The Contribution of ATOVS Data to Operational NWP

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1. Introduction

A significant part of the large improvement in forecast skill in the last 10-15 years has resulted from the improved use of satellite data in data assimilation systems. With the development of variational assimilation techniques, it has become much easier to directly assimilate satellite based radiances into operational assimilation systems. Much of this capability was developed using the TIROS Operational Vertical Sounder (TOVS) and Advanced TOVS (ATOVS) satellite data (e.g., Eyre, 1989, Andersson, et al., 1994, Derber and Wu, 1998, English et al, 2000, etc.). While new advanced instruments, such as AIR and IASI, are now available, the ATOVS data remains the core of satellite sounder data assimilation. Also, the techniques used for the ATOVS data remain the basis for the use of many of the newer data sources.

In this paper, the techniques for assimilating satellite radiances will be reviewed from the perspective of the ATOVS data. While the general techniques are presented in this paper, the details of the assimilation are extremely important to the quality of the results. Also, details of the assimilation system (forecast model, background error covariances, etc.) determine many of the capabilities of the assimilation system. Improvement in the assimilation of ATOVS data continues, as significant enhancements to the satellite radiance assimilation techniques are still under development.

2. ATOVS data

For the purposes of this paper, ATOVS data will refer to all operational satellite sounding data received from the NOAA polar orbiters (AMSU-A, HIRS, AMSU-B/MHS) and similar instruments on other platforms (such as the GOES sounder, AMSU-A on AQUA and AMSU-A, HIRS, and MHS on METOP). More specific information on the NOAA polar orbiter instruments can be found at in the user guide at http://www2.ncdc.noaa.gov/docs/podug/. The microwave instruments from these satellites remain extremely important for operational NWP and will remain state-of-the-art over the near future, since the only other operational microwave instrument available is the SSM/IS. The SSM/IS has been plagued with problems since its launch and has not yet realized its full potential. For the infrared, the HIRS and GOES instruments are being replaced with instruments with much higher spectral resolution such as AIRS and IASI.

The data is acquired from either the data provider (NESDIS, EUMETSAT, NASA, etc.) or from direct read-out stations. The direct read-out stations can acquire data from the satellite which is more timely, but only over the region within direct view of the satellite while in contact with the direct read-out station. While a single, direct read-out station can only give limited coverage, a collection of data from several direct read-out stations can provide much better coverage. This has resulted in the creation of Regional ATOVS Retransmission Services (RARS). There are 3 current or planned RARS – Eumetsat ATOVS Retransmission Service (EARS), Asian-Pacific RARS, and Southern-American RARS. Further information on these programs can be found in Dumont et al. (2006).

The radiance data can come in a 1b or 1c format. The 1b format contains the earth located and calibrated raw data with some gross quality control of the data. The 1c format has had the calibration applied to the raw data, and it has been transformed into antenna temperatures and/or brightness temperatures. The application of the antenna correction transforms the antenna temperatures to the brightness temperatures accounting for contamination of the signal from cold space and the satellite platform because of the specific antenna pattern for the instrument (Mo, 1999, Hewison and Saunders, 1996).

The availability of ATOVS data on multiple platforms results in very good spatial coverage with considerable redundancy. Currently for the AMSU-A instruments, data is available from NOAA-15, -16, -18, AQUA and METOP. The resulting coverage for one 6 hour period, centered around 06UTC 31 July, 2007 (available by + 6 hours), is shown in Fig. 1. A similar figure for the IR (AIRS, N-17, METOP, GOES-11 and GOES-12) is shown in Fig. 2. Note in Fig.2, the N-17 data (green) was extremely limited by communication problems. The coverage is better for the microwave data because of fewer instrument failures.

