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PRE-OPERATIONAL ASSIMILATION TESTING OF THE DEFENSE METEOROLOGICAL SATELLITE PROGRAM (DMSP) SPECIAL SENSOR MICROWAVE IMAGER/SOUNDER (SSMI/S)

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1. INTRODUCTION

On October 18th, 2003, the Defense Meteorological Satellite Program (DMSP) successfully launched the DMSP F16 satellite with the first Special Sensor Microwave Imager Sounder (SSMI/S) instrument aboard. The SSMI/S is a conically-scanning passive microwave radiometer that includes seven temperature-sounding channels with weighting functions peaking below 30 km (channels 1-7), and six peaking between 30 km and 80 km (channels 19-24) (Fig. 1).

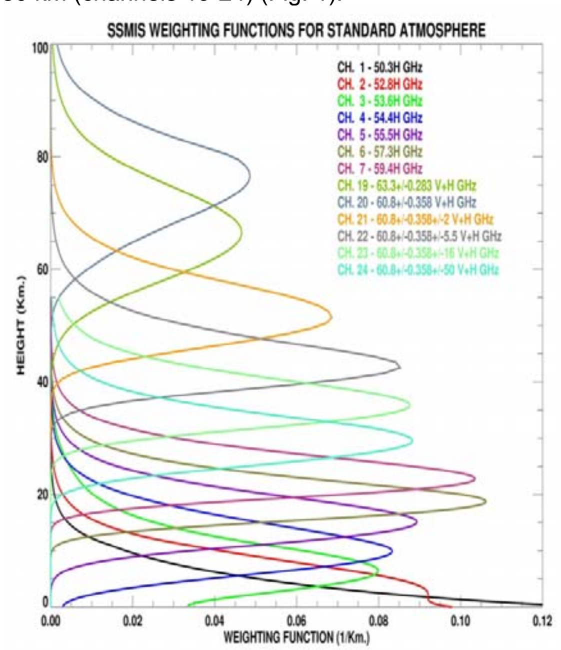

Fig. 1: SSMI/S weighting functions for the U.S. Standard Atmosphere

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The channels peaking below 40 km are similar to channels 3-14 of the cross-track-scanning Advanced Microwave Sounding Unit A (AMSU-A) instrument aboard the NOAA series satellites. Assimilation of AMSU-A radiance data into numerical weather prediction (NWP) models has provided tremendous positive impact at all of the major weather centers. We hope to address the question of whether radiance data from conically-scanning instruments such as SSMI/S can also provide positive impact, given that an uncertainty of less than 0.4K in the temperature sounding channels must be achieved to improve forecast skill.

Two calibration anomalies were discovered by the Cal/Val team, and must be corrected before the radiance data can meet the stringent requirements of NWP data assimilation systems. The first problem is that the reflector has unexpectedly large emissivity, which contaminates the scene temperatures. The second problem is that both direct and reflected sunlight intrudes onto the warm load calibration target, which affects the gain calculation and thus the recorded antenna temperatures. Both problems occur in multiple parts of the orbit, and vary with season. Both problems require a preprocessor to make the data usable for radiance assimilation.

2. SSMIS UNIFIED PREPROCESSOR (UPP)

There are currently three (NRL, NOAA and UKMO) stand-alone versions of SSMI/S preprocessors designed to mitigate the calibration anomalies uncovered in the Cal/Val efforts. These preprocessors are specifically tailored towards NWP and radiance assimilation applications. The goal is to produce a Unified Preprocessor (UPP), combining the best aspects of the stand-alone versions. The UPP software and correction algorithms should based upon the physical mechanisms causing the calibration anomalies, execute in a timely manner suitable for operations, be well-documented, and be made available to the NWP centers for testing in radiance assimilation trials.

Version 1 of the UPP consists of several parts, and includes methodologies from both the UKMO and NRL preprocessors. The Northrop-Grumman gain correction algorithm (Fourier filtering) is used to correct for solar intrusions. All SSMI/S channels are subsequently remapped to a common footprint (that of the Lower Atmospheric Sounding (LAS) channels (1-7)), and averaged to reduce noise. The averaging scheme is a 50 km footprint Gaussian convolution, which reduces the NEΔT from ~0.3K to 0.1K. Rain detection and flagging also occurs during the averaging procedure. Spillover and cross-polarization corrections are applied, along with a scan non-uniformity correction. Finally, the reflector emissivity correction is applied, using a lagged time derivative of an estimate of the reflector face temperature. Currently at NRL, we output the results of the UPP to an ASCII file, which is subsequently read in and used by our satellite data prep routines. The prep routines then perform thinning, quality control (QC), and airmass bias correction. These procedures are not part of the UPP, allowing for different approaches by individual users and weather centers.

