# Experimentation with inter-channel error correlations with AIRS and IASI at ECMWF

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## Abstract

This contribution describes assimilation experiments which explicitly take estimates of observation error correlations into account for AIRS and IASI in the ECMWF system.

Single-spectrum experiments highlight how the filtering properties of the assimilation system are altered when inter-channel error correlations are taken into account. Depending on the structure of the departures, increments can be larger as well as smaller when inter-channel error correlations are included and observation error variances are left unchanged.

Preliminary assimilation trials with AIRS and IASI show that accounting for inter-channel error correlations allows the use of observation errors that are closer to diagnosed values, without over-fitting the AIRS and IASI observations. Scaling of the observation errors can be used to partially compensate for neglecting off-diagonals in the observation error covariance matrix, but the required scaling factors are relatively large, and for humidity our experiments still indicate a benefit from taking the inter-channel error correlations into account.

## Introduction

Recent investigations have indicated significant inter-channel error correlations for infrared hyperspectral sounders such as AIRS and IASI (e.g., Garand et al. 2007, Stewart et al. 2009, Bormann et al. 2010), especially for surface-sensitive and water vapour channels. Such error correlations are not accounted for in today's assimilation systems, and instead a diagonal observation error covariance matrix is assumed, with variances that are inflated compared to estimates of the observation error.

Here we report on assimilation experiments in which inter-channel observation error correlations for AIRS and IASI are taken into account in 4DVAR. The experimentation is based on error correlation matrices and observation errors estimated following methods used in Bormann et al. (2010), e.g., Fig. 1 and Fig. 2. We will investigate how filtering properties of the assimilation system are altered when error correlations are taken into account, discuss adjustments to the diagnosed observation error covariances, and report on longer assimilation trials. The results presented here differ significantly from those presented in the poster at ITSC-18, as a bug was discovered during the preparation of the proceedings paper.

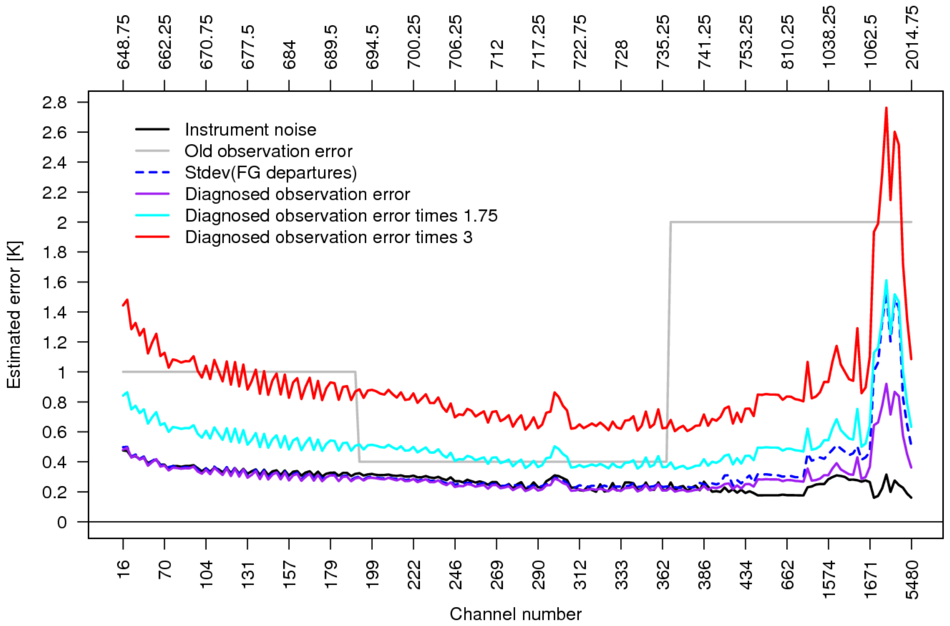


Fig. 1: Observation errors ($\sigma_O$) for assimilated IASI channels used in this study. See main text for further details. The instrument noise has been converted from radiance units using scene temperatures for the US standard atmosphere.

