Assimilating Infrared and Microwave Sounder Observations with Correlated Errors

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Abstract

Satellite observations are operationally assimilated at the National Centers for Environmental Prediction (NCEP) and are a vital part of the data assimilation system. The Gridpoint Statistical Interpolation (GSI) uses prescribed observation errors for infrared and microwave sounders and assumes that the observation errors of different channels are uncorrelated. To compensate for this, observation errors are inflated, however, in order to produce an optimal analysis, errors and error correlations must be accurately defined. The goal of this study is to enhance the specification of these errors in the operational GSI by improving their estimates and by properly accounting for these inter-channel correlations. The estimation of Infrared Atmospheric Sounding Interferometer (IASI), Atmospheric Infrared Sounder (AIRS), and Advanced Technology Microwave Sounder (ATMS) covariances are detailed in this article, as are the impacts of their inclusion in the GSI. The forecast benefits are also assessed after a two month assimilation experiment by verifying against other observations and against ECMWF analyses.

1 Introduction

Data assimilation blends observations and short range forecasts, or background state, to obtain the best possible estimate of the atmospheric state. The proper combination of the observations and background requires precise specification of their errors. In current National Centers for Environmental Prediction (NCEP) operations, observation errors in the Gridpoint Statistical Interpolation (GSI) are assumed to be uncorrelated, implying a diagonal $\mathbf{R}$ matrix in the analysis. However, for satellite observations, for example from the Atmospheric Infrared Sounder (AIRS), the Advanced Technology Microwave Sounder (ATMS), and the Infrared Atmospheric Sounding Interferometer (IASI), inter-channel error correlations are known to exist, [5, 2, 3]. These are a result of errors in radiative transfer modeling, representivity error, preprocessing and quality control, and instrument noise in the case of ATMS.

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Satellite radiances provide a wealth of information on the atmospheric state and it is important to represent these observations properly in the analysis. To counteract neglected correlations in the diagonal $\mathbf{R}$ matrix, observation errors are often increased well above their true values. However, this treatment does not provide a correct weighting of satellite data in the analysis. In this study, we use the Desroziers diagnostic to estimate the error variances and covariances of AIRS, ATMS and IASI observations, and investigate the impact of correlated error in the NCEP Global Forecast System (GFS) data assimilation scheme with the GSI. This paper is organized as follows. In Section 2, the computation of AIRS, ATMS and IASI error variances and covariances are detailed, as are the necessary modifications to the resulting $\mathbf{R}$ matrices. In section 3, the forecast impacts after accounting for correlated error are examined. We close with a brief conclusion in Section 4.

2 Methods

We estimate satellite errors and covariances by use of the Desroziers diagnostic, [4], a popular statistical technique. For a pair of analysis and background departures (observation minus guess), denoted by A and B respectively, the error covariance is calculated by estimating the expected value

$$\mathbf{R} = E[(A)^T B].$$

It should be noted that this method is sensitive to the specification of the background statistics, and requires that $\mathbf{B}$ and $\mathbf{R}$ be uncorrelated, [1]. It is also possible that the estimated $\mathbf{R}$ could be ill-conditioned, which is a problem in variational schemes. Therefore, it is necessary to modify an estimated observation error covariance matrix through reconditioning and variance inflation, to improve the conditioning, and to compensate for suboptimalities in the assimilation system and violations of the assumptions made in the Desroziers method.

AIRS, ATMS, and IASI error covariance matrices were computed from data unaffected by cloud contamination, over the sea only. The matrices were then reconditioned by setting the smallest eigenvalues of each equal to a constant, to achieve a desired condition number. This is consistent with the first reconditioning method described in [6]. For AIRS, the raw estimate of $\mathbf{R}$ was reconditioned to condition number $K = 150$; for ATMS, $K = 170$ and for IASI, $K = 200$. Next, the observation errors were inflated by a small value as

$$\mathbf{R}_{r,r} = (\sqrt{\mathbf{R}_{r,r}} + \sigma_r)^2.$$

This value of σ_r was empirically chosen by optimizing background fits to observations from ATMS, AMSUA, MHS, and CrIS, as well as temperature and humidity radiosonde measurements. For IASI and ATMS, σ was taken to be 0.06 and 0.1, respectively, for all channels. For AIRS, a value of $\sigma = 0$ for channels sensitive to water vapor and a value of $\sigma = 0.1$ for all other channels were chosen. When inflation was applied to all AIRS channels, this tended to improve fits to temperature type observations, but worsen fits to water vapor type observations. Currently, water vapor channels from IASI are not assimilated at NCEP, and this pattern was not observed for this instrument.

