ASSIMILATION OF TOVS, GOES AND ATOVS RADIANCES

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1. INTRODUCTION

Over the last 10 years, the use of satellite data in atmospheric data assimilation systems has been revolutionized by the development of variational data assimilation systems and the direct use of radiance observations. The direct use of radiances in variational techniques has become the technique of choice for incorporating satellite sounder data at many operational centers (e.g., McNally et al., 2000, Eyre et al., 1993, Saunders et al., 1999, Munro et al., 1999, and Chouinard and Halle, 1999). Because of the use of these techniques, the satellite data has had a larger positive impact on forecasts in both hemispheres.

The improvement in the impact of the data results not only from the overall technique used, but also from improved handling of the details. These details include more careful accounting for the instrument characteristics, enhanced quality control, introduction of radiance bias correction and improved radiative transfer algorithms. In the following sections, various components of the direct use of currently used satellite measured radiances will be examined. A general description of the problem will be given with specific examples from the NCEP system.

2. THE INSTRUMENTS

The proper assimilation of satellite data requires knowledge of the instrument characteristics. These characteristics enter into the techniques used to quality control and to select which channels to use in various locations. The presentation here will cover some of aspects of the current instruments that are most important for the assimilation of the radiance data.

2.1 TIROS Operational Vertical Sounder (TOVS)

Currently TOVS data is only available from NOAA-14, but TOVS data was the primary source of information until the launch of NOAA-15. Details of the instrument can be found at a NESDIS website (http://www2.ncdc.noaa.gov/docs/podug/index.htm). There are 3 main instruments making up the TOVS package, the High resolution Infrared Radiation Sounder/2 (HIRS/2), the Microwave Sounding Unit (MSU) and the Stratospheric Sounding Unit (SSU). In addition, the Solar Backscatter UltraViolet radiometer/2 (SBUV/2) instrument is located on the NOAA-14 satellite (and some of the previous satellites) for use in inferring ozone profile information.

The HIRS/2 instrument is an infrared (IR) instrument with 16 IR sounding channels plus one visible channel which has 56 Fields Of View (FOVs) across each scan with each FOV having a surface 17.4km footprint at nadir. The most important aspect of the instrument is that since it is primarily an IR instrument it cannot see through clouds. This greatly limits the coverage and makes the quality control more difficult. Channels 8, 18 and 19 are window channels with most of their signal coming from the surface. (However, the atmospheric contribution to these channels is still significant and should be included in the calculations). The window channels are useful for detecting clouds and eliminating cloud contaminated profiles. Some of the shortwave channels (strongest in channels 18 and 19) can have a significant signal from reflected solar radiation. Therefore, if the radiative transfer package does not properly account for these channels, the data becomes less useful during the day. Channel 9 has a strong ozone signal with some of the other longwave channels (1-6) having substantially smaller, but still significant, ozone signals. Channels 10-12 are moisture channels and along with longwave channels 5-7 contain much of the moisture information.

The MSU instrument is a scanning instrument with 11 FOVs in each scan line with a footprint size of about 124km at nadir. The instrument has 4 microwave sounding channels with channels 1 and 2 having a significant surface contribution. The signal from channels, peaking lower in the atmosphere (primarily channels 1 and 2), can be significantly impacted by thick clouds and precipitation.

The SSU instrument is a scanning far infrared instrument with 8 FOVs across a scan line with a footprint size of about 147km. The 3 stratospheric channels generally peak above any clouds and are useful if the model and assimilation system has sufficient resolution in the stratosphere and a high enough top. The NOAA-14 version of the SSU is expected to be the final one in space. The function of this instrument will be taken over by the Advanced MSU (AMSU) instrument on later NOAA satellites. Because of the lack of a future for the SSU, it is not used operationally at NCEP. However, for reanalysis purposes, the SSU could be important for properly defining the stratospheric temperature structure.

The SBUV/2 instrument measures profile ozone information during the daytime. The instrument is not a scanning instrument but rather only measures at nadir. The profile information is currently available in real-time from NOAA-11 as well as from NOAA-14. At NCEP, the data along with some information from the HIRS instrument provides the basis for the operational ozone analysis.

