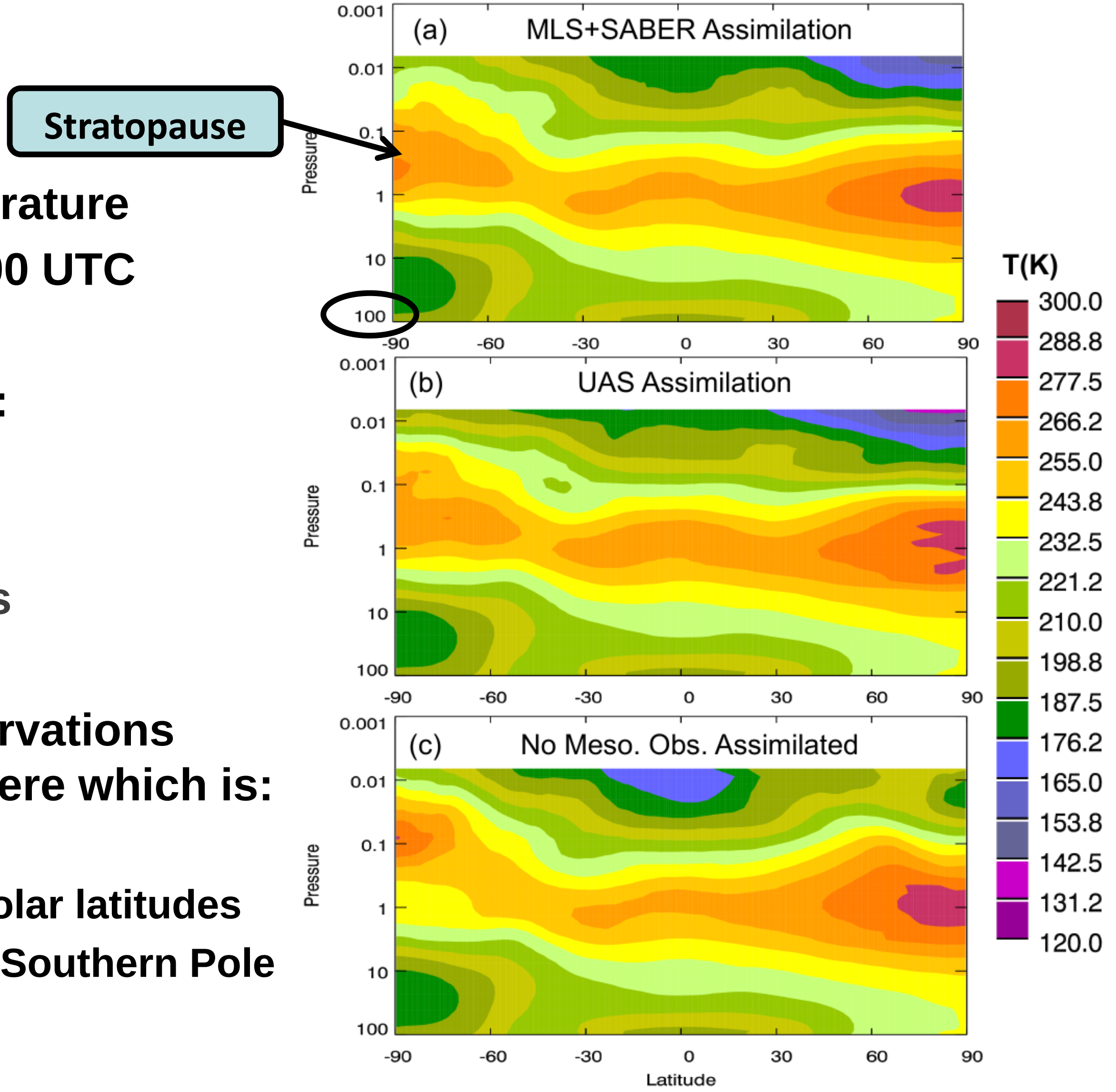
The weighting functions are sensitive to both the field strength and orientation of the field with respect to the SSMIS viewing direction.

Importance of the Zeeman Calculation



- Mean & standard deviations between UAS ch 19 Tb and SABER/CRTM simulated Tb
- Results are shown with (black) and without (blue) the CRTM Zeeman correction turned on.
- ~35000 coincident measurements from 15th day of Apr 2010 - Mar 2011 are included.

4 Mesospheric Assimilation Experiments (3 shown)



Zonal mean temperature
14 July 2010 at 1200 UTC

Experiments:

(a) MLS+SABER,

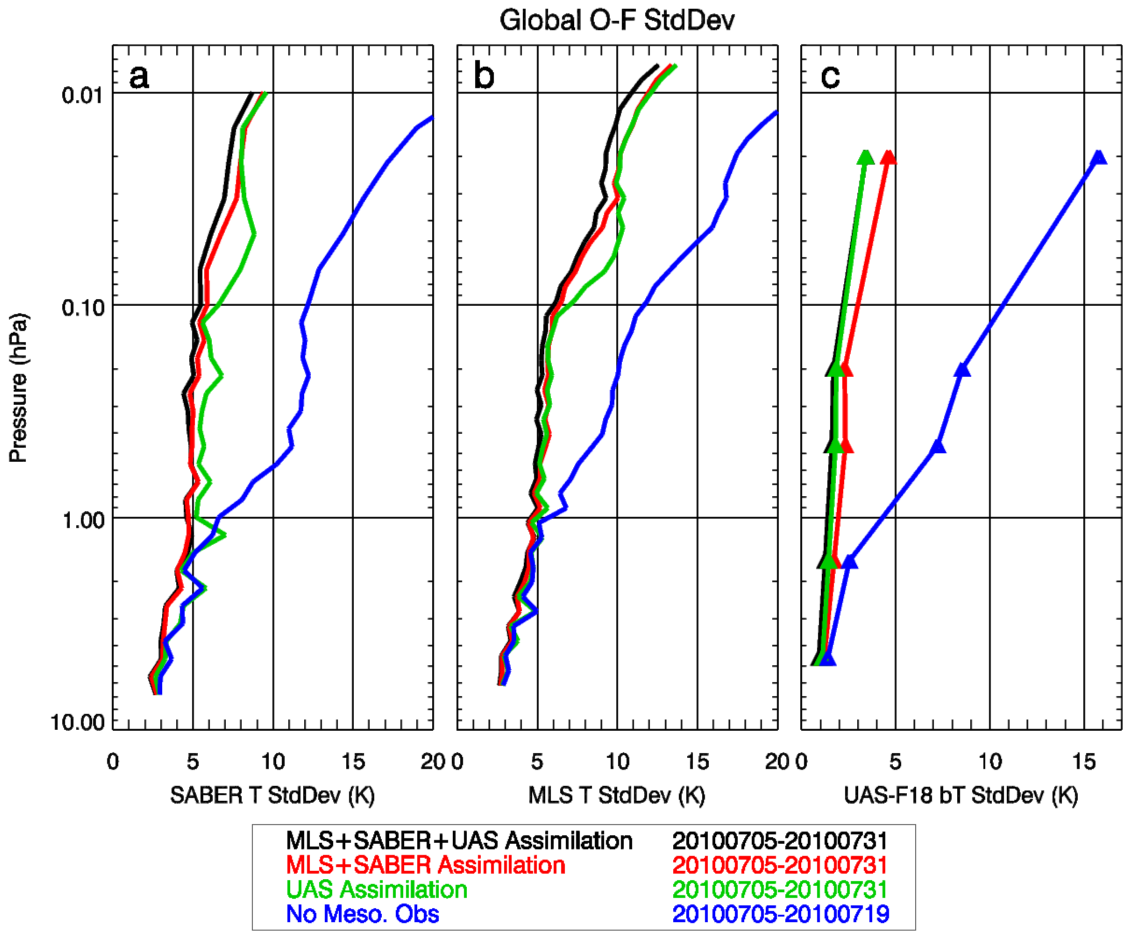
(b) UAS

(c) No Mesopheric Obs

Lack of mesospheric observations results include a mesosphere which is:

