Use of the SSU and AMSU-A observations in reanalyses

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1 INTRODUCTION

Biases in observations have to be taken into account to produce a time consistent atmospheric dataset that is appropriate for climate research. Stratospheric temperature analyses in particular can be dominated by satellite data and are strongly affected by biased observations. Changing bias characteristics are often reflected in stratospheric temperature analyses as artificial jumps that correspond to satellite transitions. These artificial jumps can mask the true climate signals and make it difficult to estimate reliable long-term temperature trends.

Biases in observations are the result of a number of processes that are not modelled properly in the assimilation system. Satellites make in general indirect observations of physical properties of the earth system. Use of satellite data in an assimilation system requires a fast radiative transfer model (RTM) that transforms the variables used in the assimilation system into the observed quantities. There are several RTMs that are routinely used in numerical weather prediction centres. When these RTMs are applied to early satellite instruments, biases can be generated by a not proper characterization of the spectral response functions or by changes in the concentration of the radiatively active constituents not reflected in the RTMs. Those biases in the RTMs have to be addressed when we deal with the biases in satellite observations used in reanalyses.

Stratospheric temperatures have been retrieved from satellite observations made by the series of the NOAA polar orbiting satellites since 1978. Data from the TIROS-N to the NOAA-14 satellite have been used to retrieve stratospheric temperatures by using the infrared channels of the Stratospheric Sounding Unit (SSU) instrument. For the later satellites from NOAA-15 onward, SSU was replaced by a higher vertical resolution microwave instrument, the Advanced Microwave Sounding Unit - A (AMSU-A). SSU radiances have previously been directly assimilated in ERA-40 (Uppala et al. 2005) and JRA-25 (Onogi et al. 2007). Both reanalyses encountered difficulties in utilising the SSU radiances due to the biases of the background model and the inadequacy of data coverage for much of the period. Particularly problematic periods are the early 1980's where SSUs had large inter-satellite biases and the late 1990's when the first AMSU-A instrument became available.

Nash and Forrester (1986) pointed out a number of reasons why biases in the SSU radiances should be expected. One of the reasons is the change in time of the SSU spectral response function, which is not taken into account in the Radiative Transfer model for TOVS (RTTOV) (Saunders et al. 1999), which is used in ERA-40 and JRA-25. It has also been earlier pointed out that the radiances of the AMSU-A stratospheric channels computed by RTTOV are significantly different from those computed by other RTMs due to the inclusion of the Zeeman splitting effect (Garand et al. 2001).

In this paper, we utilise co-located observations produced by the Simultaneous Nadir Overpass (SNO) technique (Cao et al. 2005) to evaluate the inter-satellite radiance differences for SSU, as well as between SSU and AMSU-A (Section 2). We then present a revised RTTOV model which can reproduce SSU and AMSU-A inter-satellite radiance differences more accurately. The revised radiative transfer models are validated by simulating the inter-satellite radiance differences for the co-located locations and comparing them with those evaluated by the SNO technique (Section 3). Section 4 demonstrates the impact of the changes in the radiative transfer model on the stratospheric temperature analysis. Section 5 summarises the conclusions from the investigations.

2 INTER-SATELLITE RADIANCE DIFFERENCES

To evaluate the inter-satellite biases between the SSU instruments, we utilise co-located observations produced by the SNO technique (Cao et al. 2005). This method compares the observations made by different satellites at the same time and at the same location. Since both instruments sense the same atmospheric profiles, this comparison provides us with reliable estimates of the inter-satellite biases with little ambiguity. The biases observed with this method are entirely attributable to differences in the radiometric and spectroscopic performance. Figure 1 shows the time series of the inter-satellite biases between NOAA-6 and NOAA-7 for SSU channel 3 over the Antarctic. The seasonal cycle in the time series is likely to be correlated with the lapse rate in the upper stratosphere, indicating that the weighting functions are not identical. The inter-satellite radiance differences between SSU and AMSU-A was also investigated by the SNO technique (see Figure 2) and a significant discrepancy between the measured radiance differences and those computed by RTTOV from background values was found in the springtime and the wintertime, which suggests the need to review the radiative transfer modelling for both instruments in RTTOV.

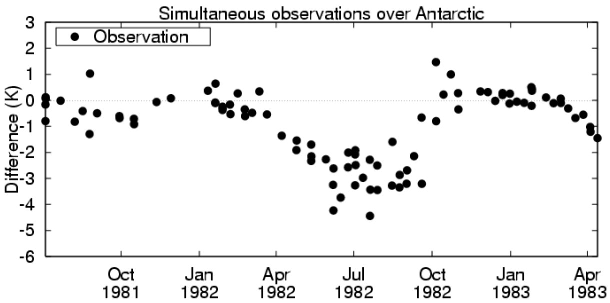

Figure 1 Inter-satellite biases between NOAA-6 and NOAA-7 for SSU channel 3 over the Antarctic.

