Experience with bias correction at CMC

L. Garand, G. Deblonde, D. Anselmo, J. Aparicio, A. Beaulne, J. Hallé, S. Macpherson, and N. Wagneur

Meteorological Service of Canada, Canadian Meteorological Center
Dorval, Qc, Canada
Corresponding author email address: louis.garand@ec.gc.ca

1. Introduction

An important aspect of data assimilation in meteorology is the identification and elimination of systematic biases which are attributed to observations. Numerical weather prediction (NWP) centers have developed comprehensive monitoring systems which allow a continuous evaluation of these biases. Typically, this is done from observed (O) minus calculated or predicted (P) differences using a short term forecast. The basic assumption is that for data volumes representing the whole globe and periods of the order of months, these differences should be zero (albeit not necessarily everywhere). While this approach can be criticized, it offers the great advantage of insuring consistency between the model “climate” and the assimilated observations of all types. It creates, for instance, a reference for the inter-calibration of satellite radiance observations.

This paper provides various examples of monitoring statistics made at the Canadian Meteorological Center (CMC). The focus is on data which are currently assimilated such as ATOVS (AMSU-A and B) and GOES and data which should soon be assimilated such as SSM/I and AIRS. Many examples are taken directly from the CMC monitoring website which can be seen from the exterior (password required). Bias issues are also discussed for ground-based GPS observations sensitive to the integrated water content, and for limb profiling measurements obtained from CHAMP and SAC-C satellites receiving signals from the constellation of GPS satellites. These examples highlight bias features that are specific to each data type. Also, more general or fundamental questions arise, related to ways to relax the working hypothesis that the forecast model has no climatological bias.

2. AMSU-A, AMSU-B, SSM/I

The procedure to remove biases from AMSU-A-B and SSM/I microwave radiance observations operates in two steps (see Hallé, 2005 describing the whole processing for ATOVS measurements):

- Scan bias correction. This is a global constant for each scan position (not symmetrical therefore as would be a scheme based on viewing angle). This step is done first.
- Air mass correction. This is based on two predictors taken from the model background field: 300-1000 hPa and 50-200 hPa geopotential thickness.

Fig. 1 provides an example of the two steps for AMSU-B of NOAA-16. It is seen that the procedure works satisfactorily. Figs 1a-b are based on the final selection after thinning and elimination of the first and last 7 scans. Figs 1c-d are based on the available data after quality control. It is seen from these plots that there is no justification to eliminate extremes of the scan. This was done to apply the same processing as for AMSU-A. Fig. 2 shows the bias and std of available AMSU-A radiances. The std slightly increases with viewing angle for channels 8-10, but not enough to justify the elimination of the corresponding scans. There is no deterioration at all for the std’s of channels 3-7. It is noted that for channels 3-4, the (O-P) std is significantly larger in the middle of the scan that at the edges. This is related to the fact that these channels are sensitive to the surface (skin temperature and emissivity) and more so at nadir than at large viewing angles.

