The assimilation of AMSU and SSM/I brightness temperatures in clear skies at the Meteorological Service of Canada

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Abstract

In recent years, the assimilation of satellite data has become a vital component of the global and regional assimilation systems at the Canadian Meteorological Centre (CMC). Moreover, the direct assimilation of satellite radiance measurements from AMSU-A, AMSU-B, and the GOES water vapor channel has resulted in notable improvements in the short and medium range CMC forecasts. This has been demonstrated in Observation System Experiments conducted by CMC.

In preparation for the operational assimilation of Special Sensor Microwave Imager (SSM/I) data in the 4D-Var global analysis system at CMC, two 3D-Var experiments are conducted. In the first experiment, the assimilation of clear-sky, open-ocean brightness temperatures from the 7 SSM/I microwave channels is added to the operational configuration of the global analysis system. In the second experiment, stricter filtering of AMSU data is applied together with the addition of the SSM/I data. More specifically, AMSU-A CH3 (50.3 GHz) is removed due to its non-negligible sensitivity to clouds, and more aggressive filtering of AMSU-B CH2 (150.0 GHz), CH3 (183.3±1 H GHz), CH4 (183.3±3 H GHz), and CH5 (183.3±7 H GHz) is invoked using CH2 to identify cloudy pixels. In the current quality control procedures for AMSU-B, an effective precipitation screen is present, however, there is no method of detecting and removing cloudy observations.

In both experiments, improvements are evident in the analysed integrated water vapour, surface wind speed, and daily precipitation rate fields when compared against independent observations. Furthermore, for the second experiment gains are realized in the forecasts when validated against radiosonde data. Other indicators such as anomaly correlation, RMSE, and QPF scores show a net positive effect. Overall, the second experiment shows better results than the first. In particular, the additional filtering of AMSU-B CH2-5 is identified as an important modification to the current operational configuration.

Introduction

At the Canadian Meteorological Centre (CMC), improvements in the global analyses and forecasts in recent years have largely been realized as a result of an increased assimilation of satellite data. Since March of 2005, the CMC global analyses are generated using a 4D-Var assimilation scheme which assimilates conventional data (e.g. radiosonde, aircraft, wind profilers), satellite derived automated motion vectors, and satellite radiances (GOES-W, GOES-E, AMSU-A aboard NOAA-15, -16, and AQUA, and AMSU-B aboard NOAA-15, -16, and -17).

One of the anticipated changes to the operational analysis system over the next year is the addition of Special Sensor Microwave Imager (SSM/I) data. In preparation for this, experiments are conducted to satisfy two primary objectives. The first is to determine the impact of the assimilation of SSM/I brightness temperatures in clear-skies and over open oceans. The second is to test a stricter filtering regime for the AMSU data currently assimilated. The motivation for this modification will be discussed in the subsequent section. This will be followed by descriptions of the setup and results of the two experiments. The paper ends with conclusions and a brief discussion of future work.

Modifications to the Selection Process for AMSU Data

Currently, the CMC assimilates from the AMSU-A instrument channels 3 through 10 over oceans and channels 6 through 10 over land. Observations in precipitating and cloudy regions are filtered using algorithms (Grody et al. 2001) which compute the scattering index and cloud liquid water (CLW) amount, respectively. The CMC's variational analysis system is not capable of assimilating cloudy observations since CLW is not an analysed variable and, moreover, the radiative transfer model assumes that CLW is zero. The cloud filter functions by removing pixels with a CLW value greater than 0.3 mm. However, AMSU-A channel 3 exhibits a moderate sensitivity to clouds (Fig. 1), which raises the possibility that the 0.3 mm threshold is not sufficiently low to properly remove observations affected by moisture. The danger is that a bias in the water vapour field might be introduced where observations in cloudy, non-precipitating regions are assimilated since a higher brightness temperature would induce a larger humidity value in the analysis. For this reason, in the second experiment all observations from AMSU-A channel 3 are eliminated from the assimilation process.

From the AMSU-B instrument, channels 2 though 5 and channels 3 and 4 are assimilated operationally over oceans and land, respectively. A precipitation screen based on the scattering index algorithm developed by Bennartz et al. (2002) removes rainy observations. However, no cloud filter is present. Due to the moderate sensitivity of AMSU-B channel 2 to clouds (Fig. 2), this channel is subjected to additional filtering in the second of our experiments. This enhanced filtering is also applied to AMSU-B channels 3 through 5, due to their small sensitivity to clouds at mid-levels (Fig 2.). This filter is essentially a pseudo cloud filter, and it is the same as that applied at Meteo-France and the European Centre for Medium-Range Weather Forecasts (ECMWF). It removes AMSU-B observations over oceans where the absolute difference between the observed and background brightness temperatures for AMSU-B channel 2 exceeds 5 K.

