Assimilation and monitoring of SSMIS, AMSR-E, and TMI data at ECMWF

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Abstract

Non-rainy data from three conically scanning microwave instruments are investigated for use in the ECMWF data assimilation system. The three instruments are the SSMIS on F-16, AMSR-E on Aqua, and TMI on the TRMM satellite. For SSMIS, the dataset pre-processed by the UK Met. Office is used, in which solar intrusions are flagged, and a correction is applied to take into account the thermal emissions from the instrument’s reflector.

Monitoring and assimilation experiments with SSMIS temperature sounding channels show that standard deviations of First Guess departures for the SSMIS channels are comparable or slightly larger than corresponding AMSU-A channels, but significant local bias anomalies remain. These anomalies are, for instance, a positive observation minus First Guess bias when the satellite emerges from the Earth’s shadow, and an apparent day/night bias in some channels. Assimilated in addition to the observational set of observations, SSMIS temperature sounding channels have an overall neutral impact on analyses and forecasts. Added to a depleted system that only assimilates conventional observations and Atmospheric Motion Vectors, SSMIS temperature sounding channels have approximately 2/3 of the impact of the NOAA-15 AMSU-A, even though 30-40% of the SSMIS data are flagged due to solar intrusions.

Monitoring of AMSR-E, TMI, and the SSMI-like channels on SSMIS highlights the potential for assimilation of these data in clear-sky regions. Assimilation experiments with SSMI-like channels from AMSR-E and SSMIS show a small positive forecast impact for lower tropospheric humidity.

Introduction

In this paper we investigate non-rainy data from three conically scanning microwave instruments for use in the ECMWF data assimilation system. The three instruments are the Special Sensor Microwave Imager/Sounder (SSMIS) onboard the Defense Meteorological Satellite (DMSP) F-16 platform, the Advanced Microwave Scanning Radiometer (AMSR-E) on the Aqua satellite, and the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) on the TRMM satellite. The conical
scan geometry means that these instruments measure radiances with a fixed polarisation state along the scan.

The first of five planned SSMIS instruments was launched on 18 October 2003. The instrument provides data in 24 channels, combining a range of temperature sounding channels (50-60 GHz, AMSU-A heritage), humidity sounding channels (183 GHz, AMSU-B heritage), and imager channels (19-92, 150 GHz, AMSU-B/SSMI heritage) with new mesospheric sounding channels (60-63 GHz). Details of the instrument and its characteristics can be found in Swadley et al. (2006).

The post-launch cal/val program revealed significant instrument anomalies, namely solar intrusions into the external calibration load, and thermal emissions from the main reflector. These anomalies were characterised and analysed with substantial involvement of passive monitoring of the measured brightness temperatures against simulations from Numerical Weather Prediction (NWP) data, and more details on the anomalies can be found in Bell (2006). Mitigation methods are being developed by groups at the Met.Office, the Navy Research Laboratories (NRL), and NOAA/NESDIS.

For our experimentation we use the pre-processed SSMIS dataset provided by the Met. Office (Bell 2006). In this dataset, data affected by solar intrusions are flagged and no correction of the intrusion effects is attempted. Corrections arising from the reflector emissions are included, based on an estimate of the reflector temperature, reconstructed from the measured reflector arm temperature via a heat transfer equation. In addition, the dataset is averaged to the locations of channels 1-7, employing a spatial Gaussian weighting function with $\sigma = 50$ km. The latter feature ensures that data for all channels is collocated, which simplifies the use of the data. The averaging is also a good way to reduce the measurement noise, especially in the sounding channels, while at the same time making use of the oversampling of the radiance field provided by SSMIS.

The other two instruments considered here, AMSR-E and TMI, provide SSM-like imaging channels, plus lower-frequency channels, namely 10.65 GHz V & H for TMI (e.g., Kummerow et al. 1998), and 6.925 GHz V & H and 10.65 GHz V & H for AMSR-E (e.g., Kawanishi et al. 2003). Both instruments benefit from a somewhat smaller field of view compared to SSMI.

In the following, we will first present results from monitoring and assimilation experiments with the temperature-sounding channels on SSMIS. This is followed by monitoring of the imager channels from SSMIS, AMSR-E, and TMI, together with assimilation trials for these channels from SSMIS and AMSR-E. The AMSU-B-like channels of SSMIS have not yet been characterised. Conclusions are provided in the last section.

