Report of Visiting Scientist mission NWP_VS16_04
Document NWPSAF-MO-VS-053
Version 1.0
06-06-16

Assessment of the mesospheric temperature sounding channels of SSMIS

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This documentation was developed within the context of the EUMETSAT Satellite Application Facility on Numerical Weather Prediction (NWP SAF), under the Cooperation Agreement dated 29 June 2011, between EUMETSAT and the Met Office, UK, by one or more partners within the NWP SAF. The partners in the NWP SAF are the Met Office, ECMWF, KNMI and Météo France.

Change record			
Version	Date	Author / changed by	Remarks
0.1	3/6/16	Benjamin Ruston	Draft version
0.2	6/6/16	Anna Booton	Some revisions
1.0	6/6/16	Benjamin Ruston	Final version

NWP-SAF Visiting Scientist Mission **NWP_VS16_04_Ruston:**

Assessment of the mesospheric temperature sounding channels of SSMIS

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Abstract

An assessment of the upper stratospheric and mesospheric channels has been performed using the Met Office NWP modeling system and the Radiative Transfer for TOVS (RTTOV; Saunders et al., 1999) version 9 forward radiative transfer model. The time period chosen covered November and December of 2015 with a second short analysis period from 25-29 February 2016. A single Special Sensor Microwave Imager Sounder (SSMIS; Kunkee et al. 2008) was used from the Defense Meteorological Satellite Program (DMSP)-F17. The channels this mission is focusing on are those impacted by the Zeeman effect from the SSMIS sensor which include channels 19-23 often called the upper atmospheric sounding channels (Swadley et al., 2008). However, channels 19 and 20 have substantial portions of their weighting functions above the model top and are not deemed suitable for operational assimilation until a higher model top is introduced. Further, the RTTOV version 9 which uses 43 levels in the vertical does not sufficiently describe the mesosphere to allow accurate simulations of these channels and as a result these channels often saw biases greater than 15K. Channels 21 – 23 however, show that RTTOV does an adequate job of accurately simulating the Zeeman effect and pursuit of these channels for assimilation is viable with these systems. The newly implemented variational bias correction scheme at the Met Office had not been fully integrated for the Zeeman effected channels at the commencement of this visiting scientist mission, and was only being examined in the final days of the mission. Subsequently, the generation of bias correction coefficients is an area which needs further exploration; however, to reiterate by the end of the mission the cycling Met Office VAR system with the Zeeman channels had been fully developed and is now in place for testing. During the mission, an offline set of bias coefficients were produced for the current operational scheme and showed expected behavior particularly with regard to scan correction, but an evolving set will be necessary. Overall, the components for the successful assimilation of the UAS channels from SSMIS appear to be in place and full cycling testing with the Met Office OPS and VAR systems can now be pursued and they can provide assistance to the other operational partners. In summary, the performance of RTTOV is adequate, and stable bias coefficients can be produced so the primary prerequisite elements are in place for operational mesospheric sounding capability.

1. Introduction

a. Importance of the Mesosphere

Mesospheric sounding capabilities are becoming a viable option for current operational weather centres. In the past the numerical weather prediction (NWP) model tops did not extend to sufficient altitudes to make this practical. With most global NWP now using a top of 0.01 hPa which is approximately 80km the assimilation of radiances with mesospheric sensitivity can and should be considered. Figure 1 shows a Northern Hemisphere (NH) minimum temperature at 10 hPa, from the Met Office model, which shows the evolution of the stratosphere through the transitions season from 2015 – 2016. Beginning in January, many rapid oscillations of the temperature are seen to occur. These are the Sudden Stratospheric Warming (SSW) events and they have a critical impact on tropospheric stratospheric exchange. There is substantial evidence that these SSW events can be traced to and begin in the mesosphere (Coy et al., 2011). Further as the NWP models have only recently begun modeling the mesosphere substantial biases remain, and it is a region ripe for data assimilation of high quality observations.

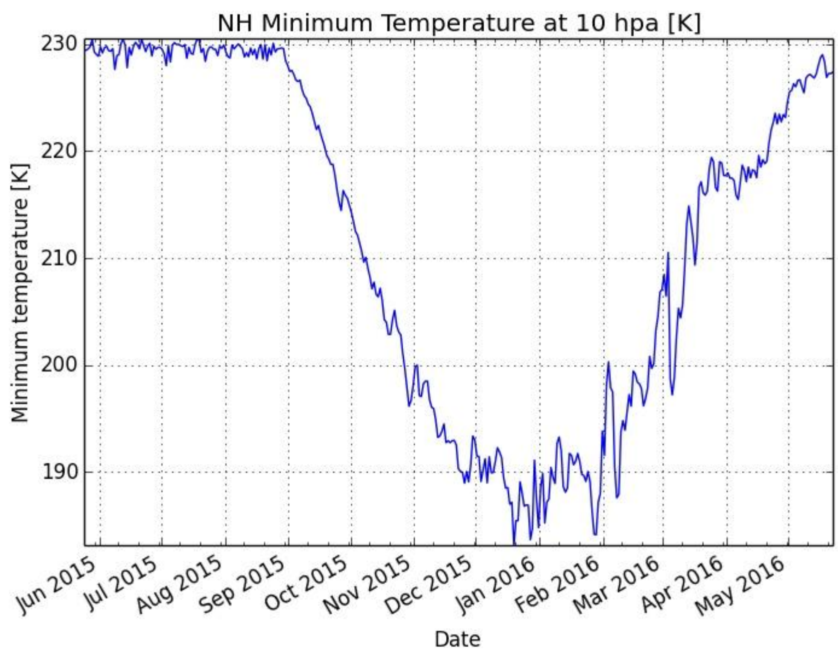

Figure 1. Minimum Northern Hemispheric (NW) temperature at 10 hPa from the Met Office operational model.