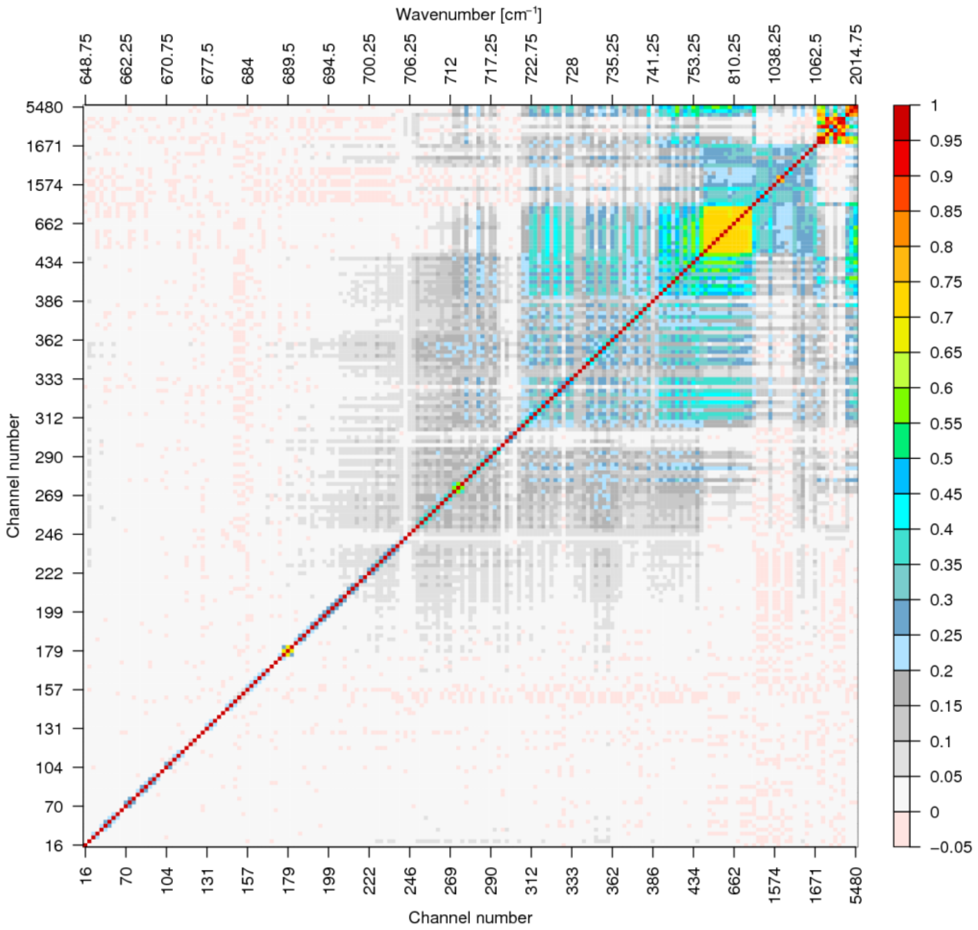


Fig. 2: Error correlation matrix for the used IASI channels, derived using the Hollingsworth/ Lönnberg method (see Bormann et al 2010).

## Single-spectra experiments

The positive inter-channel error correlations shown in Fig. 2 for certain channels mean that it is more likely for IASI observations that errors in these channels are "similar" compared to the case of no error correlations. Taking the error correlations into account therefore alters the filtering properties of the assimilation system, as it will alter how departure signals are attributed to an error in the observations or in the First Guess (FG).

To highlight this aspect, we have performed a number of single-spectrum experiments in which only one clear IASI spectrum is assimilated, and no other observations. The selected single-spectra were located towards the beginning of the assimilation window, and all channels that are considered for assimilation were diagnosed as cloud free. For each case, two experiments were performed, one in which diagonal observation errors are employed, and one in which an error correlation matrix similar to the one shown in Fig. 2 is assumed. In the experiments with inter-channel error correlations, an explicit matrix inversion is avoided by performing a Cholesky decomposition. The observation errors ($\sigma_O$) were the same in both experiments, and they were specified as currently used in operations.