**SSMIS temperature-sounding channels**

The temperature-sounding channels on SSMIS have been monitored and assimilated in the ECMWF assimilation system (e.g., Rabier et al. 2000). Unless indicated otherwise, we use a configuration with 12-hour 4DVAR, T511 (~40 km) model resolution, T159 (~125 km) analysis resolution, 91 levels in the vertical. The channels considered are 3-7 and the stratospheric channels 23-24. The mesospheric channels 19-21 are not considered here, as these are affected by Zeeman effects, and such effects are not included in the RTTOV radiative transfer model used for our calculations. Channel 22 is also not
considered here, as early monitoring indicated unstable biases. We consider channels 3-4 over sea
only. Too large cloud contributions are avoided by excluding data which shows absolute First Guess
(FG) departures in channel 2 larger than 0.7 K, or liquid water path estimates larger than 300 g/m²,
based on regressions for the liquid water path using the 22 and 37 GHz V channels. Variational bias
correction (Auligné et al. 2006) is performed as for AMSU-A, i.e., we employ a 4-predictor model,
with the predictors being FG layer thicknesses covering the troposphere and stratosphere.

**Monitoring results**

Passive monitoring of SSMIS over the period 9 March - 30 April 2006 show that standard deviations
of FG departures are broadly comparable to those typically obtained for the corresponding AMSU-A
channels. Figure 1 shows these statistics for SSMIS in comparison to AMSU-A, ignoring the
polarisation differences arising from the conical (SSMIS) versus the cross-track (AMSU-A) geometry.
Channel 3 and 4 show slightly smaller FG departures than the corresponding AMSU-A channels,
whereas channels 6-7 show somewhat larger FG departures.

![Figure 1: Standard deviation of FG departures [K] over the Southern Hemisphere for SSMIS (black) for the
experiment in which SSMIS data are passive. Also shown are statistics for AMSU-A from NOAA-18 for
comparable channels, with channel numbers indicated in red on the y-axis.](image)

While biases against FG-simulated radiances are close to zero after bias correction when averaged
globally or over long periods, significant local bias anomalies are still apparent in experimentation in
which SSMIS data are treated passively. For instance, a positive bias of several tenths of K is apparent
in all temperature sounding channels in a region around 30N in the ascending nodes (e.g., Fig. 2). This
bias coincides with an area where the DMSP-16 satellite emerges from the Earth’s shadow, leading to
very rapid changes in the reflector temperature. It appears that the currently employed simple model to
reconstruct the reflector temperature from the arm temperature is not adequate to handle this extremely
fast change. Flagging of these data in the Met.Office pre-processor would be considered beneficial.
In addition, ascending nodes and descending nodes tend to show biases with opposite signs in the FG departures for most of the temperature sounding channels. This aspect is best seen in scatter diagrams of the FG departures versus the solar zenith angle (Fig. 3). For the period considered, channel 3 displays biases of almost ±0.1K over the range of solar zenith angles encountered, whereas for channel 24 these can be as large as ±0.7K. In comparison, no such behaviour can be found for comparable AMSU-A channels (not shown), suggesting that this is an SSMIS instrument problem. The reasons for the apparent day/night bias are not fully understood, but the feature may be related to neglecting the effect of outgoing long-wave radiation in the heat-transfer equation used to reconstruct the reflector temperature. Future work will address these bias anomalies.
Forecast impact

Assimilation trials were performed with the SSMIS temperature sounding channels, despite the bias anomalies discussed above. Two sets of trials were performed: one in which SSMIS data were added to the full operational set of observations, and one in which SSMIS and NOAA-15 AMSU-A data were added, respectively, to a reference system with limited use of other satellite observations.

Forecast impact: full system

The trial with the full set of observations covered the period 9 March - 30 April 2006, with 10-day forecasts performed for every 00Z analysis. Given the remaining anomalies, fairly cautious observation errors were assigned to the SSMIS data, namely 0.5 K for channel 3, 0.7 K for channel 4, 1.0 K for channels 5-7, and 2.0 K for channels 22-24. These observation errors are 50-100% larger than corresponding AMSU-A observation errors. The anomaly arising from the satellite’s emergence from the Earth’s shadow was flagged based on a diagnostic multi-channel threshold check on the FG departures. Two experiments were conducted: the CTL experiment without using SSMIS data, and the EXP experiment in which SSMIS temperature-sounding channels were assimilated. Both experiments make use of the full operational set of observations, encompassing a range of conventional observations, Atmospheric Motion Vectors from geostationary and polar satellites, and radiances from a range of instruments, most notably 4 AMSU-As.