b. Prerequisites for Modeling the Zeeman Effect

The mesospheric channels from Special Sensor Microwave Imager Sounder (SSMIS) require the forward operator to take into account the Zeeman effect for these radiances. There are five channels from SSMIS which use narrow spectral bands near the O_2 magnetic dipole transitions (~60GHz) where Zeeman splitting of the absorption lines occurs due to interaction with the Earth’s magnetic field. Two additional pieces of required information must be provided these are the field strength of the Earth’s geomagnetic field and the angle between the antenna boresight view and the vector of the Earth's geomagnetic field. Examples of the Earth geomagnetic field strength is shown in Figure 2a with units of micro Tesla (μT), typical values range from 20-60 μT with maxima at the poles and minima at the Equator. The ascending/descending pattern is recognizable in the angle between the antenna boresight and the Earth's geomagnetic field (θ_B) shown in Figure 2b. The inclusion of this information is provided by the SSMIS Unified Pre-Processor (UPP) co-developed by the Met Office and the Naval Research Laboratory in Monterey, CA. The information on the magnitude strength and vector of the Earth's geomagnetic field is provided by the International Geomagnetic Reference Field (IGRF; Thebault et al. 2015) model which has an estimated 5% uncertainty. The SSMIS UPP provides the magnetic field strength directly from the IGRF model, while spacecraft propagation vector is computed within the UPP and used to calculate θ_B and subsequently included with the data ingested by the Met Office.

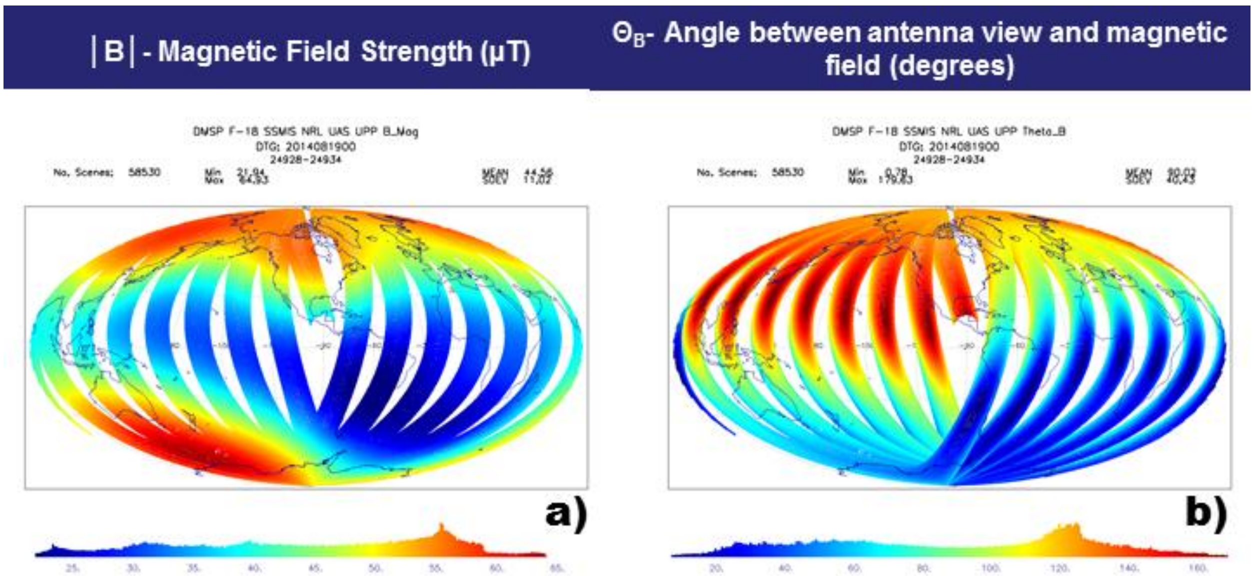

Figure 2. The Earth magnetic field strength (a) and angle between the Earth's geomagnetic field vector and SSMIS antenna boresight θ_B (b).