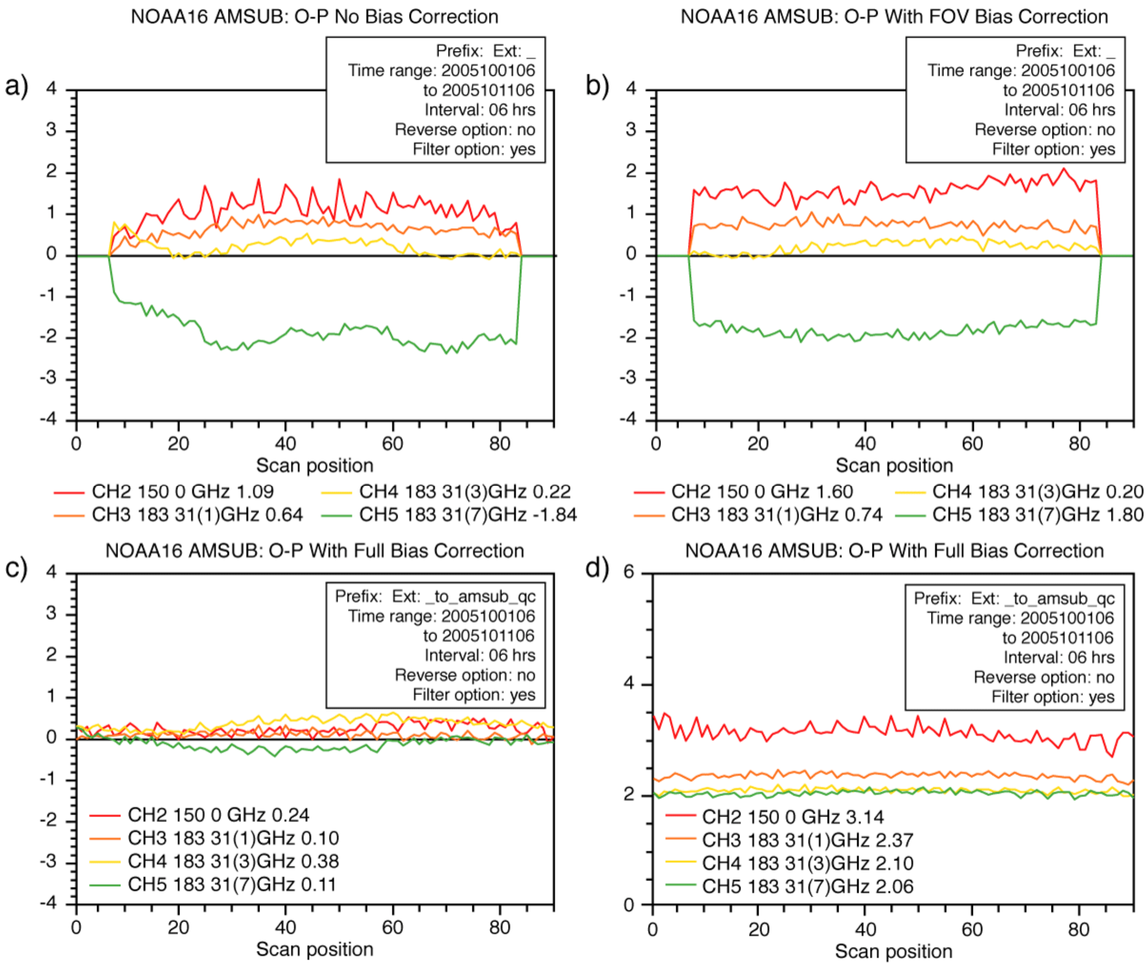

Figure 1 Mean AMSU-B (O-P) versus scan position. Raw (a); after scan bias correction (b); final (c) using air-mass predictors. Corresponding std (d). First and last 7 scans not assimilated. Panels c-d are based on all available data.

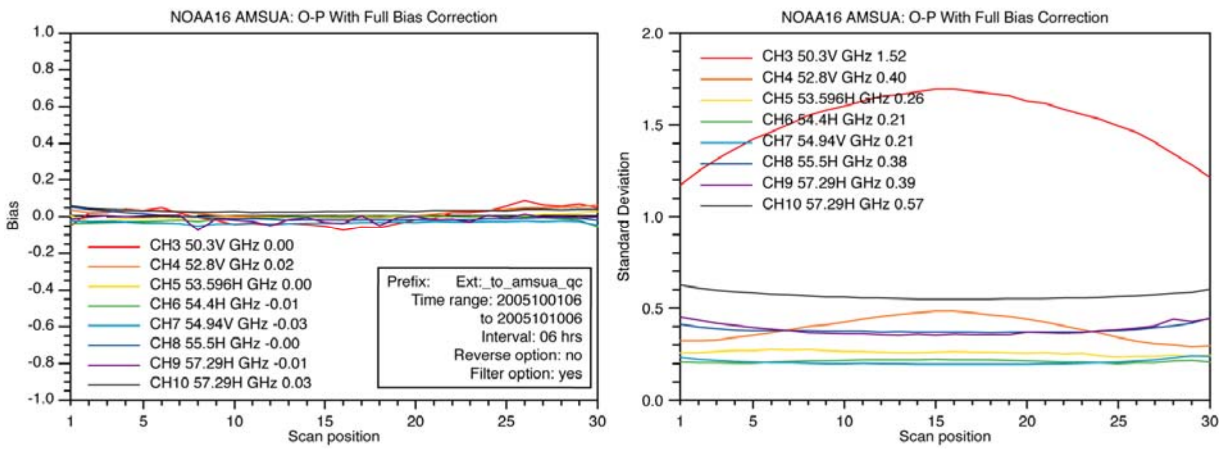

Figure 2 BT std of AMSU-A channels versus scan position. There is no justification to eliminate extreme of scans except possibly for ch 8-10. Larger std at nadir for ch 3-4 likely due to higher sensitivity to surface.

The CMC monitoring system provides a display of monthly averaged statistics for the last 15 months. An example is shown for AMSU-B of NOAA-15 in Fig. 3. It is seen that the bias value is not stable for ch-4-5. This raises the question of the frequency of renewal of the bias correction. A continuous updating may hide an erratic behavior of a given channel. At the CMC, the bias correction is redone periodically for all ATOVS sensors. The last update was done in July 2005. This did not stabilize the biases of ch-4-5. The same is true for some AMSU-A NOAA-15 channels, ch-6 in particular which was removed on 26 October 2005.