- **too cool at Equator**
- **too warm at Northern Polar latitudes**
- **stratopause too high at Southern Pole**

First-guess Departures for experiments



Standard deviation of the global first-guess departures (O-F) for:

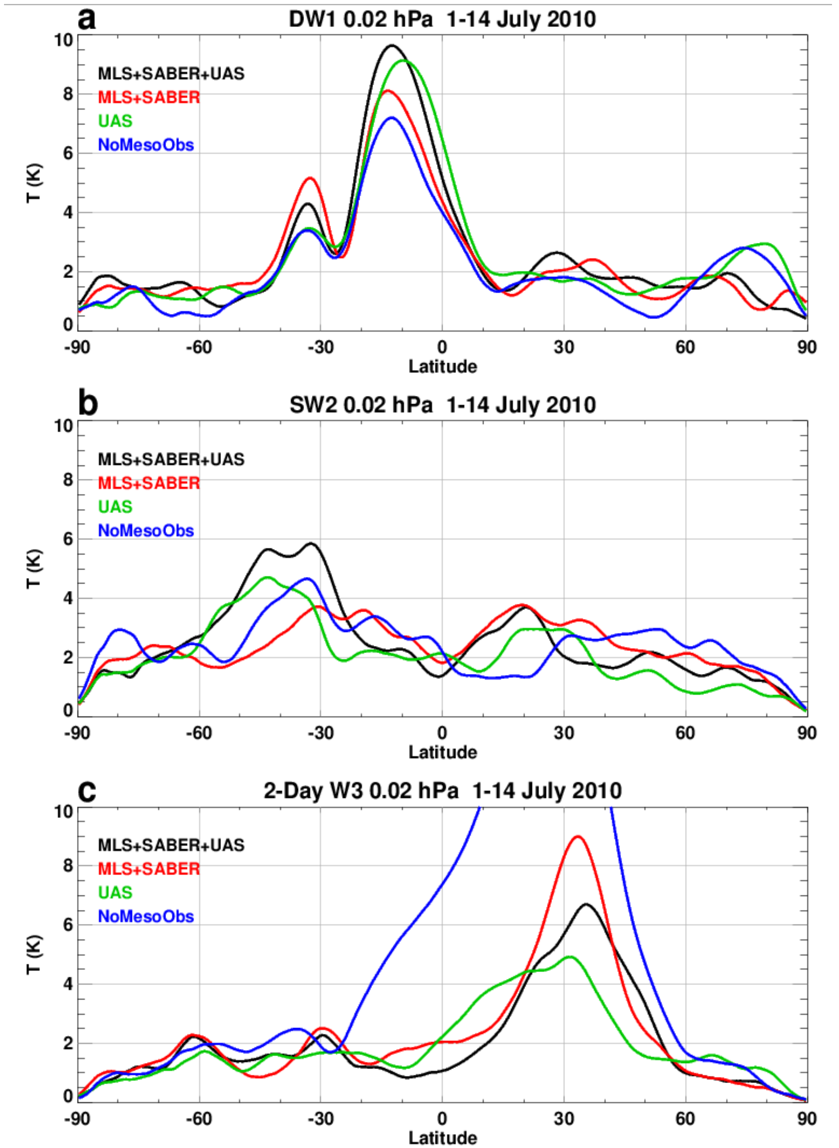
(a) MLS temperature, (b) SABER temperature, and (c) F18 UAS brightness temperature, averaged over 5-31 July 2010 for experiments:

MLS+SABER+UAS (black), MLS+SABER (red), and UAS (green).

3 Waves: Diurnal tide, Semi-Diurnal tide, 2-day wave

Peak temperature amplitude
0.02 hPa (~76 km)
01-14 July 2010

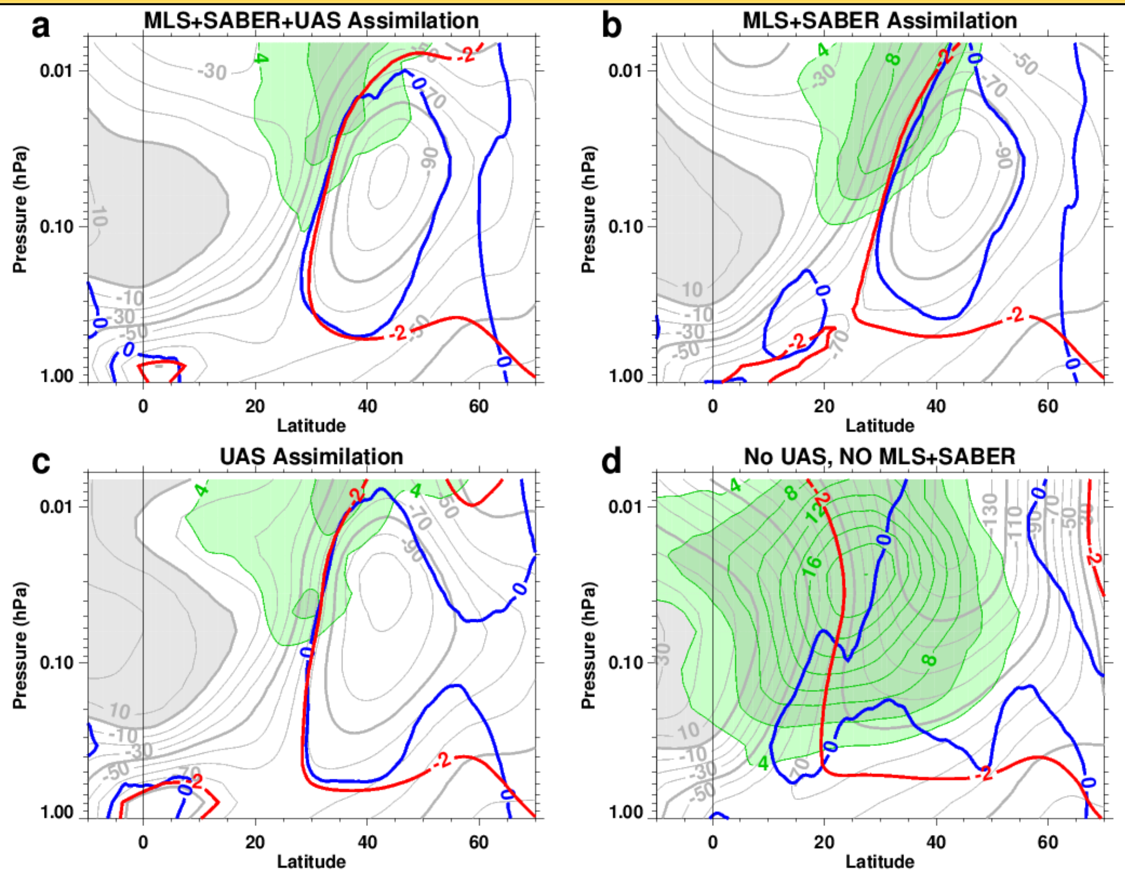
(a) DW1 (diurnal migrating tide)
(b) SW2 (semidiurnal migrating tide)
(c) Q2DW3 (quasi-2-day wave)



Experiments:
MLS+SABER+UAS
MLS+SABER
UAS
NoMesoObs

Latitudinal mean for each model level, apply 2D-FFT to these longitude-time arrays.