The impact of adding the temperature-sounding SSMIS channels to the system is generally neutral over the 53-day period. The FG or analysis fit to other observations is unaltered, suggesting that using
SSMIS data with such large observation errors is not in disagreement with other observations. Mean forecast scores are also not significantly altered throughout the atmosphere over the forecast range considered, with differences in root mean square errors less than 1% for geopotential and wind throughout the troposphere up to the day-5 forecast (e.g., Fig. 4).

Figure 4: Differences in the 500 hPa geopotential root mean square forecast error between CTL and EXP, normalised by the mean root mean square forecast error from both experiments, as a function of forecast range. Positive values indicate an improvement in the forecast error from assimilating SSMIS observations. Also shown are 90% confidence intervals, calculated based on a t-test on the score differences. The left panel shows results for the Northern Hemisphere extra-tropics; the right panel for the Southern Hemisphere extra-tropics. The experiments cover the period 9 March - 30 April 2006 (53 cases).

Forecast impact: reference system

To further characterise the impact of the SSMIS data we conducted an experiment in which the temperature-sounding channels were added to a reference system that only assimilates conventional observations and Atmospheric Motion Vectors from geostationary and polar satellites. The forecast impact is also compared to instead adding the NOAA-15 AMSU-A to the reference system, and to using the full operational observing system. Similar approaches to observing system experiments have recently been taken in the comprehensive study by Kelly and Thépaut (2006), following a recommendation from Böttger et al. (2004). One motivation for performing such experiments in a depleted system is that it is often difficult to demonstrate the impact of additional data in a well-constrained system.

In contrast to the trial described above, the experiments with the reference system use the 6-hour 4DVAR configuration, with a model and analysis resolution of T159 (~125 km), and they cover the period 12 December 2005 - 11 January 2006. An additional 8 days of experimentation were added before this period, in order to spin up/down the experiments. The radiance bias correction models for SSMIS or AMSU-A were kept fixed during the experiment, to avoid drifts arising from a fairly poorly constrained analysis.

A substantial positive forecast impact is evident from adding the temperature-sounding SSMIS channels to the reference system. SSMIS adds about 8h of forecast skill for the 500 hPa geopotential over the Southern Hemisphere, compared to about 12h for AMSU-A (Fig. 5). This is an encouraging result for SSMIS, especially considering that 30-40% of the SSMIS data are currently flagged due to solar intrusions. Over the Northern Hemisphere, a much smaller positive impact is apparent for the one AMSU-A or SSMIS.
Figure 5: Anomaly correlation for the 500 hPa geopotential forecast versus forecast range for the reference experiment (red), reference + SSMIS temperature sounding channels (blue), reference + NOAA-15 AMSU-A (orange), and the full observational system (black). Results for the Northern Hemisphere extra-tropics are shown in the top panel, for the Southern Hemisphere extra-tropics in the bottom panel. The experiments cover the period 12 December 2005 - 11 January 2006 (31 cases).

Conical imagers

The SSMI is currently the only conically scanning microwave imager for which data are operationally assimilated in clear-sky regions over oceans in the ECMWF system (the data are also assimilated operationally in rainy areas at ECMWF, see Bauer et al. 2006, but this aspect is not covered here). The data primarily provide total column humidity information, with some effect on surface winds. The coverage for these frequencies can be greatly improved by adding data from the imaging channels on SSMIS, as well as data from AMSR-E and TMI (e.g., Fig. 6). Data from these additional sensors have been monitored passively against the FG in the ECMWF system. For SSMIS, we again use the pre-processed dataset provided by the Met. Office. For technical reasons, the 89 GHz AMSR-E channels were not available for this monitoring. Cloud/rain screening is based on regressions for the liquid water path, using the 22 and 37 GHz V channels. The monitoring and assimilation experiments use the 12h 4DVAR configuration of the ECMWF assimilation system, with a model resolution of T511 (~40 km), and an analysis resolution of T159 (~125 km), and 91 levels in the vertical.
Standard deviations of FG departures from passive monitoring are comparable or better than those for SSMI for all three instruments considered (Fig. 7). For SSMIS, the standard deviations are in fact considerably smaller than is typical for SSMI, most likely primarily a result of the averaging performed as part of the Met.Office pre-processor. Note also that the standard deviations of the analysis departures are generally smaller than for the FG departures, providing also an independent validation of the quality of the ECMWF analysis.