The bias correction procedure for SSM/I is the same as that of AMSU-A-B. Even though SSM/I has a conical scan (fixed viewing angle), the extreme scan positions are removed as some deterioration of the (O-P) std was noted. Fig. 4 shows the magnitude of the correction for ch 1. The correction is substantial and increases with latitude, a behavior common to most channels.

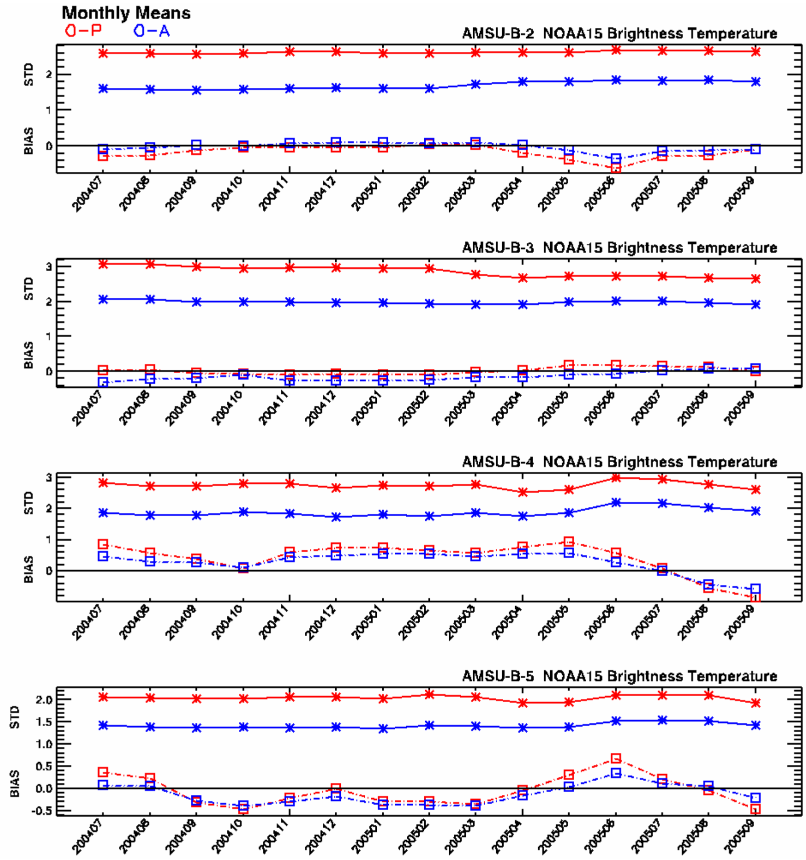

Figure 3 Monthly NOAA-15 AMSU-B monitoring statistics for the period July 2004 to September 2005. Ch 4-5 exhibit an unstable behavior.

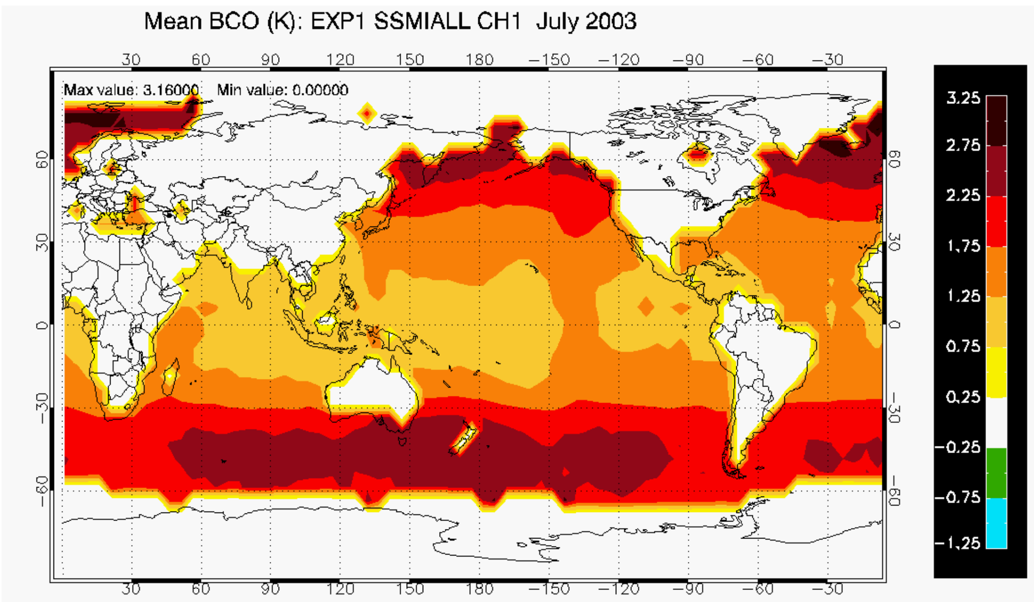

Figure 4 Mean July 2003 bias correction for SSM/I ch 1. Most SSM/I channels have a similar latitude dependence of the amplitude of the bias.