Zonal wind & temperature structure



Zonal mean cross-sections during 1-14 July 2010 of:

- Zonal(U) wind; 10 m s-1 contour interval, positive (eastward) values are gray shaded
- Q2DW3 temperature amplitudes; green shading, contour interval 2K, minimum contour 4K
- Zero contour of meridional gradient of the quasi-geostrophic potential vorticity
- 2-day wavenumber 3 critical line

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  - **SSMIS-UAS (assimilate 4 of 6 channels)**

SSMIS-UAS Experiment in Current NAVGEM

- NAVGEM v1.2.1
  - t359l50, top 0.04hPa
- NAVGEM v1.3 includes these features not in v1.2.1
  - Perturbation Virtual Potential Temperature ($p\theta_v$)
  - Non-orographic GWD
  - Water vapour photochemistry
  - t425l60, top 0.04hPa

Exp1 UAS: NAVGEM v1.3

- Use SSMIS-UAS (UAS). Channel 21 is the only additional channel assimilated (DMSP-F17, -F18)

Exp2: NAVGEM v1.3

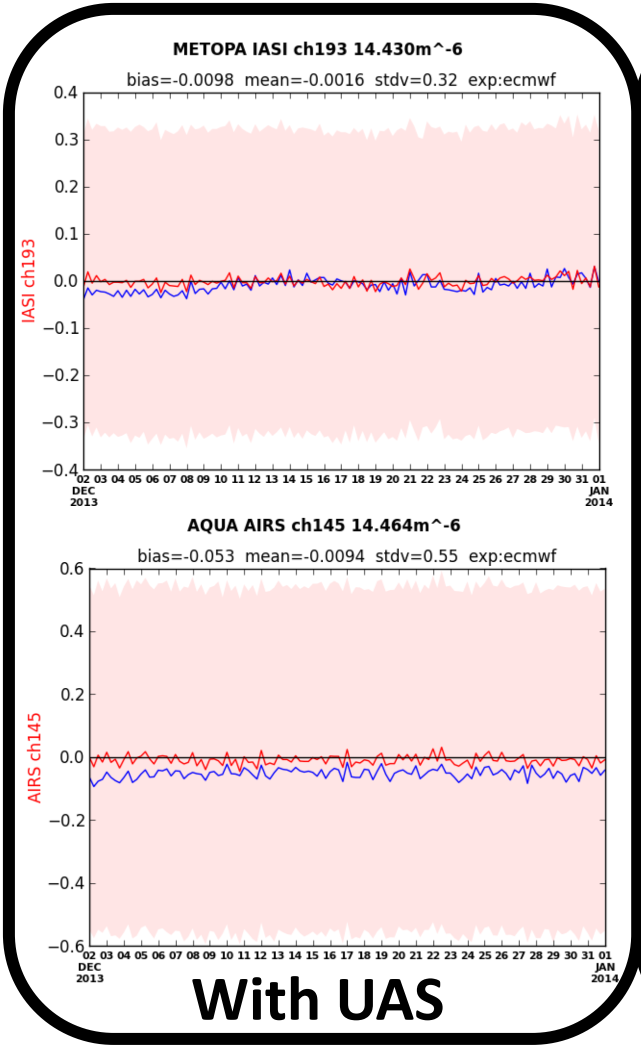
- No SSMIS-UAS (UAS)

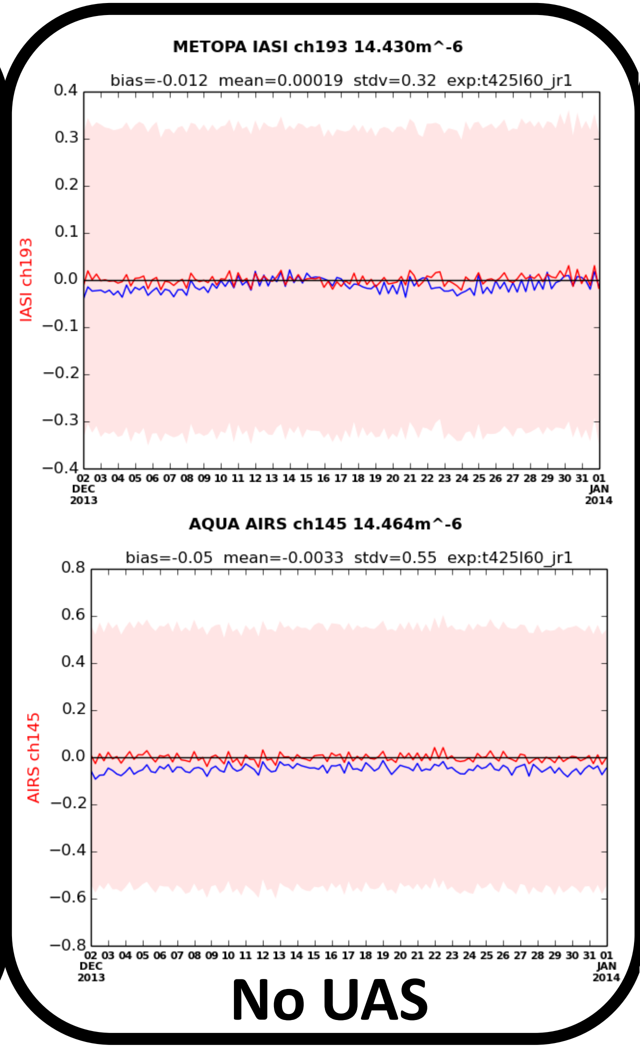
Exp3: NAVGEM v1.2.1

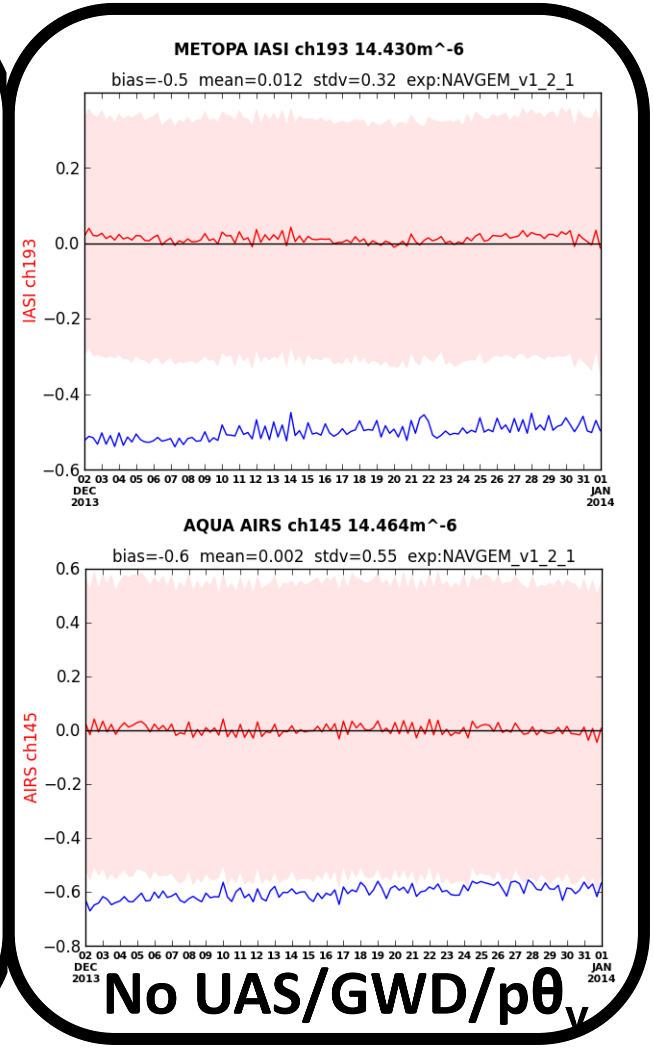
- No SSMIS-UAS (UAS)
- No non-orographic Gravity Wave Drag (GWD)
- No Perturbation Virtual Potential Temperature ($p\theta_v$)

Impacts on Other Assimilated Sensors

Infrared Radiances (~40km)