If preprocessing is not performed, the data look like Fig. 2, which shows the uncorrected innovations from 03Z to 09Z on November 5th, 2006 (ECMWF model background and the RTTOV-8 radiative transfer (RT) model). A scan bias on the left edge of the swath is obvious and easily corrected. The reflector emission anomaly can be seen in the South Pacific, just north of 30S, and near the North Pole, poleward of 60N. The reflector emission occurs throughout the orbit, but its effect on the scene temperature is governed by both the difference between the true scene and reflector temperatures, and the frequency-dependent reflector emissivity. The anomalously warm innovations indicate that the reflector is being heated to a temperature that is much warmer than the scene temperatures. The solar intrusion anomaly can be seen in the Southern Ocean and over North Africa and the Middle East. There the rapid heating of the warm calibration target increases the apparent gain, resulting in anomalously cold innovations. The UPP and UKMO correct for these effects; the resulting innovation maps are shown in Figs. 3 and 4.

The large voids are flagged because of solar intrusion, while the smaller areas are rain-flagged. In both the UPP and UKMO, the rain flagging occurs as a QC check during the Gaussian averaging, which has a tunable parameter requiring the number of contaminated footprints to be less than a certain threshold. In Fig. 3, the rain flag is the same as that in the UKMO preprocessor, but the Notrhrop-Grumman gain correction is applied in the solar intrusion regions, resulting in many more innovations. In both figures, there remain areas of strong reflector

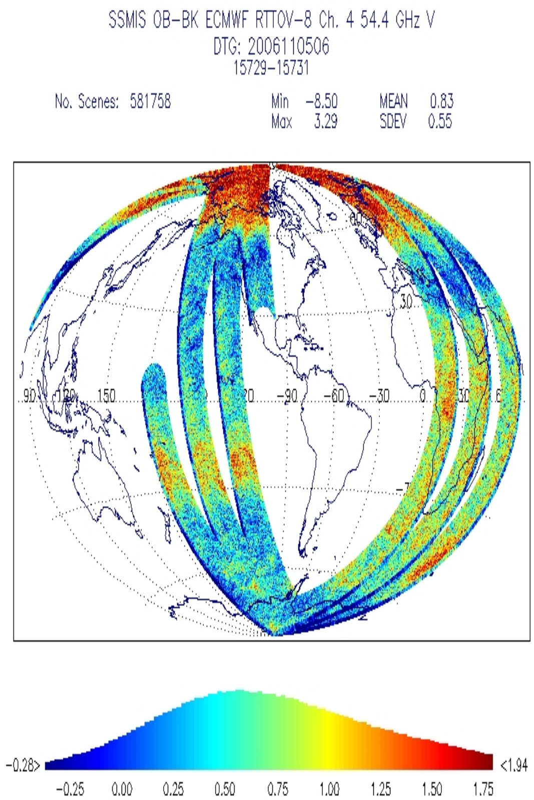


Fig. 2: Uncorrected SSMI/S Channel 4 Innovations (ECMWF background, RTTOV-8)