3. GOES, AIRS

3.1. GOES

The GOES water vapor channel (ch 3) is assimilated at MSC since 2003. The radiative transfer model used is MSCFAST (Garand et al., 2001). The processing leading to assimilation is described by Wagneur (2005). The bias correction assumes that the bias is proportional to the observed brightness temperature (i.e. bias = a BT_o + b). No correction with respect to viewing angle is applied. Viewing angles up to 70 degrees are used, which corresponds to a maximum latitude of 60 degrees. Fig 5 shows a recent example of monitoring statistics for GOES-12. The bias appears to vary significantly with time of day. A minimum in (O-P) is typically observed at 06 UTC with rapid change to a maximum at 12 UTC. This effect is less pronounced for GOES-10. This "midnight effect" (Kopken et al, 2004) is believed to be due to an exposition of the instrument to solar radiation at night. Because the effect is of the order of 0.3 K, it has not been considered so far. Also it was discussed at some point that the data would be corrected at the source. It appears that this was not done. Therefore a variation of the bias with time of day seems justified. Fig. 6 represents a map of the monthly mean of (O-P) for September 2005. Possibly, a bias is introduced at large viewing angles (60-70 degrees), especially in the case of GOES-12. Elsewhere, sectors with significant departures from zero may point to weaknesses in the forecast model such as the well known problem of spin-up (time to adjust precipitation/convection).

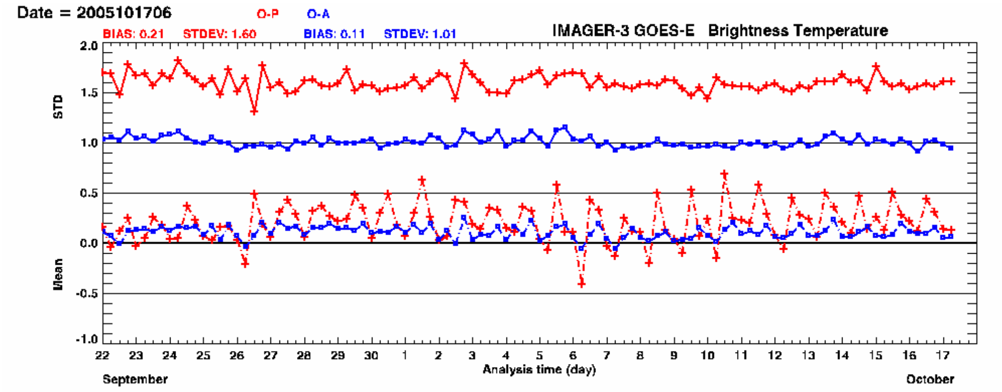

Figure 5 GOES-12 monitoring statistics for the period 22 Sep- 17 Oct 2005. A significant diurnal variation of the bias is noted.

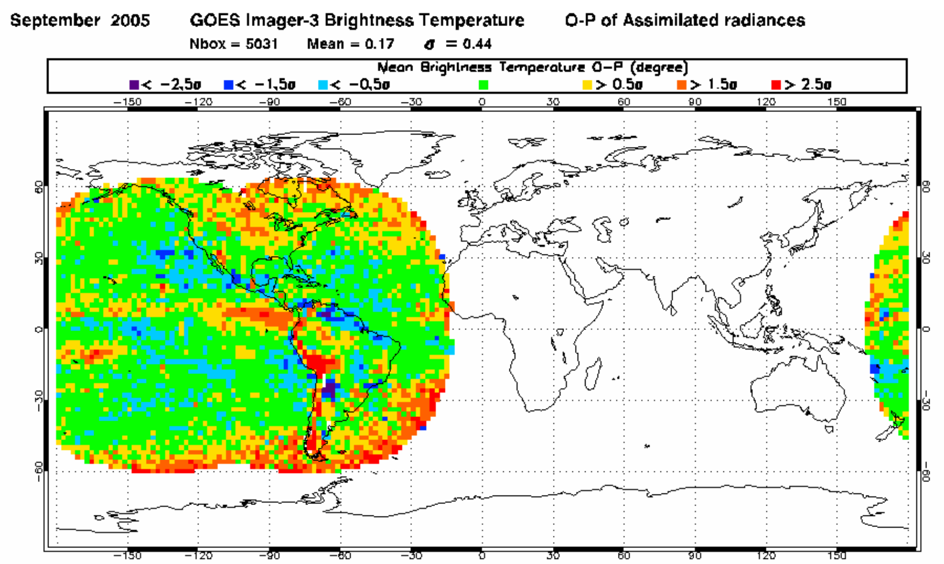

Figure 6 GOES-10 and 12 mean (O-P) for September 2005 (std units: std= 0.44). The result raises the question of a possible angular bias at large viewing angles.