The estimated correlation matrices and errors are shown for each instrument in Figure 1, after applying these modifications. The current operational observation errors are also shown (see the black curves in the bottom panels of Fig. 1). Notice that strong inter-channel error correlations, with values greater than 0.5, remain after modifying the Desroziers estimates, especially in AIRS and ATMS water vapor bands (see the top row of Fig. 1). The IASI correlation matrix retains moderate correlations with values between 0.2-0.4 in the window channels and ozone band. Except for a majority of the temperature sounding channels from ATMS, the newly computed observation errors are much smaller than the original, operational errors, even with variance inflation. As a result, the analysis should pull towards these observations more closely.

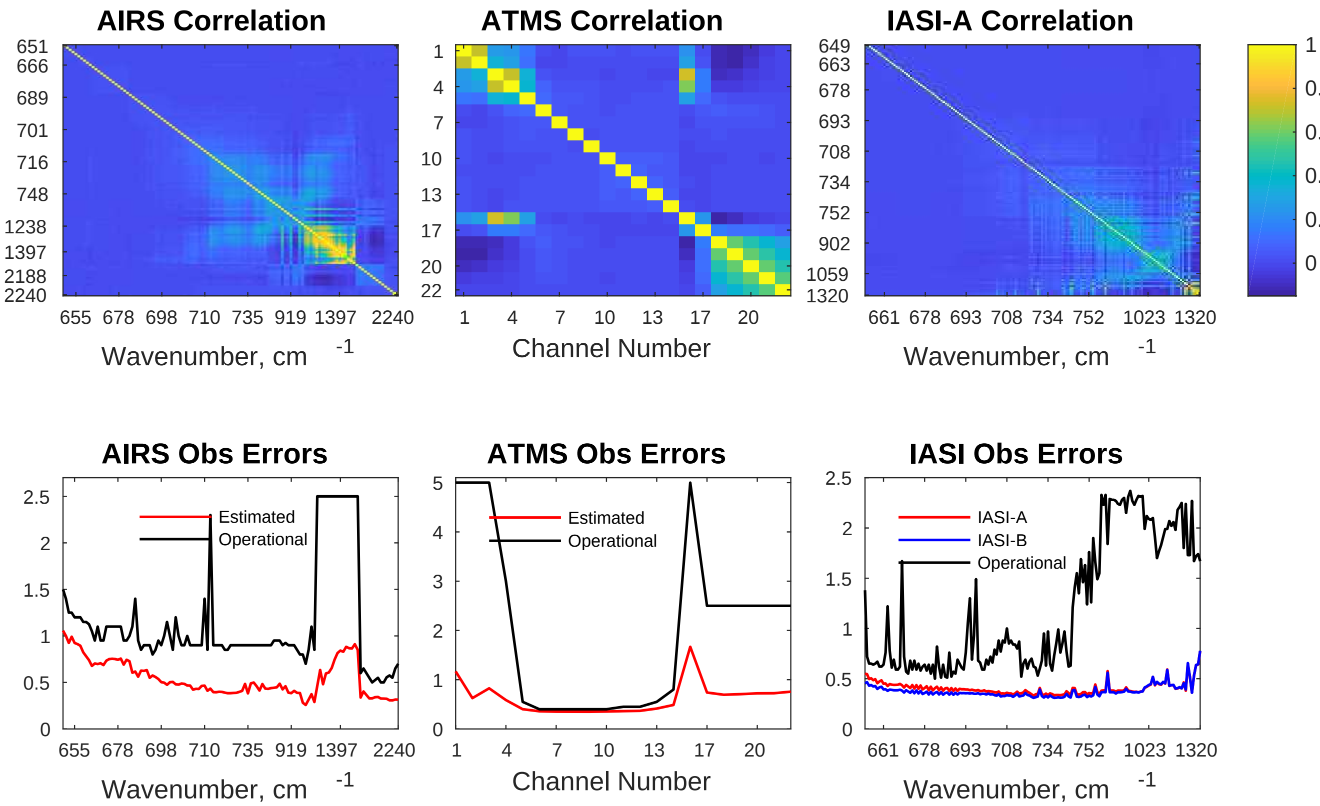

Figure 1: *The observation error correlation matrices (top row) and errors (bottom row) estimated from the Desroziers method after applying reconditioning and variance inflation, for AIRS (left), ATMS (center) and IASI (right). The black curves in the bottom panels show the operational observation errors (used when* $\boldsymbol{R}$ *is diagonal). The IASI-B correlation matrix is very similar to that of IASI-A.*