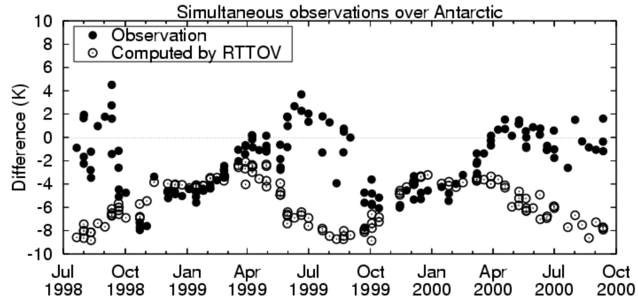

Figure 2 Difference between SSU3 on NOAA-11 and AMSU-A14 on NOAA-15 radiances.

3 REVISED RADIATIVE TRANSFER MODELS

3.1 <u>SSU</u>

SSU is a 3-channel infrared radiometer designed to measure the radiance emitted by stratospheric carbon dioxide (Miller et al. 1980). The instrument utilises the pressure modulation technique by which a signal is derived by viewing the atmosphere through an absorption cell within which the pressure of the carbon dioxide can be modulated. The spectral performance of the instrument depends on the mean pressure within the cell and thus its long-term stability is crucial for time-consistent observations. The mean cell pressure was monitored routinely by the Met Office at 6-month intervals and upon the launch of each new spacecraft. Figure 3 shows the daily values interpolated from Met Office's 6-monthly estimations by using a linear relationship between the mean cell pressure and the modulation frequency.

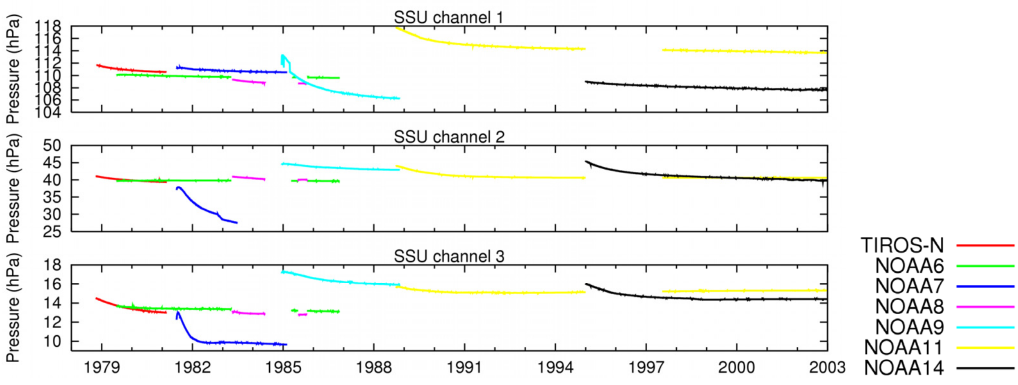

Figure 3 Daily values of the mean cell pressures of the SSU instruments.

Figure 4 shows the typical changes to the weighting functions caused by the CO_2 cell pressure loss. These weighting functions were computed for U.S. standard atmosphere 1976 by using the LBLRTM line-by-line radiative transfer model (Clough et al. 2004) and the HITRAN line parameter database (Rothman et al. 2005). The impact of CO_2 cell pressure loss is significant in channel 2 and channel 3.

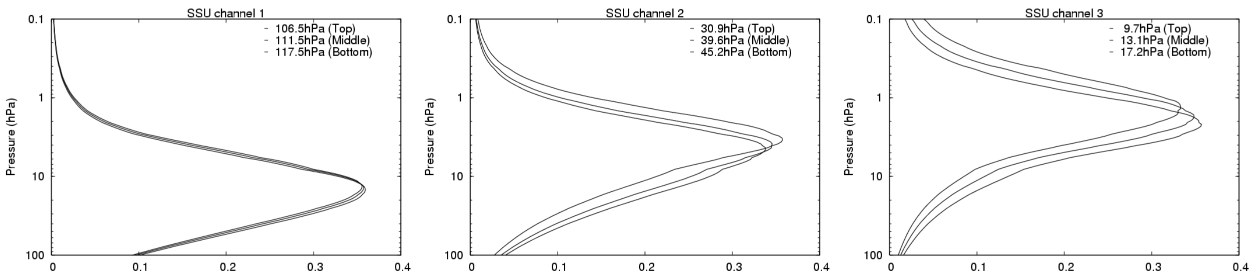

Figure 4 Impact of the changes of the mean cell pressure on the weighting functions.