2.2 Advanced TOVS (ATOVS)

With the launch of NOAA-15, the TOVS instruments were replaced with the ATOVS suite of instruments. The instruments on the NOAA-15 satellites and similar follow on satellites are described in further detail at the NESDIS website (http://www2.ncdc.noaa.gov/docs/klm/index.htm). In comparison to the instruments in the TOVS instrument, the HIRS/3 replaces the similar HIRS/2 instrument, and the Advanced MSU (AMSU) instruments (AMSU-A and AMSU-B) replace the MSU and SSU instruments. The NOAA-15 satellite does not have a SBUV instrument on the platform. NOAA-16 will have a SBUV instrument. Since HIRS/3 is similar to HIRS/2 only the AMSU instruments will be described below.

The AMSU-A is a 15 channel scanning microwave instrument with 30 FOVs across the scan (50km footprint at nadir). Channels 3-14 are in the 50Ghz region (as was the MSU) and are primarily intended for temperature sounding while the AMSU-B channels are intended for moisture sounding. Channels 1 and 2 are at lower frequencies (23.8 and 31.4 Ghz) and channel 15 is at a higher frequency (89Ghz). Channels 1, 2 and 15 are more sensitive to moisture. However channels 3-5 have some sensitivity to cloud droplets, and channels 3-7 can be sensitive to scattering from ice crystals. Channels 1-5 and 15 are sensitive to the surface and require a good estimate of surface emissivity for proper simulation.

The AMSU-B instrument is primarily intended as a moisture measurement instrument. The 5 channels scan with 90 FOVs (19.3km at nadir) across the path. Channel 1 is at the same frequency as channel 15 of the AMSU-A instrument. Channel 2 is at 150 Ghz, and channels 3-5 are in the 183Ghz region. All channels are sensitive to all forms of moisture, and all channels can see the surface (if the atmosphere is dry enough). Thus, the same channel can sense moisture at high levels of the tropics while having a strong signal from the surface in the polar regions.

2.3 GOES sounder

The GOES sounder is similar to the HIRS instrument with 18 IR channels and 1 visible channel. Since the GOES instrument is in geostationary orbit and cannot scan the whole hemisphere in an hour, the observational areas are pre-specified by programmable software. Because of other uses for the sounding data (i.e., determining higher level cloud locations to complement the ASOS instrument), the sounder is primarily directed towards observing over the continental U.S where hourly soundings are produced. The remaining time is directed towards observing in relatively small regions off of the U.S. east coast (currently GOES-8) and off of the U.S. west coast (currently GOES-10). The instrument provides small FOVs (about 8km), but several FOVs are averaged by NESDIS prior to being provided to NCEP. The averaging takes the clear FOVs in a 5x5 box (3x3 averaging is under test by NESDIS) and averages the radiances. Any box with less than 5 clear fields of view is not used. Comparison with the background shows that there is some improvement of the fit of the data with larger numbers of clear fields of view in the average. The improved fit could result from several different reasons including, a reduction in the instrument error by averaging, less residual cloud contamination in clearer regions or a better background in clear regimes.

3. THE ASSIMILATION TECHNIQUE

The technique used to assimilate the radiances at most operational centers is based on variational techniques. By using variational techniques, it is possible to use the radiances directly without transforming the observations into the analysis variables. The variational assimilation techniques minimizes a function (J) of the form:

$$J = (x - x_b)^T B^{-1}(x - x_b) + \left(H(x) - y^o\right)^T R^{-1}\left(H(x) - y^o\right) + J_c \tag{1}$$

Where x is the analysis vector containing all analysis variables, x_b is the background (usually a forecast) vector for the analysis variable, B is the background error covariance, y^0 is the observation vector containing all observations including conventional observations and radiances, H is a transformation from the analysis variables into the same form as the observations (possibly including a prediction model for 4-D variational assimilation), R is the observational/representativeness error covariance, and J_c is an additional constraint term.

The background term, the first term on the right hand side of (1), measures the fit of the final analysis to the background field. The background term ensures that the problem is well-posed and incorporates the information from previous observations into the analysis. For the large scale problem, the background is of nearly the same accuracy as the observations because of the quality of current forecast models and the accumulated information from previous observations. The background error covariance (B) controls the distribution of the information in the observations in the horizontal, vertical and between variables. For this reason, the specification of this term is extremely important for determining the quality of the analysis and the usefulness of the observations.

