Assessment of the Value of SSMIS for Data Assimilation in the Middle Atmosphere

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Objectives

Assess the value of the SSMIS Upper Atmosphere Sounding (UAS) radiance observations in support of the ongoing development of the Navy's high-altitude global model (NOGAPS-ALPHA*). The model includes the atmosphere from the ground to the lower thermosphere (~130 km), and integrates state-of-the-art developments in high-altitude weather and climate monitoring. The development also requires extending the data assimilation system (NAVDAS*) to 100 km by modifying the background error structure functions (correlations) and error variances.

*NOGAPS: Navy Operational Global Atmospheric Prediction System
*NOGAPS-ALPHA: NOGAPS Advanced Level Physics, High Altitude
*NAVDAS: NRL Atmospheric Variational Data Assimilation System

Data Assimilation Basics

In an operational NWP model, **data assimilation** is used to incorporate real-world observations. The goal of data assimilation is to give the best estimate (**analysis**) of atmospheric state for the NWP initial conditions by combining forecast model fields (**background**) and **observations**.

We minimize a penalty function:

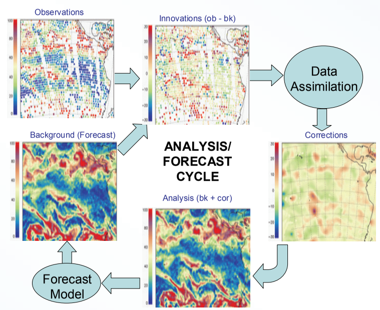
$$J(x) = (y - \mathcal{H}(x))^T R^{-1} (y - \mathcal{H}(x)) + (x - x_b)^T P_b^{-1} (x - x_b)$$

(forward operator; analysis variables; observations; observation error covariance; background; background error covariance)

This is an optimal estimation problem constrained by the error covariance matrices of the background and the observations. The solution is:

$$\vec{x}_a - \vec{x}_b = \mathbf{P}_b \mathbf{H}^T (\mathbf{H}\mathbf{P}_b\mathbf{H}^T + \mathbf{R})^{-1} (\vec{y} - \mathcal{H}(\vec{x}))$$

(correction; Jacobian; innovation)

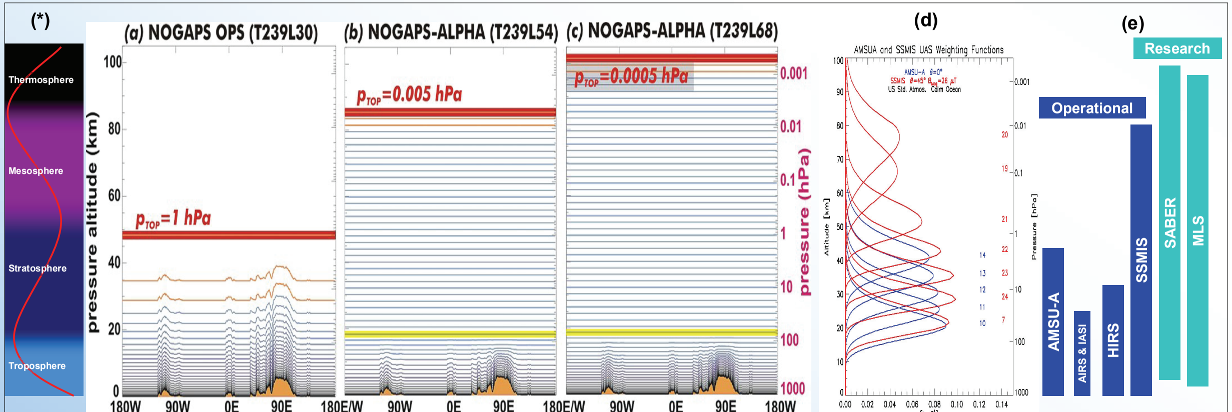


Instruments

Temperature sounding data used operationally at NWP centers include both microwave (AMSU) and infrared sounders (HIRS, AIRS, and IASI). These are effective up to about 1 mb (40 km). The recently launched EUMETSAT METOP satellite has AMSU, HIRS and IASI (infrared) sensors.