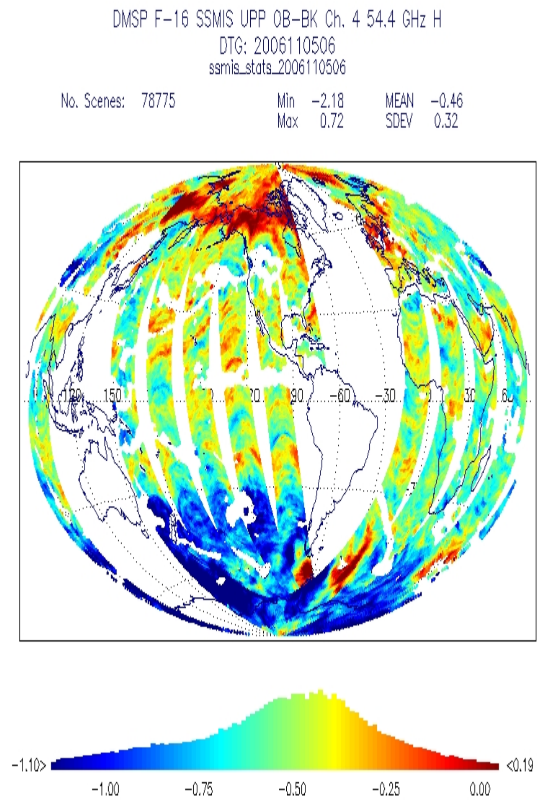
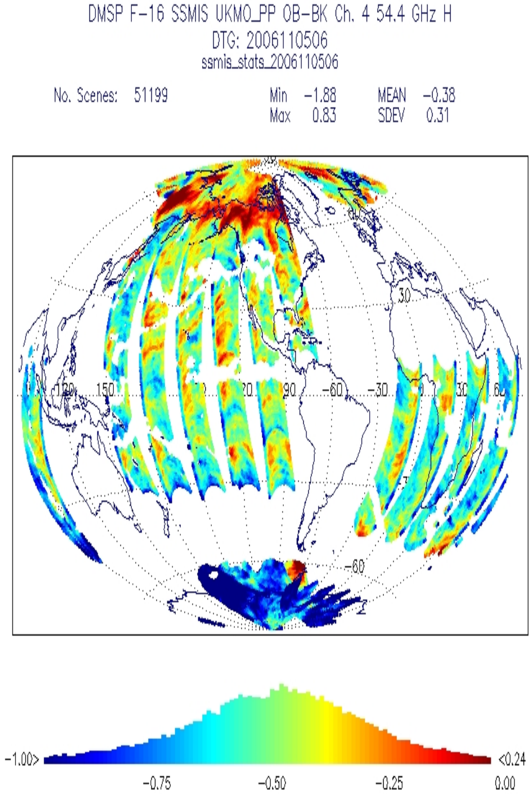


Fig. 3: UPP Emission and Gain Corrected SSMI/S Channel 4 Innovations



emissivity contamination near 60N in the Western

Fig. 4: UKMO Emission Corrected SSMI/S Channel 4 Innovations (Solar Intrusions Flagged)

Hemisphere. These are areas of very rapid heating that cannot be fully compensated for by the UPP. Currently, users will need to QC these areas for themselves, although they may be flagged or better corrected in future versions of the UPP. (Note that the left of scan cold anomaly is still present after the UKMO preprocessing, and is removed in subsequent bias correction code. The UPP eliminates that anomaly with a simple global scan correction.) More details of the calibration anomaly detection and mitigation are discussed in Swadley et al. (2006) and Bell et al. (2006).

It is important to realize the contributions of data assimilation and NWP modeling, which offer global spatial and temporal coverage, towards detecting calibration anomalies that vary in space and time. Aircraft underflights, while crucial for obtaining absolute radiometric calibration, are not up to the task of detecting anomalies that depend on orbital position, time of day, time of year, and instrument inclination relative to the Sun, because of their very limited spatial and temporal coverage. On the other hand, innovation time series and maps by themselves do not tell us the causes of calibration anomalies. Sophisticated CAD/CAM software models of the spacecraft and orbital geometries allowed the Cal/Val team to pinpoint what exactly was happening in terms of both the solar intrusions and the changes in reflector temperature (and thus emission). The resulting physical understanding led to an effective physically-based correction. But without the where and when provided by data assimilation, the what may never have been identified. Having understood and (partially) corrected the anomalies, we must test if the assimilation of SSMI/S data can lead to improved forecasts.