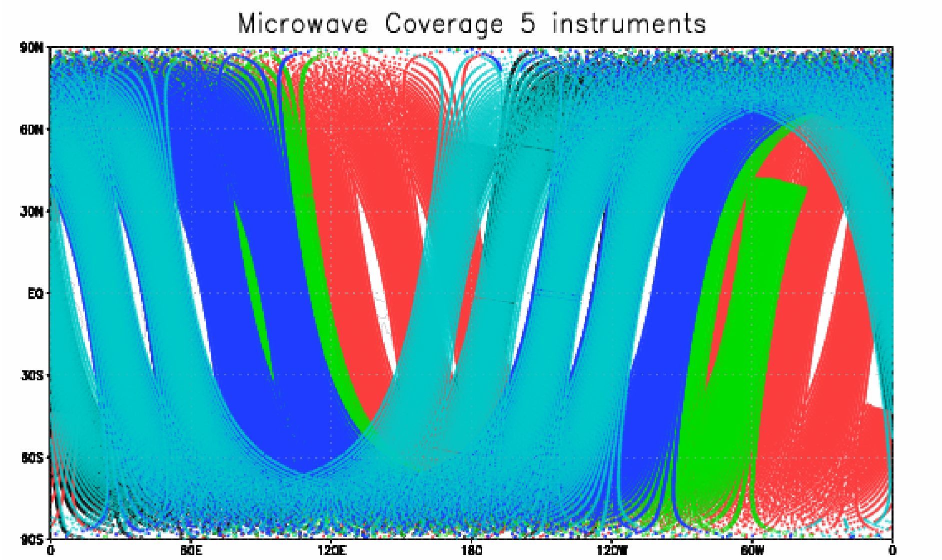

Figure 1: Microwave data coverage for 06UTC July 31, 2007. AQUA (black), N-15(green), N-16(blue), N-18(light blue) and METOP(red)

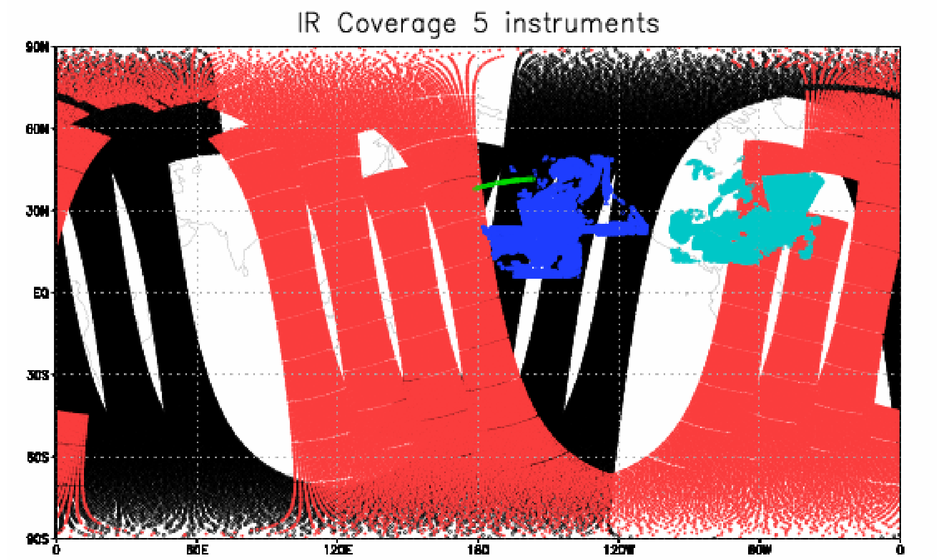

Figure 2: Same as Fig. 1 except for IR. AIRS (black), N-17(green), METOP(red), GOES-11(blue) and GOES-12(light blue)

While not absolutely necessary, the development of the direct use of radiances in the assimilation system was conducted in conjunction with variational assimilation techniques. The impacts of the development of both variational assimilation and direct radiance use have had a tremendous impact on the quality of NWP forecasts. Complete separation of the two effects is not really possible because developments in each have been influenced by the other. However, it is clear that there are some impacts directly attributable to the direct use of radiances. Prior to the direct use of radiances, the impact of the satellite retrievals in the Northern Hemisphere was small or negative. In the Southern Hemisphere, the impact was positive. With the direct use of radiances, the impact in the Northern Hemisphere became positive and much larger in the Southern Hemisphere. Also, with the inclusion of radiances, the SH variability became much larger and more realistic. Further information on the impact of radiance data can be found in the G. Kelly's presentation in this volume.

