Configuration of All-Sky Microwave Radiance Assimilation in the NCEP's GFS Data Assimilation System

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ABSTRACT

At the National Centers for Environmental Prediction (NCEP), the clear-sky approach for radiance data assimilation is employed in the current operational hybrid 3D EnVar Global Forecast System (GFS). This study focuses on the development of all-sky microwave radiance assimilation capability in the Gridpoint Statistical Interpolation (GSI) analysis system, and the cloudy radiances from the Advanced Microwave Sounding Unit-A (AMSU-A) microwave radiometer over ocean are included. The configuration of all-sky microwave radiance assimilation in the pre-implementation package for the FY16 GFS upgrade is presented. The observation error, which is a combination of the symmetric observation error and a new situation-dependent observation error inflation, a new bias correction strategy for all-sky conditions, and static background error variance for cloud water are discussed in more detail. The all-sky approach is found to improve the relative humidity analysis at the continental western boundaries at 850hPa.

1. Introduction

In the recent decade, many studies have been performed on the assimilation of cloudy radiance data in the major Numerical Weather Prediction (NWP) centers and research institutions across the world (Bauer et al. 2010; Geer et al. 2010; etc). With the improvements to the forecast model and the Community Radiative Transfer Model (CRTM), the efforts of all-sky radiance assimilation in the GSI (Derber et al. 1991; Parrish and Derber 1992; Purser et al. 2003ab; Wu et al. 2002) analysis system have been actively engaged at NCEP in the past several years. In the all-sky approach, more cloudy radiances in the meteorologically important areas are assimilated, cloud profiles are taken into account in the CRTM, and radiance information is projected onto analysis fields including clouds, therefore, we expect more realistic analysis fields are produced. Moreover, in this study, a new situation-dependent observation error inflation is applied to all-sky radiances in addition to the symmetric observation error method proposed in Geer and Bauer (2011a), and a new bias correction strategy for all-sky radiances (Zhu et al. 2014b) is added on top of the enhanced radiance bias correction (Zhu et al. 2014a). The cloud background error variance is also examined.

This paper is organized as the following. The clear-sky approach in the current operational GSI analysis system is described briefly in Section 2. The configuration of all-sky radiance assimilation included in the pre-implementation package for FY16 GFS upgrade is presented in Section 3, and the GSI changes in observation error, radiance bias correction, and cloud background error variance for all-sky conditions are discussed in more detail. The impact of all-sky radiance assimilation is presented in Section 4, and the conclusion and future work are summarized in section 5.

2. The clear-sky approach in the operational GFS system

In the clear-sky approach (Derber and Wu 1998) of the NCEP's operational GFS system, AMSU-A channels 1 to 13 and 15 have been assimilated with the 3 window channels at 24, 31 and 89 GHz being sensitive to variability in water vapor, cloud and precipitation. A thick cloud filtering and a precipitation screen are employed to exclude any radiance data affected by thick cloud and precipitation. For those FOVs that include thin clouds, the cloud signal is removed by a cloud liquid water difference term in the radiance bias correction scheme. The cloud liquid water (CLW) for AMSU-A over ocean is calculated using the retrieval formula of Grody et al. (2001) and Weng et al. (2003). Moreover, cloud information from the first guess are not used in the CRTM in the calculation of brightness temperature.

In the GFS forecast model, cloud water, the sum of cloud liquid water and cloud ice, is a prognostic variable with moist physics. The cloud water control variable has also been explicitly employed in the GSI, which was constructed to assimilate the retrieved precipitation product from TMI (Treadon 1997) in the clear-sky operational GFS system. Hence, in the current operational 3D EnVar GSI analysis system, despite of the fact that retrieved precipitation data are no longer used, cloud analysis increments are generated via the background error cross-covariance of cloud with temperature and moisture variables.

3. The configuration of the all-sky radiance assimilation

In this study, cloud-affected AMSU-A radiance assimilation has been limited to FOVs with non-precipitating clouds over ocean, since the first guesses of snow and precipitation profiles are not available from the model output at this moment. To allow the cloudy radiance data to get into the GSI, the preference given to the clear-sky radiance data in the thinning, the thick cloud filtering, and the bias correction term of cloud liquid water difference are removed.