3. MET OFFICE ASSIMILATION TESTS

A control run for one month from December 12th, 2005, through January 11th, 2006, used the Met Office unified model at N216 horizontal resolution and 50 vertical levels to 0.1 hPa. The data assimilation system was 3DVar, and included the three AMSU instruments aboard NOAA-15, 16, and 18, plus the Atmospheric Infrared Sounder (AIRS), Special Sensor Microwave Imager (SSM/I) wind speeds, feature-track winds, and scatterometer winds (QuikSCAT and ERS-2). Channels 2-7 and 23, all of which are temperature sounding channels peaking below 40 km, were assimilated after footprint averaging and thinning to approximately 4000 obs/channel/6-hour window. Thirty to forty percent of the data is typically intrusion-flagged, and not assimilated. Observation errors were set to approximately twice that of their AMSU-A analogs (0.5K in channels 2-4, 1.0K in channels 5-7, and 2.0K in channel 23). The radiative transfer model used was RTTOV-7 with 43 levels to 0.1 hPa. The reflector emissivity was estimated to be 0.010 in channels 2-5, and 0.020 in channels 6-7 (Bell et al., 2007). The airmass bias correction scheme for the AMSU and AIRS instruments was a two-predictor Harris & Kelly scheme (Harris and Kelly, 2001), using 850-300 hPa thickness and 200-50 hPa thickness, along with a simple global scan bias correction applied after airmass bias correction. Note that this experiment was performed prior to the implementation of the full UPP; the remapping, averaging, and reflector emissivity correction were performed, but data contaminated by solar intrusions was simply flagged and not used.

The first test run added the DMSP F16 SSMI/S instrument to the full operational system. The results showed small but significant positive impact (Fig. 5). Southern Hemisphere (SH) mean sea-level pressure (PMSL) forecasts improved by 1-3% at days 1-4 and 500 hPa height anomaly correlations (AC) improved by 1-2% at days 2 and 3. The root-mean-squared error (RMSE) of the Tropical 850 hPa winds at day 3 and 250 hPa winds at day 1 improved by ~1%. Northern Hemisphere (NH) results were neutral, except for a 2% PMSL forecast degradation at 5 days.

Along with some further testing not reported here, the results of the Met Office SSMI/S assimilation tests were sufficiently positive for operational implementation; SSMI/S transitioned to operations in late September, 2006.

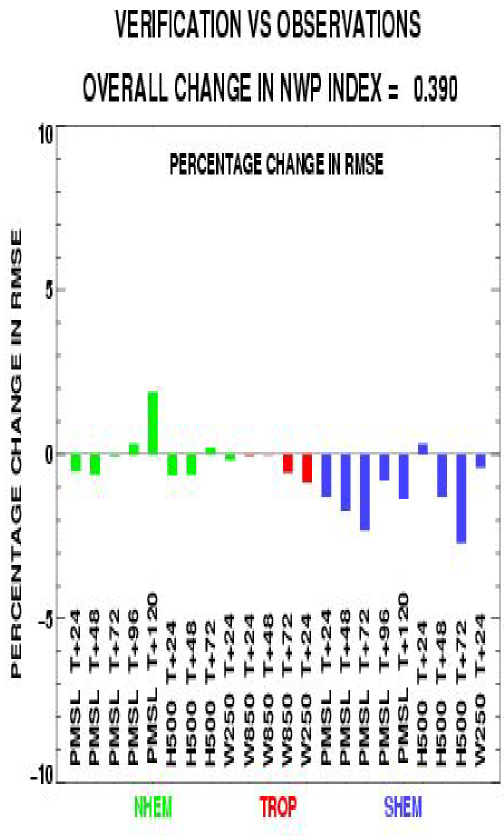


Fig. 5: RMSE change for Met Office (negative indicates improvement)

4. NRL ASSIMILATION TESTS

A control run for 17 days from November 8th, 2006, through November 26th, 2006, used the Navy Operational Global Atmospheric Prediction System (NOGAPS) at T239 horizontal resolution and 30 vertical levels to 4.0 hPa. The data assimilation system was 3DVar (the NRL Atmospheric Variational Data Assimilation System, NAVDAS), and included the three AMSU-A instruments aboard NOAA-15, 16, and 18 plus SSMI wind speeds and total precipitable water (TPW), feature-track winds, and scatterometer winds (QuikSCAT and ERS-2). No AIRS or AMSU-B data were included. Channels 2-7, temperature sounding channels peaking below 30km, were assimilated after footprint averaging and thinning to approximately 8000 obs/channel/6-hour window. Observation errors were set to approximately twice that of their AMSU-A analogs (0.5K in channels 2-4, 1.0K in channels 5-7). The radiative transfer model used was the Community Radiative Transfer Model (CRTM) with 30 layers to 4.0 hPa. The reflector emissivity was estimated to be 0.010 in channels 2-5, and 0.020 in channels 6-7. The airmass bias correction scheme for the AMSU-A instruments was a three-predictor scheme based on Harris & Kelly, 2001, using 850-300 hPa thickness, 200-50 hPa thickness, and a cloud liquid water predictor based on innovations in channels 1 and 2. Prior to airmass bias correction, a simple global scan bias correction was applied.