c. RTTOV simulation with Zeeman Effect

For this study Zeeman coefficients are needed in the observation operator which in this case is the forward radiative transfer model Radiative Transfer for TOVS (RTTOV). The Zeeman coefficients were produced for RTTOV version 11 and then processed to RTTOV version 9 for compatibility with the Met Office's current system. The results presented here should be an appropriate validation of both the RTTOV 9 and RTTOV 11 Zeeman coefficients. Figure 3 shows the side-by-side comparison of SSMIS channels 19-24 with (figures a-f) and without (figure g-l) the Zeeman correction applied for a cycle on 20 November 2015. The highest peaking channel is SSMIS channel 20 shown in figure 3a and 3g, here the large first guess departures or observed minus simulated (O-B) show this channel is not appropriate for operational assimilation with the current model top; however, there is still a dramatic drop in the both the range of the departure values and the standard deviation of the departures drops from ~15K to ~10K. Similarly the next highest peaking channel channel 19 in Figures 3b and 3h show a dramatic reduction in the range of values and drop of standard deviation from ~12K to ~5K. For the remaining channels which will be treated with Zeeman correction in the operational system channels 21-23, the change is not as dramatic and there is a slight, but not significant increase in the standard deviation for channels 22 and 23. However, the behavior of the spatial bias is much improved with the Zeeman correction and the remaining bias is more reflective of that seen for other sounding channels while the regional biases in the non-Zeeman runs are a reflection of the missing geomagnetic field information. Further, the histogram of the departures seems to take on a more Gaussian nature when the Zeeman effect is included which continues to be a fundamental assumption in the data assimilation systems. Lastly channel 24 is included for completeness as the Zeeman effect is not significant enough that if desired it can be neglected in operational assimilation. Figure 3f and3l show the departures for channel 24 and a visual inspection of the first guess departures, or O-B, cannot easily determine any difference with and without the Zeeman effect included, either in the regional biases or in the histogram. Through this precursory examination there is sufficient evidence the application of the Earth field strength and angle between Earth's geomagnetic field and antenna boresight (θ_B) have been implemented correctly from the SSMIS UPP into the forward model calls and the inclusion of the Zeeman effect in the forward radiative transfer calculations is performing as expected. With this established, the report will now move onto examine multiple cycles of the SSMIS simulations with Zeeman correction applied.

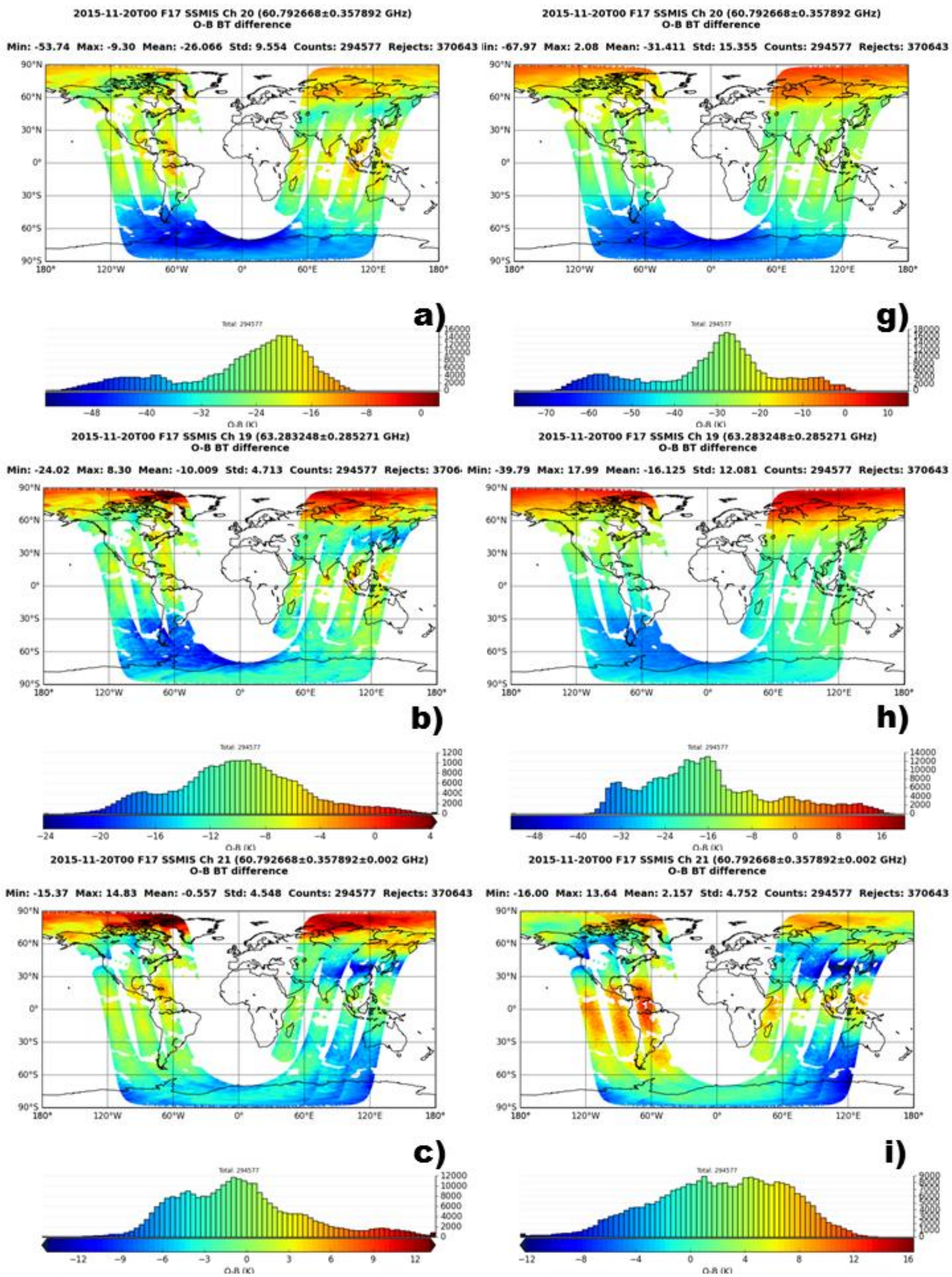

Figure 3. The first guess departures or raw observed minus simulated brightness temperature for SSMIS from an update cycle on 20 November 2015 with the Zeeman correction (left) and without (right). *[shown are channels 20, 19 and 21, ordered by highest to lowest peaking]*