3 Forecast Impact

These error covariance matrices were used in NCEP's data assimilation system, the GSI, in separate two month GFS experiments from April 1, 2014 to June 8, 2014. This resulted in a total of four experiments: Full AIRS, Full ATMS, and Full IASI, which used correlated errors for their respective instruments over the sea only, and Diag, which used diagonal covariance matrices for all observations and the operational observation errors. These experiments used hybrid 3D ensemble variational assimilation, at T670 resolution, with a resolution of T254 for the ensemble members. In each case, accounting for correlated error had a strong influence on the analysis. Not surprisingly, the background and analysis fits to observations from other satellite instruments were impacted, and in most cases, improved. Figure 2 shows, for example, the fits to a passive CrIS water vapor channel resulting from the Full AIRS and Diag experiments. Comparing the red and green curves, it is clear that using correlated AIRS errors improves the analysis fit to this channel. Comparing the blue and yellow curves shows a smaller improvement in the background fit with correlated error. The AIRS channel set includes several channels in the water vapor band. The operational observation errors for these channels are set to 2.5, much higher than the Desroziers estimates (see Fig. 1). The inflation is meant to make up for the strong, neglected correlations among these channels. The improvement in fits to independent water vapor channels from CrIS in the Full AIRS experiment suggests a better use of AIRS data in this case; simply inflating errors cannot provide a proper representation of these observations in the analysis. Similar results were observed in the Full ATMS and Full IASI experiments.

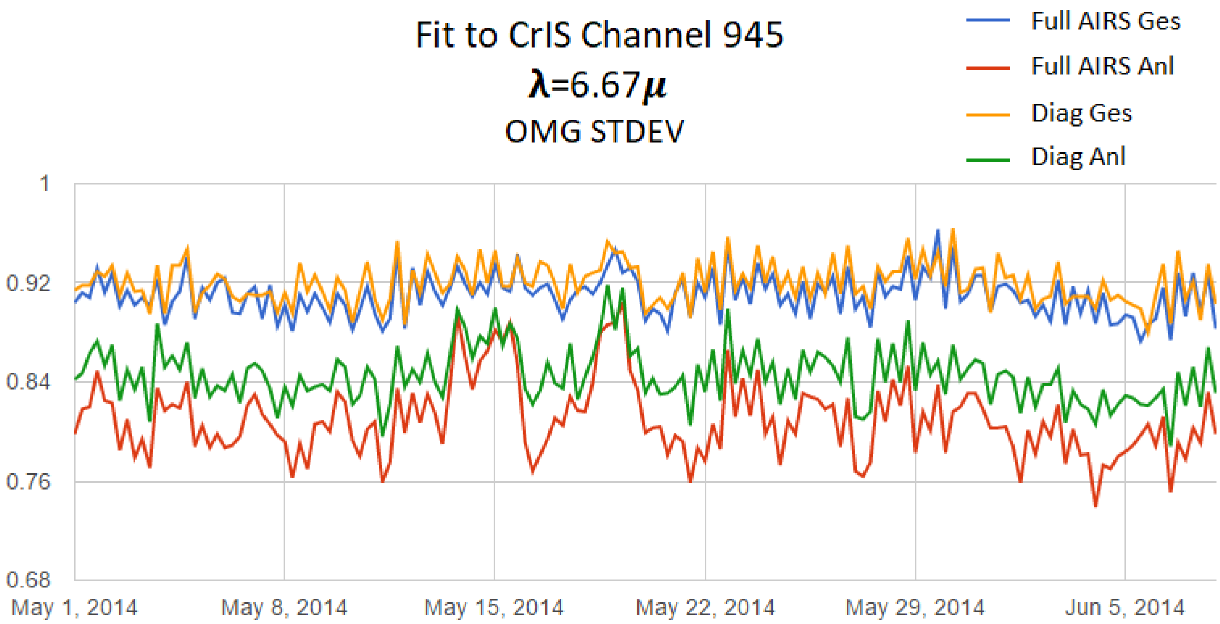

Figure 2: *The fits to a passive CrIS water vapor channel. The red and green curves show the Full AIRS and Diag analysis fits, respectively, while the blue and yellow curves show the Full AIRS and Diag background fits, respectively.*

