Assimilating Infrared Sounder Observations with Correlated Error

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The goal of data assimilation: combine observations and short-range forecasts to obtain the best possible estimate of the atmospheric state.

The cost function:

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

$\mathbf{x}^b, \mathbf{B}$: background state (forecast) and background error covariance
$\mathbf{y}^o$, **R**: observations and observation error covariance
H: observation operator
$\mathbf{x} = \mathbf{x}^a$: analysis state, minimizes J.

Observation error is the difference between the true observation and what is actually measured. Diagonal terms of **R** contain estimates of the error variances, while the off-diagonal terms contain estimates of error covariances.

Currently at NOAA/NCEP, **R** is a diagonal matrix, meaning that observation errors are uncorrelated with each other. However, for satellite observations, inter-channel error correlations do exist. To account for this, **R** remains diagonal, but errors are inflated.

Introduction

At NCEP, data assimilation is executed with the Gridpoint Statistical Interpolation (GSI).

Satellite observations have had a tremendous impact on numerical weather prediction. In this study, brightness temperature observations from the Atmospheric Infrared Sounder (AIRS) on Aqua and the Infrared Atmospheric Sounding Interferometer (IASI) on Metop-A and Metop-B are used.

Passive satellite instruments like AIRS and IASI detect radiation emitted by the Earth and its atmosphere. Channels are measurements at a particular frequency and can be associated with temperature, water vapor concentration, etc.

In the GSI, 616 IASI channels and 281 AIRS channels are used, of which 164 from IASI and 117 from AIRS are actively assimilated.

AIRS channels: longwave upper and lower temperature sounding channels, longwave window channels, water vapor channels, and a few shortwave window and temperature channels.

IASI channels: longwave upper and lower temperature sounding channels, longwave window channels, and ozone channels.

Introduction

What are the sources of observation error?

- Instrument noise

- Pre-processing, quality control and bias correction errors

- Forward model errors: radiative transfer modeling errors

- Representivity errors: unresolved spatial scales, temporal or spatial mismatch between observations and model forecast

Each bullet can contribute to inter-channel error correlations.

Goal: Enhance the specification of observation errors by improving their estimates and accounting for these inter-channel error correlations.

Estimating Observation Errors and Covariances

Full covariances for AIRS and IASI will be computed. To compute observation variances and covariances, the Desroziers diagnostic is used.
Main Assumptions:

- Observation and background errors are uncorrelated,
- **R** and **B** are perfectly specified in the analysis,
- **R** and **B** have sufficiently different length scales.

For a pair of analysis and background departures (observation minus guess), denoted by A and B respectively, the error covariance is given by the expected value

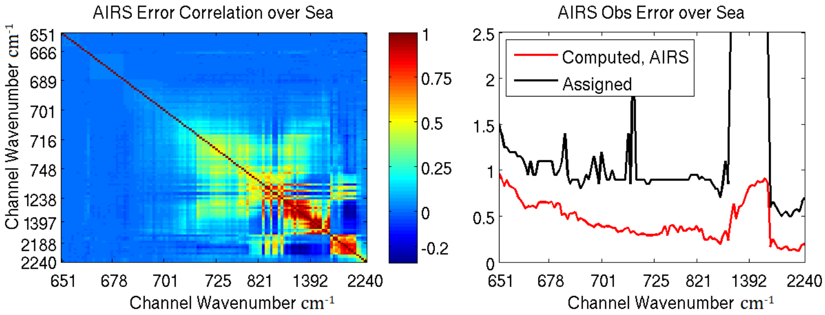
$$\mathbf{R} = E[(A)^T B].$$

For two channels denoted by r and c, their covariance is given by

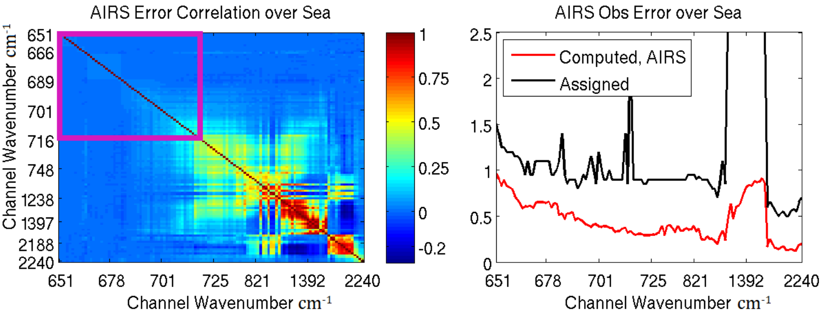
$$\mathbf{R}_{r,c} = \frac{1}{p} \sum_{k=1}^{p} A_{k,r} B_{k,c} - \frac{1}{p^2} \sum_{k=1}^{p} A_{k,r} \sum_{k=1}^{p} B_{k,c},$$

where p denotes the size of a set of departure pairs.