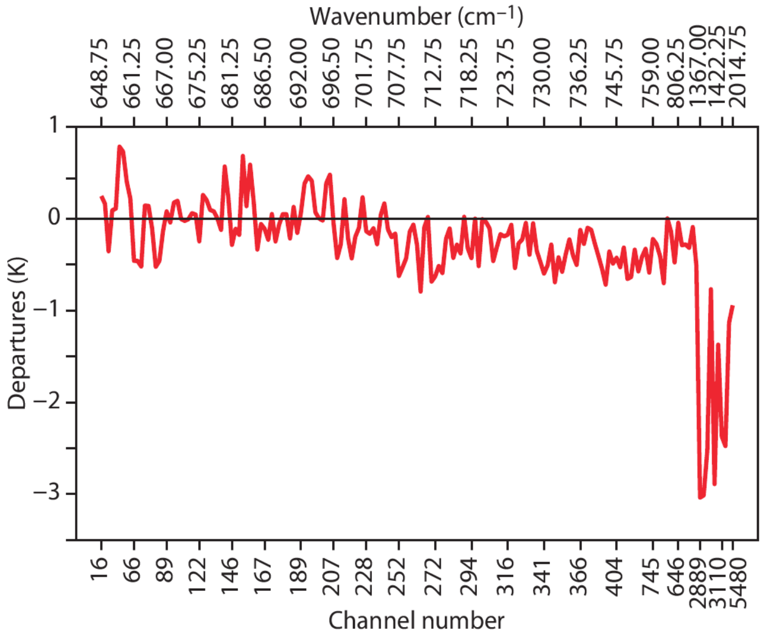


Fig. 3: FG-departures (observation minus FG, after bias correction) for assimilated IASI channels for case 1.

Departures for case 1 are shown in Fig. 3. For this case, taking the error correlations into account leads to smaller increments in the analysis (Fig. 4). This is because the similar sign of the departures for the lower sounding/window/water vapour channels means that the departures are assumed to be more likely due to errors in the observations (or the radiative transfer) if error correlations are taken into account compared to when these are neglected. So the analysis system makes smaller adjustments to the FG when error correlations are taken into account.

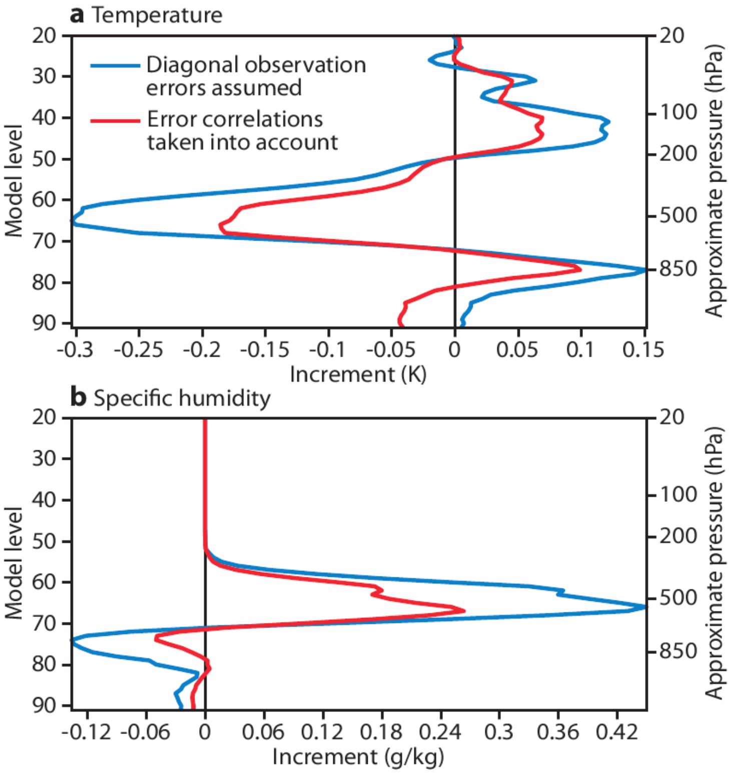


Fig. 4: Profiles of increments (differences between analysis and FG) extracted at the observation location for case 1. Blue: without taking error correlations into account in the assimilation; red: with taking error correlations into account. a) Temperature; b) Humidity.