To assess the effectiveness of taking into account the CO_2 cell pressure loss, the inter-satellite biases at the co-located locations were simulated and compared with those evaluated by the SNO technique. Apart from the mean cell pressure, changes in the atmospheric CO_2 concentration were taken into account. The atmospheric profiles corresponding to the co-located observations were obtained from ERA-40. Figure 5 shows the time series of the inter-satellite biases computed by LBLRTM for the same pair of the satellites as shown in Figure 1 together with those evaluated by the SNO technique. The seasonal cycle of the inter-satellite biases is well captured in the simulation for channel 2 (not shown) and channel 3 (see Figure 5), indicating that the mean cell pressure is a dominant factor in determining the instrument performance. For channel 1 (not shown), changes of the mean cell pressure have little impact on the computed radiances, indicating a possibility of other dominant causes of the biases, e.g. uncertainties in the band-pass filter and the calibration algorithm. The remaining difference between the measured and computed inter-satellite biases in channel 2 and channel 3 could be due to similar causes. Further examination is needed to identify the causes of the remaining biases. Nevertheless, taking into account the changes of the mean cell pressure is expected to reduce the biases in the RTM.

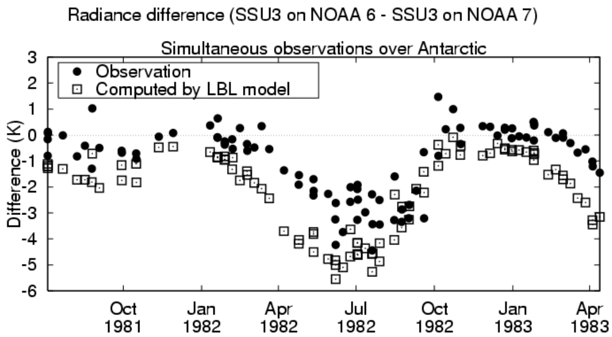

Figure 5 Same as Figure 1 for the computed inter-satellite biases.

3.2 AMSU-A

AMSU-A is a multi-channel microwave radiometer designed with the aim to be able to calculate the vertical temperature profiles from about 3 hPa (45 km) pressure height to the Earth's surface (Goodrum, Kidwell and Winston 2000). The AMSU-A stratospheric channels measure the radiance originating from the 60-Ghz oxygen absorption lines. These absorption lines result from magnetic-dipole transitions and exhibit Zeeman splitting because of the terrestrial magnetic field. This splitting is appreciable for line widths at the low pressures. This effect is important for the upper atmospheric channels that cover frequencies within a few MHz from the centre of the absorption lines (Rosenkranz and Staelin 1988).

In RTTOV, the Zeeman splitting effect is represented by the scalar approximation described by Liebe et al. (1993), which models the effect simply by increasing the line-broadening parameter for the O_2 absorption lines. Figure 6 shows a comparison of the attenuation rates computed by three different radiative transfer models for the frequencies around the pass bands of AMSU-A channel 14. The radiative transfer models used are with 1) the scalar approximation as in RTTOV, 2) the explicit representation of the Zeeman splitting effect and 3) no Zeeman splitting effect. All of these models are based on a version of the Liebe line-by-line model (Rayer 2001), and utilised Millimeter-wave Propagation Model (MPM) 89 (Liebe 1989) for water vapour spectra and MPM92 (Liebe et al. 1992) for oxygen spectra. The scalar approximation proved to be very accurate at the frequencies near the centre of the absorption line. In the frequencies within the pass bands, however, this approximation overestimates the attenuation rates, which results in anomalous upward shift of its weighting function (see Figure 7). The weighting function of the no Zeeman effect model is much closer to that of the explicit Zeeman effect model, indicating that the calculations of the no Zeeman effect model would be more accurate than those of the scalar approximation model. Although the explicit Zeeman effect model is undoubtedly the most accurate model, the implementation of this model into RTTOV requires a long term effort. As a practical short-term solution, we simply excluded the Zeeman splitting effect from the line-by-line computations used to train the fast RTM.