The first test run added the DMSP F16 SSMI/S instrument to the full operational system. The results were quite positive. In the SH, the 500 hPa height AC showed improvement of 6 hours at 5 days, and the 1000 hPa height AC showed improvement of 12 hours at 5 days (Figs. 6 and 7). In the NH, the

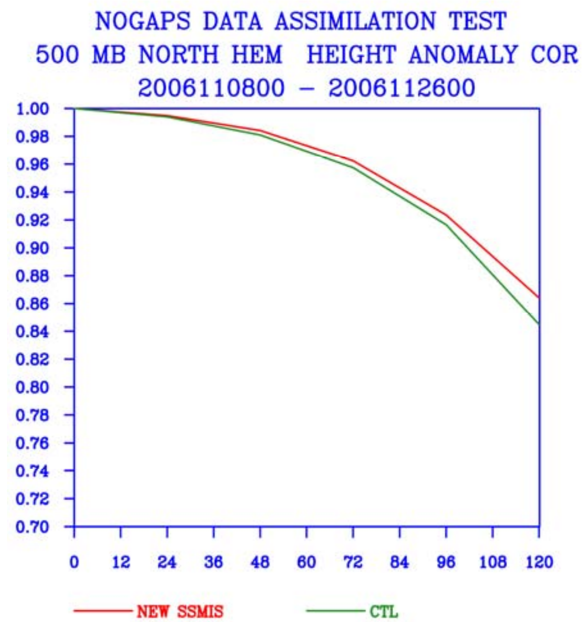


Fig. 6: Southern Hemisphere 500 hPa Height Anomaly Correlation (20S to 80S)

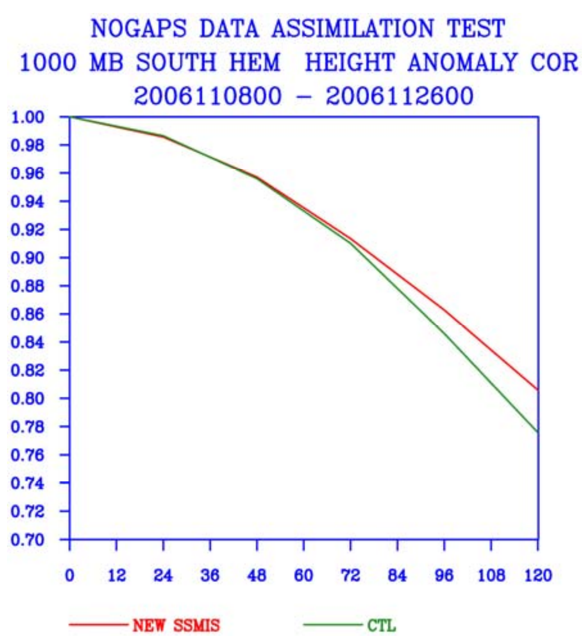


Fig. 7: Southern Hemisphere 1000 hPa Height Anomaly Correlation (20S to 80S)

results were similar: the 500 hPa height AC showed improvement of 8 hours at 5 days, and the 1000 hPa height AC showed improvement of 4 hours at 5 days (Figs. 8 and 9). The vector RMS wind errors in the Tropics were neutral at 250mb at 3 days (Fig. 10), but showed significant (99% confidence) improvement at 850 hPa at 3 days (Fig. 11).