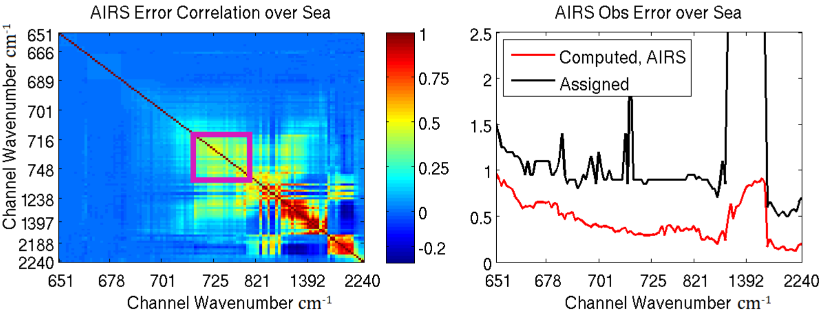
Desroziers Results: AIRS



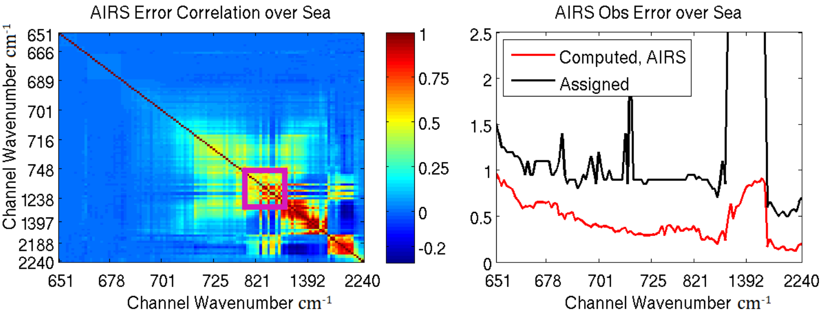
Desroziers Results: AIRS



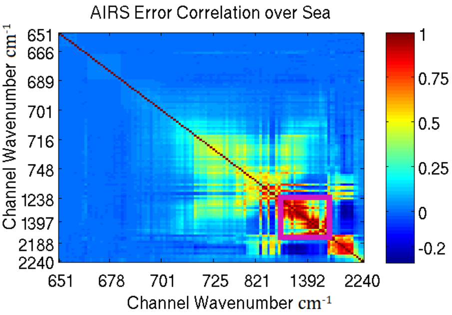
Desroziers Results: AIRS

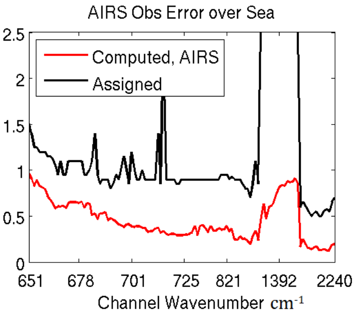


Desroziers Results: AIRS

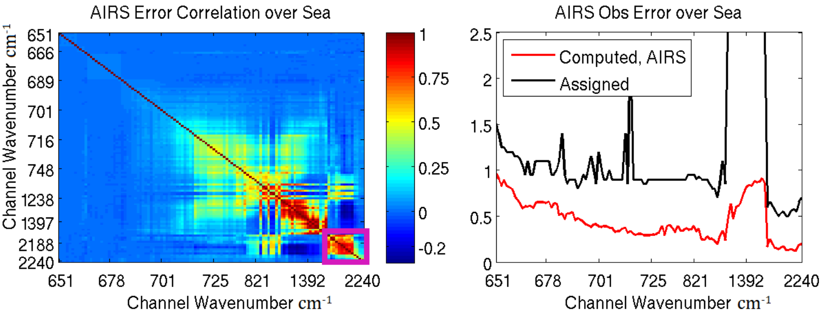


Desroziers Results: AIRS

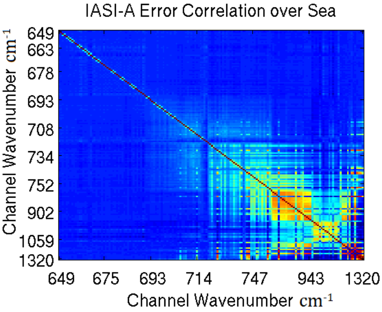


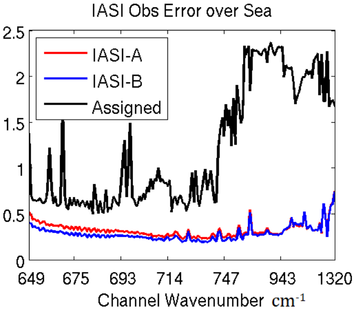


Desroziers Results: AIRS

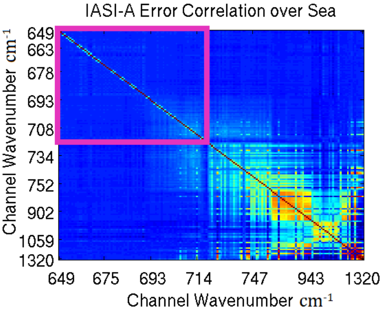


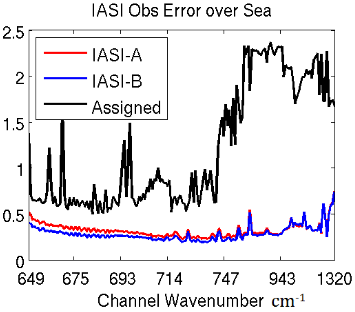
Desroziers Results: IASI



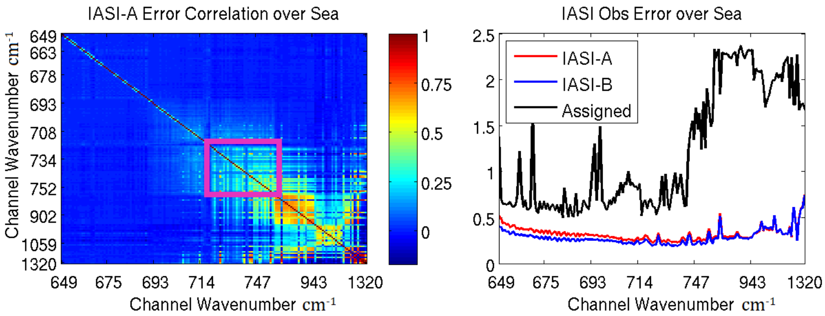