The short and medium range forecasts were verified against European Centre for Medium-Range Weather Forecasts (ECMWF) analyses. Figure 3 shows the differences between the temperature RMSE of each Full **R** experiment and the Diag temperature RMSE, in the Northern and Southern Hemispheres, as well as in the tropics. When accounting for correlated error, the forecast impact is generally positive in the troposphere, and negative in the stratosphere. In Figure 3, this is illustrated by areas of green in the troposphere, where Diag has the larger RMSE, and areas of red in the stratosphere, where Diag has the smaller RMSE. A possible reason for this pattern is that satellite observations are sensitive to the troposphere, which can constrain the analysis in this part of the atmosphere, while aliasing errors into the stratosphere. Notice also in the tropics and Southern Hemisphere that the Diag experiment tends to have better forecast skill at day 6, especially compared to the Full ATMS experiment. Overall, the Full IASI experiment had the best forecast impact of the Full **R** experiments, while Full ATMS had the worst.

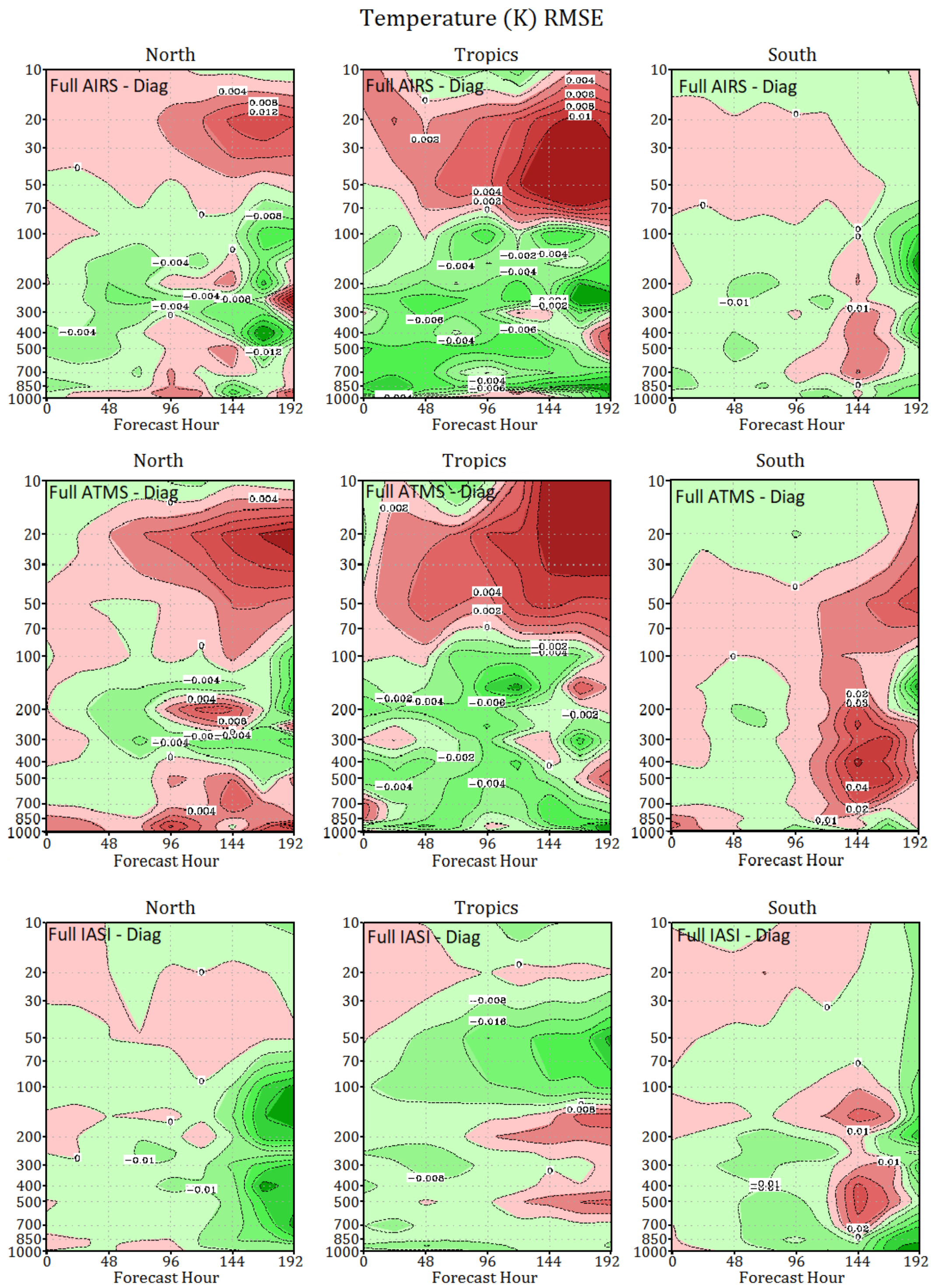

Figure 3: *The differences in forecast temperature RMSE between the Full AIRS (top row), ATMS (middle row) and IASI (bottom row) and Diag experiments, in the Northern Hemisphere (left column), tropics (middle column) and Southern Hemisphere (right column). Forecasts are verified against ECMWF analyses. Shades of green indicate an improvement in the forecast with correlated error, while shades of red indicate a degradation. The darkest shades are significant at the 95% level.*

Forecasts were also verified against radiosonde observations. The 6 hour RMSEs demonstrate a neutral to slightly positive impact with correlated error in several areas. Figure 4 shows the differences between the Full **R** and Diag 6 hour forecast RMS fits to temperature and humidity radiosonde measurements. A negative value indicates that the fit is improved with correlated error, whereas a positive value means the opposite. For temperature, fits in the Northern and Southern Hemispheres are slightly improved in the troposphere with correlated error. In the tropics, fits are improved around 100-150 hPa and 500 hPa. The impact in the stratosphere tends to be neutral to negative. The Full AIRS experiments generally exhibits improved fits to humidity observations globally. This could be a result of the improved use of the AIRS water vapor channels. The Full IASI and Full ATMS humidity impacts are mostly negative in the lower troposphere, but positive in the Northern Hemisphere and tropics near 700 hPa.