In contrast, in case 2 departures vary the sign with spectral channel (Fig. 5). This is less likely due to errors in the observations if the error correlations are taken into account compared to in the diagonal case. Hence increments are larger for this case (Fig. 6). This is the opposite of what happens if inflated diagonal observation errors are used, highlighting that inflating diagonal observation errors cannot fully compensate for neglecting observation error correlations.

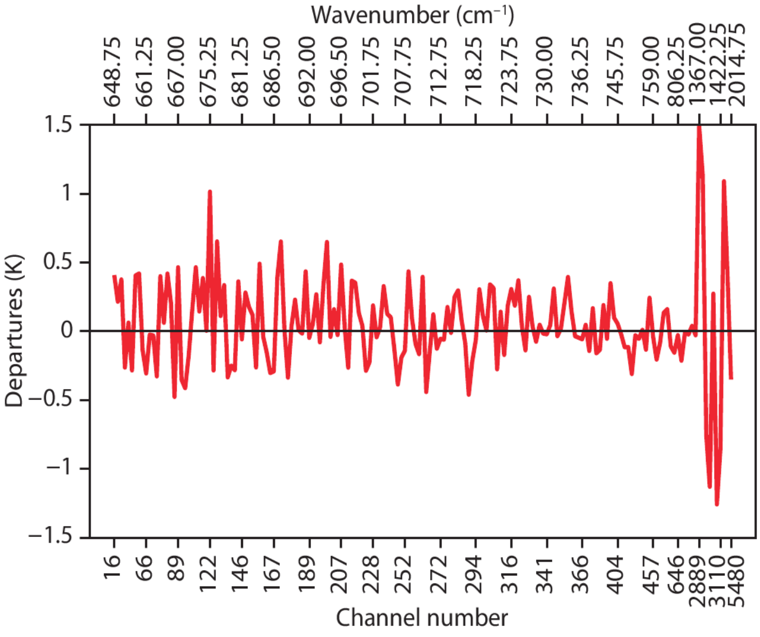


Fig. 5: As Fig. 5, but for case 2.

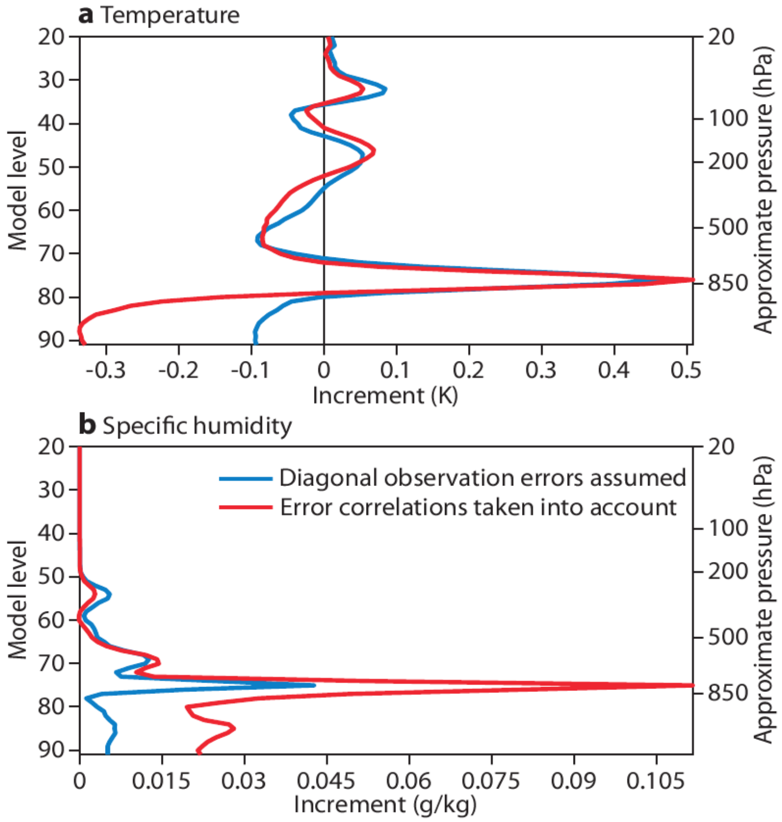


Fig. 6: As Fig. 4, but for case 2.