Other satellite instruments that measure the temperature of the stratosphere and mesosphere include:

- DMSP SSMIS includes Upper Air Sounding (UAS) channels in the 60 GHz oxygen absorption band which extend the range of downward-viewing microwave radiometers to around 85 km altitude.
- NASA's IR and microwave limb sounders, SABER and MLS, sample the atmosphere from about 10 km to 100 km with high vertical resolution (but poorer horizontal resolution).

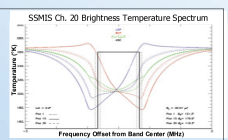


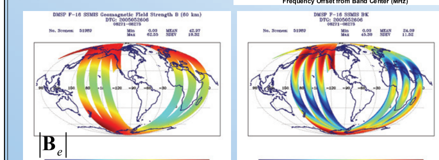
(*) Typical temperature profile of the atmosphere. (a) Plot of operational NOGAPS (L30) sigma levels. (b) NOGAPS-ALPHA L54 hybrid levels. (c) L68 hybrid levels. (d) Weighting functions of highest-peaking channels on AMSU-A and SSMIS
(e) Approximate altitude range of some satellite temperature-sounding instruments

Zeeman Effect

- Interaction of oxygen molecule absorption spectrum with geomagnetic field (B_e) leads to Zeeman splitting of absorption lines.
- Important for upper atmosphere remote sensing (above ~40 km) within the microwave oxygen spectrum
- Leads to a shift in peaks of the weighting functions depending on B_e
- Upper atmosphere radiative transfer (RT) calculations require anisotropic polarized radiative transfer to resolve Zeeman splitting due to the interactions of the directional geomagnetic field and the permanent dipole moment of the O_2 molecule.

SSMIS channel 20 T_B spectrum under weak geomagnetic conditions in an ascending node for various polarizations and scan positions. Dashed vertical lines represents an 80 kHz uncertainty in the center frequency stability, which also represents the equatorial maximum magnitude of the Earth rotation Doppler shift.





Geomagnetic field $\mathbf{B_e}$ (left) and $\mathbf{B_e}\cdot\mathbf{k}$ (right) for SSMIS observation locations.

Upper Atmosphere Radiative Transfer (RT) Models

Data assimilation requires both the forward RT model and its adjoint (Jacobian).

Forward RT model computes brightness temperatures from the model background model fields and geomagnetic field parameters with respect to the SSMIS viewing angle.

The Jacobian maps differences between the observed and background brightness temperatures (i.e., innovation) back to changes in the background temperature profiles (i.e., the correction).

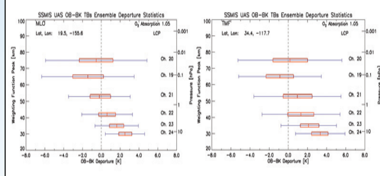
Operational data assimilation requires a fast and accurate RT model and adjoint -- 6 hours of satellite radiances in under 5 minutes

The fully polarized NRL line-by-line model is computationally intensive. Plans are to use the Community Radiative Transfer Model including the Zeeman parameterization (CRTM-Z), developed by the Joint Center for Satellite Data Assimilation (JCSDA).

Results

SSMIS T_B Calibration vs. LBL RTM and Lidar

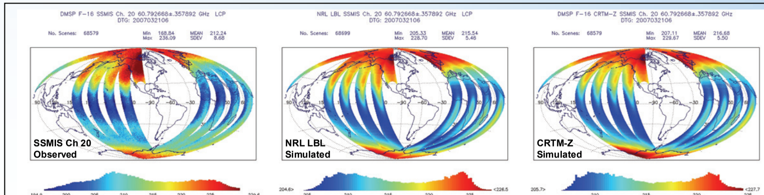
- Compared T_B from line-by-line (LBL) RTM using coincident Lidar profiles from Table Mountain, CA and Mauna Loa, HI, merged with (ECMWF and COSPAR) for all scenes within spatial and temporal matchup criteria (150 km and ±1.5 h)
- SSMIS Observed $|\mathbf{B_e}|$, $\mathbf{B_e}\cdot\mathbf{k}$ and θ_B used for each scene in RTM
- Compare to observed SSMIS T_Bs (SDR)
- SSMIS Observations Agreed within Calibration Uncertainties