The constraint term, J_c, contains dynamical and physical constraints on the analysis. For example, at NCEP, the constraints include both a divergence tendency term and a penalty for negative and unrealistically supersaturated moisture values. The constraint term is generally of smaller magnitude than the other two terms on the right hand side of the equation but can be extremely important for ensuring a balanced start (in both the dynamics and precipitation) to a forecast model.

The observation term, the second term on the right hand side of (1), measures the fit of the final analysis to the observations. The radiance observations enter the analysis through the observation term. It should be emphasized that the background term is equally important in determining the usefulness of the data. Note that the observation vector contains all observations including conventional and satellite based observations. Thus, the information contained in one observation type may influence how other observations are used.

For purposes of this paper, we will divide the H(x) operation into two operations P(L(x)), where L transforms the analysis variables into a profile of standard variables (i.e., T, U, V, O_3, P_s, etc.) at the observation location, and P transforms the profile of standard variables into the form of the observations. Thus, in the simplest case, the P operator would do an interpolation in the vertical to the observation location for a conventional observation of the standard variables. For a radiance observation, the P operator would be the creation of a simulated brightness temperature for the profile of standard variables. For other observations, such as precipitation or GPS bending angles, the same principle holds with the P operator becoming quite complex.

The solution to (1) is given by

$$B^{-1}(x-x_b)+H^T R^{-1}(H(x)-y^o)+\frac{\partial J_c}{\partial x}=0 \tag{2}$$

where H is the linearization of *H()* and the superscript T indicates the transpose. Even though a direct solution is possible if H is linear, the solution to the equation is usually found by iterative means (e.g., conjugate gradients, etc.) because of the size of the matrices involved. Since *H(x)=P(L(x))*, then $H^T=L^TP^T$. Thus, the solution to (1) requires H^T, the adjoint of *H()*, and to calculate H^T, it is necessary to have the adjoints of the individual transformation operators (P^T). Thus, not only is it necessary to have a forward model for radiance observations, but it is also necessary to have the adjoint of the forward model.

4. SIMULATION OF OBSERVED BRIGHTNESS TEMPERATURES

The simulation of observed brightness temperatures is done through a forward model made of two components, a radiative transfer model and a bias correction.

The radiative transfer model must compute the simulated radiances fast enough to allow its use on a large number of profiles and be accurate enough to use the information in the observed brightness temperatures. With the current state of the art, only clear or simple cloud structures can currently be properly simulated. Scattering processes are not currently well simulated in fast models. At the surface, a good surface emissivity model is necessary for any channel with a non-trivial signal from the surface. The microwave portion of the spectrum has greater variation in the surface emissivity than the IR, but the IR emissivity changes as a function of local zenith angle over the ocean (the most uniform surface) are large enough to have a significant impact. Over land or ice, the surface emissivity can have large changes over short distances because of changes in surface properties (i.e., from bare land to snow cover). Therefore, the surface emissivity is not modeled well enough to use surface sensing channels over many areas of land or ice. Two of the more widely used radiative transfer codes are RTTOV-6 and OPTRAN.

For many channels, a large bias between the simulated brightness temperatures and the observations exist. The bias results from errors in the radiative transfer, observational errors, and biases in the background field. Note that the radiative transfer component of the bias can result from both mischaracterization of the instrument as well as errors in the radiative transfer. The intention of the bias correction is to remove only the radiative transfer and observational biases. If the bias correction removes the biases in the background field, then useful information in the data will be removed.

