Assimilating Infrared and Microwave Sounder Observations with Correlated Errors

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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. It is common to assume that observation errors are uncorrelated with each other, therefore using a diagonal error covariance matrix. However, for infrared and microwave satellite observations, error correlations do exist. To account for these correlations, the covariance matrix remains diagonal, but errors are inflated. Thus the observations and their correlations are typically not accurately represented in the analysis.

The Desroziers diagnostic is popular method for estimating observation error covariances, and its use has been shown to have a positive impact on numerical weather prediction. However, in this method, observation and background errors are assumed to be uncorrelated with each other, and error covariances should be computed iteratively. At NCEP we are planning to upgrade our data assimilation system, the Gridpoint Statistical Interpolation (GSI) to account for correlated satellite error. The purpose of this study is:

- To determine when the iterative application of the Desroziers method will yield a reasonable approximation to the true observation error covariance and
- To ultimately improve the specification of observation errors in the operational GSI by improving their estimates and by properly accounting for these inter-channel error correlations.

Theory

The best estimate of the atmospheric state is the analysis $\mathbf{x}^a$, which minimizes the cost function

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}^b)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b) + \frac{1}{2}(\mathbf{y}^o - H(\mathbf{x}))^T\mathbf{R}^{-1}(\mathbf{y}^o - H(\mathbf{x})).$$

Observations $\mathbf{y}^o$ and background state $\mathbf{x}^b$ are weighted by their error covariance matrices, $\mathbf{R}$ and $\mathbf{B}$, respectively, and it is important for these matrices to be correctly specified.

In the Desroziers method, $\mathbf{R}$ and $\mathbf{B}$ are assumed to be uncorrelated with each other, and these error statistics are assumed to be exact. 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

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

Applying the Desroziers method iteratively yields a recursive sequence

$$\mathbf{R}_{i+1} = \mathbf{R}_i(\mathbf{HBH}^T + \mathbf{R}_i)(\mathbf{HB}_{\text{true}}\mathbf{H}^T + \mathbf{R}_{\text{true}}).$$

It can be shown that:

- If $\mathbf{HBH}^T = \mathbf{HB}_{\text{true}}\mathbf{H}^T$ then $\mathbf{R}_i \to \mathbf{R}_{\text{true}}$
- If $\mathbf{R}_{\text{true}} + \mathbf{HB}_{\text{true}}\mathbf{H}^T - \mathbf{HBH}^T$ is positive definite then $\mathbf{R}_i \to \mathbf{R}_{\text{true}} + \mathbf{HB}_{\text{true}}\mathbf{H}^T - \mathbf{HBH}^T$
- If $\mathbf{R}_{\text{true}} + \mathbf{HB}_{\text{true}}\mathbf{H}^T - \mathbf{HBH}^T$ is not positive definite then $\mathbf{R}_i$ diverges to a singular matrix.

Results with the Desroziers Method

When using the Desroziers method, convergence can be achieved in just a few iterations.