## Tuning the observation errors

The diagnosed observation error covariances have been used in 4DVAR assimilation experiments, run at relatively low spatial resolution (T319 ~ 60 km) with the full operational observing system. In these initial experiments we compare using diagonal observation error covariance matrices for IASI and AIRS (based on diagnosed values, e.g., Fig. 1), with using the full diagnosed observation error covariance matrices (including inter-channel error correlations, e.g., Fig. 2, but neglecting spatial error correlations). For spectra for which only a sub-set of channels is classified as clear, the error covariance matrices are sub-sampled. Using the Cholesky decomposition method means that taking inter-channel error correlations into account is only marginally more costly computationally than using a diagonal matrix.

Standard deviations of FG-departures for a range of other assimilated observations have been used to evaluate the impact on the short-range forecast for the above experiments (observations such as radiosondes, AMSU-A, MHS, radio occultation data). These statistics tend to be more robust than verification measures against analyses for which characteristics of analysis errors can give misleading results for short-range forecast scores, especially for humidity.

In the case of using diagonal versions of the diagnosed observation error covariance matrices, the departure statistics indicate a very poor performance, with standard deviations of FG-departures for many observations being larger than for an experiment in which AIRS and IASI are not used at all (e.g., Fig. 7). It appears that the system attempts to over-fit the AIRS and IASI observations, leading to a degradation of the short-term forecasts. In contrast, when the inter-channel error correlations are taken into account, the statistics look much more reasonable, with standard deviations of FG-departures for other observations mostly lower than when AIRS and IASI are not assimilated, suggesting a reduction in short-term forecast errors. The exceptions are lower tropospheric AMSU-A channels, which indicate that some over-fitting still takes place.