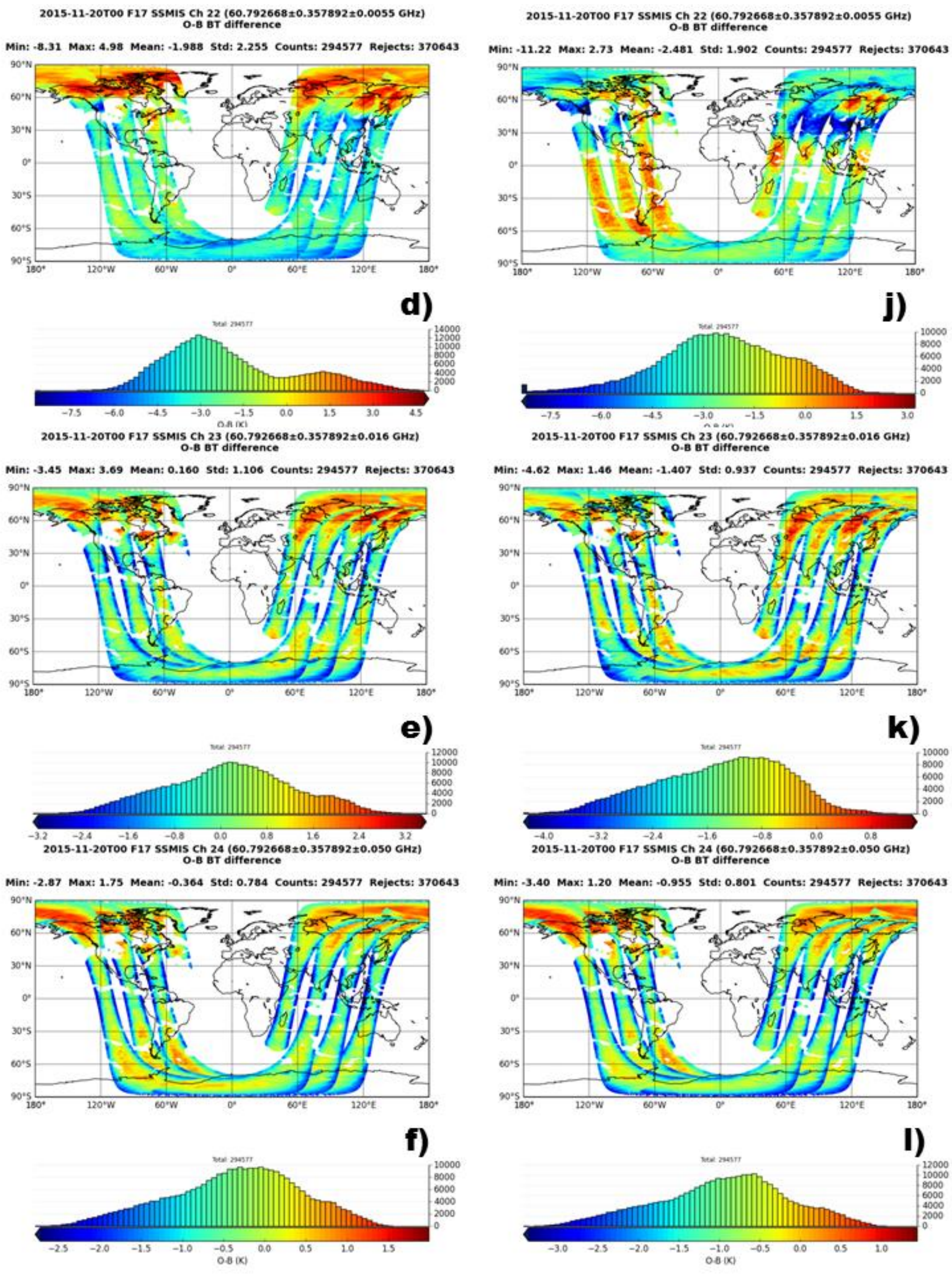

Figure 3 *(continued)*. The first guess departures or raw observed minus simulated brightness temperature for SSMIS from an update cycle on 20 November 2015 with the Zeeman correction (left) and without (right). *[shown are channels 22, 23 and 24, ordered by highest to lowest peaking]*