Experiment Setup

The experiments are executed over a five week period during the summer of 2003, from June 24th to July 31st. To avoid any spurious effects that can occur when changes are made to the analysis system, the first week of analyses are discarded. A control simulation (CNTL) is produced using the same configuration as that employed operationally during July 2003. At this time the 3D-Var assimilation scheme was active and the trial fields were produced using the CMC's 0.9^{o} resolution global model with 28 terrain-following vertical levels. The conventional observations included in CNTL are from surface, dropsonde, radiosonde, and aircraft sources. Input data also consists of the direct assimilation of radiances from the GOES-W geostationary satellite and brightness temperatures from the AMSU-A and AMSU-B instruments aboard the NOAA-15, -16, and -17 polar orbiters.

The first experiment (EXP1) is produced by adding clear-sky, open-ocean observations from the SSM/I instruments aboard the DMSP-13, -14, and -15 satellites to the CNTL setup. All 7 channels of SSM/I are assimilated. The frequencies and polarities of these channels are 19.35 V,H, 22.235 V, 37.0 V,H, and 85.5 V,H GHz. The SSM/I is an imager and, therefore, provides information on vertically integrated quantities such as IWV and CLW. It is not characterized by a strong sensitivity to air temperature. The horizontally polarized channels also show a moderate sensitivity to SWS. In the second experiment (EXP2), the SSM/I data is added while select AMSU data is removed. This refers to the complete rejection of AMSU-A channel 3, as well as the application of the pseudo cloud filter to AMSU-B channels 2, 3, 4, and 5, as described in the previous section.

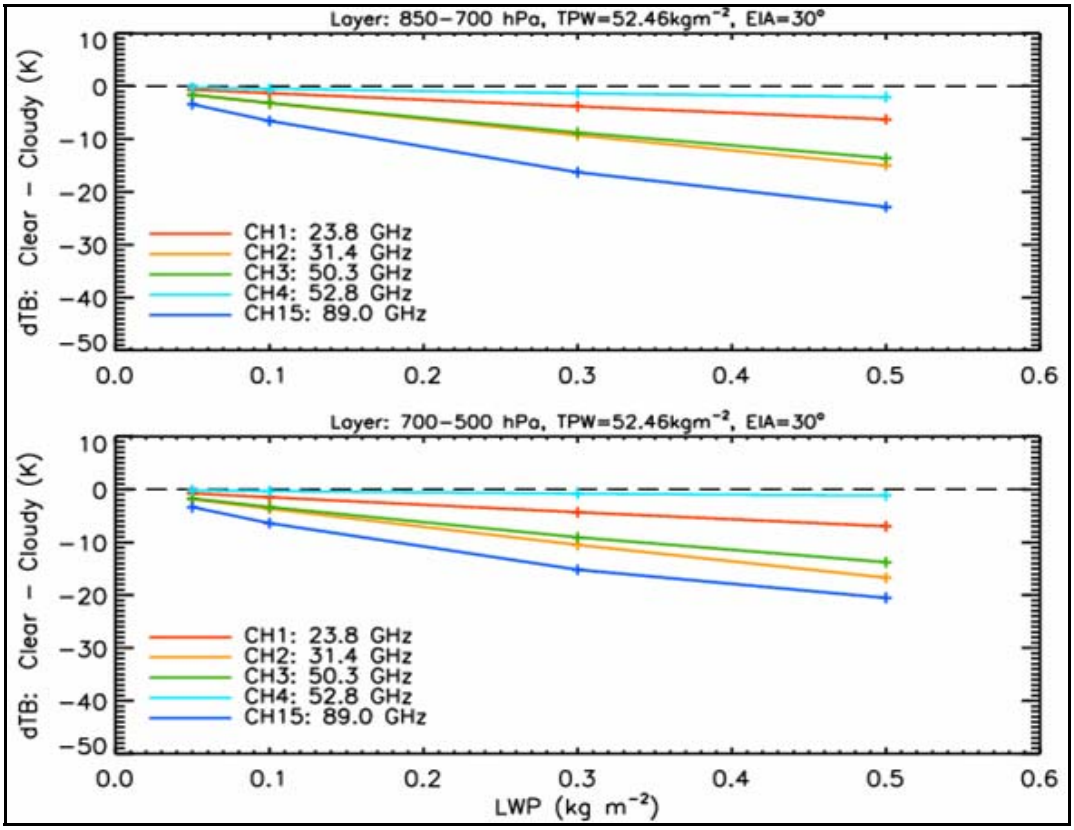

Fig. 1: Sensitivity of AMSU-A channels to clouds (LWP = Liquid Water Path in kg m^{-2}). Top (bottom) panel represents a cloud layer between 850 and 700 hPa (700 and 500 hPa).