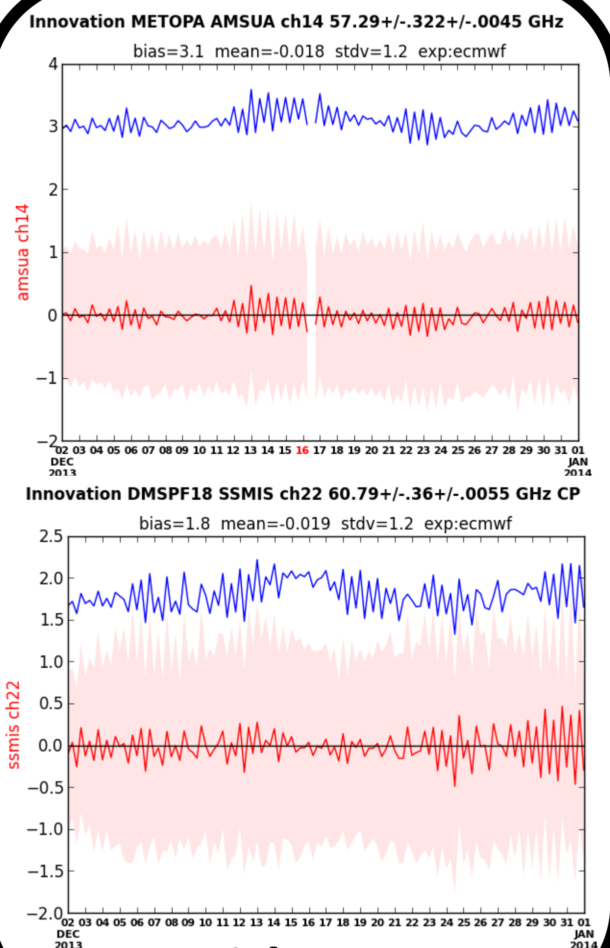




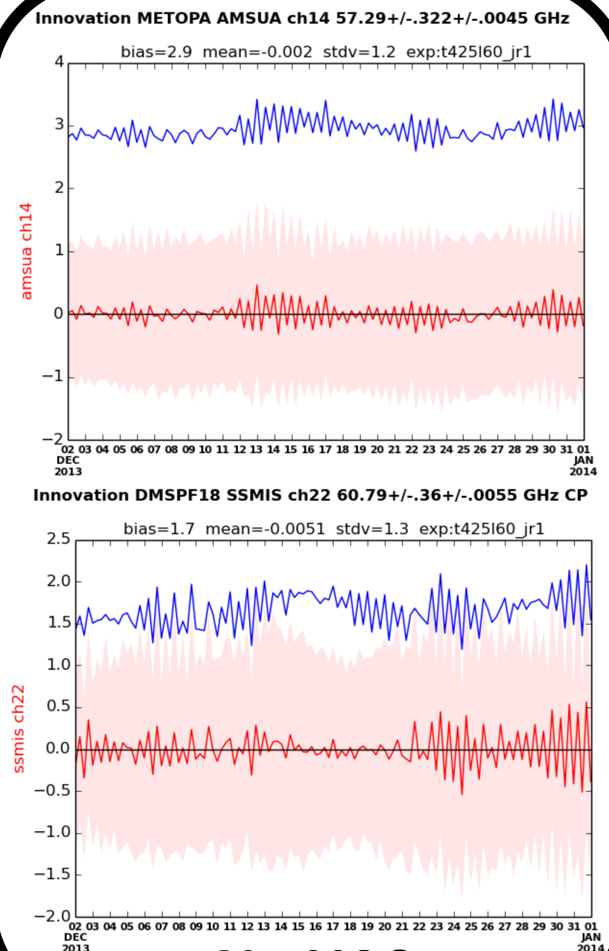
Both IASI and AIRS stratospheric channels show consistent improvement of fit after inclusion GWD and $p\theta_v$

Impacts on Other Assimilated Sensors

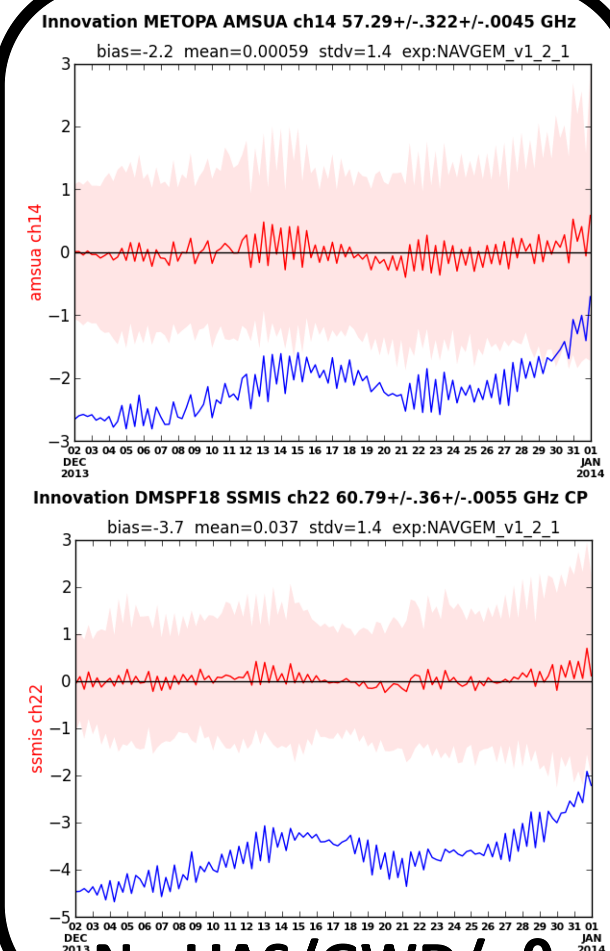
Microwave Radiances (~50km)