One direct benefit of all-sky approach is the more realistic simulations of satellite radiances due to the inclusion of the cloud information in the inputs to the CRTM in the satellite-radiance observation operator. Furthermore, with the introduction of the individual hydrometeors into the GSI as the state variables, the radiance data information is mapped onto not only the temperature and moisture fields as in the clear-sky approach, but also cloud fields via the brightness temperature Jacobians with respect to hydrometeors. Regarding cloud control variable(s), capability is available in choosing either individual hydrometeors or cloud water as cloud control variable(s) in the all-sky approach in the GSI. A normalized cloud water control variable is used in this study to reduce spurious clouds that may be generated from the static part of the background error covariance. While cloud analysis increments are produced through the background error cross-covariance in the clear-sky approach, additional analysis increments are generated for temperature, moisture, and clouds due to the projection of the radiance data information onto the cloud fields in the all-sky approach.

More detailed information is provided below on observation error assignment, bias correction, and static background error variance.

3.1. Observation error

In order to properly assimilate all-sky radiances, the so-called symmetric method proposed in Geer and Bauer (2011ab) is adopted to avoid the asymmetric sampling problems. The method prescribes the observation error e^o as a function of $\overline{CLW}$ in the fitting to the OmF (Observed-minus-First guess) standard deviation, where $\overline{CLW}$ is the average of the estimates of CLW from the observation, CLW_{obs}, and the first guess, CLW_{fg}.

In addition to the symmetric observation error, additional observation error inflation is applied to AMSU-A data based on several situation-dependent factors. The factors considered in this study include the cloud liquid

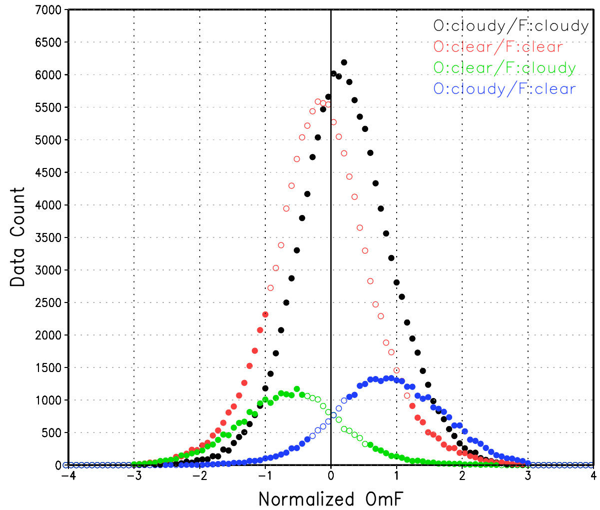

Figure 1. Histogram of normalized OmF (normalized by symmetric observation error) for AMSU-A NOAA19 channel 1 for the period from Nov. 1 to 15, 2013. The radiance data are grouped into four cloud categories: red circles for O:clear/F:clear, black circles for O:cloudy/F:cloudy, green circles for O:clear/F:cloudy, and blue circles for O:cloudy/F:clear. The closed circles represent the bins with averaged observation weight less than or equal to 0.25.

water difference between the first guess and the observation, scattering index larger than 9, the mismatched cloud information between the first guess and the observation, as well as the surface wind speed.