2. Analysis of SSMIS with Zeeman

a. Comparison with an Independent System

For select dates a comparison with an independent system is of benefit to vicariously verify that the observation processing and Zeeman corrections are performing reasonably. The Naval Research Laboratory (NRL) assimilation system NRL Atmospheric Variational Data Assimilation System (NAVDAS) – Accelerated Representer (AR; Xu et al. 2005) is embedded in the global NWP system NAVy Global Environmental Model (NAVGEM; Hogan et al., 2014) and operationally assimilates the Zeeman effected channels 21-23. Due to the experience the NAVGEM system has had with these channels it is a good choice to use to help confirm that the forward modeling and subsequent assimilation is performing adequately. To undertake these comparisons, not only the Zeeman effect is needed, but bias correction coefficients also must be applied. The Met Office and the NAVGEM systems both employ a variational bias correction methodology. At the time of the visiting scientist mission not all the elements for the inclusion of a cycling variaional bias correction methodology were in place, so in lieu of a dynamically updating variational bias correction method a static set of bias correction coefficients were created valid for 19 November 2015 and used for the experiments using the Met Office system. Figure 4 shows the simulations from the Met Office system on the left (Figure 4a-c) and those from NRL on the right (Figure 4d-f). A comparison of the Met Office simulations in Figure 4a-4c can be compared to Figure 3c-e, where one can see the obvious scan dependence in Figure 3c-e has been mitigated in the subsequent images 4a-4c. Further the histogram of values is substantially improved, showing a nearly Gaussian nature for channels 21-23. Next, comparing to the NRL NAVGEM simulations, very similar magnitudes for the range of values and standard deviations are seen for all channels. The NRL NAVGEM system does consistently show slightly smaller standard deviations; however, it should be noted that the NAVGEM system has been continually assimilating these channels and presumably has a slightly improved mesosphere, and additionally the NAVGEM system has bias coefficients which are being updated each assimilation cycle. With these caveats, the distributions from the Met Office system are very plausible, and the regions of observation signal is consistent between the two systems, particularly for channels 21 and 22 in the northeastern region of Asia, and in the northern tropical latitudes around the Americas.

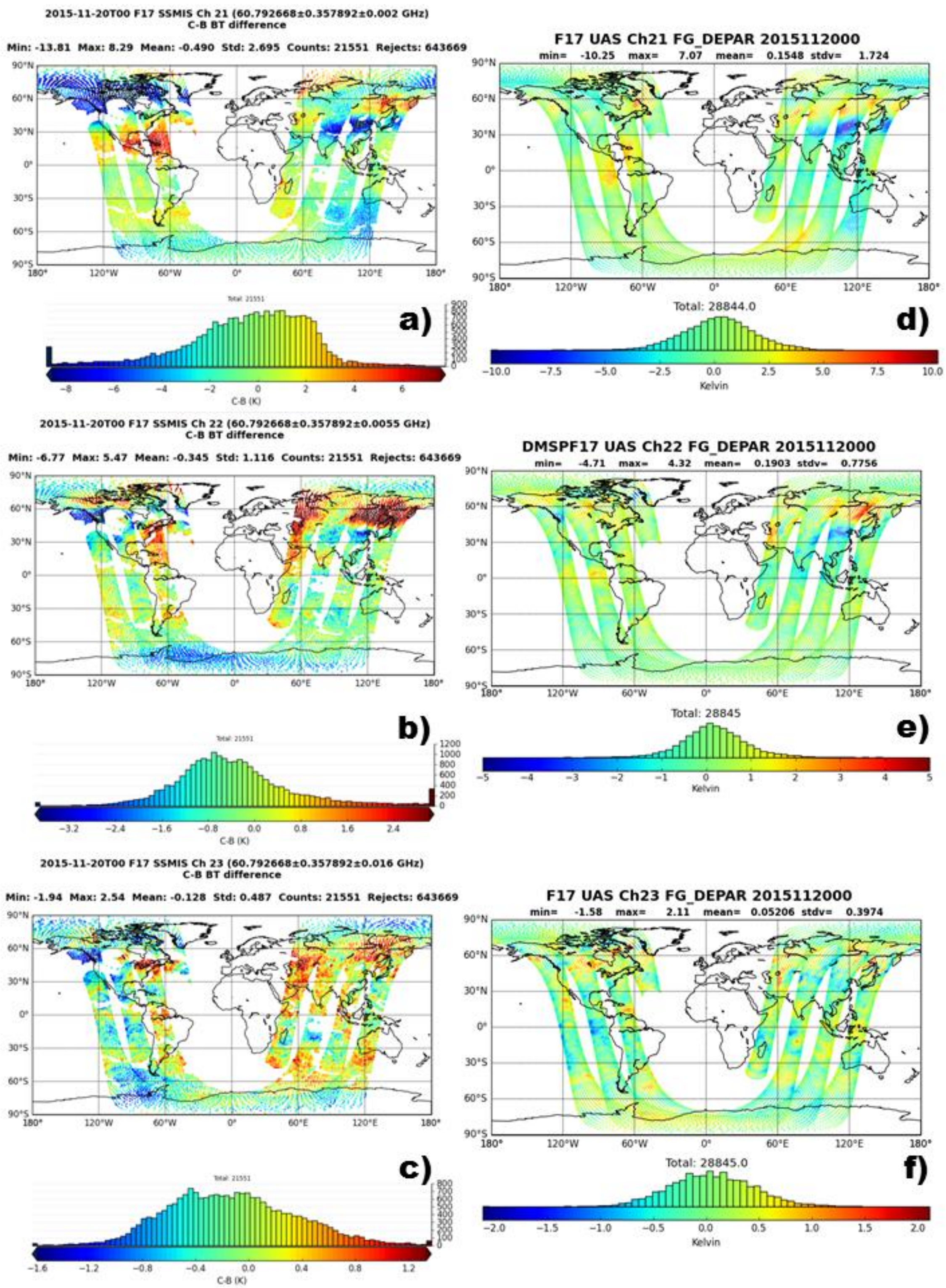

Figure 4. The first guess departures or observed minus simulated brightness temperature for SSMIS from an update cycle on 20 November 2015, with Zeeman correction and bias corrections applied from the Met Office system (left) and NRL NAVGEM system (right) for channels 21, 22 and 23.