With UAS



No UAS

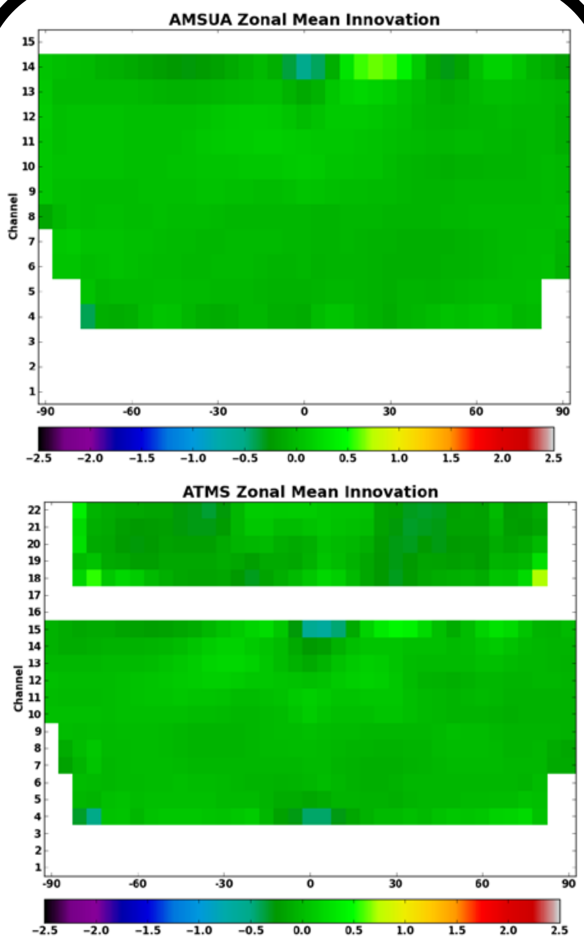


No UAS/GWD/pθ_v

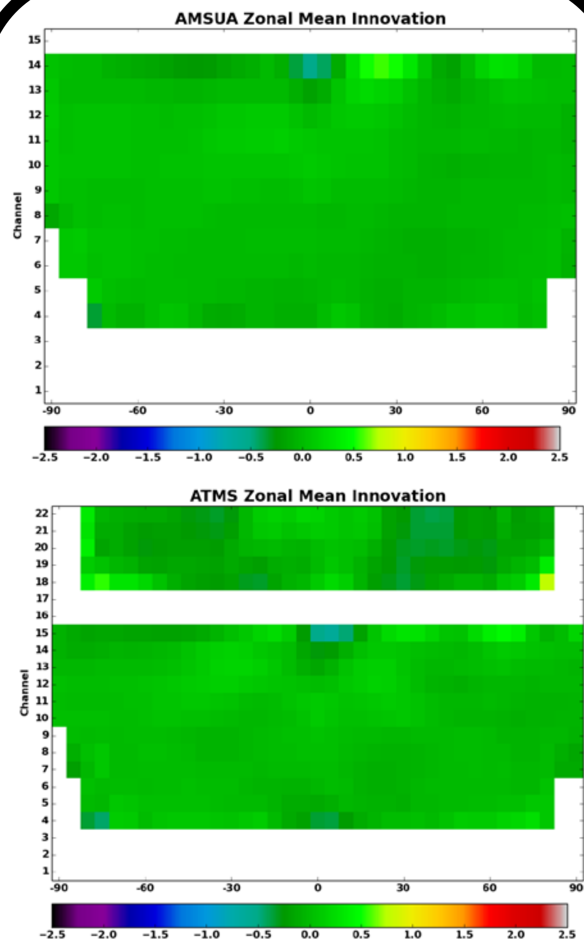
Both AMSU-A and SSMIS stratospheric channels show consistent improvement of fit after inclusion GWD and pθ_v

Impacts on Other Assimilated Sensors

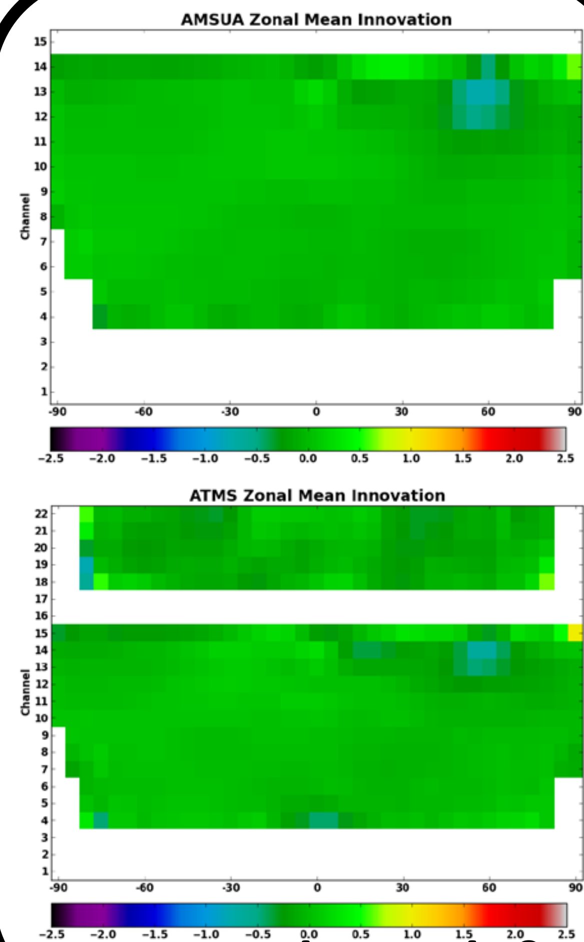
30-day Zonal Mean Innovation 02Dec2013-01Jan2014



With UAS



No UAS

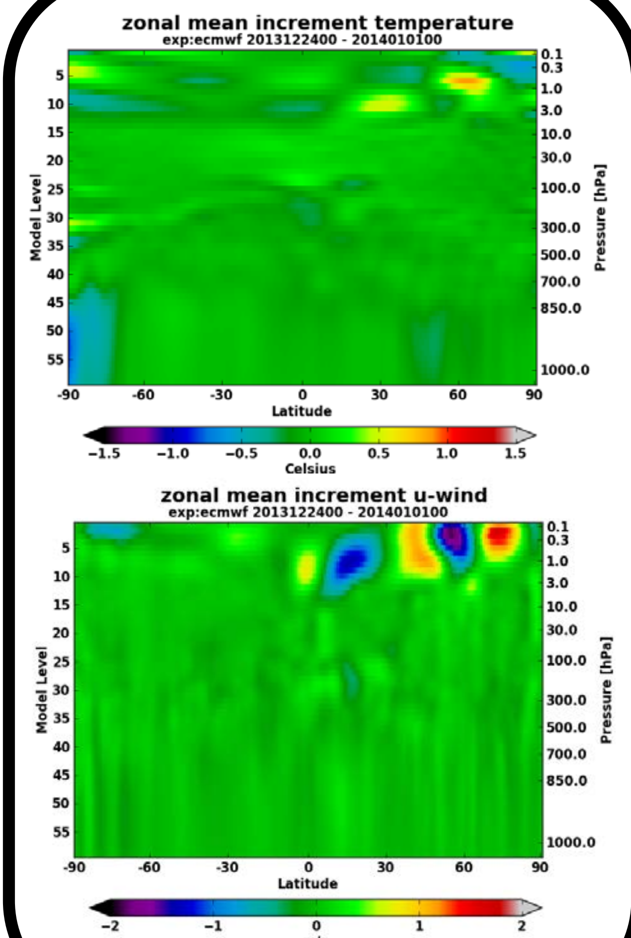


No UAS/GWD/$p\theta_v$

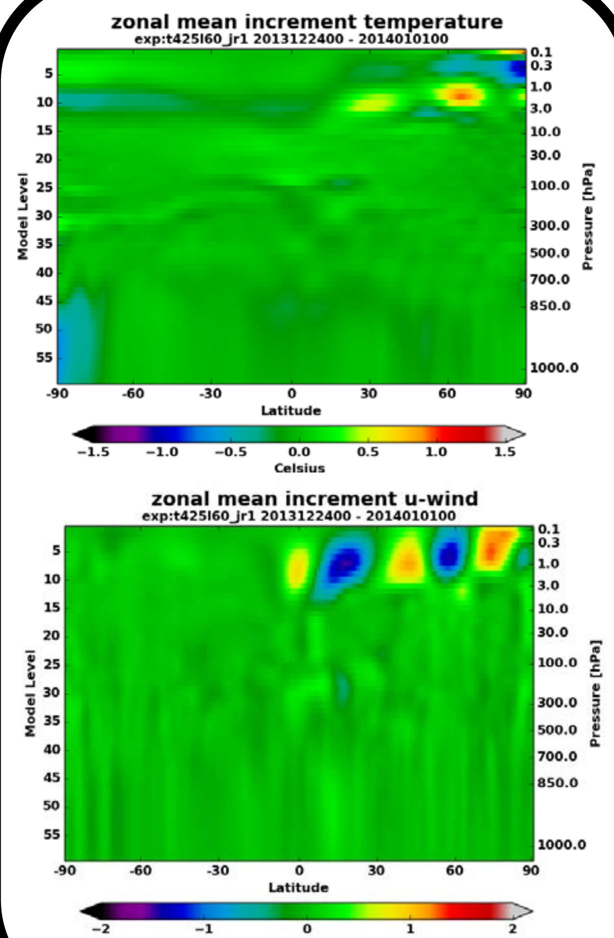
Including SSMIS-UAS shows little impact on first-guess departure for AMSU-A and ATMS channels (14 and 15); however, the inclusion of non-orographic GWD and perturbation-theta has an effect seen in the high latitudes of winter hemisphere (shown Dec2013).