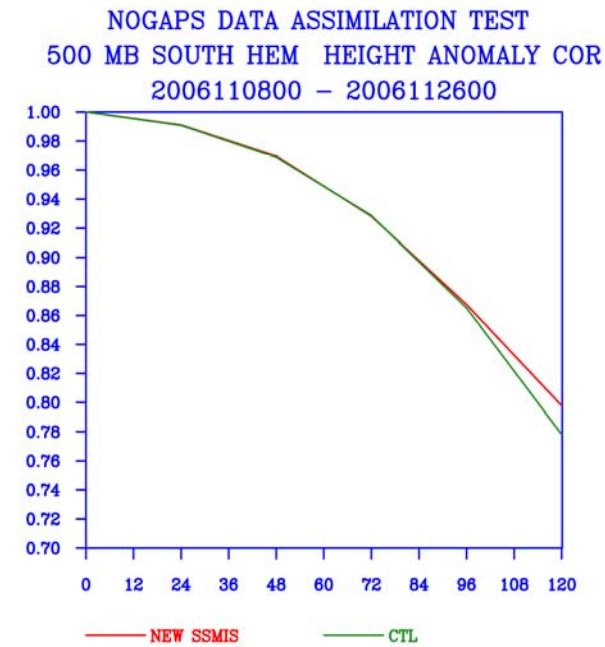


Fig. 8: Northern Hemisphere 500 hPa Height Anomaly Correlation (20N to 80N)

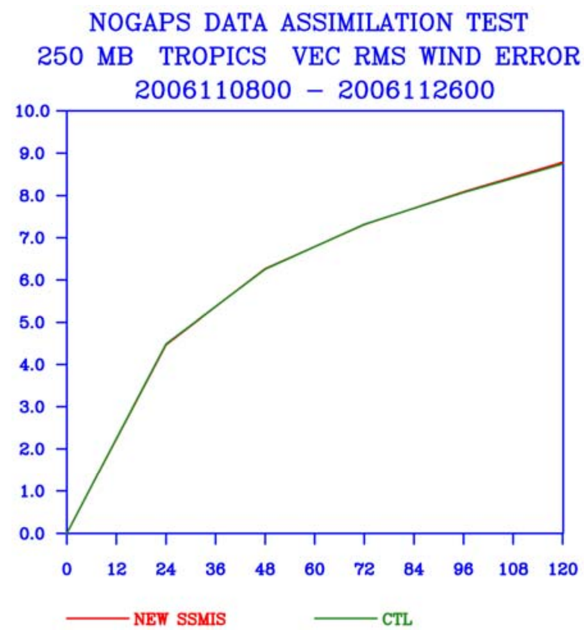


Fig. 10: Vector RMS Wind Error at 250 hPa in the Tropics (20S to 20N)

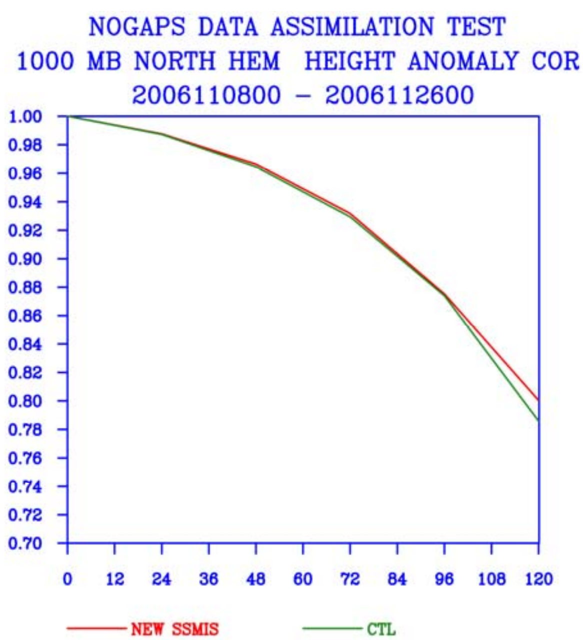


Fig. 9: Northern Hemisphere 1000 hPa Height Anomaly Correlation (20N to 80N)