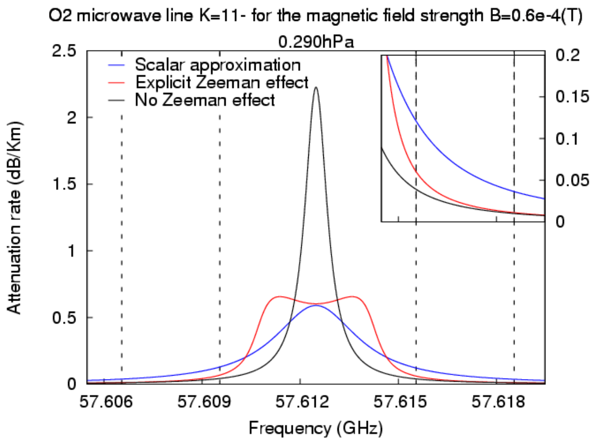

Figure 6 Attenuation rates at the frequencies around the pass bands of AMSU-A channel 14

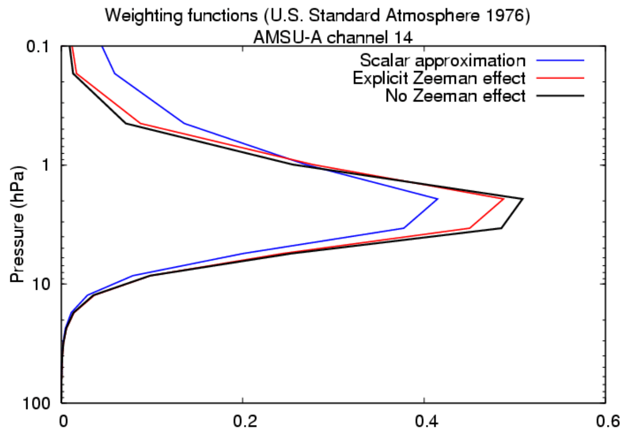

Figure 7 Weighting functions for AMSU-A channel 14.

Figure 8 shows the time series of the inter-satellite radiance differences computed by the revised radiative transfer model for the same pair of satellites as shown in Figure 2 together with those evaluated by the SNO technique. Remarkable agreement between the measured and the computed radiance differences indicates a significant improvement of the accuracy of the RTM.

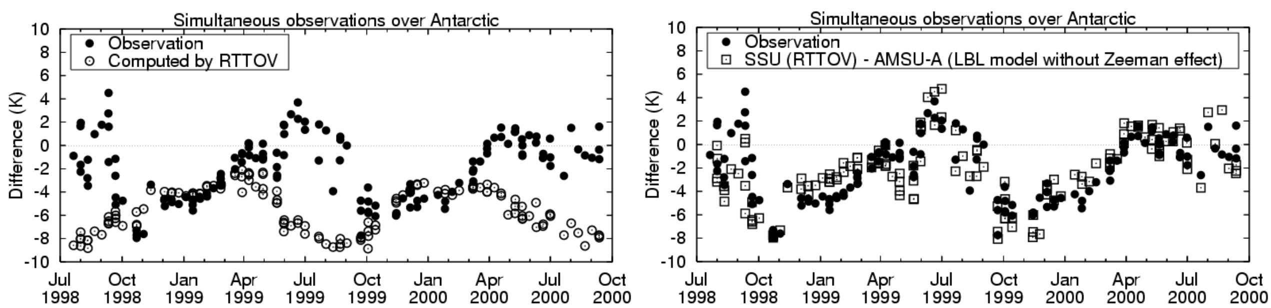

Figure 8 Difference between SSU3 on NOAA-11 and AMSU-A14 on NOAA-15 radiances.
Left: RTTOV was used for the AMSU-A computations. Right: No Zeeman effect model was used.

4 IMPACT ON THE STRATOSPHERIC TEMPERATURE ANALYSIS

To assess the impact of the new RTTOV coefficients for AMSU-A on the analysis fields, assimilation experiments have been performed. The control assimilation utilised the ERA-Interim system configuration (T255L60) with the current RTTOV coefficients, and the new RT experiment utilised exactly the same system configuration except for the new RTTOV coefficients for AMSU-A. Figure 9 shows the evolution of the vertical temperature structures in the Polar Regions. The control assimilation tends to create spurious peaks around model levels 6 and 10 (2 and 5 hPa respectively) when the strong polar vortex develops in winter. This is because the weighting function for AMSU-A channel 14 in the current RTTOV is located too high, which results in too warm radiance simulations when the mesosphere is warmer than the stratosphere. Such a situation occurs in the Polar Regions in winter. In the new RT experiment, these spurious peaks have been reduced and the vertical temperature structure varies more smoothly with seasons. The monthly averaged zonal mean temperatures also demonstrate the significant reduction of the spurious peaks in the Polar Regions (not shown).