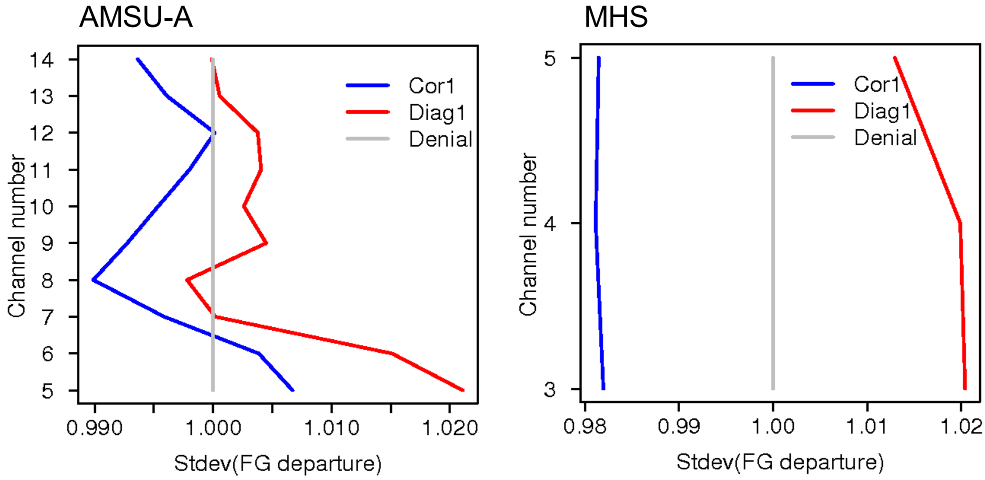


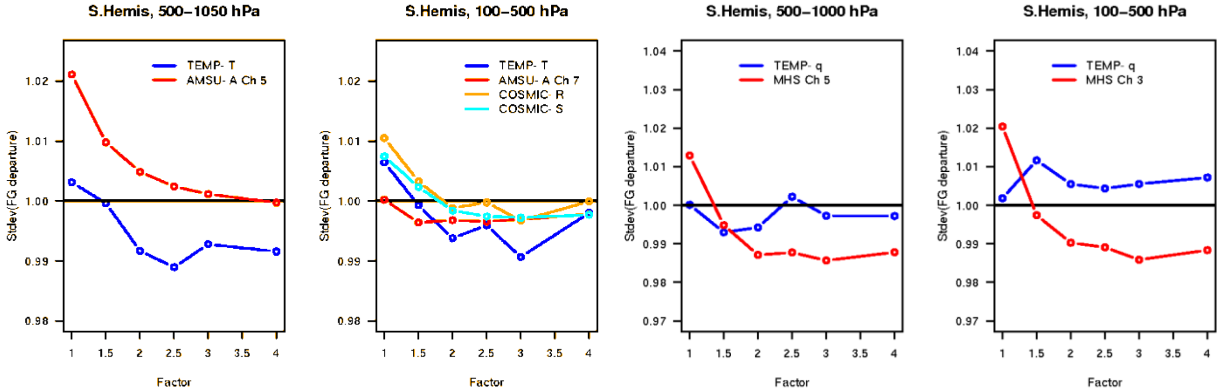
Fig. 7: Standard deviations of FG departures for all assimilated AMSU-A (left) and MHS (right) data over the Southern Hemisphere combined (after bias correction). Results for the experiment using the diagnosed observation error covariances with error correlations are shown in blue and those from the experiment without error correlations in red, both being normalised by the standard deviations of FG departures for the Denial experiment. Statistics are accumulated over the period 15 December 2011 – 14 January 2012.

Given the above results, the question arises whether it is possible to improve on these by adjusting the assumed observation error covariance matrices. As a first simple adjustment, we introduce a single scaling factor for the observation errors ($\sigma_O$), relative to the originally diagnosed observation errors. Two series of 1-month experiments were conducted in which this scaling factor was varied, one for diagonal observation error covariances for AIRS and IASI, and one using the full diagnosed observation error covariances.

Fig. 8 shows the evolution of the standard deviation of FG-departures for several observing systems as a function of the scaling factor. For both series of experiments, introducing a scaling factor larger than one tends to lead to smaller standard deviations of FG-departures, with a minimum usually in the range of 1.25 – 3, depending on observing system, geographical region, and series of experiments. For the experiments with a diagonal observation error, a rather large scaling factor of 2.5-3 gives overall the best results. For such a scaling factor, standard deviations of FG-departures for other observations are mostly reduced relative to an experiment in which no AIRS and IASI data are used, suggesting that the analysis was successful in extracting some information from the additional observations after the error inflation, leading to improved short-term forecasts. For the series of experiments with full observation error covariance matrices, some scaling of the observation errors appears beneficial as well, but a much smaller scaling factor of around 1.5-1.75 gives overall the best results. Comparing the experiments with these optimised scaling factors, the FG-fit for humidity-sensitive observations tends to be significantly better in the experiment with the full error covariance matrix, whereas for temperature-sensitive observations the difference is less clear. This may be related to the presence of particularly significant error correlations for the water vapour channels in the diagnosed error covariance matrices, so accounting for these shows clearer benefits.

In summary, it appears that accounting for inter-channel observation error correlations allows the use of an observation error ($\sigma_O$) for AIRS and IASI close to diagnosed values and therefore close to values more consistent with standard deviations of FG-departures for these instruments. If the inter-channel error correlations are neglected, inflation can be used to partially compensate for this. However, the required scaling factors are rather large (2.5-3), and the compensation appears to be less successful for humidity channels in our experimentation. In both cases, further optimisation may be possible by using different scaling factors for different types of channels.