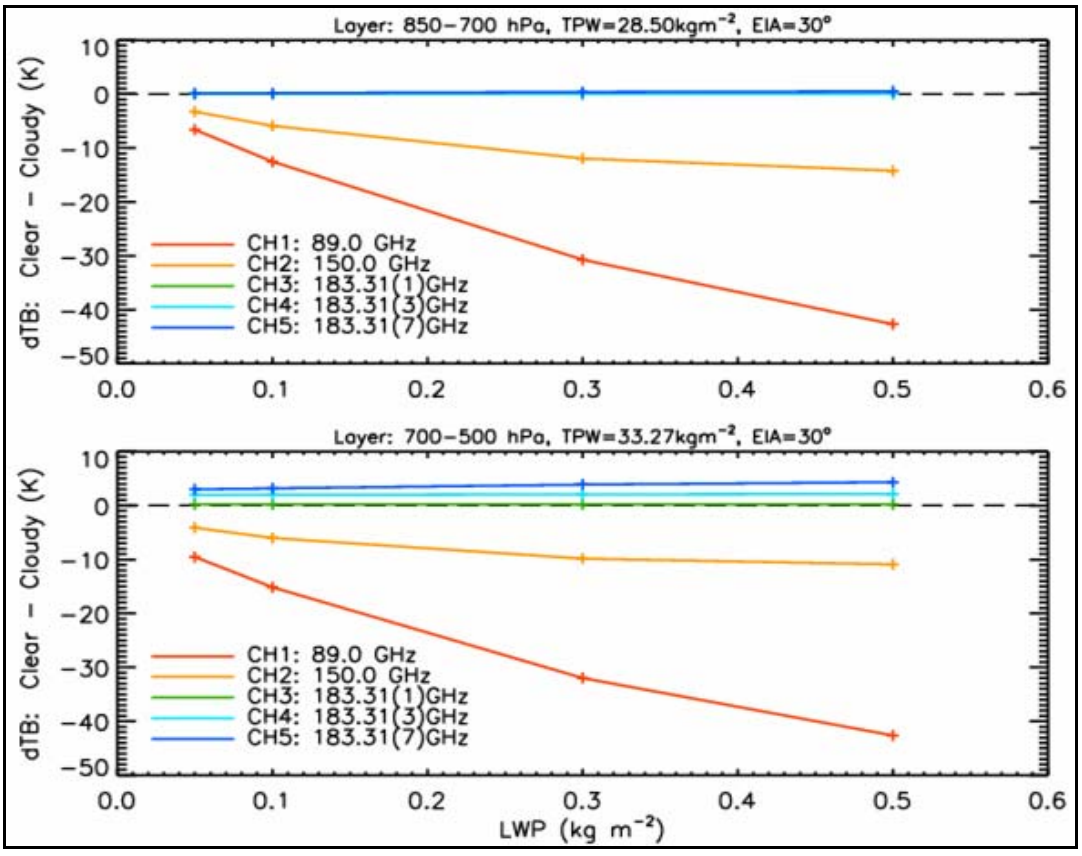

Fig. 2: Same as in Figure 1, except for AMSU-B channels.

The analyses generated from each of the cycles are studied using monthly averaged fields of integrated water vapour (IWV) and surface wind speed (SWS) derived from the Advanced Microwave Scanning Radiometer (AMSR-E) aboard the AQUA spacecraft and QuikSCAT, respectively. Daily precipitation rates (DPR), computed by accumulating the 6-hr forecast amounts extracted from the trial fields, are evaluated using observed values from the Global Precipitation Climatology Project (GPCP). Ten-day forecasts for each of the cycles are validated using both radiosonde observations (RAOBS) and analyses from the same experiment. As part of the validation, standard deviation (SD), bias, root mean square (RMS) error, and anomaly correlation (AC) statistics are generated. Finally, quantitative precipitation forecasts (QPFs) over North America are verified using 3 categorical measures – bias, threat score, and equitable treat score.