b. Evolution of Biases

A series of simulations were performed for the SSMIS instrument from 19 November -25 December, 2015. These were used to examine the evolution of the simulations both globally and regionally. A time series of the departures over this period are shown in Figure 5. The raw observed minus simulated departures (shown in blue) and the bias corrected departure (shown in red) do not show significant change over the time period. The standard deviation of the global departures, shown as shading around the bias corrected departures, shows very little evolution over the time period. Arguably a slight growth is evident as the static set of coefficients becomes less appropriate for the scene as the experiment moves forward from the time from which they were developed. Previously it was shown the scan dependence seen in channels 21, 22, and 23 was qualitatively removed by the static set of bias coefficients. From Figure 5, the remaining global bias offset is handled well for channels 22 and 23; although, for channel 21 little difference is seen between regarding the global offset. However considering the magnitudes of the distributions of the departures typically seen for channel 21 these residuals are relatively small. Also, an improved and evolving variational bias correction should be able to better handle these changing biases.

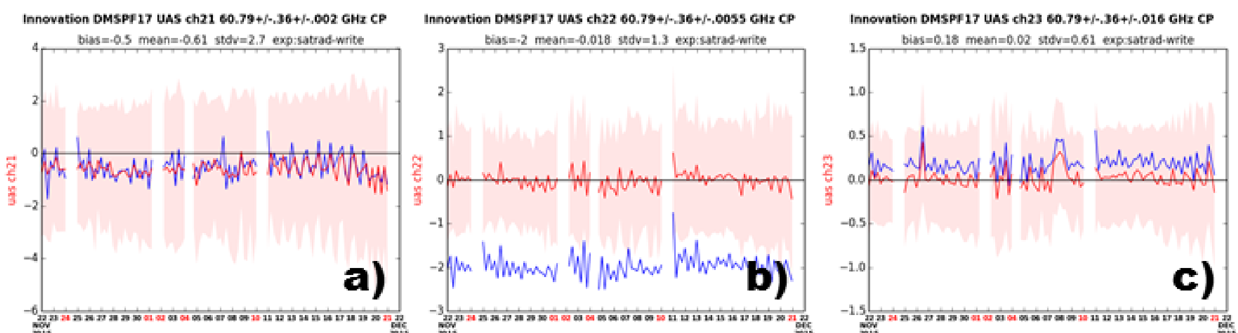

Figure 5. A time series of the global bias and standard deviation for SSMIS channels 21 (a), 22 (b) and 23 (c). The global mean departure without bias correction is shown in blue, after bias correction in red, and the standard deviation is for the bias correct departure is shown in red shading.

To further examine the residual biases, time regional means of the departures or observed minus background (O-B) were computed for the 19 November – 25 December, 2015 experiment. These means were computed over 5-days on a 5x5-degree grid for channels 21, 22 and 23 and are shown in Figure 6. These mean departures show regional biases with considerable variation throughout the period. This again emphasizes the relatively short timescales on which the stratosphere and lower mesosphere can evolve. In particular, for channel 21 a bias is beginning to develop over Antarctica by the end of the time period that is creating a noticeable distribution in the histogram, while for channels 22 and 23 a bias over the North American continent begins to establish itself. For all the channels, the histograms change from fairly Gaussian distributions to ones which gradually lose their look of Gaussianity. This would be detrimental to a fully cycling VAR experiment.