The final observation errors of AMSU-A data are examined for a 15-day period, and the results are presented in the histogram Fig. 1 of normalized OmF for AMSU-A NOAA19 channel 1. The radiance data in the figure are grouped into four cloud categories based on the cloud information from the first guess and observation: both observation and first guess are considered cloud-free (O:clear/F:clear, red circles); both are cloudy (O:cloudy/F:cloudy, black circles); observation is cloud-free but first guess is cloudy (O:clear/F:cloudy, green circles), or vice verse, observation is cloudy but first guess is cloud-free (O:cloudy/F:clear, blue circles). The averaged weight given to observations (inverse of observation error) in each OmF bin is calculated, and the bins with the averaged weight less than or equal to 0.25 are marked by closed circles. It is shown that for this channel, all bins for the category O:cloudy/F:cloudy have smaller weights as expected; While the observations in the middle of the histogram for O:clear/F:clear are given larger weights, the observations at the two ends of the histogram tails are assigned smaller and asymmetric weights; For the other two cloud-mismatched categories, the observation bins are given smaller weights except the bins around zero normalized OmF, and the patterns are not symmetric as well.

3.2. All-sky radiance bias correction

On top of the enhanced radiance bias correction scheme (Zhu et al. 2014a), the new strategy proposed in Zhu et al. (2014b) for all-sky approach is adopted in this study. As mentioned earlier that the radiance data can be grouped into four categories in the all-sky approach, i.e., O:clear/F:clear, O:cloud/F:cloud, O:cloud/F:clear, and O:clear/F:cloud, the latter two categories with mismatched cloud information are the locations where we would expect to generate/eliminate cloud via the assimilation of all-sky radiance data. In this strategy, all quality-controlled radiance data are used to produce the analysis, but bias correction coefficients are derived using only a selected data sample with consistent cloud information between the first guess and the observation, and the radiance data with mismatched cloud information are bias corrected using the latest bias coefficients available. Thus, the observation operator $\tilde{h}$ of the AMSU-A radiance data can be written as

$$\tilde{h}(\mathbf{x},\beta) = \begin{cases} h(\mathbf{x}) + \sum_{k=1}^{N} \beta_{bk} p_k(\mathbf{x}) & \text{if with mismatched cloud, over ocean,} \\ h(\mathbf{x}) + \sum_{k=1}^{N} \beta_k p_k(\mathbf{x}) & \text{otherwise,} \end{cases} \tag{1}$$

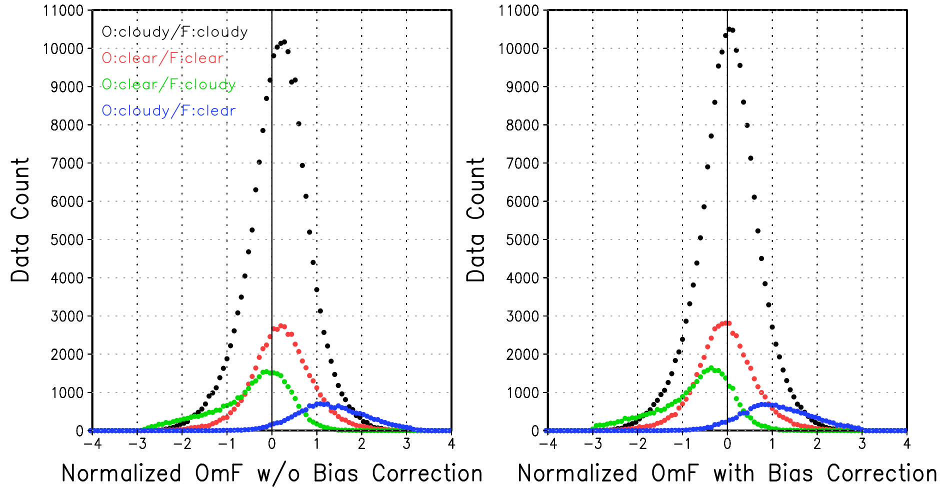

Figure 2. Histograms of OmF with (right panel) and without (left panel) bias correction for AMSU-A METOP-A channels 15 for a 15-day period from Nov. 1 to 15, 2013.

where $\mathbf{x}$ is the model state or GSI control vector, $h(\mathbf{x})$ represents the radiative transfer model. Letting β_k denote predictor coefficients and β_{bk} the latest available estimate of β_k, the total bias is written as a linear combination of a set of predictors $p_k(\mathbf{x}), k = 1, 2, ..., N$, and $p_1 = 1$. The histograms of OmF are shown in Fig. 2 for AMSU-A METOP-A channel 15 for a 15-day period. The histograms of OmF before bias correction are in the left panel and the histograms after bias correction are in the right panel. It seems that the bias correction strategy works well for channel 15. After bias correction, the two cloud-consistent categories (O:clear/F:clear and O:cloud/F:cloud) are centered around zero-bias, and the other two cloud-mismatched categories are on opposite sides of the zero-bias line.