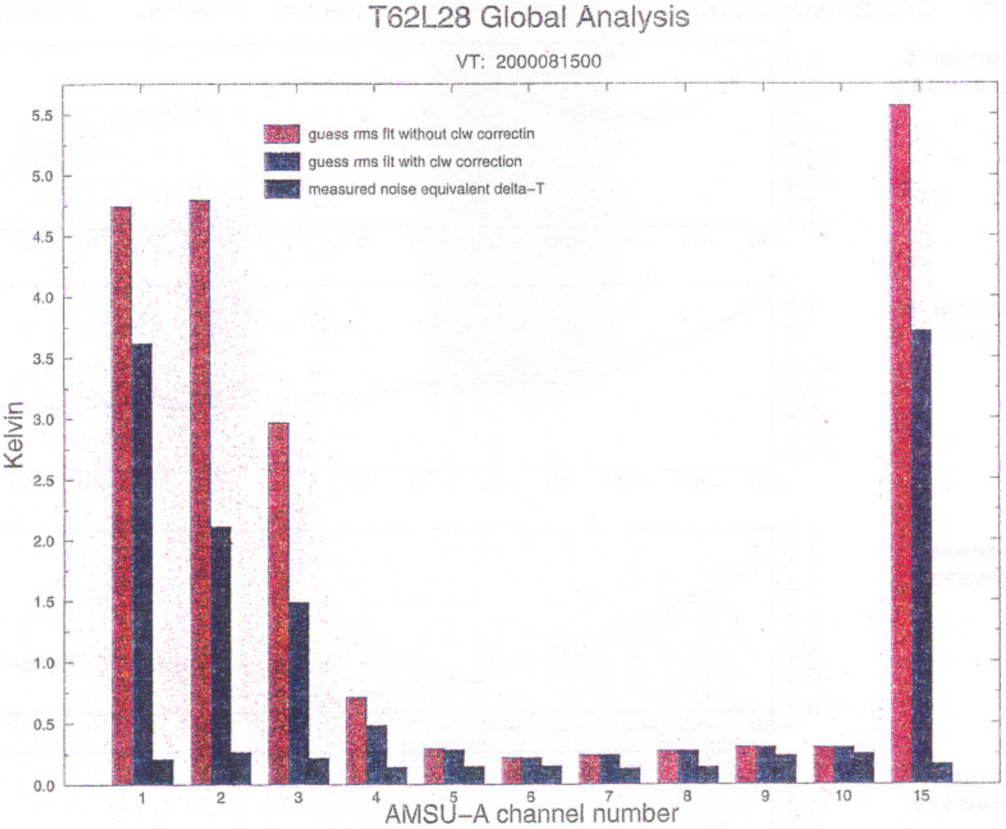

Fig. 1: RMS fits of simulated AMSU-A brightness temperatures to observations with and without cloud liquid water bias correction. In addition, the expected noise for each channel is shown.

As an example of the bias correction, a three step experimental version of the NCEP bias correction is described. First a scan position bias correction is applied. The values for the scan position dependent bias correction are estimated by calculating the bias between the simulated observations and the actual observations and then removing the mean over all scan positions. The assumption in this estimate of the bias is that the background error has no scan dependent bias. As a second step, a cloud liquid water bias correction is applied to the AMSU-A channels 1-5 and 15. Based on an estimate of the cloud liquid water in the observation and the scan angle, a simple linear equation is used to remove much of the cloud liquid water signal from these channels. In Fig. 1, fits of the simulated observations to the data are compared with the bias correction with the cloud liquid water (clw) correction, without the cloud liquid water (clw) correction and to the instrument errors (measured noise equivalent delta-T). While the cloud liquid water correction eliminates a substantial portion of the noise, some remains possibly due to errors in the surface emissivity. Also note in Fig. 1, that for channels not influenced by the surface (6-10), the fit of the background radiances to the observations is close to the expected observational error.

Finally, as a third component of the bias correction, a linear equation with four predictors is used to create final bias correction. These predictors are a constant, the square of the normalized path length through the atmosphere, the integrated lapse rate over the weighting function and the square of the integrated lapse rate. The coefficients for these predictors are analysis variables and are contained in the x vector of equation (1).