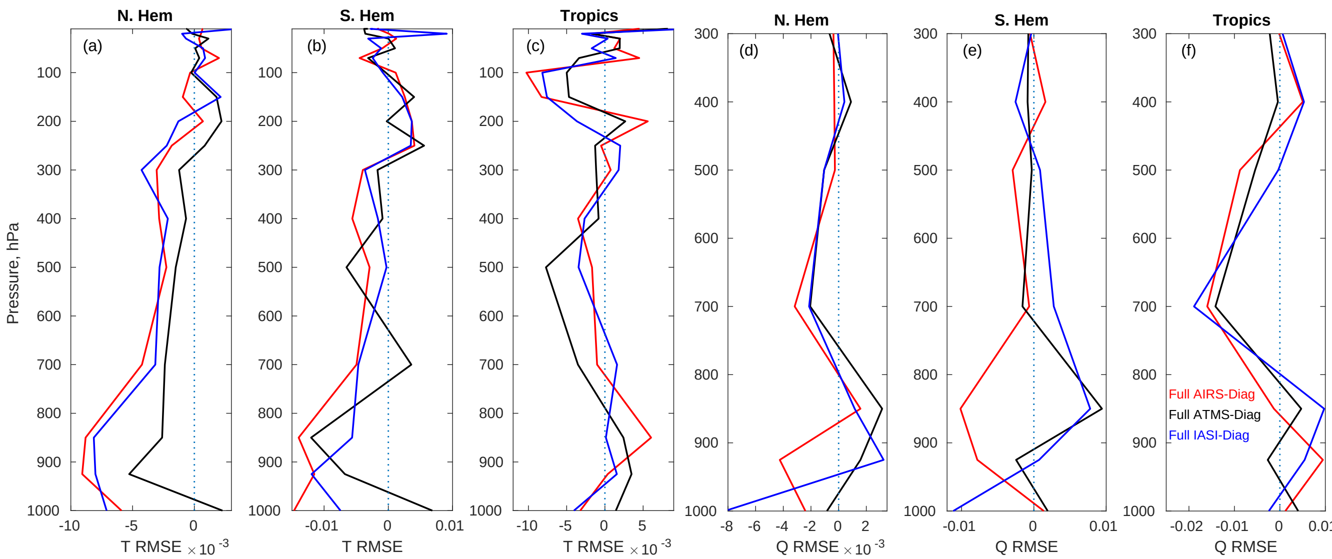

__Figure 4:__ The differences between the Full __R__ experiment RMSEs and the Diag experiment RMSE. The 6 hour forecasts are verified against temperature (a-c) and humidity (d-f) radiosonde measurements taken in the Northern Hemisphere (a and d), Southern Hemisphere (b and e) and tropics (c and f). The red curves show the RMSE difference between the Full AIRS and Diag experiments, the black curves show the RMSE difference between the Full ATMS and Diag experiments, and the blue curves show the RMSE difference between the Full IASI and Diag experiments.

The 120 hour forecast fits show larger differences between the Full **R** and Diag experiments (see Fig. 5). In the Full IASI experiment, fits to tropospheric temperature and humidity are improved over the Diag fits everywhere except in the tropics. On the other hand, the Full ATMS and Full AIRS experiment fits tend to be worse than the Diag fits, except in the Northern Hemisphere in the case of humidity, and near the surface in the Full AIRS experiment. The Diag fit to humidity in the tropics near 850 hPa is better than those of the correlated error experiments. Across the three correlated error experiments, humidity analysis increments were