3.3. *Background error variance for cloud water*

In the GFS 3D EnVar system, the background error covariance is comprised of ensemble covariance and a static term, with 87.5% weight given to the ensemble part and 12.5% to the static term. The static term is usually generated by the National Meteorological Center (NMC, now called NCEP) method (Parrish and Derber 1992). In general, the ensemble provides flow-dependent background error covariance information, and the static term offers information, e.g., in a climatological context. However, for clouds, which are discontinuous, localized, and strongly constrained by temperature and moisture, applying such a static cloud water background error variance to the all-sky approach would produce cloud increments at many locations that may not be consistent with the model physics and may not be retained by the forecast model anyway. Therefore, in the all-sky approach, in order to reduce spurious cloud increments, a normalized cloud water (normalized by cloud water background error standard deviation) is used as the control variable. The new static cloud water background error variance is assigned to be large only where clouds already exist. In this study, for simplicity, the cloud water error variance is specified as 5% of the cloud water first guess, and a small variance value is given for cloud-free locations or locations having very little clouds.

4. Impact of all-sky radiance assimilation

The impact of the all-sky approach on analysis increment is examined with a pair of stand-alone single analysis tests at 00Z Nov. 3, 2013. The two tests use the same first guess, but one in the clear-sky approach and the other in the all-sky approach. For the two tests, the analysis increments from the two approaches are found to be similar except several spots. Figure 3 displays the cloud liquid water at one of these spots, with the cloud liquid water of observations on left panels (upper panel for AMSU-A NOAA19 and lower panel for AMSU-A NOAA18), and the corresponding column-integrated cloud liquid water of the first guess on the right panels. It is seen that for the area to the south of 8N the observations (both AMSU-A NOAA18 and NOAA19) indicate cloud free or very small amount of cloud while the first guess has clouds in this area. The resultant analysis increments at level 10 (about 900hPa), as shown in Fig. 4 (upper panels for clear-sky and lower panels for all-sky), exhibit larger reduction in moisture (left panels) and cloud water (right panels) fields in a wider area in the all-sky approach than in the clear-sky approach, which is the right direction as would expect.

As the current operational GFS 3D EnVar data assimilation system uses T1534 horizontal resolution for deterministic forecast model and T574 for the analysis and ensemble forecast (T1534/T574) as well as 64 vertical levels, the all-sky microwave radiance assimilation has been tested in the cycled experiment using the same operational observations but with a low resolution of T574/T276 (thereafter referred as All-Sky). The control experiment (ClrSky) is the same as All-Sky, but like the operational GFS the radiance data are used in the clear-sky approach. It is observed that about 10% more radiance data from AMSU-A channels 1 to 5 and 15 are used on each analysis cycle. Compared to ClrSky, while the all-sky approach reduces relative humidity analysis at continental western boundaries (left column of Fig. 5) at 850 hPa, where the GFS has too much stratus cloud, temperature analysis increases correspondingly at 850 hPa, but decreases slightly at 700 hPa (right column of Fig. 5). The anomaly correlation results of geopotential height at 500 hPa (Fig. 6) indicate that the assimilation of all-sky radiance data has neutral impact in the Northern (left panel) and Southern Hemisphere (right panel).