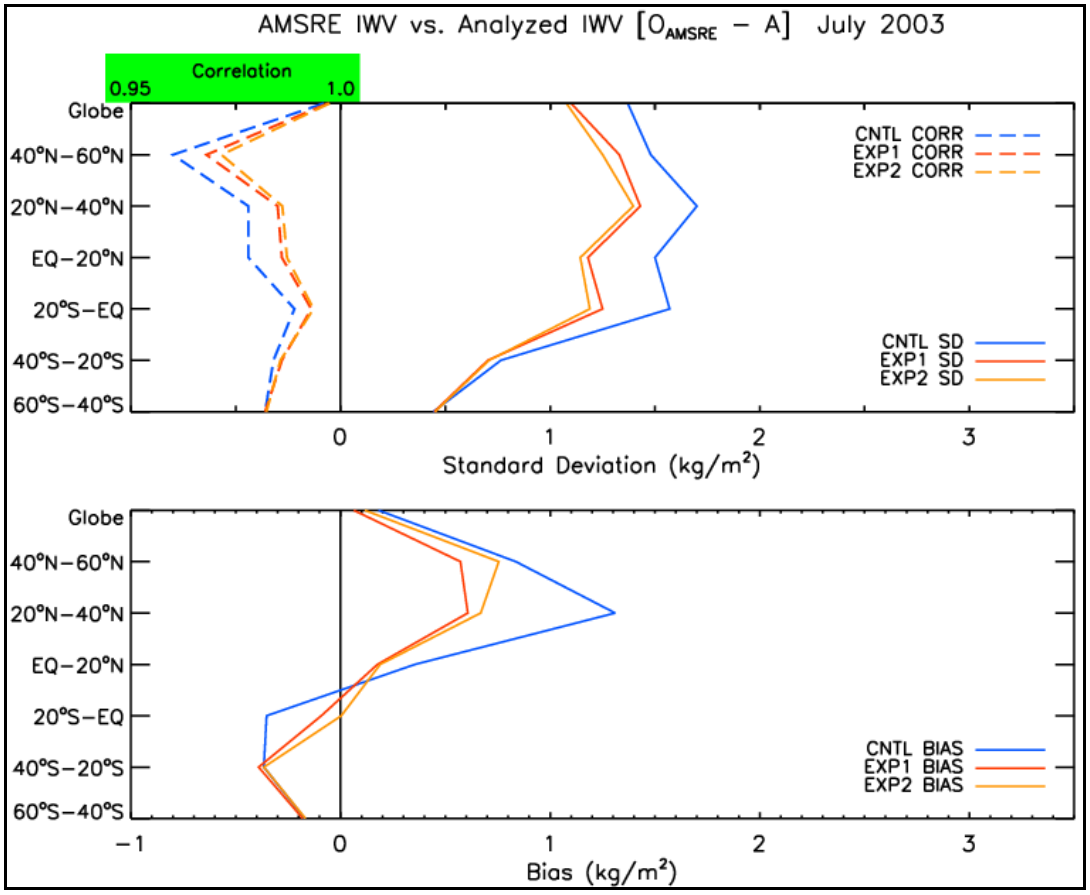

Fig. 3: A comparison of monthly mean IWV (kg m^{-2}) from the CNTL, EXP1, and EXP2 analyses against that observed by the AMSR-E. The top diagram shows correlation on the left and standard deviation on the right. The bottom diagram shows bias.

Experiment Results

With the addition of SSM/I data to the CNTL configuration (EXP1), improvements are evident in the mean analysed fields that are evaluated using independent observations. The largest impact of SSM/I is illustrated in the comparison of the mean analysed IWV for July against that observed by the AMSR-E (Fig. 3). In every 20 degree latitude band between 60°S and 60°N positive gains are made with respect to correlation (CORR), SD, and bias. In the comparison of SWS to QuikSCAT observations, small gains in CORR and SD are made almost everywhere on the globe (not shown). However, the bias deteriorates a very small amount everywhere except in the Southern Hemisphere

(SH) between 40° and 60°S. In this region the addition of SSM/I data has improved the analysed SWS by increasing it to more closely match that observed by QuikSCAT. Over the SH circumpolar ocean, the operational analysed winds are generally underestimated. With respect to DPR, small improvements are evident in all of the statistical fields, but primarily over tropical regions (not shown).