3.2. AIRS

CMC is now conducting assimilation cycles using 105 AIRS channels from the 281 channel subset (out of 2378) that we receive. Channels sensitive to ozone, trace gases or with significant response above the model top (10 hPa) are not assimilated. The monitoring site is not yet operating in real time. The data preparation is described in Garand and Beaulne (2004). As is done at ECMWF, the aim is to assimilate clear radiances, that is radiances not affected by lower clouds.

The approach to bias correction is the same as that adopted for GOES. The bias is assumed to be a linear function of the observation itself. This may be interpreted as an adjustment to the calibration of the instrument. Alternatively, it may be seen as an air-mass dependent correction to the radiative transfer model. Comparison of AIRS monitoring with that at other centers may help to determine the cause of the bias. The variation of the bias with the observed brightness temperature (BT_o) is the largest for water vapor channels, where it can differ by as much as 2.5 K from a constant bias. This can be seen in Fig. 7 (channel index 175-214). Two-week assimilation cycles were made differing only by the bias correction: flat or linear with BT_o. Fig. 8 presents the result in terms of 500 hPa correlation anomaly in the southern hemisphere for forecast up to 5 days. There appears to be a slight advantage for the linear bias correction. Results for the northern hemisphere (not shown) were closer to neutral.

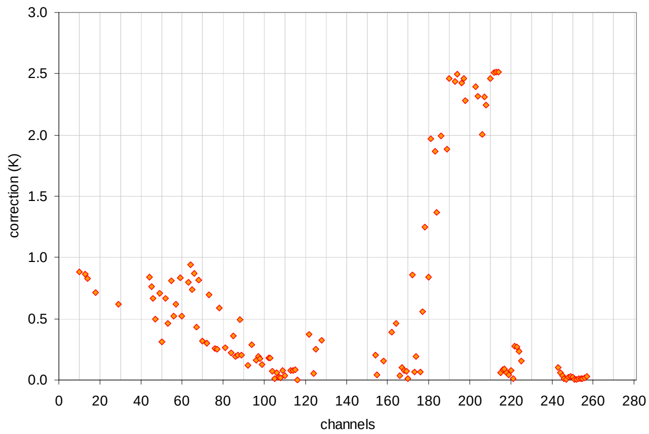

Figure 7 Maximum departure from flat bias versus channel index.

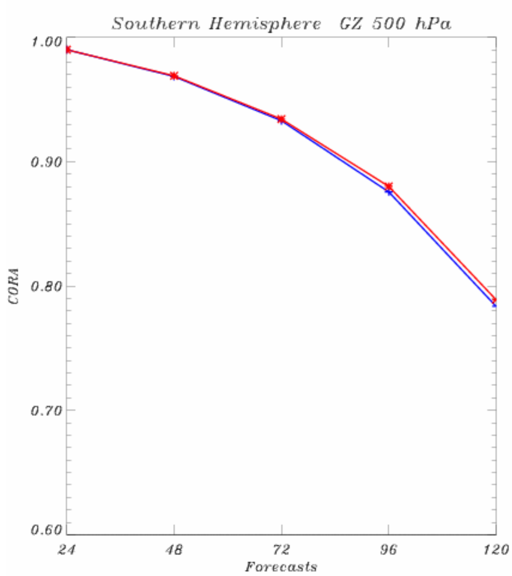

Figure 8 500 hPa correlation anomaly up to five days for assimilation period 14-29 Feb. 2004. AIRS bias correction is either flat (blue) or linear with the observed BT (red).

4. Ground-based GPS

Estimates of zenith tropospheric delay (ZTD) are available from networks of ground-based GPS receivers worldwide. The ZTD can be related to surface pressure (P_s) and precipitable water (PW) at each GPS site. The main impact of ZTD observations in variational data assimilation is on the analysis of lower tropospheric specific humidity. At CMC we receive since August 2004 near real time ZTD observations every 30 minutes from NOAA for a network of GPS sites covering the United States (including Alaska and Hawaii). The data are currently being evaluated for possible assimilation in the operational CMC 4D-Var system. The data are monitored by comparison of the ZTD observation (O) with 6-h forecasts of ZTD from both regional and global versions of the Canadian GEM model (P). Collocated surface observations of pressure, temperature and humidity are also monitored. The global ZTD bias (O-P) averaged over all sites is generally low relative to the standard deviation of the differences, as seen in Figure 9 for the month of August 2005. However, site-specific biases of magnitude comparable to the std (15-30 mm) are noted at some locations, as seen in Fig.10. A large bias of similar magnitude affects a group of stations in California. This is likely due to larger forecasting errors in that sector. However, where a station stands out with a large bias, this is an indication of a site-specific error. A usual source is an error in the location of the receiver. The procedure of extraction of the ZTD is very sensitive to an accurate knowledge of the receiver's location, and an error of only a few cm can translate to a noticeable ZTD bias.