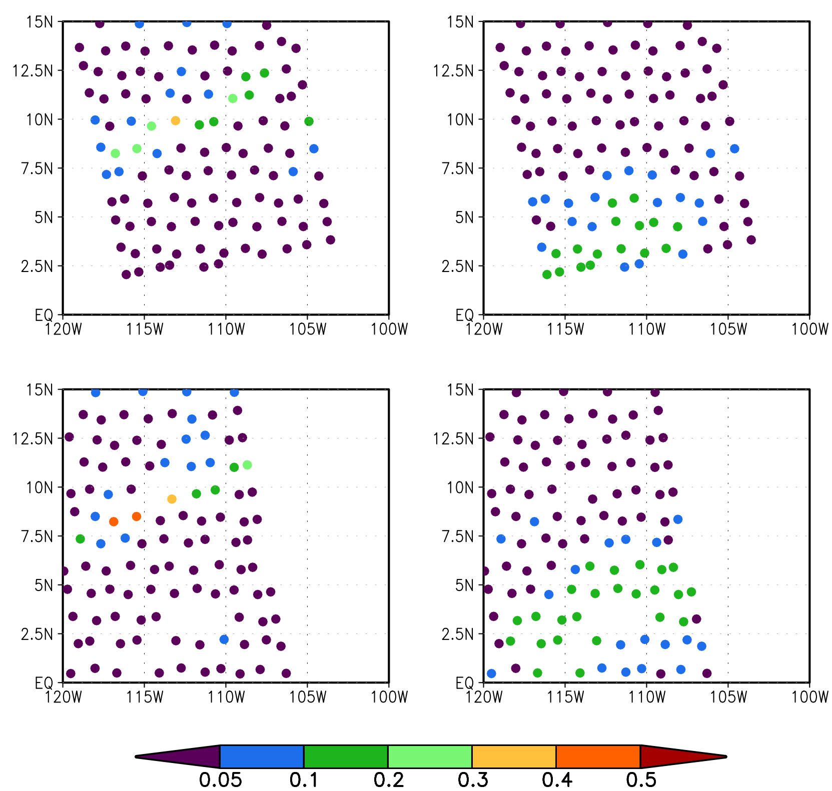

Figure 3. An example of cloud liquid water (kg/m^2) of observations (left panels) from AMSU-A NOAA19 (upper panels) and NOAA18 (lower panels) at 00Z Nov. 3, 2013 and the corresponding column-integrated cloud liquid water of the first guess (right panels).

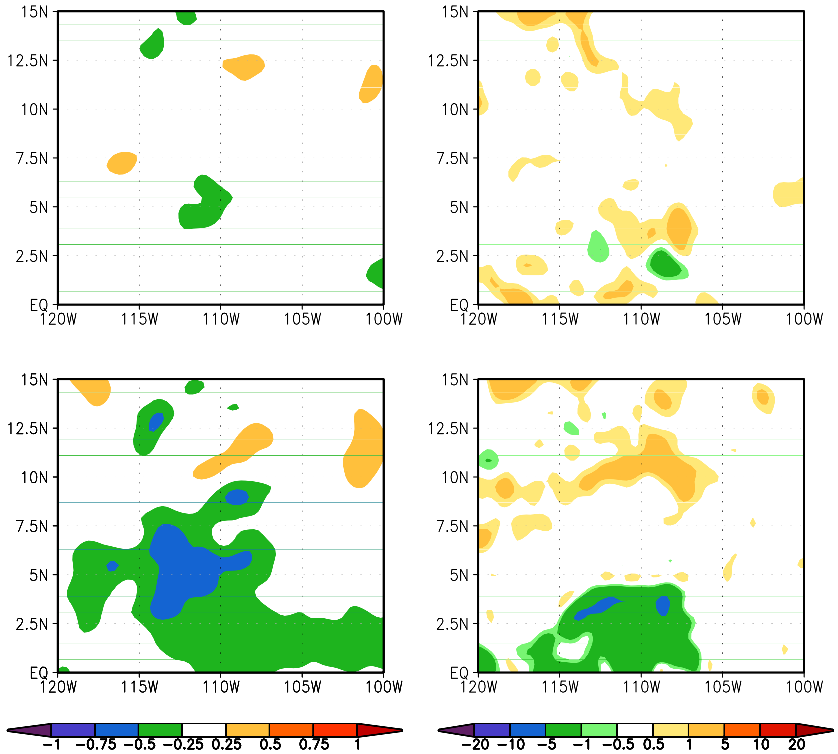

Figure 4. Analysis increments at level 10, corresponding to Fig. 3, for the clear-sky (upper panels) and all-sky (lower panels) approaches at 00Z Nov. 3, 2013: Specific humidity analysis increment ($\times 1.0e^3$, left panels, kg/kg) and cloud liquid water analysis increment ($\times 1.0e^5$, right panels, kg/kg).