Desroziers Results: IASI





Desroziers Results: IASI



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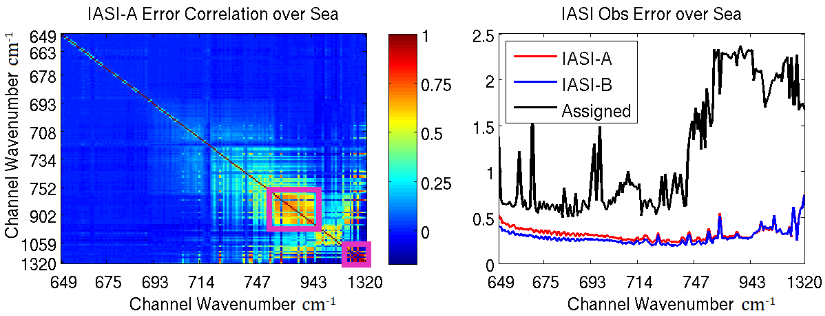
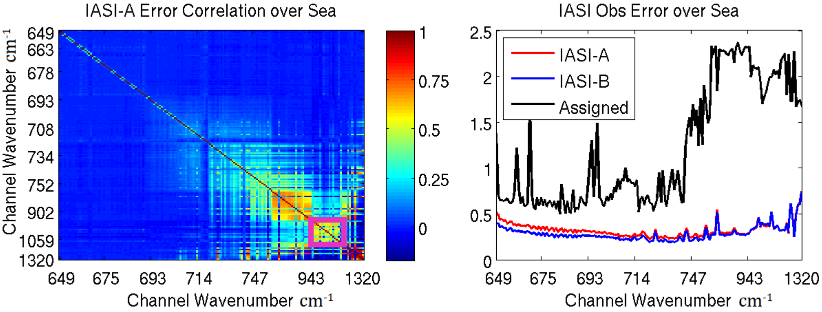


Desroziers Results: IASI



Reconditioning and Modifying **R**

The condition number of a matrix is defined as the ratio of its largest eigenvalue to the eigenvalue that is closest to zero.

$$K = \frac{\lambda_{max}}{\min[\text{abs}(\lambda)]}.$$

The conditioning of **R** is directly related to the conditioning of the Hessian. If K is too large, the minimization convergence may be slow, or it may even fail.