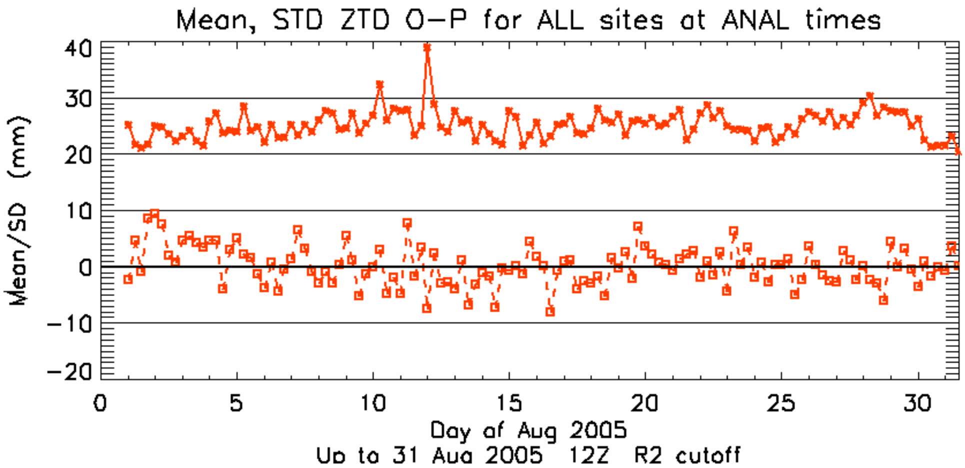

Figure 9 ZTD bias and std at 6-h intervals for August 2005 for the ensemble of stations seen in Fig. 10.

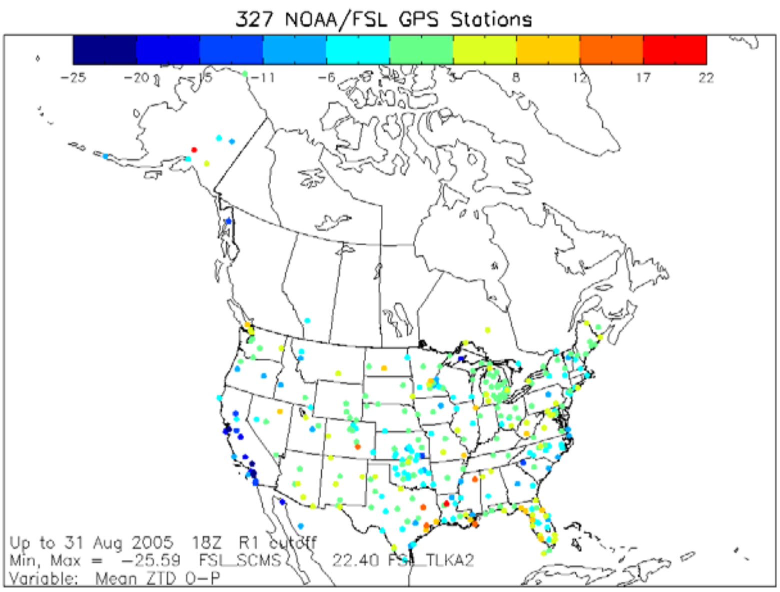

Figure 10 Monthly ZTD bias associated with the ground GPS network for August 2005.

An O-P bias results from the combination of different systematic bias errors in the observation (O) and in the forecast (P). Bias errors in forecast ZTD may be attributed to

- bias errors in forecast surface pressure (a 1 mb error in pressure gives ~ 2.3 mm error in ZTD).
- bias errors in forecast PW (a 1 mm error in PW gives ~ 6.2 mm error in ZTD)
- bias errors introduced in the forward operator used to compute ZTD from the model state vector (P_s, T(z), ln(q(z))

Biases in 6-h forecast surface pressure are of insufficient magnitude (< 1 mb) to contribute significantly to the larger observed biases (> 10 mm) in P ZTD. Bias errors in forecast humidity (PW) are more likely to dominate. One potential source of error associated with the forward operator is the adjustment of model ZTD to the GPS antenna height. However, given the mostly small height differences (< 100 m), any such errors will be minimal. Bias errors in the ZTD observations are most likely due to inaccurate specification of a-priori GPS receiver antenna height in the GPS data processing.