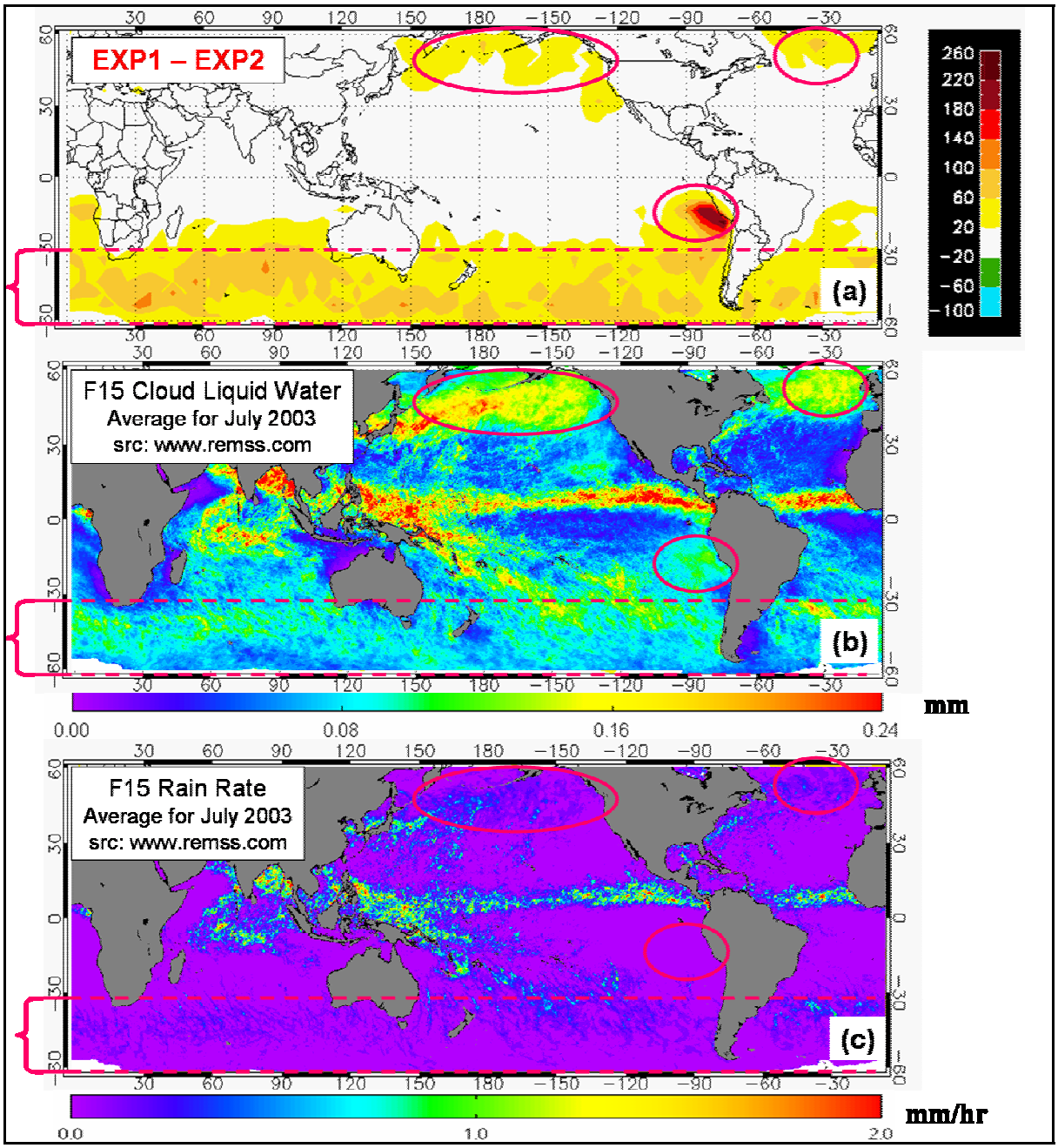

Fig. 4: Difference in the number of observations assimilated for AMSU-B channel 3 between EXP1 and EXP2 (a). Mean CLW (mm) (b) and surface rain rate (mm hr^{-1}) (c) derived from DMSP-15 SSM/I observations for July 2003 (from Remote Sensing Systems: www.remss.com).

Charts comparing the monthly mean analysed IWV, SWS, and DPR from EXP2 to the observed quantities exhibit very similar characteristics to those found with EXP1. Two exceptions are noted.

The first consists of slightly improved CORR and SD scores for the IWV and DPR fields over most of the globe for EXP2 over EXP1. The second is a small increase in SWS bias from EXP1 to EXP2 within the 40° to 60°S region. Thus, the complete removal of AMSU-A channel 3 and partial removal of AMSU-B channel 2, which are both slightly sensitive to SWS in mid-latitude atmospheres, results in a slower SWS over the SH circumpolar ocean. This offsets slightly the gains made by adding SSM/I data.

The effectiveness of the AMSU-B channel 2 pseudo cloud filter applied in EXP2 is demonstrated in Figure 4. The global distribution of the observations rejected by this filter over the month of July for AMSU-B channel 3 is plotted in Figure 4a. The distributions for channel 4 and 5 are very similar. Globally, the filter results in a 7% reduction in the number of observations assimilated for each channel. Note that the areas outlined in pink match quite closely those areas in the CLW chart (Fig. 4b) that are characterized by persistent cloudiness. The surface rain rate chart (Fig 4c) indicates that these areas are not precipitating much of the time, such that the precipitation screen would rarely be active. Therefore, in the absence of the pseudo cloud filter, it may be concluded that many AMSU-B observations are currently assimilated in cloudy, non-precipitating conditions in the CMC's operational analysis system.

In the validation of the 10-day forecasts for both experiments using RAOBS, small modifications are mostly observed. In fact, for EXP1 the effect is almost entirely neutral. This is not completely unexpected since SSM/I is assimilated only over oceans, and the majority of RAOBS are land-based. For EXP2 the overall impact is small but almost entirely positive. The most dramatic effect is an improvement in atmospheric humidity in the layer between 100 and 200 hPa over the SH, which appears in the comparison of observations to the 6-hr forecasts (Figure 5). The reduction in bias shown persists to day 6 of the forecasts. Other positive effects appear in the geopotential and wind fields, but mostly after day 5 (not shown).