Reconditioning **R** can correct any negative eigenvalues, and lower the condition number.

Making further modifications to **R**, like inflating diagonal values, may be necessary to compensate for sub-optimality in the assimilation scheme or violations of the assumptions made in applying Desroziers' method.

There are numerous ways to recondition **R**. Here, the smallest eigenvalues are adjusted. First, all eigenvalues that are smaller than λ_{max}/K are set equal to this value, where $K = 150$ for AIRS and $K = 200$ for IASI. Next, a subset of the diagonal values of **R** are inflated as

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

The value of σ is empirically tuned, by optimizing background and analysis fits to AMSUA, CrIS, MHS, ATMS and conventional observations. For IASI, this gave $\sigma = 0.06$ for all channels and for AIRS this gave $\sigma = 0.1$ for all channels except H_2O channels.

Experimental Setup

At NCEP, data assimilation is executed with the GSI. The following experiments use 3D Hybrid EnVar with 80 ensemble members at T254 resolution and T670 model resolution.

Correlated errors for AIRS and IASI will be considered separately, and will be used over the sea only. These covariances are used in a two month assimilation experiment from April 1 2014 to June 8, 2014, using the Global Forecast System (GFS).

Three experiments:

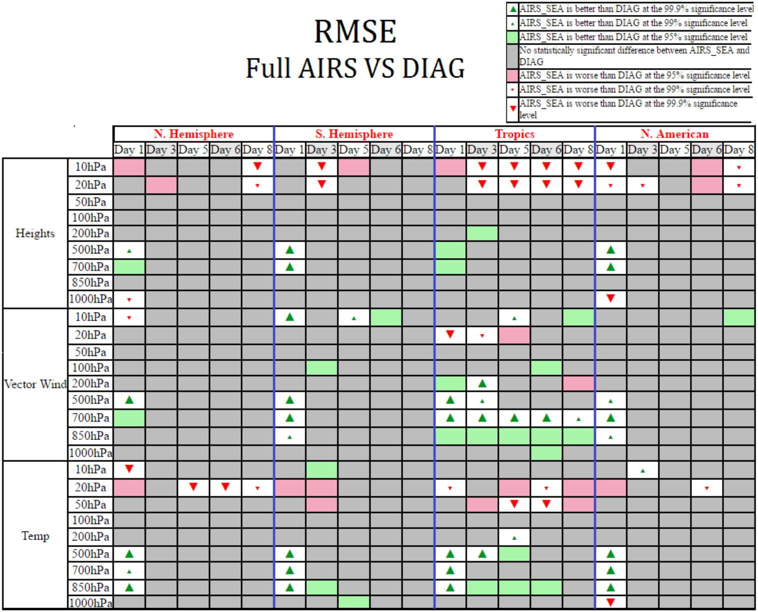
Diag: diagonal **R** is used for IASI and AIRS, with operational observation errors,

Full AIRS: Full covariance matrix for AIRS,

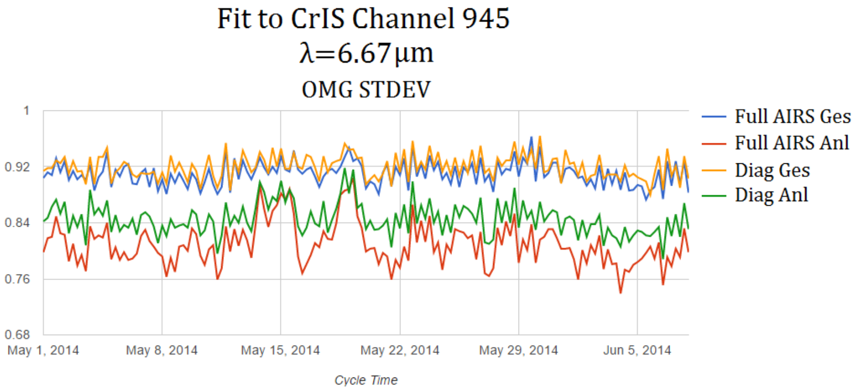
Full IASI: Full covariance matrices for both IASI instruments

Forecast results are verified against ECMWF analyses, conventional observations, and other satellite observations.