Analysis of the site O-P biases over a one-year period suggests that the biases can be split into constant and variable components. The variable component produces variability of the bias at time scales of weeks to seasons. A strong diurnal dependence of bias at some locations has also been noted. Options for bias correction are currently being investigated. One possible approach to bias correction would be to first remove the constant component and then apply air-mass dependent bias corrections in a similar fashion than what is done for ATOVS radiances. Another approach uses a running mean of O-P for the bias correction. Averaging intervals of 10 days to a month are being considered. Macpherson et al. (2006) describes the recent progress made at MSC on this subject.

5. GNSS occultations

The MSC is conducting research in view of assimilating operationally COSMIC data which will become available in 2006. Experience was gained using real observations from low orbiting satellites CHAMP and SAC-C. Global Navigation Satellite System (GNSS) satellites (currently ~30, altitude ~20000 km) send signals that are received by CHAMP and SAC-C. For each occultation event, delays between emission and reception times translate into a vertical profile of refractive index, which in variational assimilation creates analysis increments in terms of temperature, surface pressure and humidity. The effective horizontal resolution is of the order of 300 km, whereas the vertical resolution is about 500 m. The data are available in all weather conditions over both land and sea. Because the measurement of time delays are very precise and the forward operator relatively simple, the observational bias is thought to be small at the spatial scales mentioned above. Thus these data should prove useful both for assimilation into NWP analyses, and for long-term climate studies. Impact studies from assimilation cycles (Aparicio and Deblonde, 2004) are very promising.

A forward model for the refractivity $N=10^6(n-1)$, with n the atmospheric refraction index, allows (O-P) statistics to be done. Fig 11 shows statistics of (O-P)/P for the quantity N for CHAMP data versus height. It is seen that relative biases are low, not exceeding 0.5%. As well standard deviations are of the order of 1 %. Furthermore, results obtained with SAC-C (not shown) were very similar . The larger bias and std below 4 km are caused by along-the-path variations of the refractive index, mostly due to the presence in the low troposphere of non-stratiform structures, mainly of water vapor. Radio occultation data below 4 km will likely be assimilated with a lower weight than data from upper layers. Similar statistics were obtained at ECMWF, notably the negative bias of about 1 % near in the tropopause region, indicating that differing models have similar deficiencies in the upper atmosphere. The bias and std were computed for the two

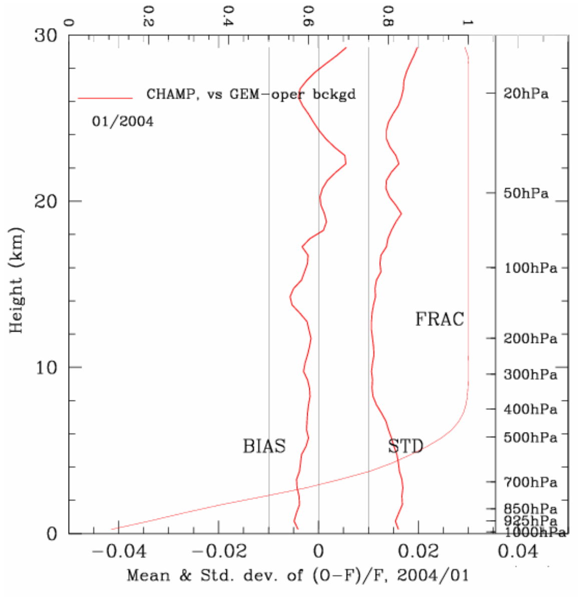

Figure 11 Global bias and std profiles of (O-P)/P associated with N for CHAMP for January 2004. FRAC is the fraction of profiles that cover a given height (upper axis). The lower troposphere is often lost. However, above approximately 8 km, the fraction is nearly 100%, which strongly limits the possibility of a bias due to sampling in a large fraction of the atmosphere.