Diagonal observation errors



Observation errors with error correlations

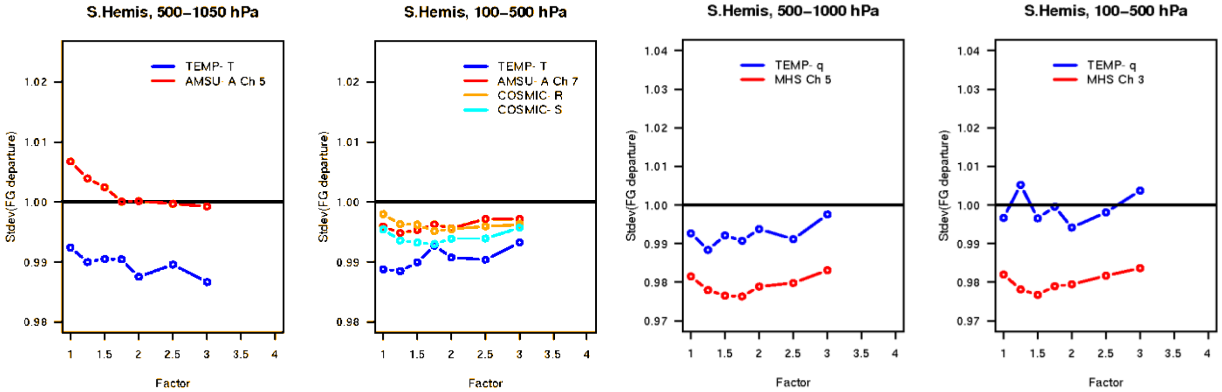


Fig. 8: Standard deviations of FG-departures over the Southern Hemisphere for several observation types as a function of the scaling factor applied to the diagnosed observation errors for AIRS and IASI. The standard deviations are normalised to 1 for the Denial experiment. Data are for 15 December 2011 – 14 January 2012. Top row: diagonal observation errors are assumed; bottom row: error correlations are taken into account. For radiosondes (TEMP-T for temperature, TEMP-q for humidity) and GPS radio occultation bending angles (COSMIC-R, rising; COSMIC-S, setting), departure statistics have been combined in the approximate layers indicated above the three panels.

## Assimilation trials with and without inter-channel error correlations

Several 2-month assimilation trials have been performed with updated observation error covariance matrices, using diagonal or full observation error covariances for AIRS and IASI with the optimal scaling factors determined above. The experiments were conducted over the period 15 December 2011 - 15 February 2012 (62 cases), using ECMWF's, 12-hour 4DVAR system with a spatial resolution of T319 (~60 km), and an incremental analysis resolution of T159 (~125 km). The following experiments were performed:

- **CTL** – Diagonal observation errors for AIRS and IASI as in operations (e.g., Fig. 1)
- **Cor** - Correlated observation errors, with $\sigma_O$ 1.75 times the diagnosed estimate for AIRS and IASI
- **NoCor** - Diagonal observation errors, with $\sigma_O$ 3.0 times the diagnosed estimate for AIRS and IASI
- **Denial** - As CTL, but without using AIRS and IASI data

Statistics of FG-departures against other observations indicate smaller errors in the FG in the Cor experiment compared to the CTL or the NoCor experiment, especially for humidity in the tropics. For instance, standard deviations of FG-departures for MHS data are reduced compared to the CTL or the NoCor experiment (e.g., Fig. 9). In contrast, the CTL and NoCor experiment give more similar departures for MHS, suggesting that accounting for the inter-channel error correlations provides a more sophisticated weighting of the data in the analysis than the inflation used in these experiments.

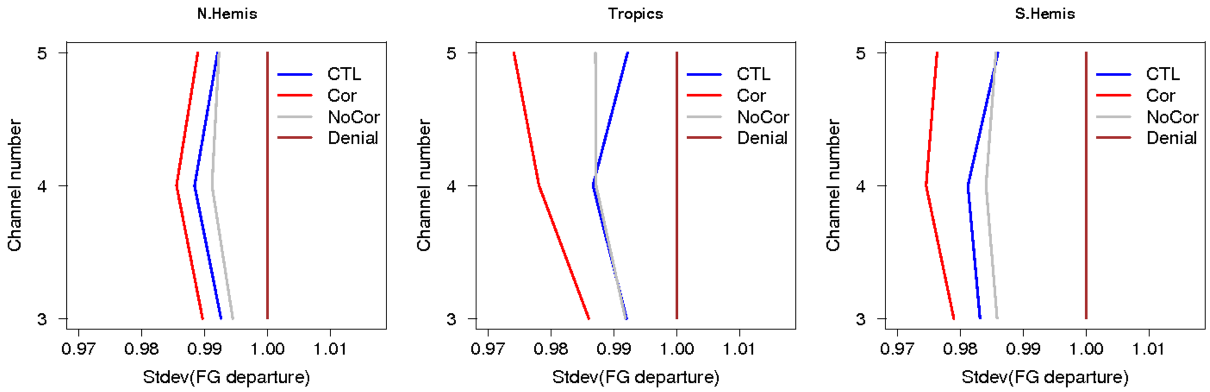


Fig. 9: Standard deviations of FG-departures for all MHS instruments combined over the period July/August 2009 for the four experiments discussed here. Standard deviations are normalised to 1 for the Denial experiment.