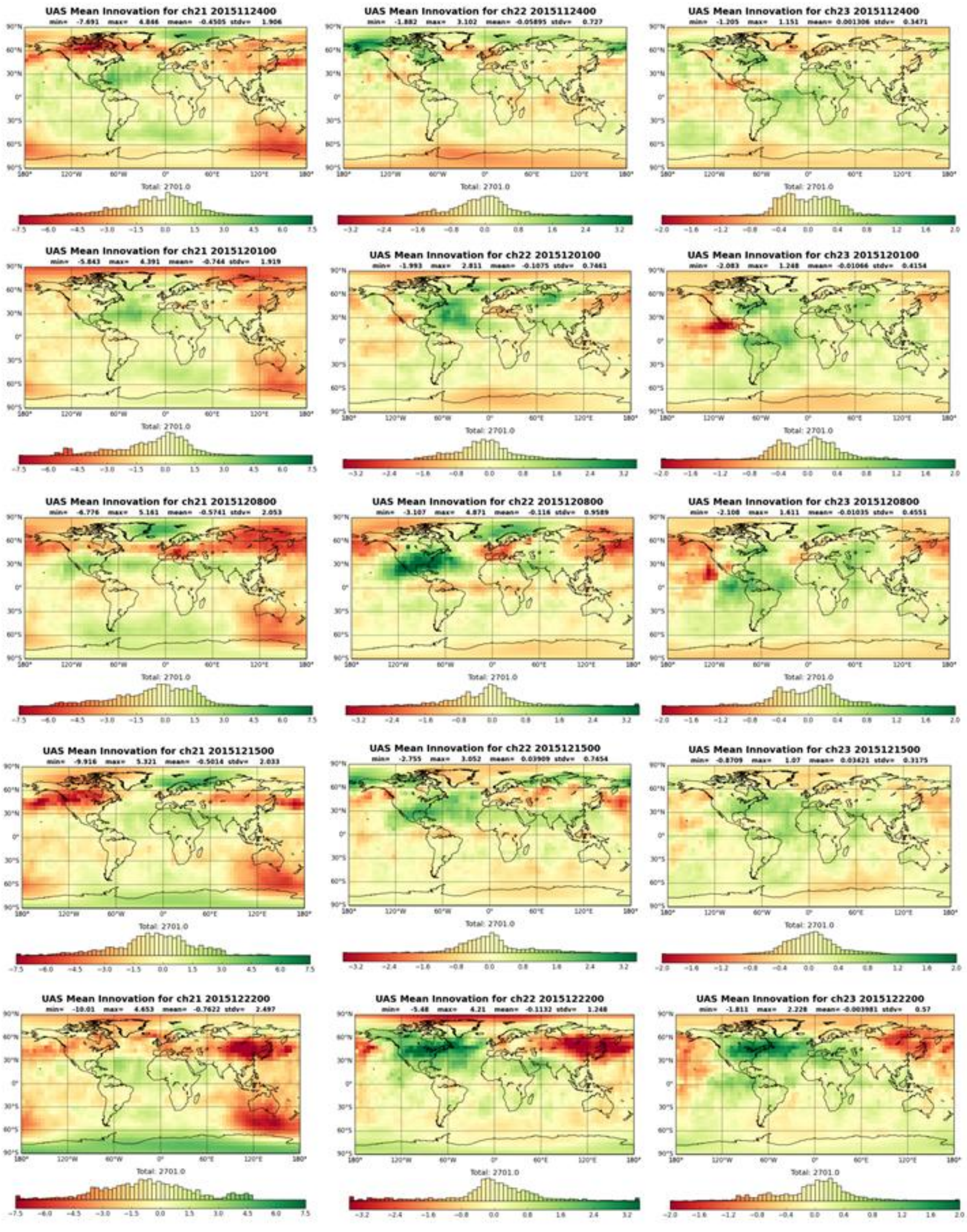

Figure 6. A sequence of 5-day averages of bias corrected first guess departures for SSMIS channels 21 (left column), channel 22 (center column) and channel 23 (right column) on a 5x5-degree grid.

To illustrate the importance of the bias correction and rapid change in the stratospheric and mesospheric environment to which these observations are sensitive, the Met Office experiment was run for 4 consecutive days in 25-29 February 2016. The resulting 5-day averages and standard deviations of the bias corrected first guess departures are shown in figure 7 along with those from the beginning of the experiment on 24 November 2015. It can clearly be seen that the state of the upper atmosphere has become inappropriate for the set of bias coefficients which were developed for 19 November 2015, with the histogram particularly showing very little characteristic of a Gaussian distribution.

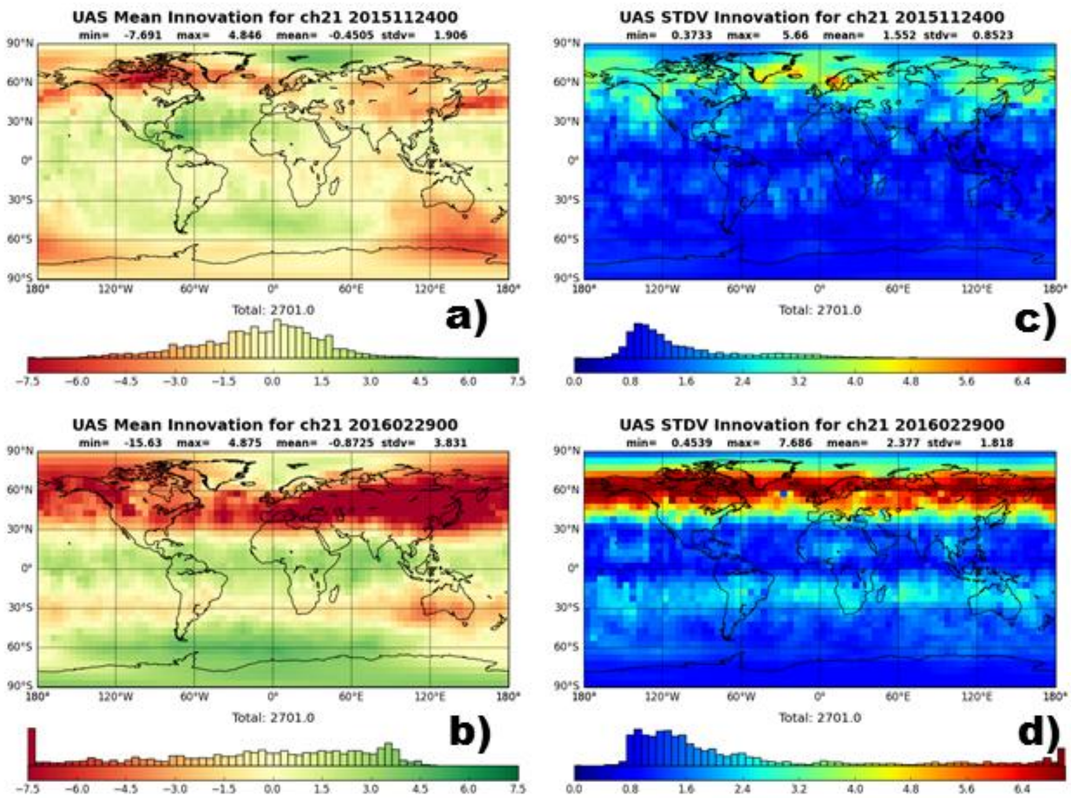

Figure 7. The 5-day averages (a and b) and standard deviations (c and d) of bias corrected first guess departures on a 5x5-degree map for SSMIS channels 21 ending 24Nov2015 (left column) and 29Feb2016 (right column).