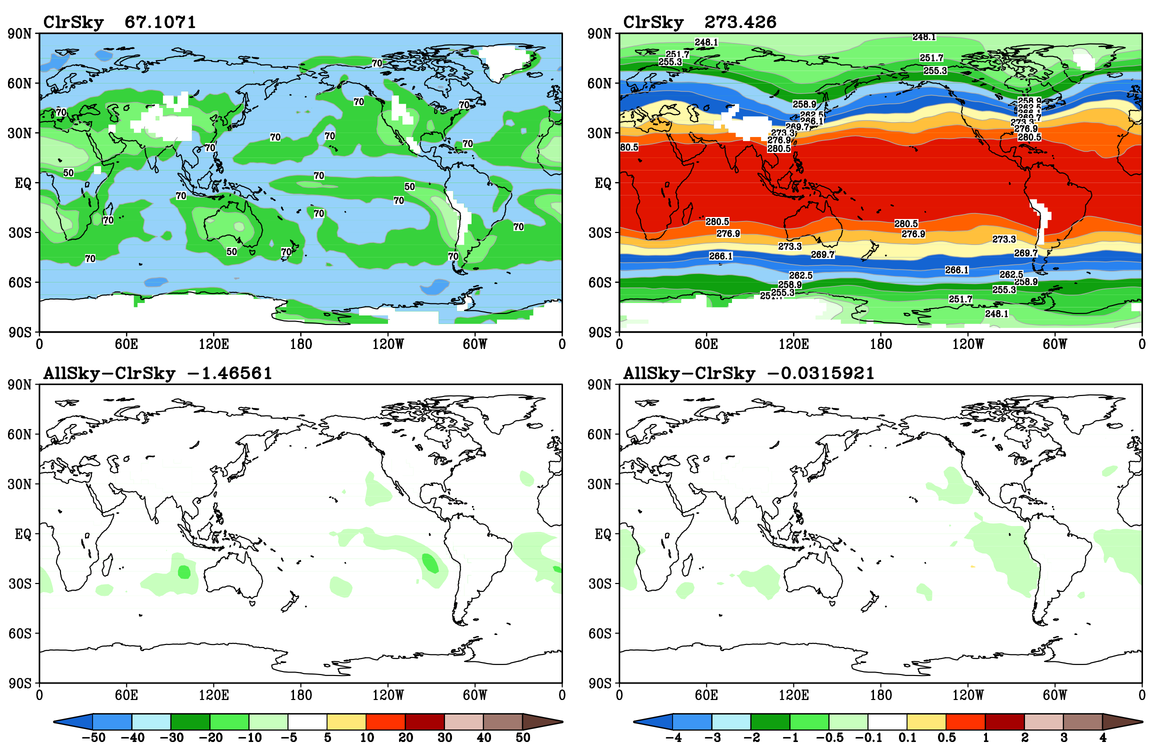

Figure 5. Left column: Averaged relative humidity analysis for ClrSky experiment (upper panel) and the difference between AllSky and ClrSky (lower panel) at 850 hPa for the period from Oct. 27 to Dec. 1, 2013; Right Column: Same as the left column but for temperature analysis at 700 hPa.