3. Radiance Assimilation

The variational assimilation of data is based on minimizing the equation:

$$J[\mathrm{x}] \;=\; \tfrac{1}{2}\,(\mathrm{x}-\mathrm{x}_b)^T\,\mathrm{B}^{-1}\,(\mathrm{x}-\mathrm{x}_b) \;+\; \tfrac{1}{2}\,(\mathrm{y}_o-H[\mathrm{x}])^T\,(\mathrm{E}+\mathrm{F})^{-1}\,(\mathrm{y}_o-H[\mathrm{x}])$$

Where x contains the analysis state, x_b is the background estimate of x (a short-range forecast), B is the error covariance of x_b, y_o is vector of measurements, H[...] is "observation operator" or "forward model" mapping state x into "measurement space", E is error covariance of measurements, and F is error covariance of forward model. To use the radiances in the variational assimilation, one must define the forward model (H[x]) to transform the analysis variables into the same form as the observations and the measurement error covariance matrices.

The forward model includes several components - the transformation of the analysis variables into the form needed for the fast radiative transfer model, an interpolation to the observation location, the fast radiative transfer model and bias correction (if necessary). Note that for a variational solution to the analysis system, the adjoint of all parts of the forward model are necessary as well. The transformation of the analysis variables and the interpolation technique are primarily characteristic of details of the analysis system and will not be discussed further here. The fast radiative transfer and the bias correction are more specific for the radiance data.

Fast radiative transfer models are use to simulate brightness temperatures from the model variables. The two most commonly used fast radiative transfer models are RTTOV[1] and CRTM[2]. Other fast radiative transfer models and information on these models can be found at the RTWG website[3]. The fast radiative transfer models attempt to account for all contributions to the brightness temperature including reflected, scattered and emitted radiation, the view geometry, and the specific instrument characteristics in a computationally efficient manner. Line-by-line codes which may be more accurate are too computationally expensive to use directly for these problems. The fast radiative transfer codes are calibrated against the line-by-line code and then used within the analysis system.

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[1] http://www.metoffice.com/research/interproj/nwpsaf/rtm

[2] http://www.ssec.wisc.edu/~paulv/Fortran90/CRTM/Developmental

[3] http://cimss.ssec.wisc.edu/itwg/groups/rtwg/fastrt.html

Bias correction is necessary when there are systematic differences between the simulated observations and the observations which cannot be explained by systematic errors in the background. These differences can arise because of biases in the observations, errors in the specification of the instrument characteristics, or inadequacies in the fast forward model. The difficulty is in separating errors resulting from background errors from the others since we do not want to correct for errors in the background.

The bias correction can be performed as either an off-line or integrated system. The off-line systems (Eyre, 1992, Harris and Kelly, 2001) estimate the bias correction based on match-ups between collocated radiosondes and brightness temperatures. This technique suffers from an inability to adapt quickly to changes in the biases because of a need for a large number of match-ups. The integrated (or variational) system includes the bias correction coefficients as a part of the analysis vector with a corresponding background error. This system will allow the bias to adjust fairly quickly to changes in the biases, but suffers from an increased possibility of incorporating background biases in the bias correction.

For either bias correction technique, the form of the bias correction is important. Most bias correction schemes have a field of view (FOV) dependent component and an air mass component. The FOV dependent component corrects the bias differently for each scan position of the instrument and thus corrects for errors in the antenna correction or systematic cross track errors. The air mass component attempts to correct an error which results more from errors in the radiative transfer that are dependent on the state. Thus, appropriate predictors of the bias could be the 1000-500hPa mean temperature, the lapse rate integrated over the weighting function, etc.

Bias correction can be essential for using radiance data. In Fig. 3, a time series of the bias and standard deviation of the difference between simulated brightness temperatures and observed antenna temperatures is shown with (a) and without (b) bias correction. Without bias correction, the bias is larger than the standard deviation, making the observation difficult to use. Note that both the bias and standard deviation are significantly reduced by the bias correction making the data much more useful for the data assimilation system.