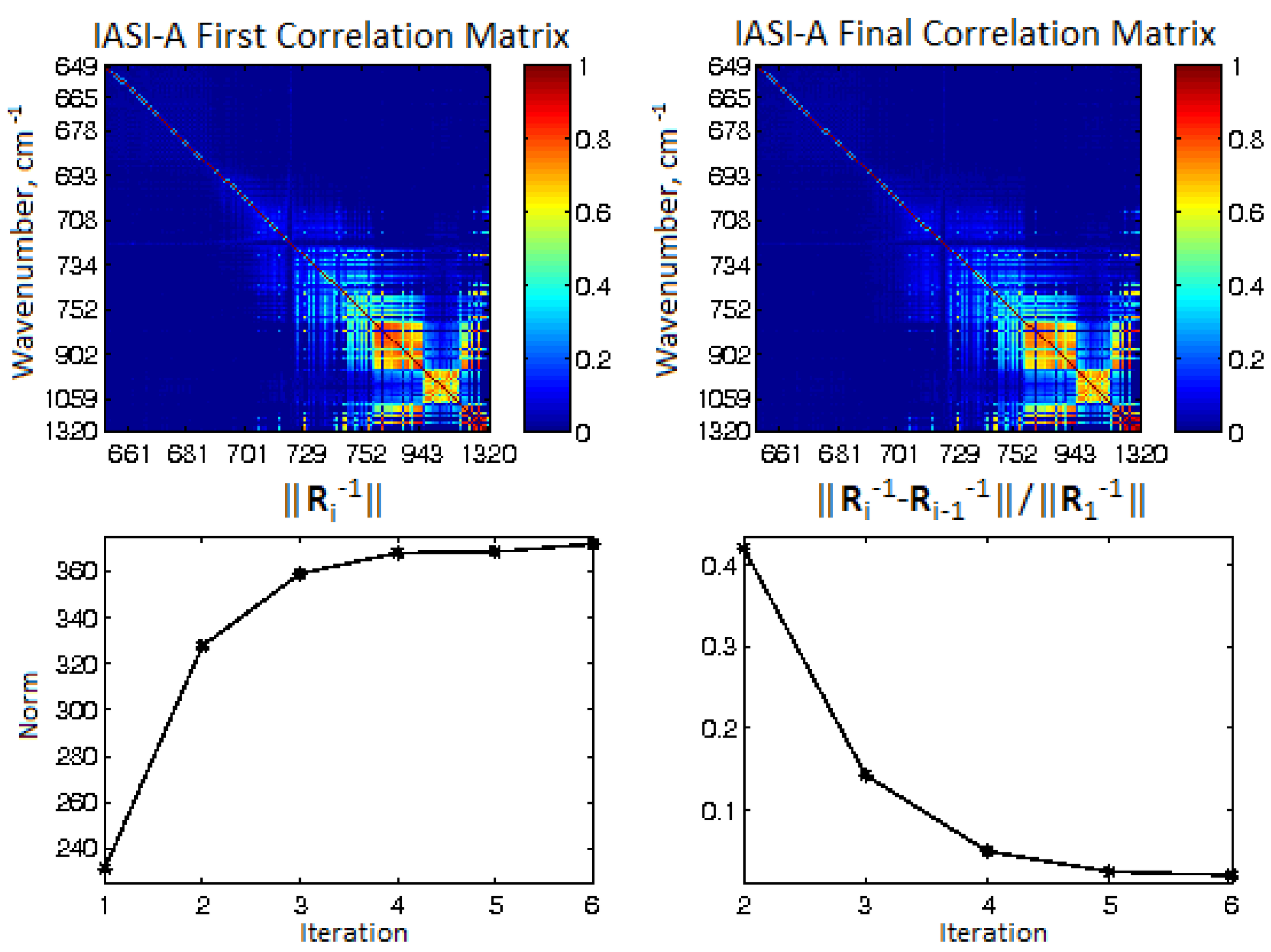

Figure 1: Error correlation matrix for IASI after one application of the Desroziers method (top left) and six applications (top right), $\left\|\mathbf{R}_i^{-1}\right\|$ (bottom left) and $\left\|\mathbf{R}_{i+1}^{-1} - \mathbf{R}_i^{-1}\right\| / \left\|\mathbf{R}_1^{-1}\right\|$.

Pre-processing procedures such as cloud clearing or quality control checks can create correlations between the background and observation errors. It is also possible for model error to feed into the forward model.

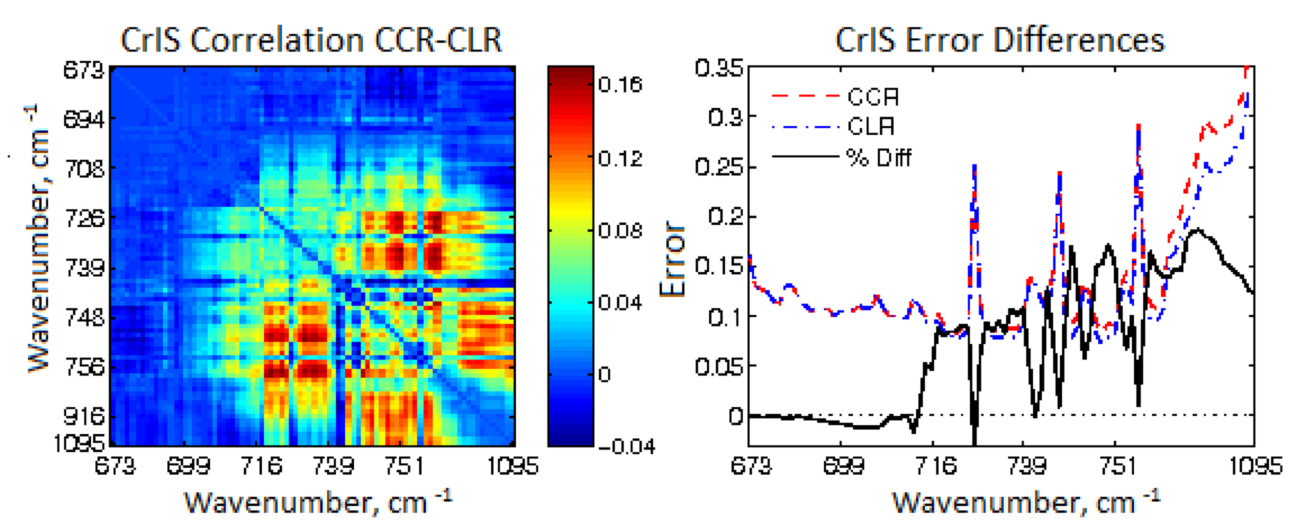

Figure 2: The difference between the estimated CrIS error correlation matrices with (CCR) and without (CLR) using cloud-cleared data (left) and the difference between the estimated observation errors (right).