large, peaking in the tropics between 900 - 700 hPa, and were considerably larger than the Diag humidity increments (not shown). This was true even in the Full IASI experiment, which did not assimilate channels in the main water vapor band. The humidity analysis is therefore quite sensitive to the weighting of satellite observations, especially in the tropics.

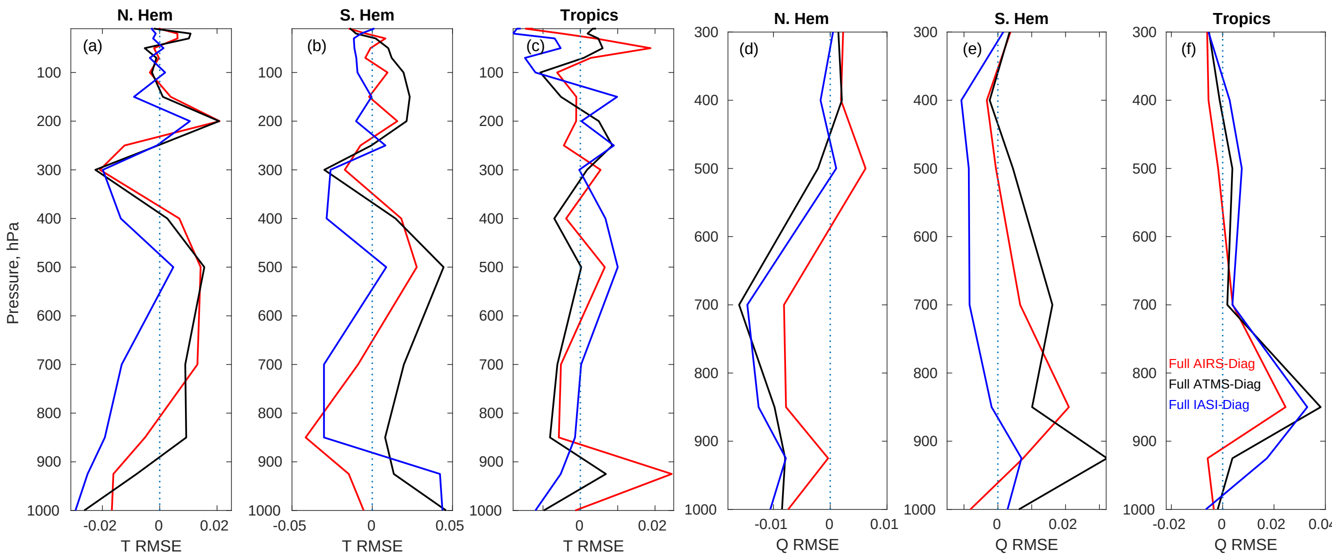

Figure 5: *Same as Figure 4, but for forecast hour 120.*

Closer examination of the stratospheric temperature fits reveals a potential issue in the Full AIRS and Full ATMS experiments. Figure 6 shows the differences in fits to temperature observations at 30 hPa, versus forecast lead time. For the Full AIRS and Full ATMS experiments, there is a degradation over Diag in the Northern and Southern Hemispheres, significant at the 95% level. The Full IASI fits, on the other hand, are improved, and significantly so in the Southern Hemisphere and tropics. Referring back to Figure 3, the Full AIRS and Full ATMS forecast impacts (verified against ECMWF analyses) were negative at 30 hPa in the Northern Hemisphere and tropics. The consistency between these two verification metrics indicates a problem in the stratosphere when accounting for correlated error.