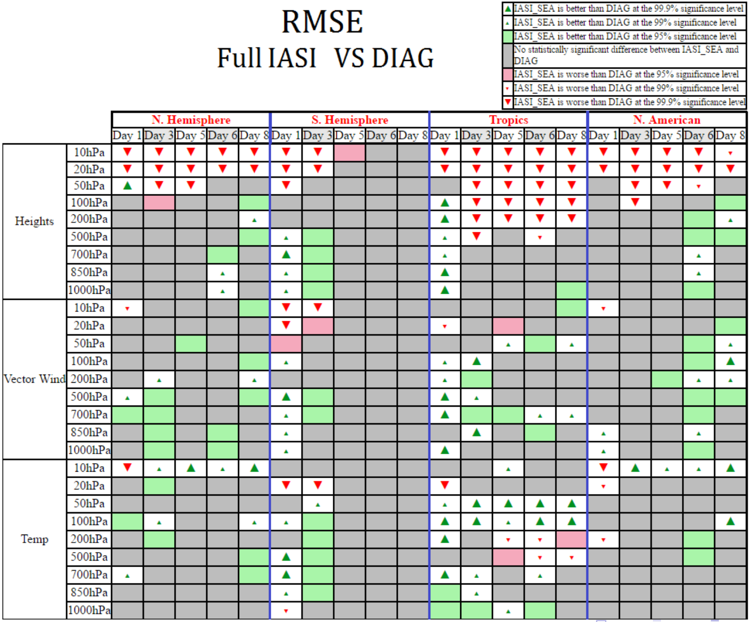
Results: Correlated Observations for AIRS



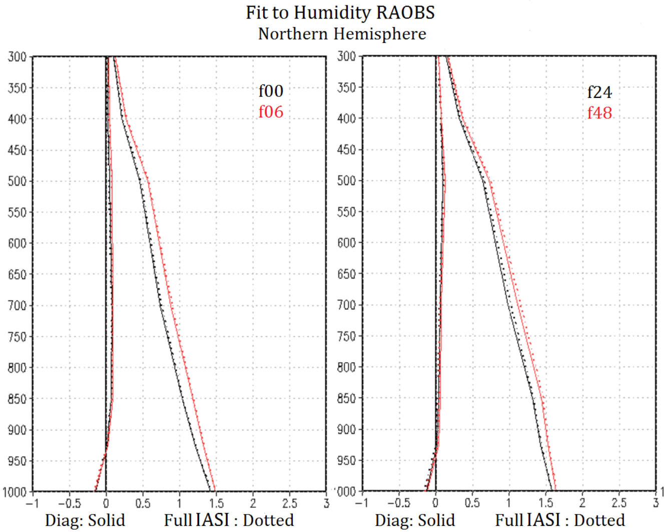
Results: Correlated Observations for AIRS



Results: Correlated Observations for IASI



Results: Correlated Observations for IASI



Summary: Correlated Observations for AIRS and IASI

AIRS Summary:

• Forecasts impacts are negative for upper level temperatures and heights, but are mostly positive elsewhere. The fit to temperature observations also suffered in the stratosphere.

• Fits to tropospheric temperature, wind, humidity and height observations were improved in the southern hemisphere and tropics, but degraded over North America.

• OMA and OMB fits to water vapor channels of several satellite instruments, such as HIRS, MHS, ATMS, CrIS and IASI were improved.

Summary: Correlated Observations for AIRS and IASI

IASI Summary:

- Forecast impacts are negative for upper level heights, and there are some issues with temperature and wind biases. Otherwise the forecast impact is generally positive.

- Fits to humidity observations were degraded and there were biases in the fit to temperature observations. Fits to wind and height observations were improved in the northern hemisphere.

- OMA and OMB fits to ozone channels from HIRS, CrIS and AIRS were improved, as were the fits to most channels from MHS and HIRS. Fits to water vapor channels from IASI were improved.

- Fits to SBUV and MLS (ozone profile observations) were improved.

Conclusions

The Desroziers diagnostic was used to estimate observation error covariances for IASI and AIRS. Computed errors were smaller than the operational values, and there were significant inter-channel error correlations in the lower temperature sounding channels, window channels, ozone channels, water vapor channels and shortwave channels.

Reconditioning **R** is necessary to aid the cost function minimization, and further modifications compensate for deficiencies in the assimilation system. Evidence suggests that inflating all channels except for water vapor channels benefits the analysis.

Using correlated observations had a strong impact on the analysis. Forecast impact was generally positive in the troposphere, but had issues in the stratosphere. The fit to other observations were generally improved, with the exception of humidity in the case of IASI.

Using water vapor channels from IASI can potentially improve on these results. However, water vapor channels are strongly correlated with one-another. A more careful selection of channels may yield better results.