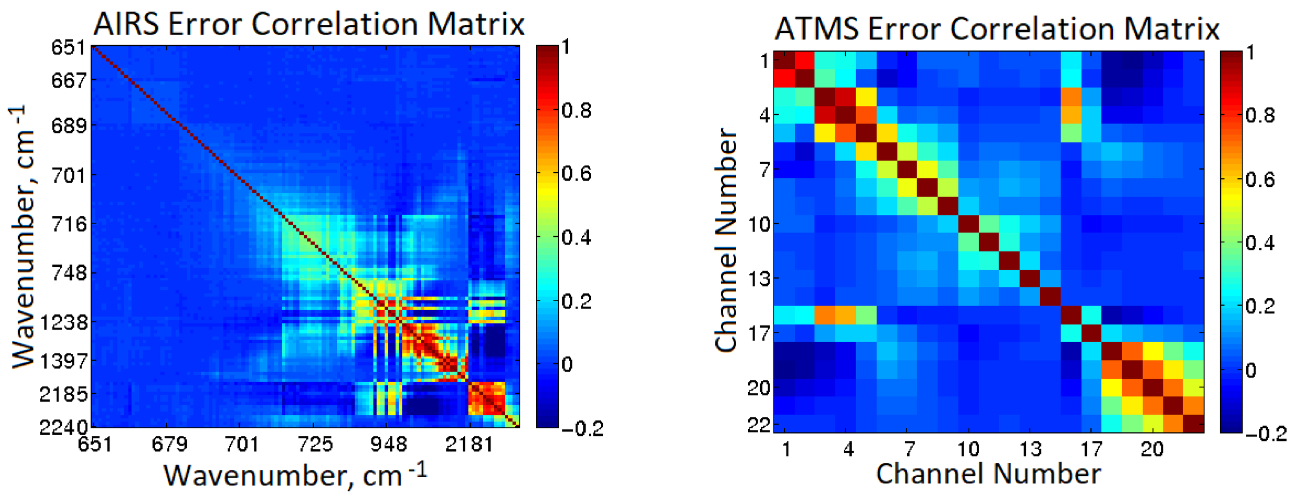

Figure 3: The diagnosed AIRS (left) and ATMS (right) error correlation matrices.

Forecast Impact

Full observation error covariances for IASI, AIRS and ATMS were used (separately) in a two month long assimilation experiment using the Global Forecast System (GFS). Each experiment used observations from the same instruments and channel sets.