To confirm that it is possible to track this evolution, and properly constrain these innovations another comparison with the NRL NAVGEM system, is presented. This is shown in Figure 8, with the first guess departures for SSMIS channel 21. The bias corrected departures from the Met Office system are shown on the left, while those from NRL NAVGEM system are on the right. Opposed to the earlier comparison shown in Figure 4, there are now stark differences in the departures for channel 21 between the Met Office and NAVGEM systems. Not only does the NAVGEM system display the characteristic Gaussian histogram while the Met Office departures do not, but the departure regional bias pattern particularly over the Asian continent are opposite signs. This reinforces the idea that it is possible to assimilate these observations, and a variational bias correction scheme can adapt to the changing stratosphere and mesosphere allowing effective assimilation of these channels.

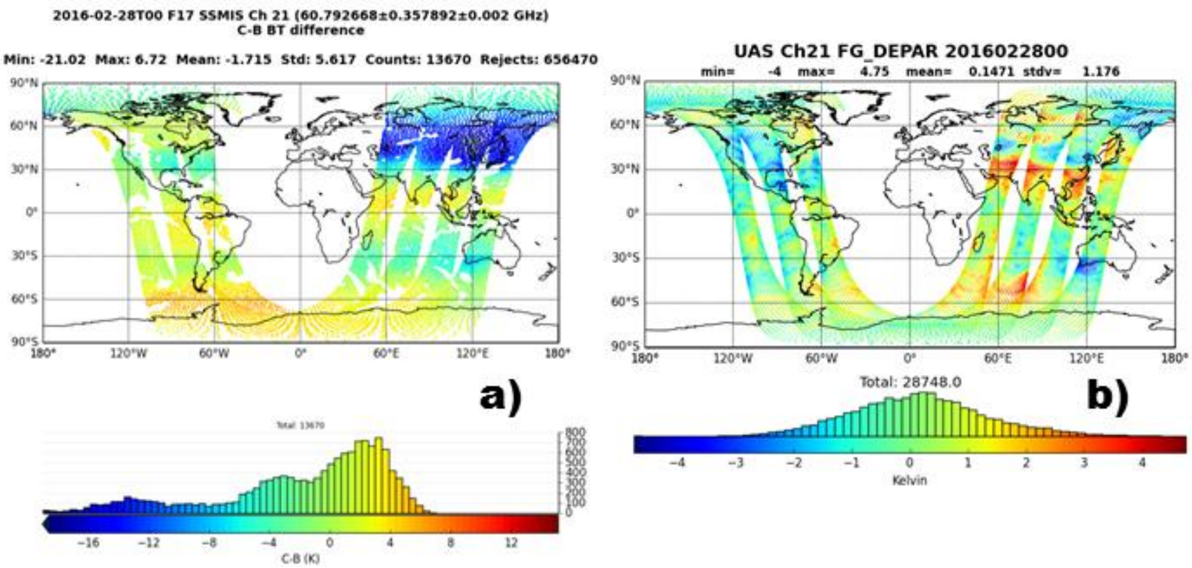

Figure 8. The first guess departures or observed minus simulated brightness temperature for SSMIS from an update cycle on 28Feb2016, with Zeeman correction and bias corrections applied from the Met Office system (left) and NRL NAVGEM system (right) for channel 21.

Summary and Conclusions

A visiting scientist mission was undertaken to examine the feasibility of stratospheric and mesospheric radiances from SSMIS, and assess the performance of the RTTOV and Met Office systems to appropriately use this data. A recent study period covering a transition season was chosen to evaluate the SSMIS observations and the corresponding model simulations. The RTTOV model was found to adequately simulate the channels impacted by the Zeeman effected, removing the obvious Earth magnetic field contribution to the SSMIS channel departures. Further, a set of coefficients for the Met Office variational bias correction methodology were developed and applied to the experiment period. A comparison of a cycle using these bias coefficients against the NRL NAVGEM system showed that the Met Office and NAVGEM systems had very similar regional bias as well as similar ranges of departures. A further examination of the residual biases in the departures from the Met Office found that when the bias coefficients were applied they sufficiently removed the global biases and in particular the scan dependent biases; however, the remaining regional bias grew as the experiment update cycle moved further from the date on which the bias coefficient files were produced. This was seen clearly in a series of time averaged departures and standard deviations. Lastly, a short run near the end of February 2016 clearly shows that the evolution of the stratosphere and mesosphere must be taken into account or the departures can lose a reasonable distribution; however, it was demonstrated that a cycling system with updating variational bias correction such as NAVGEM can maintain a reasonable distribution of departures. It is of importance to note, that by the end of the visiting scientist mission the technological challenge of including the channels impacted by the Zeeman effected in the variational bias correction had been overcome. Other technological contributions to the mission included creation of appropriate SSMIS quality control namelists, and a delivery of additional monitoring software developed during the mission. In short, the system is now prepared for full cycling testing and future open collaboration and scientific exchange are encouraged.

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