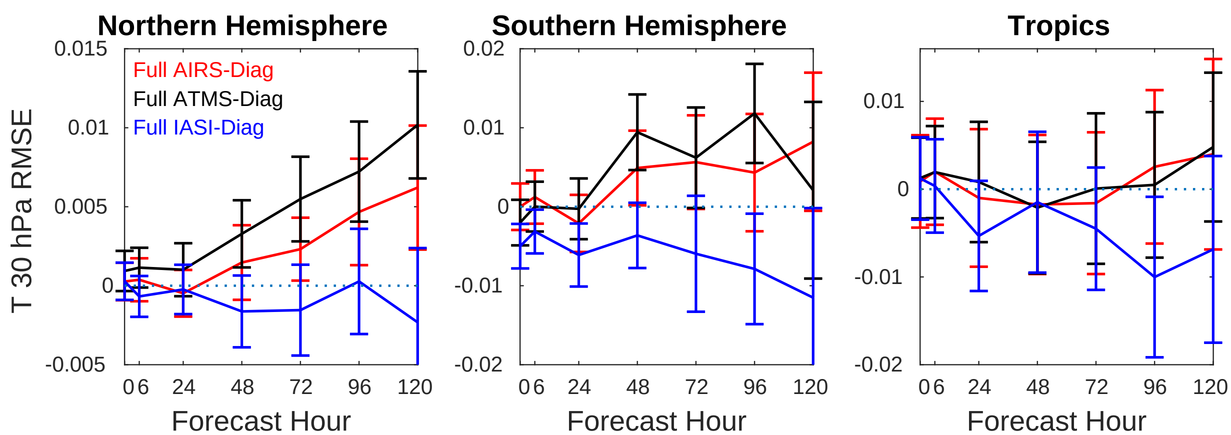

Figure 6: *The differences between the Full* $\boldsymbol{R}$ *experiment RMSEs and the Diag experiment RMSE. The forecasts are verified against temperature radiosonde measurements taken at 30 hPa in the Northern Hemisphere (left), Southern Hemisphere (center) and tropics (right). The red curves show the RMSE difference between the Full AIRS and Diag experiments, the black curves show the RMSE difference between the Full ATMS and Diag experiments, and the blue curves show the RMSE difference between the Full IASI and Diag experiments. Error bars portray a 95% confidence interval.*

4 Conclusion

We examined the specification of AIRS, ATMS and IASI errors and inter-channel error correlations in the GSI. The Desroziers diagnostic can provide reasonable estimates of these statistics, but it is still necessary to recondition the resulting matrices and inflate the error estimates. We also examined the forecast impact after accounting for correlated AIRS, ATMS and IASI errors, separately. The use of correlated errors tended to improve the forecast skill in the troposphere, while degrading it in the stratosphere. The reason for the issues in the stratosphere remain under investigation. As mentioned before, it is possible that these satellite observations, which are sensitive to the tropospheric state, are being over-fitted, negatively affecting the analysis in the stratosphere. The weights given to the stratospheric temperature sounding channels in these instruments may also be too great. Such channels exhibit minimal inter-channel error correlations, yet the errors assigned to them in the Full $\mathbf{R}$ experiments are much lower than the operational values. Finally, it is possible that the GFS model is less accurate in the stratosphere.

We also continue to investigate the issues with the Full ATMS experiment, which had poor forecast impact, especially in the Northern Hemisphere. The choice of reconditioning method or variance inflation could have led to an improper treatment of these channels, negatively affecting the forecast skill and fits to radiosondes. Different channel sets may require different amounts of variance inflation. The Full IASI experiment, in comparison to the Full AIRS and Full ATMS experiments, had a largely positive forecast skill. Because there are two IASI instruments, and because we do not assimilate channels from the IASI water vapor band, this experiment differs from the other two. This suggests that the treatment of waver vapor channels may not have been optimal. Nevertheless, the initial results shown here are promising. Further efforts to refine the variance inflation should lead to forecast benefit.

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