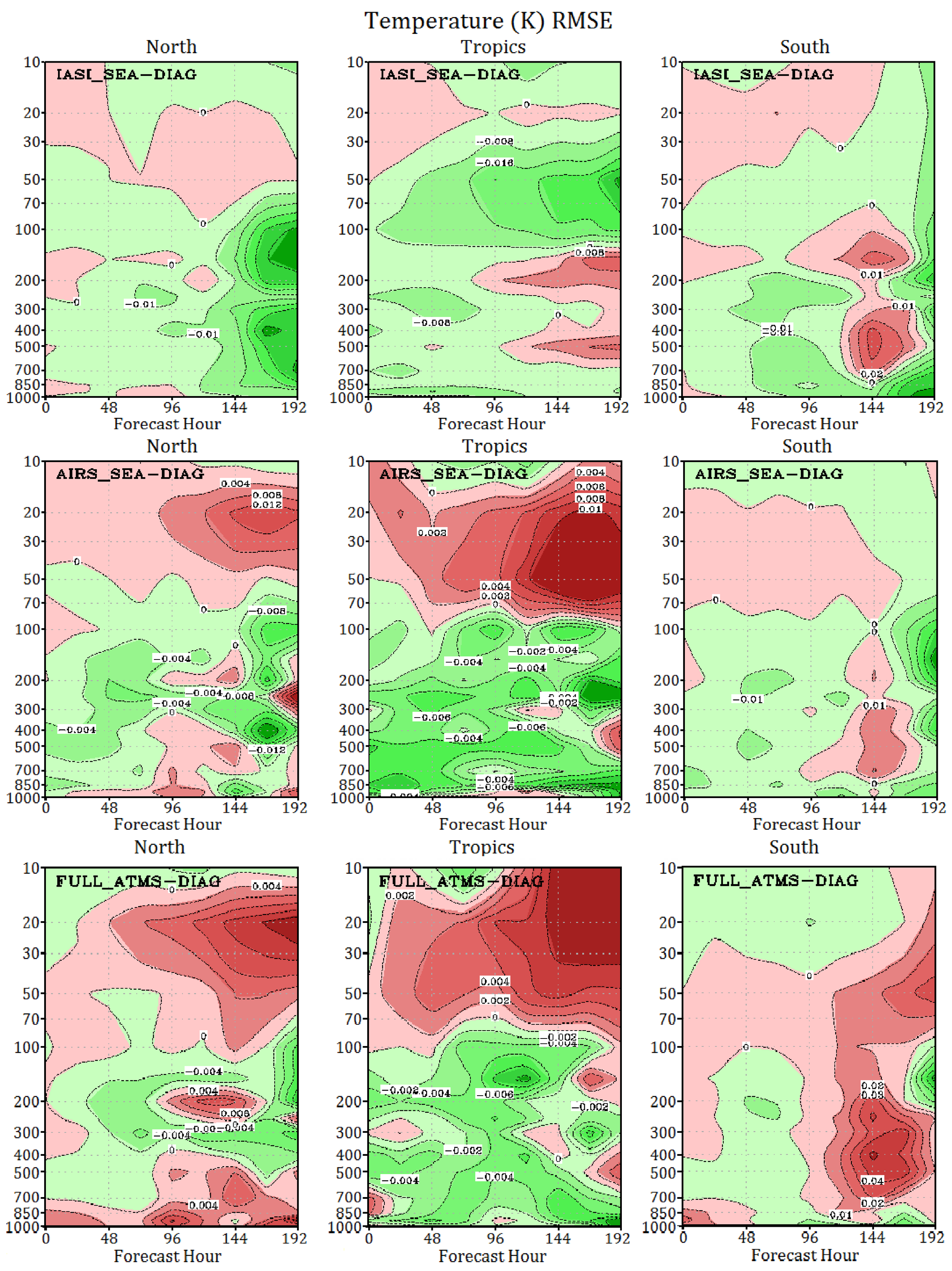

Figure 4: The difference in temperature RMSE in the Northern Hemisphere (left column), Tropics (middle column) and Southern Hemisphere (right column) with and without full covariances for IASI (top row), AIRS (middle row) and ATMS (bottom row). Green indicates a positive forecast impact with the correlated errors, while red indicates a negative forecast impact. The strong impacts are significant, except in the long range forecasts.

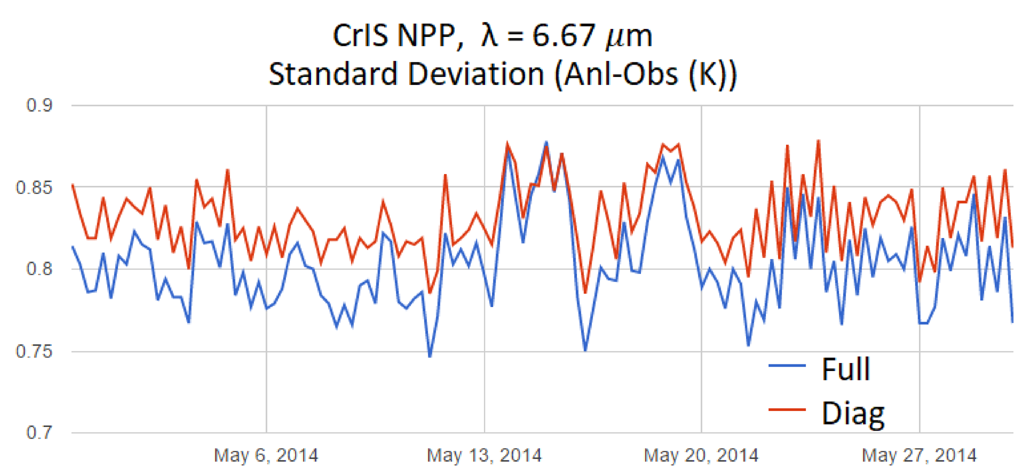

Figure 5: The analysis fit to a passive CrIS channel (water vapor). Full refers to the experiment with correlated error for AIRS and Diag refers to the control experiment with no correlations.

Summary of Results

- The convergence of the iterative Desroziers method depends on the assumed background error statistics. Only a few iterations may be practically necessary.
- Using the Desroziers method when **R** and **B** are correlated will increase the error and error correlation estimates by a relatively small amount.
- Overall, using full error covariances improved the fits to numerous observation types, including temperature and winds (not shown). The fits to various channels from CrIS and other satellite instruments were also improved.
- Forecast impacts are generally positive in the troposphere, and negative in the stratosphere (with significance), especially in the case of AIRS and ATMS.
- Using full **R** for IASI degraded fits to humidity observations (not shown). However, turning on water vapor channels from IASI with correlated errors can improve these fits.

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