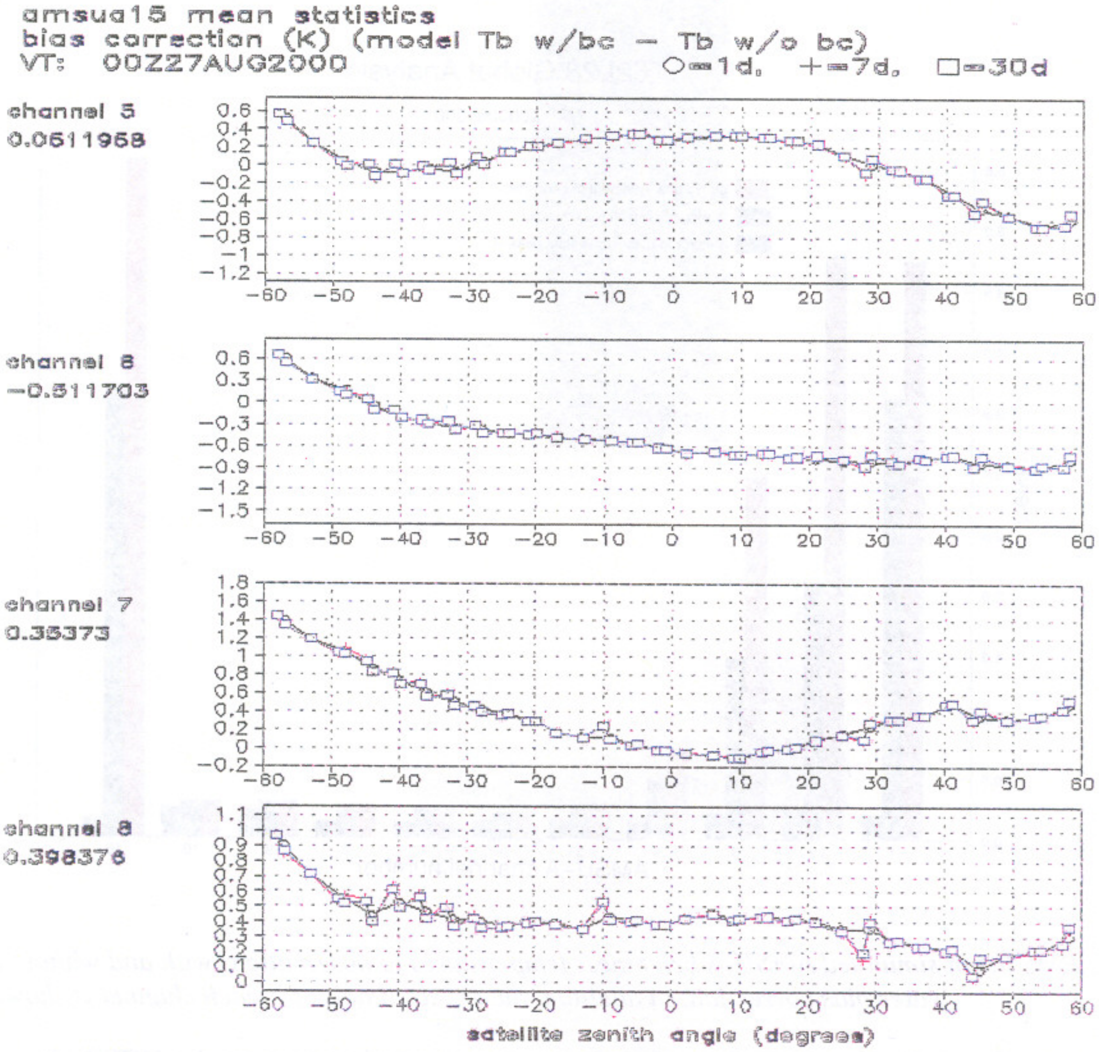

Fig. 2: Bias correction of AMSU-A channels 5-8.

The background values are the coefficients from the previous analysis time. By including the coefficients in the analysis equation, the coefficients are adjusted to give the best fit to the analyzed (not the background) atmospheric state and are allowed to adjust to short term instrument drift.

The bias correction as a function of scan position for 4 AMSU-A channels can be seen in Fig. 2. Note that the biases are shown for 1 day, 7 days and 30 days and are very stabile over this period. Also, that the magnitude of these errors is often larger than the signal shown in Fig. 1. In Fig. 3, the mean differences between the simulated observations with the bias correction and observations are shown for the same channels. Note the success in removing the bias as a function of the local zenith angle.

Additional current examples of the bias correction and monitoring of the instruments can be found at http://sgi62.wwb.noaa.gov:8080/RTPUB/stats/radiance.html for the NCEP monitoring page and at http://www.met-office.gov.uk/sec5/NWP/SRAG/Daily_ATovs_Monitoring/html/tovs-menud.html for the UKMO monitoring page.