Impacts on Increments from NAVDAS-AR

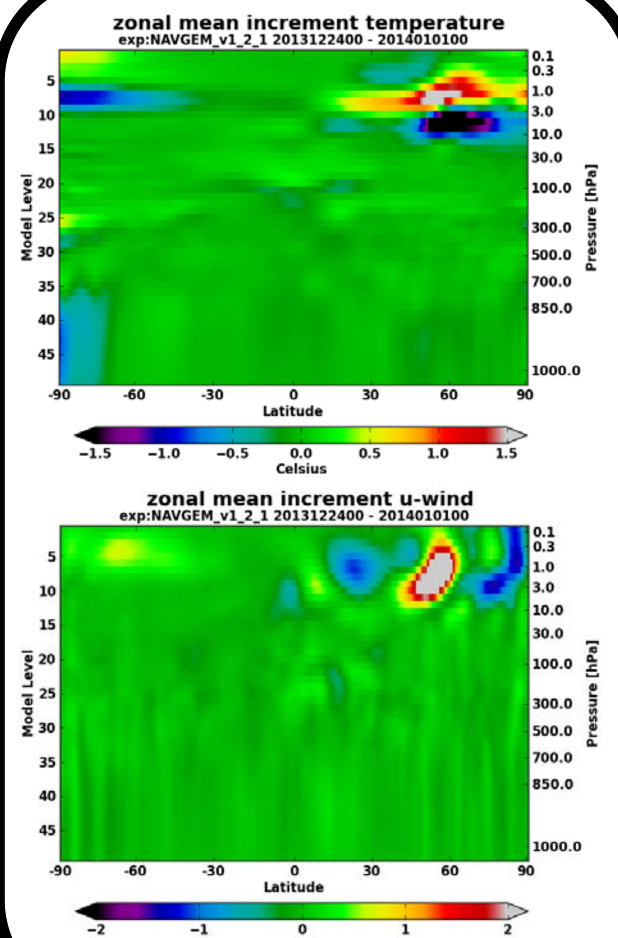
8-day Zonal Mean Innovation 24Dec2013-01Jan2014



With UAS



No UAS

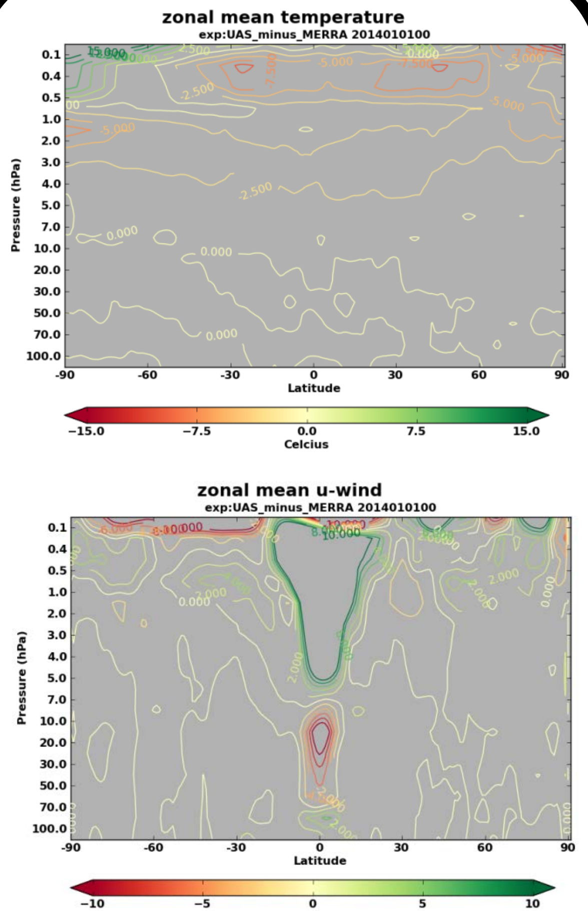


No UAS/GWD/pθ_v

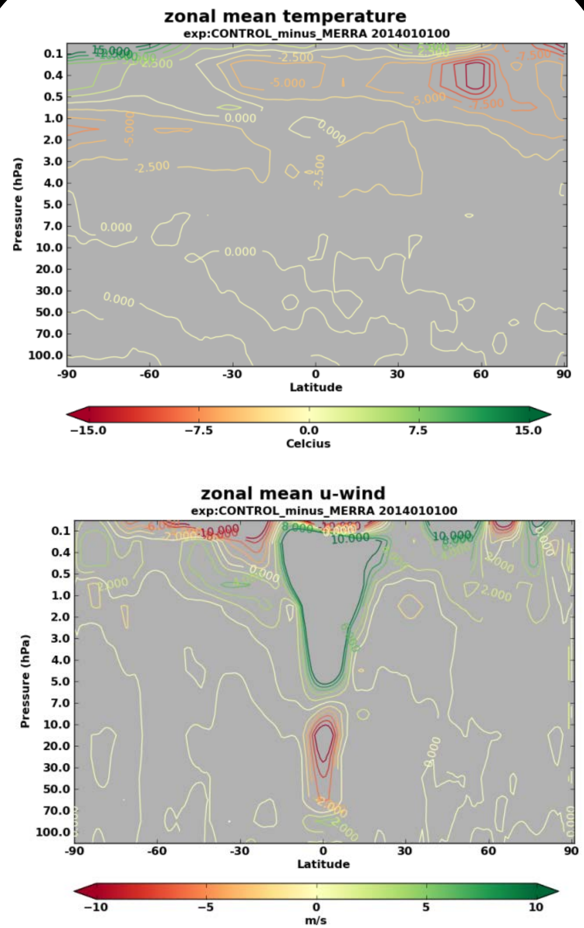
Largest difference is again between NAVGEM v1.2.1 and NAVGEM v1.3 (with GWD and θ_v). However, the structure of the temperature and wind increments begin to diverge above 1.0hPa with the inclusion of SSMIS ch21.

NAVGEM difference with MERRA reanalysis

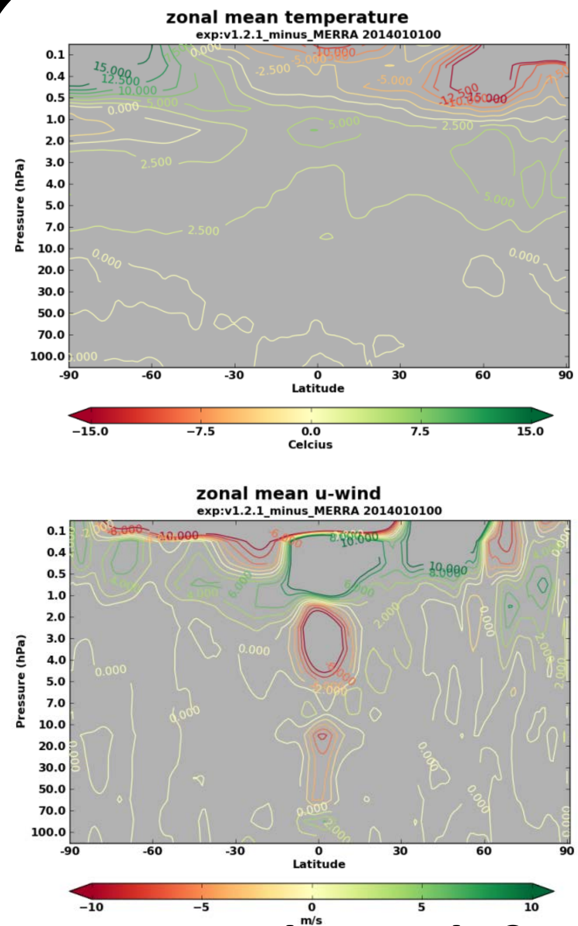
Comparison of Analyses from 00UTC on 01Jan2014



With UAS



No UAS



No UAS/GWD/pθ_v

Largest difference is again between NAVGEM v1.2.1 and NAVGEM v1.3 (with GWD and θ_v). However, there is a reduction in the temperature and wind differences with the reference analysis after the inclusion of SSMIS ch21.

Addition of SSMIS-UAS radiances

The Earth geo-magnetic field and direction vector are needed to create input needed for a Zeeman correction for SSMIS-UAS channels 19, 20, and 21. These are provided with SSMIS-UAS UPP.

Inclusion of SSMIS-UAS channels has a small impact on the fit of the model to other Infrared and Microwave radiances already assimilated in the stratosphere and lower mesosphere when there is an inclusion of a realistic GWD scheme.