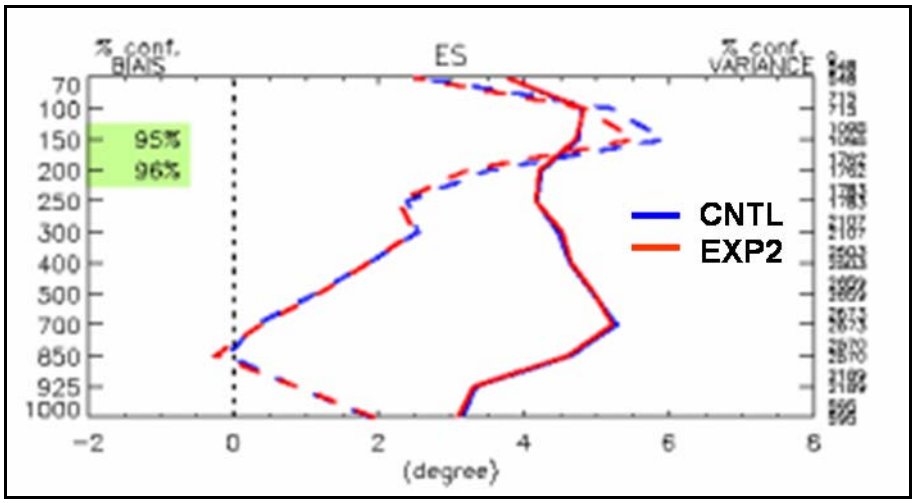

Fig. 5: Validation of the first-guess dewpoint depression (ES, units=K) from EXP2 using RAOBS for the SH (20° to 90°S). Bias is indicated by dashed lines and SD by solid lines. Statistical significance greater than 90% is highlighted by green shading.

In the validation of forecasts using their own analyses, other interesting impacts are documented. The improvements to the moisture field previously illustrated at high altitudes in the SH are also evident in the plot of RMS for EXP2 as shown in Figure 6. Further positive effects are evident in Figure 7, where the AC for the 850 hPa temperature field in the tropics is plotted. These scores are

improved for EXP2, with a negligible change for EXP1. This plot, as well as many others not shown, illustrate that in many instances, a greater positive impact is realized by the combination of adding SSM/I and removing select AMSU data, rather than by adding SSM/I by itself. Most of these improvements appear in tropical and SH regions.

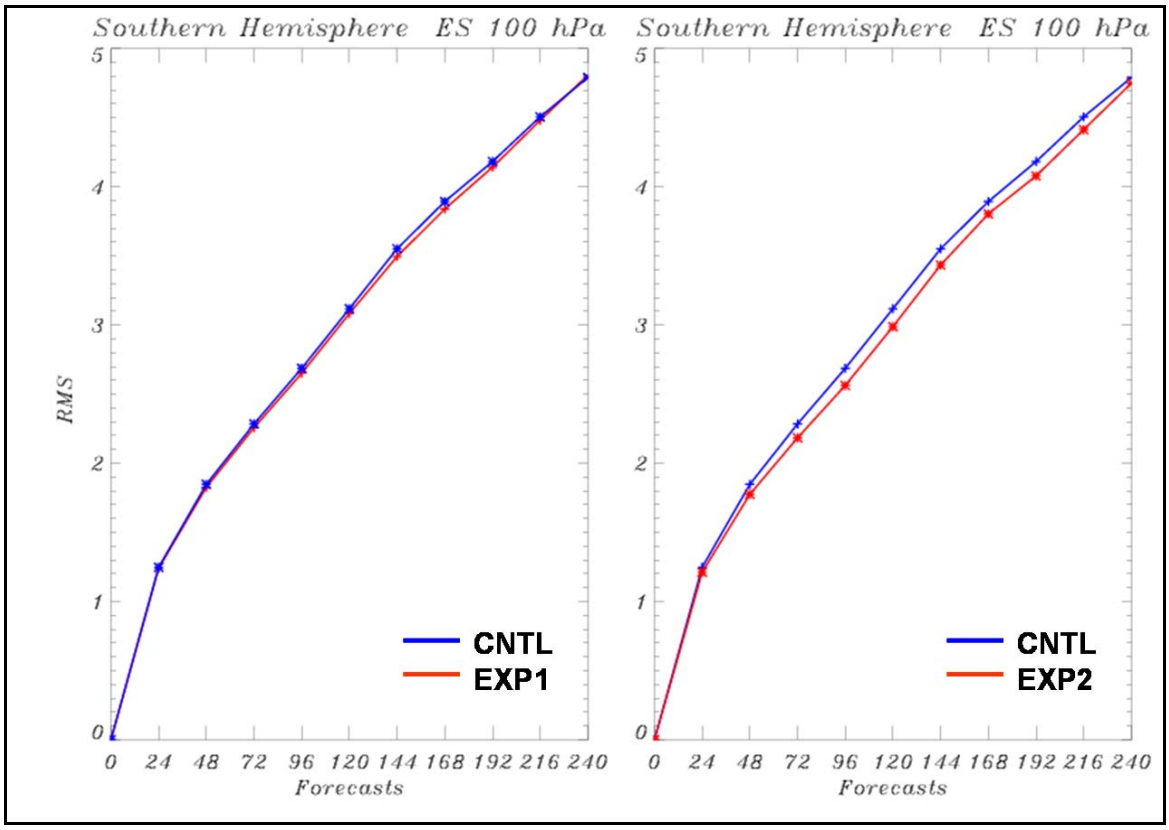

Fig. 6: RMS error of the 100 hPa dewpoint depression field in the SH plotted for EXP1 and EXP2 against CNTL.