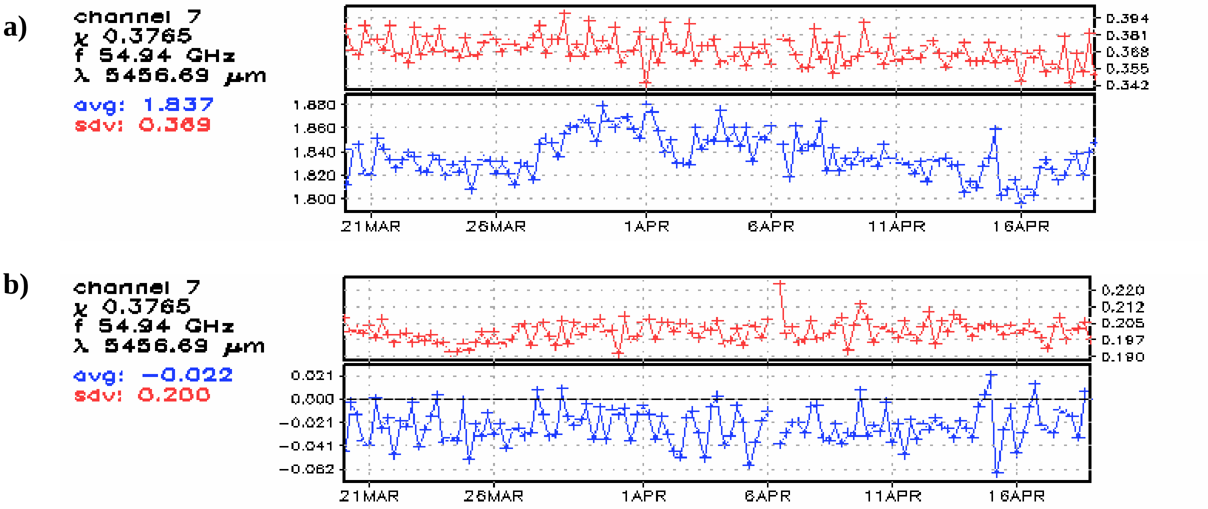

Figure 3: Standard Deviation and Bias for Channel 7 on NOAA-18 for a 30 day period of 2007. Panel a shows results prior to bias correction and panel b after bias correction.

In conjunction with the bias correction, quality control of the observations must be performed. The quality control removes observations which cannot be properly simulated by the forward model. The improper simulation can occur either from errors in the observations or from inadequacies in the forward model. For satellite data, most of the quality control occurs because of the inability of the forward model to properly simulate the effect of clouds, aerosols, trace gases or surface radiative characteristics and instrument failures.

In addition to the normal quality control procedures, an additional step is performed at most NWP centres. This step involves reducing the amount of input data to reduce correlated error, amount of redundancy, and computational cost. When observations are located close to each other, often the errors can have strongly correlated errors both through the observations and through the errors in the forward models. Since the radiance observations generally measure deep layers of the atmosphere, often the horizontal scales of the large vertical scale are also large and the information in many of the observations can be redundant. Finally, the computational expense of including all of the radiance observations is prohibitive. For all of these reasons, the data is thinned in the NWP system. The thinning can be done in a manner which retains the observations which contain the most information and are most likely to pass other quality control procedures.

The measurement and forward model error must be specified appropriately for the analysis system since they basically specify the weight given a particular observation. Since they are additive they are usually specified as a single matrix, with contributions from both terms. A lower bound on the measurement error can be made from the numbers from the instrument developer. An upper bound on the sum of the measurement and forward model error is the difference between the observations and the background. This difference also includes the errors in the background, so the true sum should be smaller. The range between the lower and upper bounds is often not large, and in these cases the empirical specification of the errors is straightforward. There are also techniques such as Desroziers and Ivanov (2001) to computationally estimate the appropriate observational errors.

Generally, observational errors for the ATOVS instruments have assumed a diagonal error covariance matrix. This is probably not correct. It is likely that the forward model error will contain strong components of correlated errors. Often the diagonal components are increased to help account for the lack of off-diagonal components to the error covariance matrix.

The final essential component of a radiance assimilation system is a observation and data assimilation monitoring capability. The monitoring of the system is essential to ensure that the bias correction and quality control in the assimilation system and the observational instruments are properly functioning. The data assimilation systems are sensitive to relatively small changes in the quality of the data. Often the first notification of instrument problems comes from other NWP centres rather than from the data providers. Since incorrect data can quickly contaminate an assimilation system, the monitoring must be ongoing and real-time.

An example of the monitoring system detecting a problem with the data is shown in Fig. 4. On March 25, AIRS channel 453 showed a sudden increase in the standard deviation. With the change in the noise in the channel, the use of this data was turned off in the assimilation at NCEP and other operational assimilation systems. When problems such as these occur, the NWP centres will usually consult the monitoring web pages from other operational centres to confirm the result and to ensure that the problem is the data rather than a change in the local system. The International TOVS Study Conference maintains a web site with links to operational centres monitoring sites http://cimss.ssec.wisc.edu/itwg/nwp/monitoring.shtml.