Inclusions of the SSMIS-UAS channels somewhat reduces the temperature increment output by NAVDAS-AR. The new analysis appears to be giving a more consistent fit to an independent model re-analysis in the upper atmosphere.

Additional comparisons to reference analyses, as well as to passively monitored SABER and MLS can and should be performed.

A re-investigation of the correlation length scales of the temperature and wind is necessary. Hybrid-DA should help (blended static and ensemble 'B'), but even a newly diagnosed 'B' should help.

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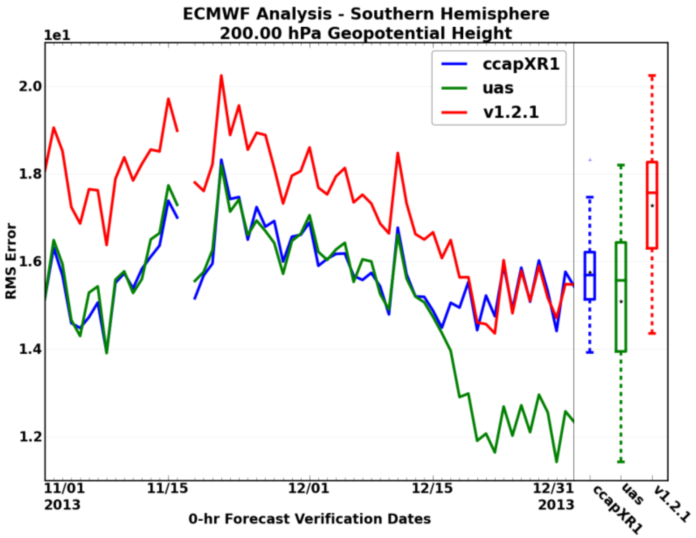
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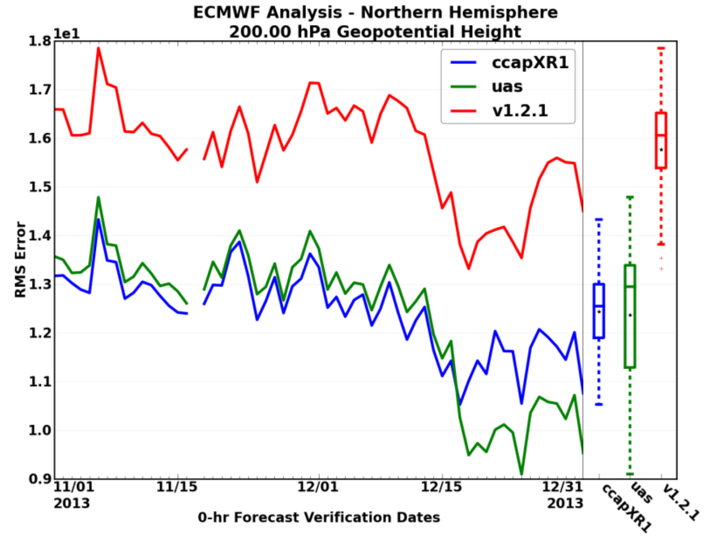
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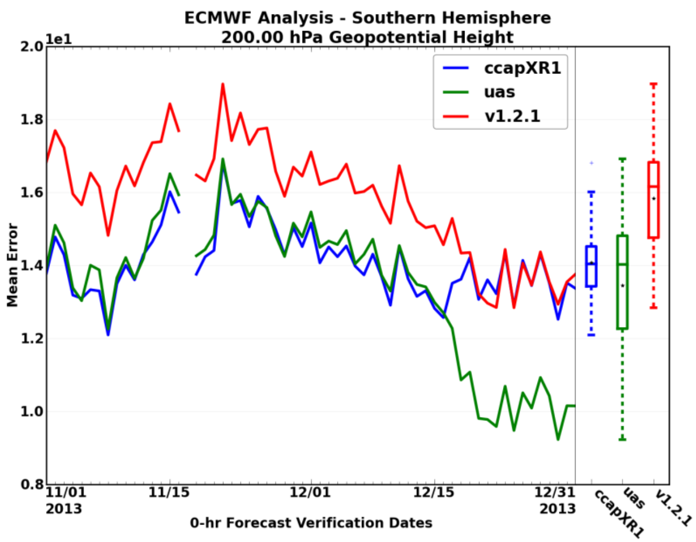