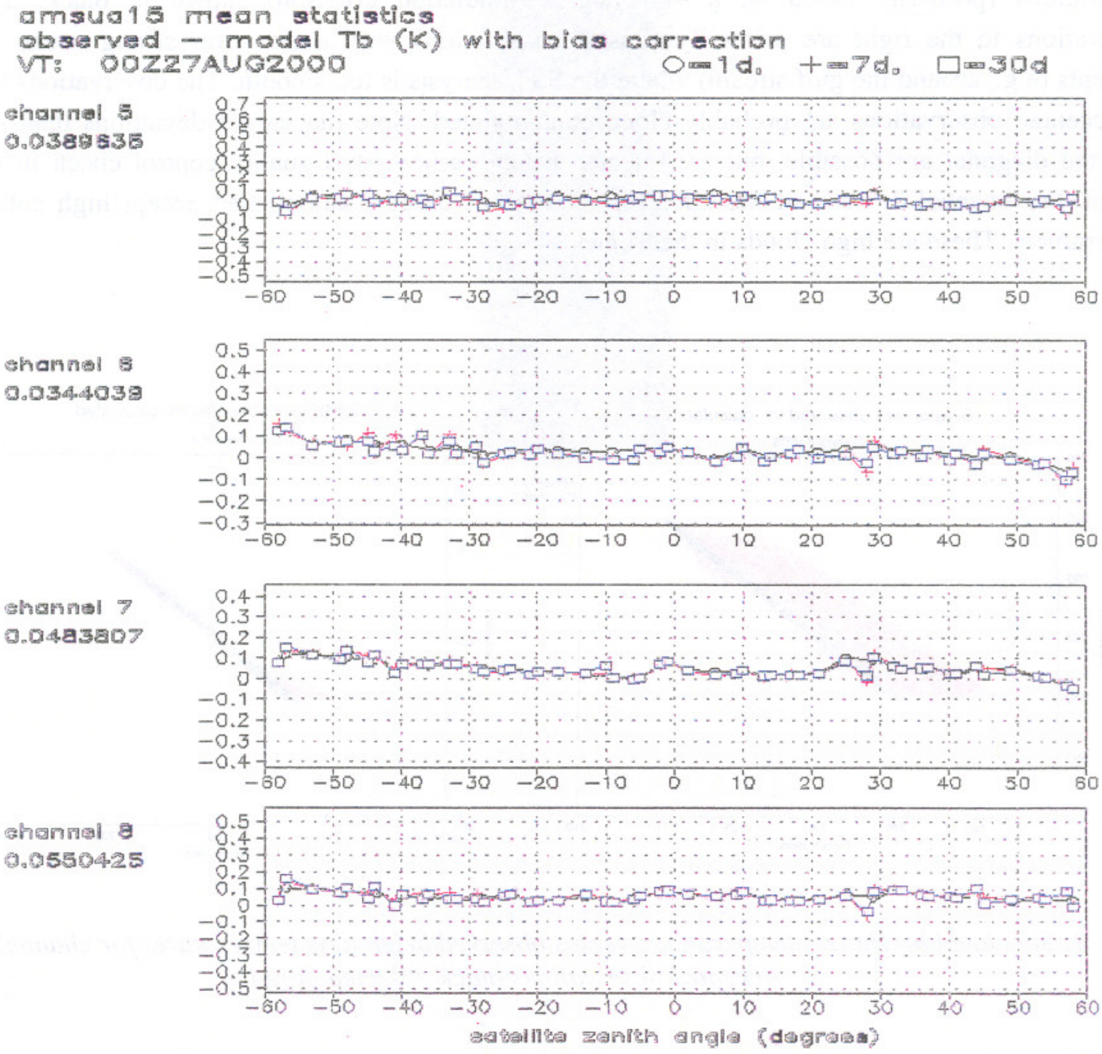

Fig. 3: Differences between simulated brightness temperatures with bias correction and observations as a function of satellite zenith angle

5. QUALITY CONTROL AND DATA SELECTION

The quality control should remove from the data set observations which cannot be properly simulated. The inability to simulate the observation may be due to inadequacies in the fast radiative transfer (e.g., not including absorption/reflection/scattering from clouds and ice, unknown surface emissivity, strong impacts due to variations in trace gases), inadequacies in the background field (e.g., poor vertical resolution, model top too low), instrument problems (improperly characterized spectral response functions, high instrument noise, instrument failure), or an inability to detect clouds. In the NCEP system, currently the primary reasons for quality controlling out observations are instrument failure, inadequate resolution near the model top, clouds in the IR and precipitation in the microwave. For the IR, the primary quality control check for clouds is based on the ability to simulate surface sensing channels over the ocean. In Fig. 4, the fit of the simulated observations to the real observations for oceanic channel 8 observations are shown with the accepted observations (primarily based on a +/-1 degree simulation criterion) shown in black. The rejected observations to the right are primarily coastal observations with a few over strong ocean temperature gradients (e.g., around the gulf stream) where the SST analysis is too smooth. The observations to the left of the accepted observations are probably cloud contaminated. Note that larger deviations than ~10 degrees from the diagonal are possible, but are rejected by an earlier gross quality control check in the analysis system. For channel 3, most of the observations are not cloud contaminated except high cold brightness temperatures. These are high clouds in the tropics.