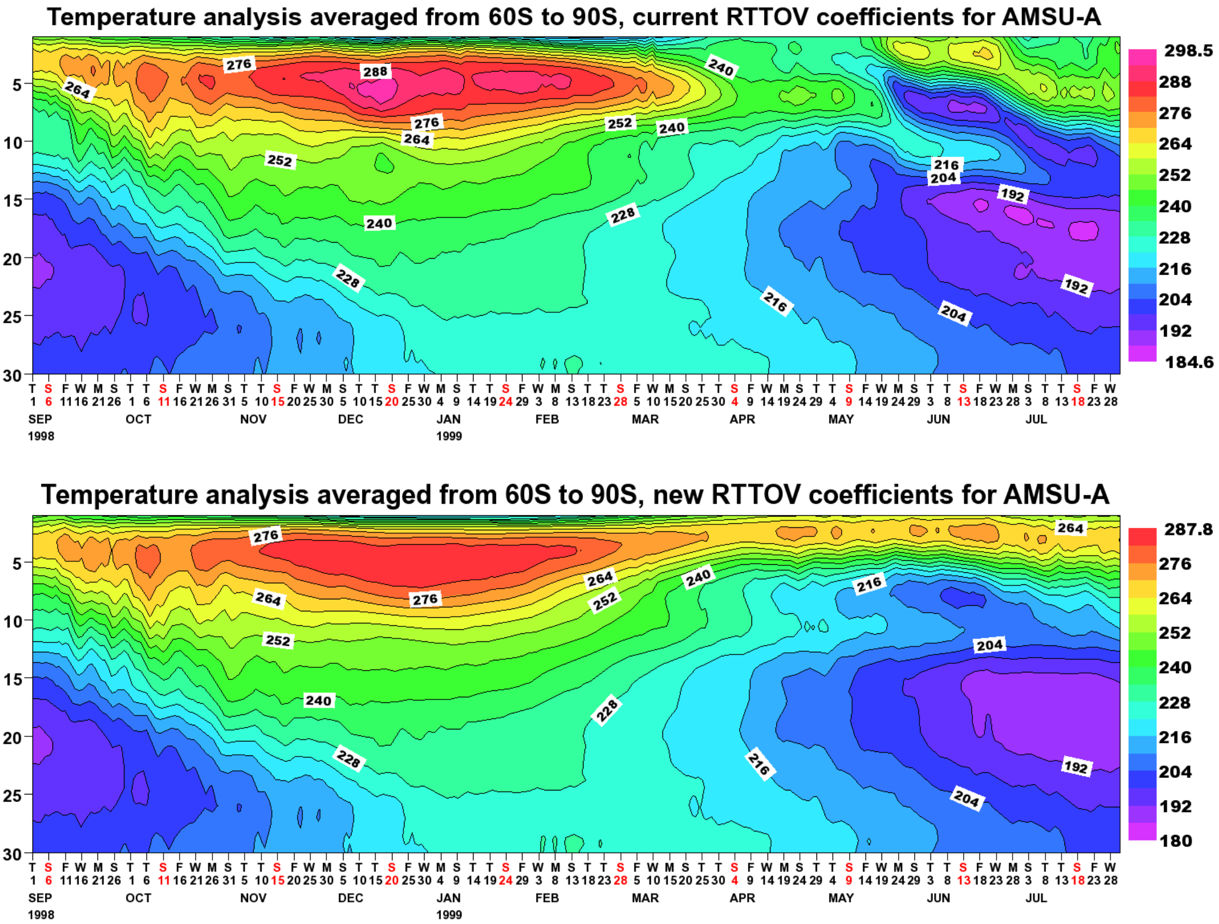

Figure 9 Evolution of the vertical temperature structures over the Antarctic from September 1998 to July 1999 in the control assimilation (top) and the new RT experiment (bottom). The vertical axes represent model levels.

5 CONCLUSION

For a better use of the SSU and AMSU-A observations in reanalyses, this study addressed the biases in the radiative transfer modelling for these instruments. The radiative transfer coefficients for SSU in RTTOV were updated using more appropriate spectral response functions and introducing variable CO_2 as a state vector in RTTOV. For AMSU-A, the inaccurate treatment of the Zeeman splitting effect in RTTOV was found to result in a overestimation of the optical depths. To correct this, the radiative transfer coefficients for AMSU-A were also updated by not taking into account the Zeeman splitting effect. The updated RTTOV was validated by computing the inter-satellite radiance differences for the co-located locations and comparing them with those evaluated by the SNO technique. The results demonstrated a clear reduction of the biases due to the improvement of the accuracy of the radiances simulated by the updated radiative transfer model. This improvement of the radiative transfer modelling for SSU and AMSU-A is expected to increase significantly the time consistency of stratospheric temperature analyses.

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