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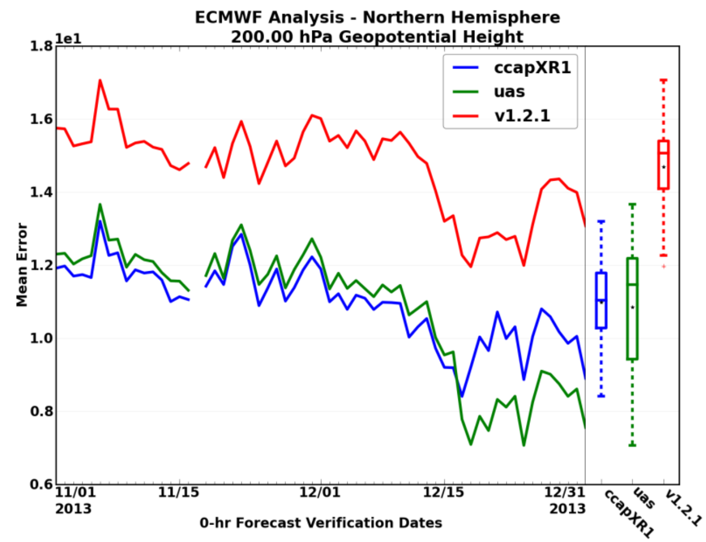
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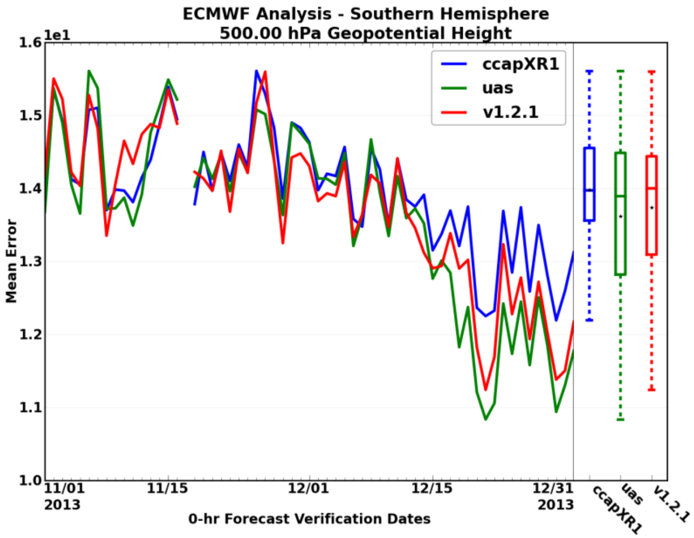
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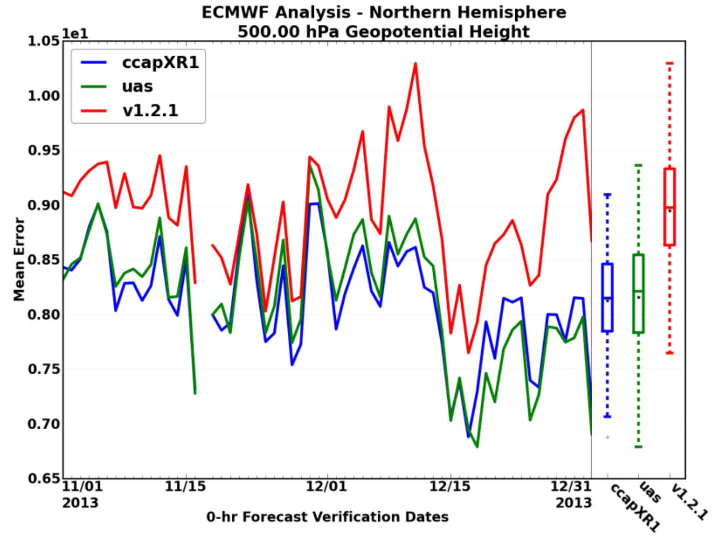
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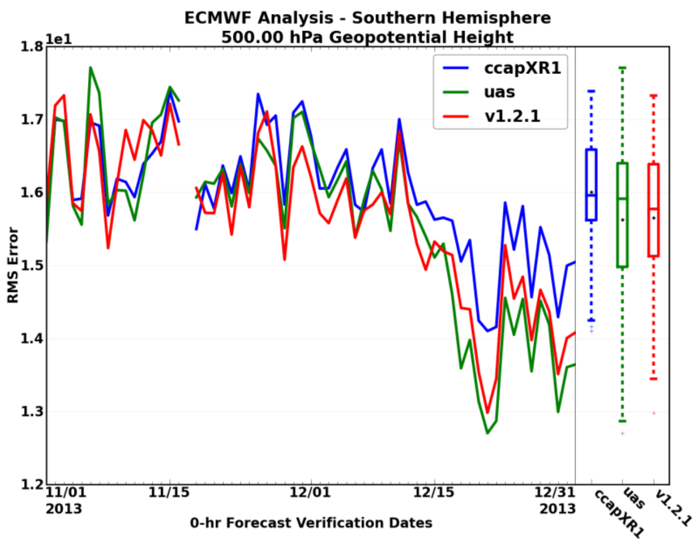
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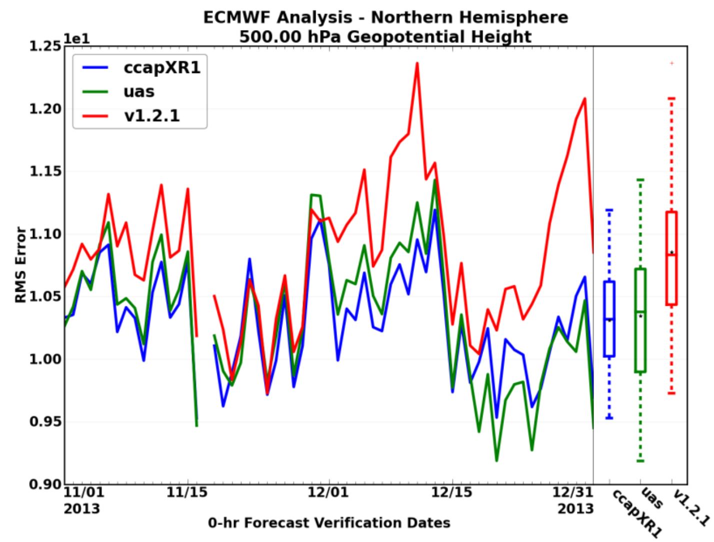
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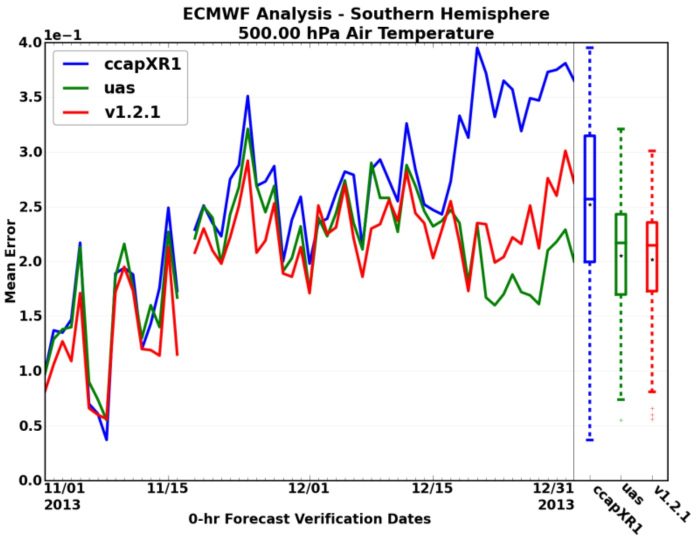
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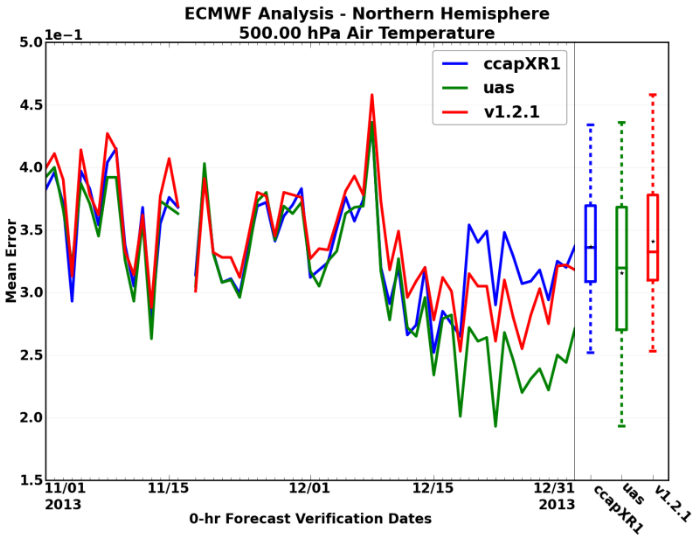
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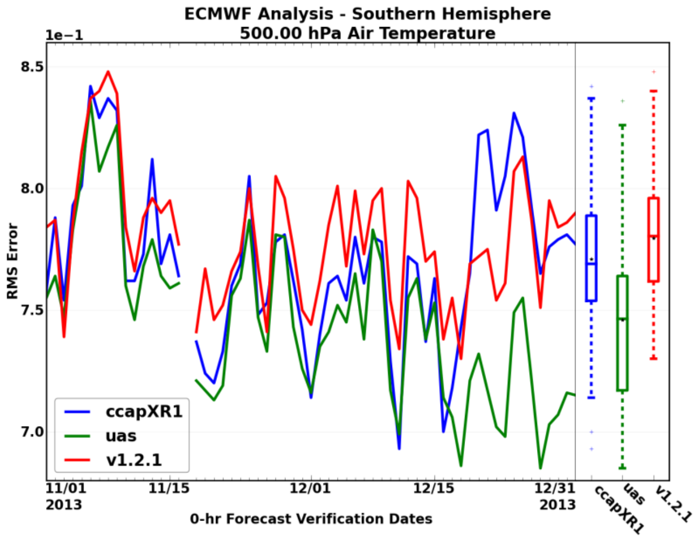
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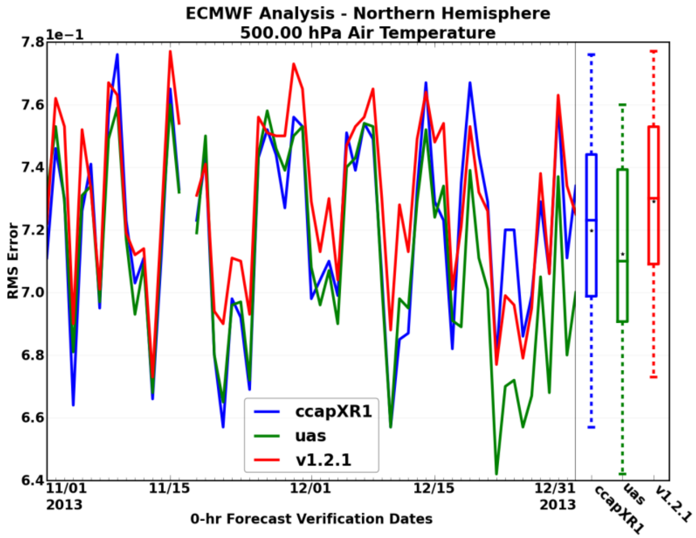
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