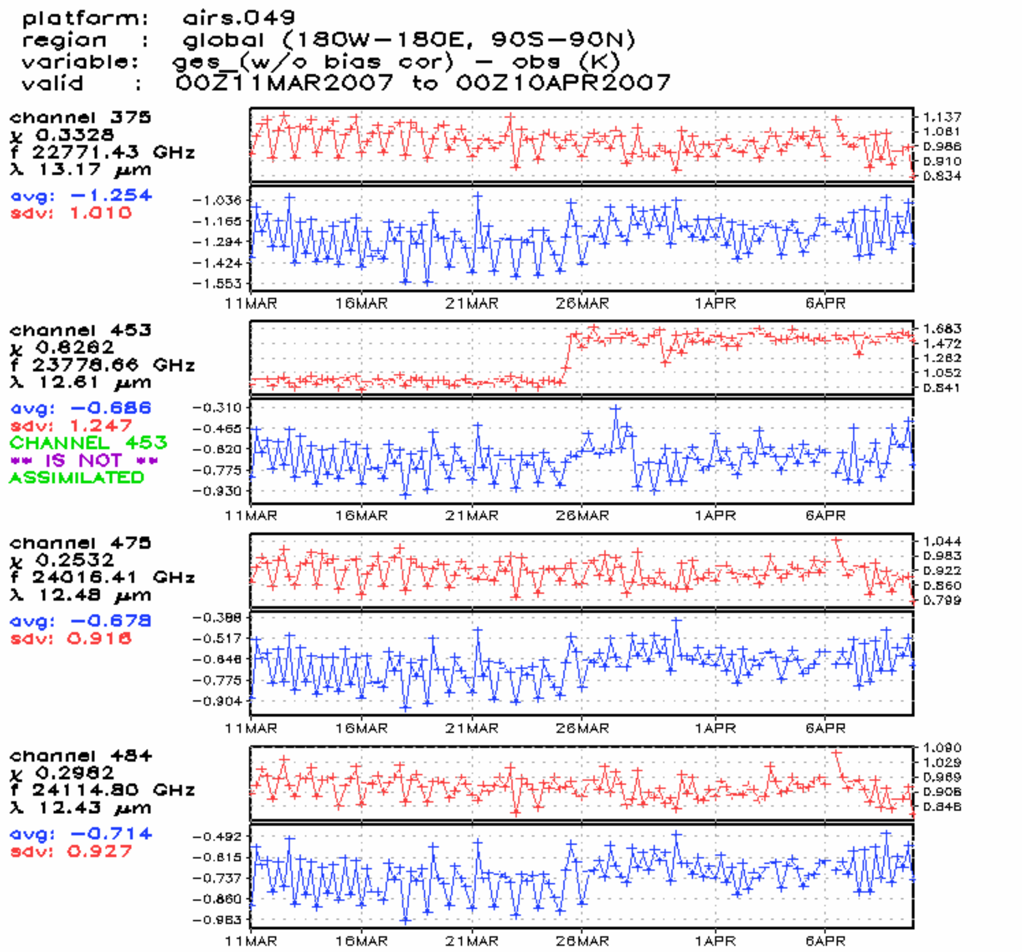

Figure 4: Monitoring page for AIRS channels for 1 month period. Note increase in standard deviation on 25 March, 2007.

4. Final comments

The assimilation of radiance data was developed with the use of TOVS and ATOVS data. The assimilation of ATOVS data remains the core of satellite radiance assimilation. The use of the radiance data has resulted in substantial improvements to forecast skill. To use this data, one must carefully use the information in the radiance data by properly defining the forward model, bias correction and quality control and monitoring the system to ensure its proper functioning.

The use of ATOVS data is an important component of our assimilation systems. However, the problem is not completed. There are many components of the system which still could be done better. For example, properly accounting for the variability of the underlying surface over the size and shape of the observations field of view in the emissivity calculations can result in large changes in the simulated brightness temperatures. Also, improvements in the antenna correction, the radiative transfer calculations, accounting for the slant path and including additional analysis variables such as clouds, precipitation, aerosols and trace gases, would improve the use of the radiance data.

5. References

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