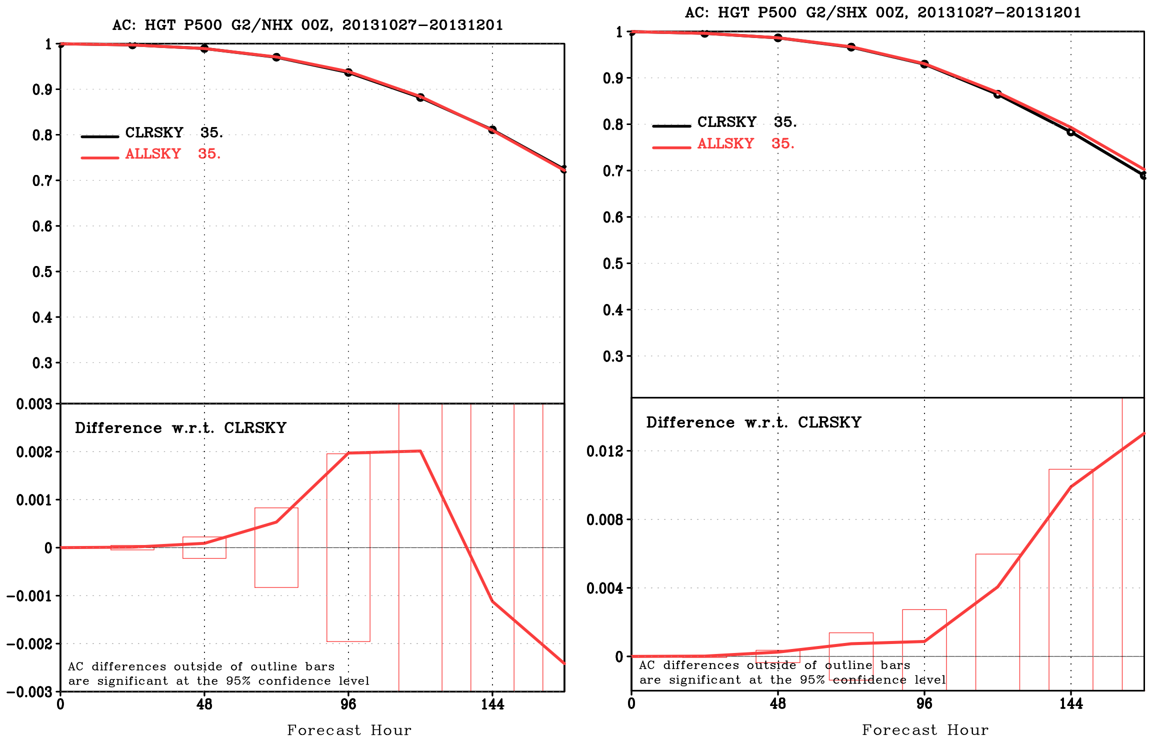

Figure 6. Geopotential height anomaly correlation at 500 hPa for the Northern (left panel) and Southern (right panel) Hemispheres during the period from Oct. 27 to Dec. 1, 2013.

5. Conclusions and future work

The capability for all-sky microwave radiance assimilation in the GSI analysis system has been developed at NCEP, with the flexibility of selecting either cloud water or individual hydrometeors as the cloud control variable(s) in the GSI. Since the current operational GFS system assimilates the radiance data in the clear-sky approach, necessary changes have been made on quality control, observation error assignment, bias correction, and cloud background error variance for all-sky conditions. The non-precipitating cloudy AMSU-A radiance data over ocean are assimilated in this study, and have been tested extensively in the 3D EnVar GFS system. The results show that the all-sky approach utilizes about 10% more data from AMSU-A channels 1-5 and 15 and improves relative humidity analysis at continental western boundaries in the GFS. The all-sky microwave radiance assimilation is included in the GFS pre-implementation package for the FY16 upgrade, and has been tested together with other upgrade components in the 4D EnVar GFS parallel experiment at NCEP.

As further refinements of all-sky assimilation continue, the GSI all-sky capabilities are expected to expand to other microwave instruments. Experiments to include the Advanced Technology Microwave Sounder (ATMS) instrument in the all-sky assimilation have been underway. Moreover, as the snow and precipitation profiles from the GFS forecast model become available in the future, the validation of scattering handling in the CRTM is important as we move forward to the assimilation of precipitating clouds.

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