The only negative impact of note is the effect on the 850 hPa RMS for moisture in the SH (Fig. 8). In this case EXP1 once again shows virtually no change, and EXP2 shows a small increase in RMS. This, however, is a small cost in relation to the gains made at other levels. Changes over other areas of the globe and in other fields are negligible for both experiments.

It is evident that the gains made in the analyses by the addition of SSM/I data alone do not translate into significant changes in the forecasts. This may be attributed to the presence of AMSU-B data, which has been shown to provide a considerable amount of information on atmospheric moisture to the CMC analysis and forecast systems (Chouinard and Hallé 2003, Anselmo and Deblonde 2003). Recall, that the SSM/I mainly provides information on atmospheric moisture.

Finally, the validation of QPF for the two experiments using bias, threat, and equitable threat scores over North America did not show any significant changes when compared to CNTL. This is not surprising since none of the modifications directly affected the assimilation of observations over land.

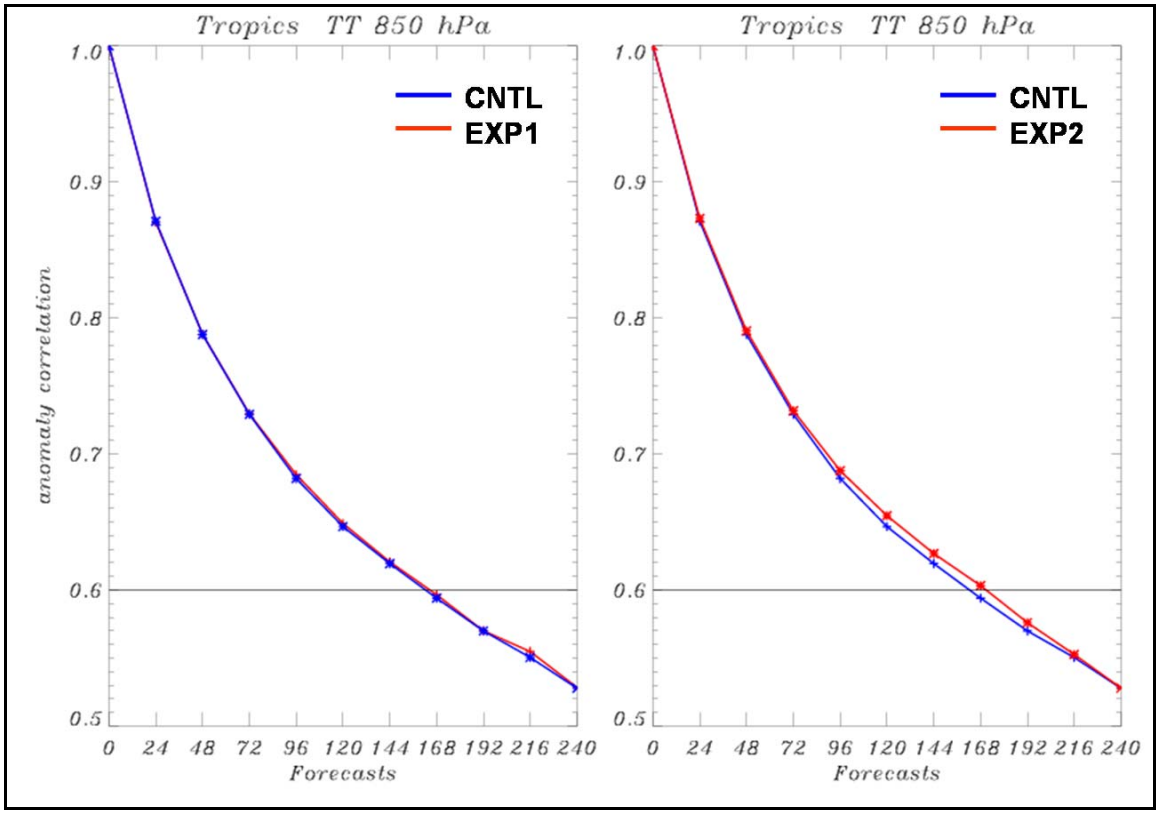

Fig. 7: AC of the 850 hPa temperature field in the tropics plotted for EXP1 and EXP2 against CNTL.