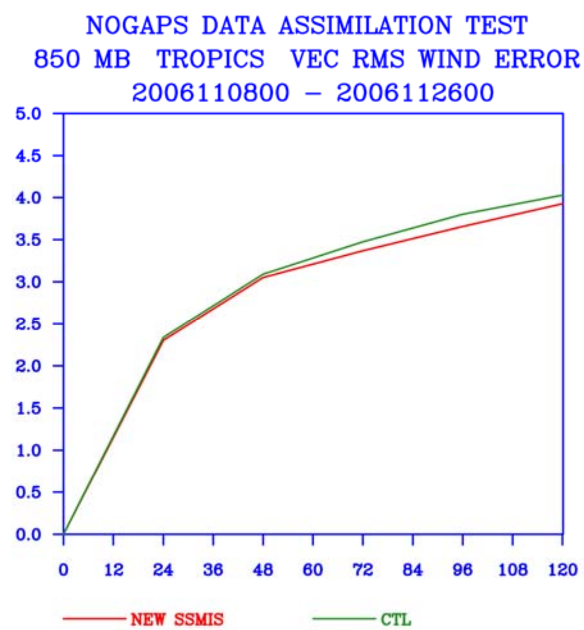


Fig. 11: Vector RMS Wind Error at 850 hPa in the Tropics (20S to 20N)

5. FUTURE SSMI/S INSTRUMENTS

The second in the series of SSMI/S instruments, onboard DMSP F17, was successfully launched at 5:53 a.m. PST on November 4th, 2006. The SSMI/S instrument began operation and data transmission in early-orbit modes on November 9, 2006. F17 SSMI/S hardware modifications include a small fence mounted to the top of the canister, to prevent direct warm-load solar intrusions. The rim-mounted thermistor has been moved to the center on the back of the mirror, in order to provide a more accurate measure of the reflector temperature, yielding a better emissivity correction (should it be needed). In addition, the satellite has been placed in a terminator orbit, so that the spacecraft will always be in the sun, although the SSMI/S will be shaded by the solar panels for a large portion of the orbit. These changes, plus the prior experience of the Cal/Val team with DMSP F16, should lead to a better-characterized and more useful instrument than the first SSMIS.

6. SUMMARY AND CONCLUSIONS

Assimilation testing of the DMSP F16 SSMI/S instrument shows a neutral to slightly positive impact on top of current sensors in Met Office tests. In addition, the SSMI/S can partially compensate for a failed AMSU instrument. These results led the Met Office to transition SSMI/S to operations in late September, 2006. Despite the significant calibration problems of the instrument, these assimilation results warrant cautious optimism about the use of conically-scanning temperature sounders in NWP.

At NRL, assimilation testing showed even more positive results than the Met Office tests. This is in part due to a less accurate baseline score, but also to the use of gain-corrected data that went unused in the earlier Met Office experiments. After further testing we expect to transition SSMIS assimilation to operations in first quarter FY08.

Future SSMI/S instruments will correct design flaws and calibration problems, and the performance of both existing and future SSMI/S instruments will improve as calibration anomaly mitigation strategies mature. We also hope to use the upper air sounding channels when NWP models extend through the mesosphere and into the thermosphere, and when fast radiative transfer models can effectively incorporate the Zeeman splitting of the atmospheric oxygen lines. Although the upper air channels are noisier, NWP models are much less good in the upper atmosphere, so the SSMI/S data should be quite valuable.

Finally, data assimilation experiments have shown their worth as part of the Cal/Val process. Aircraft underflights and cross-calibration with other satellites offer only limited spatial and temporal coverage, and would not have sufficed to pinpoint the calibration anomalies and suggest their physical origin.

7. REFERENCES

Swadley, S., G. Poe, N. Baker, C. Blankenship, W. Campbell, B. Ruston, D. Kunkee, D. Boucher, W. Bell, 2006: Calibration Anomalies and Radiance Assimilation Correction Strategies for the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager Sounder (SSMIS). 15th International TOVS Study Conference, Maratea, IT, 2006.

Bell, W., S. English, B. Candy, F. Hilton, S. Swadley, G. Kelly, 2006: An Initial Evaluation of SSMIS Radiances for Radiance Assimilation Applications. 9th Specialist Meeting on Microwave Radiometry and Remote Sensing Applications, San Juan, PR, 2006.

Bell, W., S. English, B. Candy, F. Hilton, N. Atkinson, N. Baker, S. Swadley, W. Campbell, N. Bormann, G. Kelly, M. Kazumori, 'The Assimilation of SSMIS Radiances in Numerical Weather Prediction Models', submitted to TGARS Special Issue on SSMIS, January 2007

Harris, B.A., and G. Kelly, 2001. A satellite bias correction scheme for radiance assimilation. *Quart. J. Roy. Meteor. Soc.,* **127**, pp. 1453-1468.

8. ACKNOWLEDGEMENTS

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