Forecast scores suggest an overall comparable performance for the Cor and the CTL experiment for geopotential, temperature, and wind (e.g., Fig. 10), although the CTL experiment performs better for the geopotential for the upper troposphere in the extra tropics. The NoCor experiment tends to perform more poorly than the CTL experiment, suggesting that the diagonal observation errors used in this experiment are better tuned, possibly by inflating observation errors for certain groups of channels more than for others (e.g., surface-sensitive channels, water vapour channels).

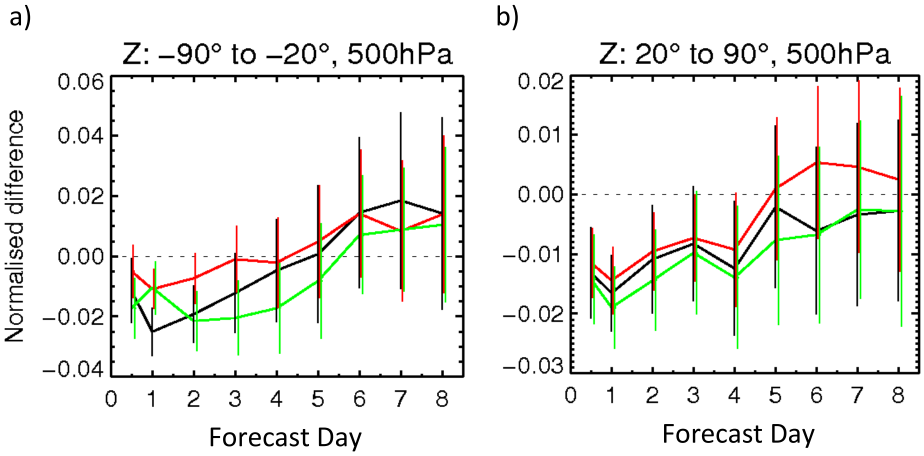


Fig. 10: Normalised difference in the root mean square of the forecast error for the 500 hPa geopotential as a function of forecast range between the CTL and the Denial experiment (green), Cor and Denial (black), and NoCor and Denial (red). Negative values indicate a better performance with respect to the Denial experiment. Error bars indicate 95 % significance intervals, and each experiment has been verified against its own analysis. a) Southern Hemisphere, b) Northern Hemisphere.

## Conclusions

In this contribution we have experimented with inter-channel error correlations for AIRS and IASI in ECMWF's 4DVAR assimilation system, and the main findings are:

- Taking inter-channel error correlations into account for AIRS and IASI alters the filtering properties of an assimilation system.
- Taking inter-channel error correlations into account allows the use of observation errors that are more consistent with departure statistics for AIRS and IASI, without over-fitting the AIRS and IASI observations. In contrast, significant error inflation has to be used to compensate for neglected inter-channel error correlations when diagonal observation errors are assumed.
- Our diagnostics suggest the largest benefits from taking inter-channel error correlations into account are for humidity: consistent with considerable error correlations diagnosed for water vapour channels of AIRS and IASI.
- Computationally, taking inter-channel error correlations into account does not add a prohibitive extra cost to the 4DVAR system.

The current results are preliminary in the sense that further experimentation over several seasons and at higher resolution are required, and several aspects require further examination. For instance, ozone channels also show considerable error correlations, and the influence of this on the ozone analysis deserves further attention. Also, the influence of using inter-channel error correlations on residual cloud contamination should be explored further.

However, it is very encouraging that taking inter-channel error correlations into account allows the use of observation errors that are more consistent with departure statistics, and further work in refining observation error covariances for AIRS and IASI appears worthwhile. While it appears that error inflation can be similarly successful in compensating for neglected inter-channel error correlations, accounting for inter-channel error correlations may offer more robust and less ad-hoc approaches of specifying observation error covariances. Nevertheless, reliable specifications for inter-channel error correlations are needed for this. While estimates are available for these, a better characterisation of the sensitivity of the assimilation to misspecifications of the observation error correlations is advisable. This includes a better characterisation of the scene-dependence of observation error covariances, and possibly other properties such as the conditioning of the specific observation error covariance used.

## References

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