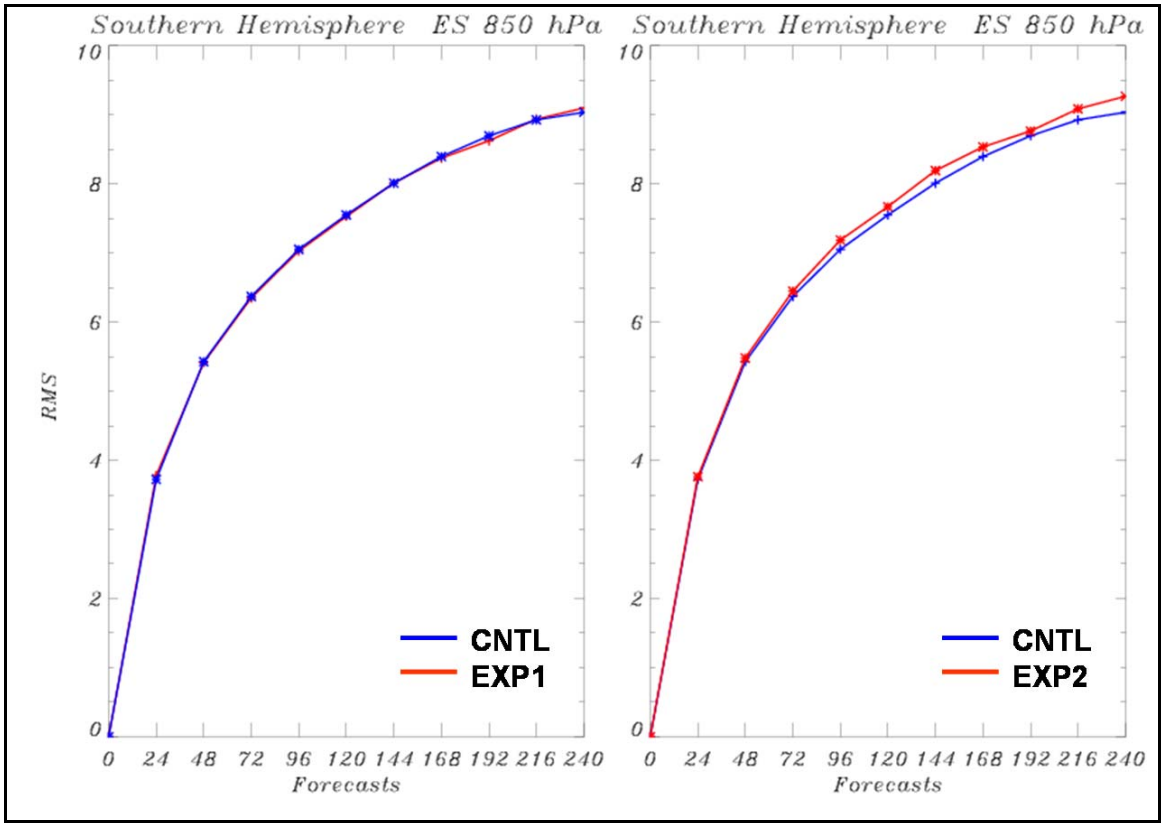

Fig. 8: Same as in Figure 6 except for 850 hPa.

Conclusions

Brightness temperatures from three SSM/I polar orbiting instruments are successfully assimilated in the CMC's 3D-Var scheme over a one month period during the Northern Hemisphere (NH) summer of 2003. In a second experiment, more strict filtering of AMSU data is tested concurrently with the assimilation of SSM/I data. An important component of the enhanced filtering is the application of a pseudo cloud filter to AMSU-B observations. Currently, AMSU-B data is assimilated operationally at CMC after rejecting observations in areas of precipitation. However, observations in cloudy, non-precipitating areas are not removed by the quality control measures in place today. It is shown in the second experiment that the application of the cloud filter results in the rejection of these observations. Therefore, it is highly recommended that this modification be considered for implementation into operations.

The addition of SSM/I data alone gives improvements to the analysed IWV, SWS, and DPR fields averaged over the month, however, the forecasts are not largely affected. The addition of SSM/I data plus the removal of AMSU-A channel 3, and the rejection of cloudy observations for AMSU-B channels 2, 3, 4, and 5 provides the same positive impact, but with additional improvements to the forecasts. The most notable of which appears in atmospheric moisture above the SH tropopause. Other less significant advances are evident in other fields and in other regions, mostly at longer forecast times. One small deterioration is observed in the statistics for humidity at 850 hPa in the SH.

Although the additional assimilation of SSM/I data by itself does not greatly change the forecasts generated by the global analysis system which already included AMSU data, its inclusion remains highly beneficial to the system. One reason is that because the observations from the two independent monitoring systems are complementary, a failure of any of the instruments assimilated would not have as large a negative impact on operational products. As well, an increase in the number and in the global coverage of satellite observations ingested should decrease the chances of missing extreme weather events.

Future Work

The same configurations used to generate EXP1 and EXP2 will be applied to a NH winter month to verify whether similar results are obtained. Following this work, simulations with the now operational 4D-Var global analysis system will be executed over two 2-month periods, one in NH summer and another in NH winter. A similar vigorous analysis of the output will subsequently be applied.

References

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