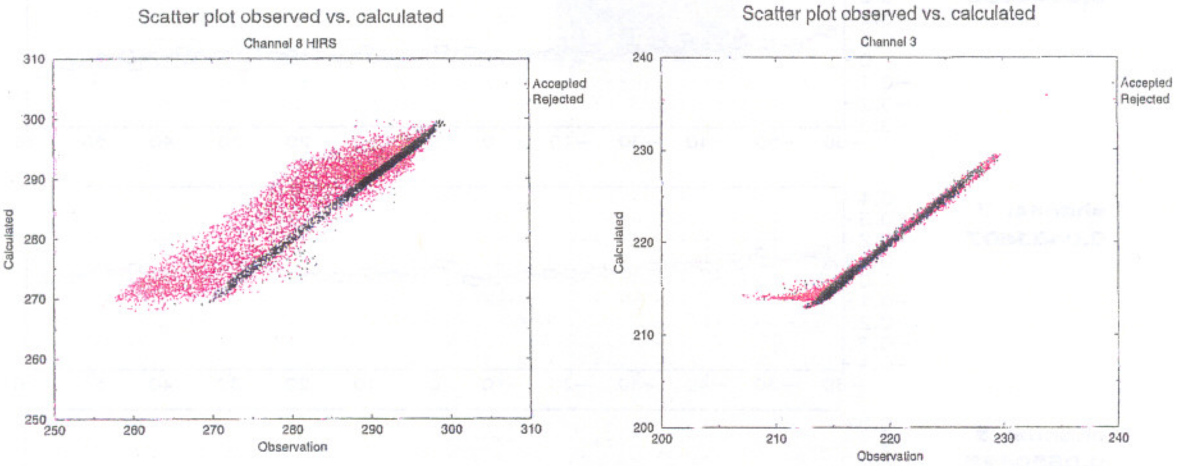

Fig. 4: Simulated brightness temperatures versus observed brightness temperatures for channels 3 and 8. Accepted observations black, rejected in red.

The operational assimilation centers also perform data selection or thinning of the observations because of the small horizontal spacing of the observations significantly increase the computational costs but do not significantly add to the information content. For the current set of satellites, the lack of additional information in the data results from the deep weighting functions for the sounding instruments. Therefore, only features with large vertical scales are being observed. Since these large vertical scale features generally have large horizontal scales observing them frequently in the horizontal is not necessary. Also, note that the correlation functions contained in the background error covariance matrix are currently of fairly large scale not allowing the small horizontal scales to be well analyzed even if they were observed. Note that there are exceptions. For the moisture field and for hurricanes, features can have quite broad vertical structures while having small horizontal scales. In future instruments, there also may be significant redundancy in terms of channels where several channels are observing the same information. As an example, at NCEP we are currently operationally using every seventh AMSU-A footprint, every 3rd GOES footprint, every 5th HIRS footprint and every MSU footprint (except the outside 2 footprints).

6. SPECIFICATION OF OBSERVATIONAL/REPRESENTATIVENESS ERROR.

The R matrix in (1) represents the observational and representativeness error covariance. Included in the matrix should be the errors resulting from instrument error, errors in the radiative transfer, and errors resulting from the scales of the observations being inappropriate for the scale of the analysis. Most centers use a diagonal observational error covariance matrix. A diagonal matrix is probably not realistic since the errors in the radiative transfer will be correlated between channels as will the errors in the scales of the observations. The main difficulty is in the specification of the matrix. Generally the operational centers have taken the view that using a diagonal matrix is probably not any worse than improperly specifying the correlations. The diagonal error variances used in the operational centers are quite small. In Fig. 4, the observational error variances for NOAA-14 HIRS and AMSU-A as used at NCEP are shown. For the HIRS, channels with larger surface signals and those channels having larger moisture or ozone signals tend to have larger error covariances because of our uncertainty in the forward modeling for those channels. For the AMSU-A variances, channels 1-3 and channel 15 have strong precipitation, cloud and surface signals and are primarily used for quality control and are thus given large variances. Channels 4 and 5 still have some residual surface signal, cloud and precipitation signals.