Figure 7: Standard deviations [K] of First Guess (solid) and analysis (dotted) departures for the 30 day period 1-30 April 2006. The three panels show statistics for SSMIS, AMSR-E, and TMI in black, respectively, versus those for SSMI in red. Note that SSMI was actively assimilated, whereas the other sensors were not.
Biases against the FG for the three instruments are relatively large, especially for the lower-frequency channels of AMSR-E and TMI, where observation minus FG biases can reach -6 to -10 K (not shown). This is most likely due to biases in the model fields and shortcomings in the surface emissivity model (FASTEM) employed for these calculations. FASTEM is a fast parameterisation of an emissivity model based on geometric optics, and such models provide poor emissivity estimates for microwave frequencies below 20 GHz.

Assimilation experiments have been performed with the imaging channels of SSMIS, and with channels 5-9 of AMSR-E. The fit to other observations used in the system is generally unaffected by adding the new data, except for FG and analysis departures for SSMI over the tropical region. These show a reduction in the standard deviations, suggesting an improved quality of the FG.

The separate assimilation of the imager channels of SSMIS and AMSR-E leads to a small, but significant improvement of lower tropospheric humidity forecasts over the tropics (e.g., Fig. 8). For the geopotential or surface wind the forecast impact is mainly neutral, except for a slight degradation in the 5-10 day range around the tropopause for the Southern Hemisphere.

Conclusions

In this paper we investigated the use of three conically scanning microwave instruments, namely SSMIS, AMSR-E, and TMI. The main findings are:

- Monitoring of the SSMIS temperature-sounding channels indicates reasonable noise performance, but considerable bias anomalies still remain in the data. For instance, a positive anomaly is present in all temperature sounding channels around the satellite’s emergence from the Earth’s shadow, and several channels exhibit an apparent day/night bias. Improved methods to correct these anomalies are desirable before the data can be used operationally in the ECMWF system. Trials with the current data indicate a neutral forecast impact.

- Adding the temperature-sounding channels from SSMIS to a reference system that uses conventional observations and AMVs only results in a significant positive impact that is comparable to about 2/3 of the impact obtained from adding AMSU-A on NOAA-15 to the reference system. This is despite the remaining SSMIS instrument anomalies and despite the fact that 30-40% of the data are flagged due to solar intrusions. Adding SSMIS to the full operational set of observations results in a neutral forecast impact.
Experiments with the non-rainy imager data over ocean from SSMIS or AMSR-E show that adding these data to the full set of observations used in the ECMWF system results in improvements in forecasts of the lower tropospheric humidity. TMI data shows similar standard deviations of FG departures, and assimilation trials with TMI data will commence shortly.

The experimentation with SSMIS data is encouraging in the sense that the instrument anomalies identified during the cal/val phase have been greatly reduced, such that the data now appears much closer to useable within an operational system. Future work on the corrections will hopefully result in further improvements. Also, the SSMIS instrument onboard F-17 has been launched on 4 November 2006. Modifications to the instrument should ensure that the problems encountered with the first instrument are not repeated. A fence has been added to avoid solar intrusions into the calibration load. Also steps were taken to avoid the degradation of the instrument’s reflector, combined with modifications to the positioning of the reflector’s thermistor in order to allow better emission corrections in the unlikely event that degradation does occur. As a result, there is considerable optimism that the F-17 will provide much improved data quality.

The above experiments do not yet make full use of the capabilities of SSMIS data. Firstly, the AMSU-B-like channels have not yet been assimilated, and these channels have the potential to further improve the moisture analysis. Secondly, and more importantly, our experiments do not make use of the wider range of window channels together with the fixed polarisation states provided by SSMIS, for instance in order to better specify surface emissivity over land, snow, or ice for assimilation of surface-sensitive sounding channels. Further work is required in this respect to exploit these strengths of the SSMIS instrument over cross-track scanners such as AMSU-A. Also, ECMWF now assimilates rainy radiances from SSMI, and the same approach could be adopted for the assimilation of SSMIS, AMSR-E, or TMI data in rainy areas.

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References