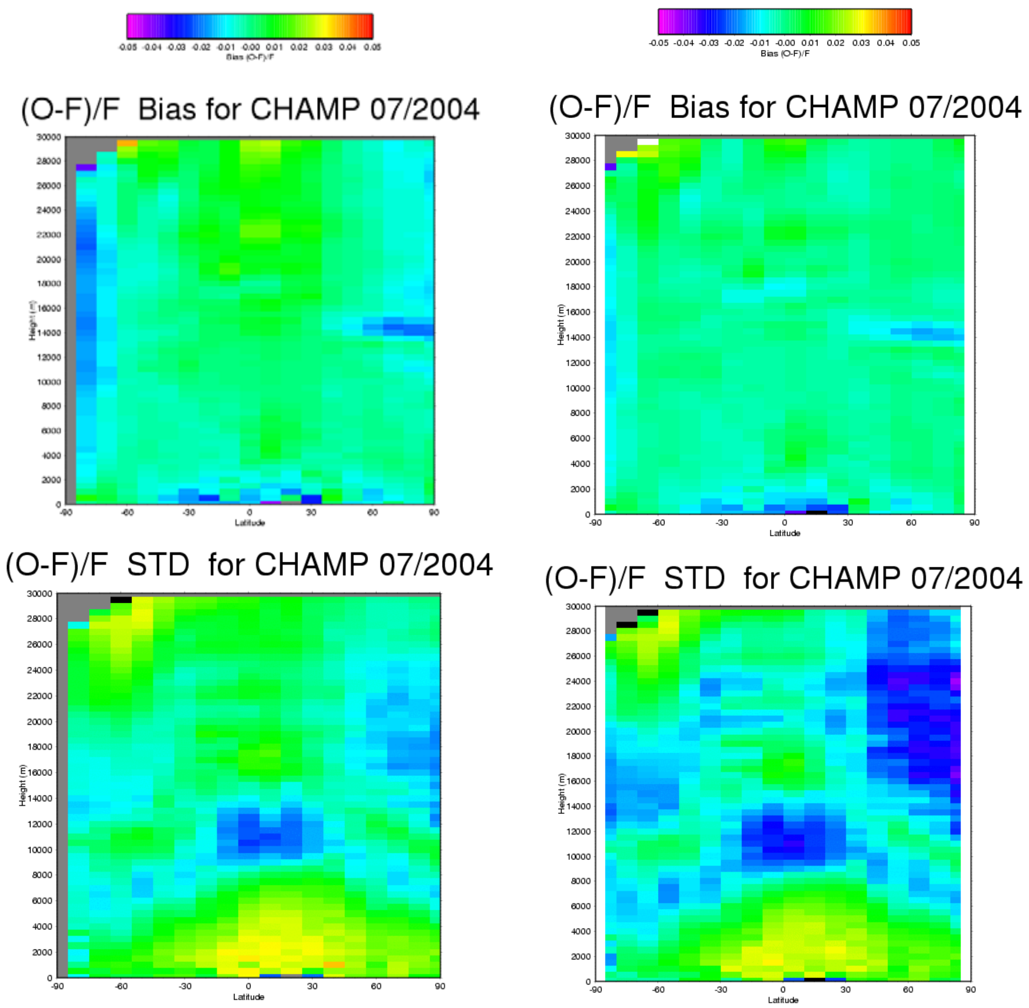

Figure 12 Normalized bias/std (%) of N as a function of latitude and height associated with CHAMP in July 2004 before (a/c) and after (b/d) accounting for the latitudinal variation of gravity in the topographic height. Normally the meteorologically relevant parameter of the topography is the geopotential of the surface, rather than its height. The relationship between both is latitude-dependent. The effect is particularly important over mountains, and was leading to a bias in south polar areas, as the Antarctica has a high topography. (left before correction and right after correction)

satellites in 10 deg boxes and at 500 m resolution. Recently, a source of bias was traced back to the fact that the forecast model outputs geopotential heights which are based on the assumption of a perfectly spherical

earth and constant gravity g. The model geopotential height was corrected, resulting in a reduction of both the bias and the std of (O-P)/P, as seen in Fig. 12. This is indicative of the high level of precision of the measurements. In fact, it is unclear whether it is best to assume that there is no observation bias, or to remove the bias seen in Fig. 12 in order to align the observations with the model climatology (a question often raised for other data types). In the specific case of GNSS data, the observed bias is probably in a large part caused by deficiencies in the model rather than in the observations.

6. Conclusion

This paper briefly reviewed the bias correction procedures applied at MSC for operationally assimilated data as well as for data envisioned for assimilation. The procedures are similar to those followed at other NWP centers. The CMC monitoring site provides both global statistics versus time and monthly statistics of mean (O-P) and std in the form of global maps. That site is accessible from the exterior upon permission. While not explored here, the comparison of the monitoring statistics among NWP centers should help to better understand the nature of the biases.

Specific points noted in this study include:

- The practice to eliminate AMSU scans at the edges of swaths does not appear justified.
- Air-mass dependent biases often appear large for AMSU and SSM/I, pointing to possible deficiencies of the radiative transfer model. Such biases appear small for longwave radiances.
- There is possibly a bias introduced at large viewing angles (60-70 deg) for GOES-12 and to a lesser degree GOES-10. In addition the bias of the water vapor channel of GOES-12 varies significantly with time of day.
- GNSS occultation data evaluated for CHAMP and SAC-C satellites show very similar biases and std. It is argued that these biases are attributed in large part to the model. In other words, these data could eventually be used as “truth” at the horizontal scales (300 km) measured. In comparison, ground-based GPS data show biases of a more complex nature involving both model and observation errors.

7. References

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