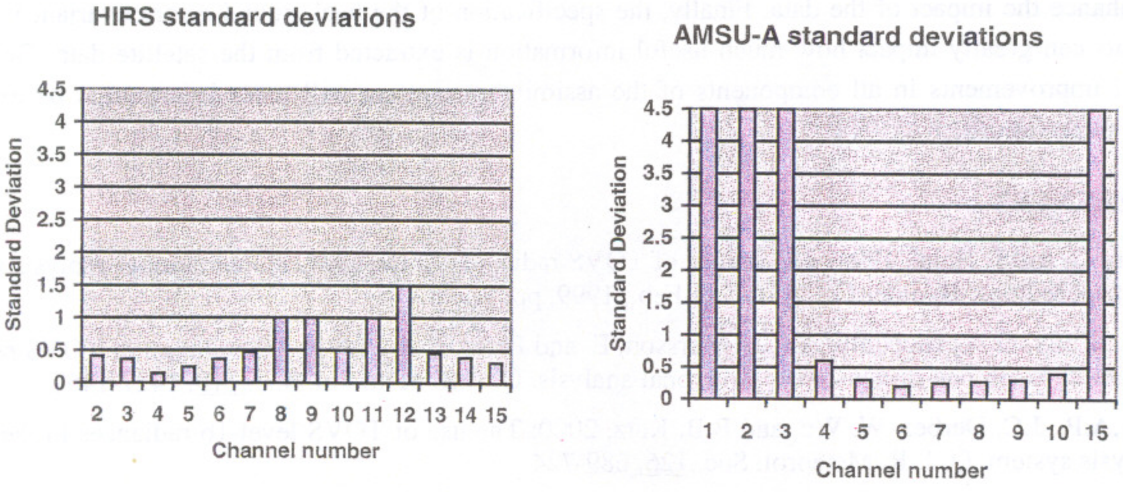

Fig. 4: NOAA-14 HIRS and NOAA-15 AMSU-A standard deviations.

7. SUCCESSES AND FUTURE IMPROVEMENTS IN THE USE OF GOES, TOVS AND ATOVS DATA

The direct use of TOVS, GOES and ATOVS radiance data has been very successful. The use of the radiance data has resulted in significant improvements in forecast skill in both hemispheres but with especially large improvements in the Southern Hemisphere. As a part of the improvement in the Southern Hemisphere, significantly stronger circulations in the Southern Hemisphere have been noted. Because of the simplification of the path from the observations to the assimilation systems, the direct use of radiances has allowed a much quicker incorporation of new satellite. For example, for NOAA-15, the radiance data was being used operationally 10 months after launch in the NCEP assimilation system. With the direct use of the radiance data, the observations are being monitored much closer than previously. Since the simulated observations from the background field (after bias correction) fit the observations quite well, small changes in the observations (either in the bias or random error) can significantly impact the analysis. Also, monitoring of the differences can improve understanding of the characteristics of the satellite data. For these reasons, most operational centers have established real time monitoring web pages for the radiance data. Finally, by directly using the radiances, many scientific questions concerning the data have been brought to the fore. For example, the proper modeling of the surface emissivities over ocean, land, and ice have become a priority.

While tremendous improvements in the use of satellite radiance data has occurred over the last 10 years, it should not be thought of as a solved problem. There are many ways in which the use of this data can be enhanced and more information can be extracted from the data. One improvement would be in the use of the data over land and ice which would require enhancements in our ability to detect clouds and precipitation and improved estimates of surface emissivity and skin temperature. Fast radiative transfer should not be considered a finished problem. Additional effects from many different factors (e.g., reflected solar radiation, variable trace gases, clouds, precipitation, etc.) could and probably should be included. With the improvement in the radiative transfer, one source of bias could be reduced. However, other sources resulting from errors in the instrument characterization, the line-by-line algorithms or other sources should also be reduced. In addition, the inclusion of a more correct observational/representativeness error covariance matrix could enhance the impact of the data. Finally, the specification of the background error covariance and the constraints can greatly impact how much useful information is extracted from the satellite data. Only with continual improvements in all components of the assimilation system will more information be extracted from the observations.

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