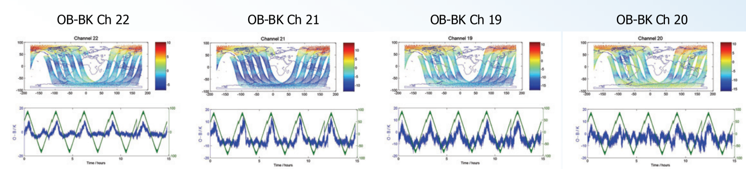
Observed minus background T_B distribution for channels 19-24. Boxes show the median and interquartile range. Whiskers show range of data out to 1.5 times the interquartile range.

Forward Model Intercomparison (LBL vs. CRTM-Z)

- Global Simulations using ECMWF and CIRA-86 Climatology
  - ECMWF NWP Model extends to 0.01 hPa (~80 km)
  - CIRA-86 Climatology extends T(p,z) to 100 km
- NRL LBL RTM vs Fast Model with Zeeman Effects Included
  - CRTM-Z compares to LBL within 1.0 K in the mean
  - NRL LBL -- 6 Hours of CPU time per SSMIS rev
  - CRTM-Z -- under 30 seconds per SSMIS rev
- Zeeman effect included using regression based predictors such as:
  - $|\mathbf{B_e}|$, $\mathbf{B_e}\cdot\mathbf{k}$ and $\cos(\theta_B)$
  - Integer powers (-2, -1, 2, 3) of $|\mathbf{B_e}|$, $\mathbf{B_e}\cdot\mathbf{k}$ and $\cos(\theta_B)$
- Global Simulations and Radiance Assimilation of SSMIS UAS data now possible with CRTM-Z
- Software developed to compute propagation vector from the TDR file and extract geomagnetic field components from SSMIS data base files (geomag_db)
- Software Outputs ASCII SSMIS UAS TB file including geomagnetic parameters, and the background temperature profile to 100 km at 500 m increments
- Initial OB-BK show large departures in the polar regions for channels 19, 20, and 21
- SSMIS UAS Radiance data have potential to improve current Upper Stratospheric and Mesospheric temperature analyses



Radiance Assimilation of SSMIS Upper Atmospheric Sounding Channel Radiances Requires:
1) NWP background T(p) to 100 km 2) A Fast Radiative Transfer Model including Zeeman Splitting effects

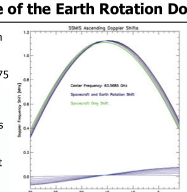


Time Series of UAS OB-BK

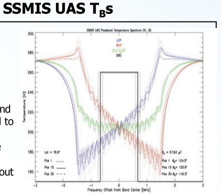
Importance of the Earth Rotation Doppler on Circular Polarized SSMIS UAS T_Bs

Doppler shift due to spacecraft motion is compensated to first order by Local Oscillator tuning in the hardware based upon scan position to within 0.75 to 15 kHz (a small fraction of the narrowest UAS sideband, 1.3 MHz)

Doppler shift due to Earth rotation has a maximum magnitude of ~80 kHz at the equator and is an odd function of the scan position. The sign of the shift also depends upon the orbital mode (ascending/descending)



Simulated Brightness Temperature Spectrum for SSMIS Ch 20 for a strong magnetic field case across the channel passband for beam positions 1, 15, and 30 (left, center and right of scan). The slope of the spectrum across passband denotes the greater sensitivity of LCP and RCP to small frequency shifts compared to the $(T_V+T_H)/2$ measurement originally planned for the SSMIS. The dashed line about the passband (black rectangle) represents an uncertainty of 80 KHz about the center frequency.



Future Work

- Further validation of JCSDA CRTM-Z to determine the importance of including the Earth rotation Doppler effects into RTM
- Determine which polarization (LCP or RCP) best fits the SSMIS data
- Develop methodology to utilize NOGAPS-ALPHA as the background for LBL and CRTM-Z simulations
- Develop and validate NAVDAS assimilation of SSMIS radiances for upper atmospheric analysis and modeling
- Develop and validate NAVDAS assimilation of AIRS, HIRS, and IASI radiances for upper atmospheric analysis and modeling.

Acknowledgements

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