Estimates of Spatial and Inter-channel Observation Error Characteristics for AMSU-A and IASI and Applications in the ECMWF System

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Abstract

Three methods are used to estimate observation errors and their correlations for clear-sky radiances from AMSU-A and IASI in the ECMWF assimilation system. The analysis is based on covariances derived from pairs of First Guess and analysis departures. The methods used are the so-called Hollingsworth/Lönnberg method, a method based on subtracting a scaled version of mapped assumed background errors from FG-departure covariances, and the Desroziers diagnostic.

The findings suggest that mid-tropospheric to stratospheric temperature sounding channels for IASI and all AMSU-A sounding channels show little or no inter-channel or spatial observation error correlations, and estimates for the observation error are close to the instrument noise. Channels with stronger sensitivity to the surface show larger observation errors compared to the instrument noise, and some of this error is correlated dqyj spatially and between channels. The three methods show good consistency for these estimates. "
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Estimating observation errors for IASI's humidity sounding channels appears more difficult. A considerable proportion of the observation error for these channels appears correlated spatially for short separation distances, as well as between channels. Observation error estimates for humidity channels are generally considerably larger than those provided by the instrument noise.
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The findings are being used to revise observation error and thinning scale choices in ECMWF's assimilation system. Halving the thinning scale for AMSU-A results in a significant positive forecast impact, and initial results from taking inter-channel error correlations for IASI into account are encouraging.

Introduction

This paper summarises results of a study aimed at estimating observation errors and their correlations for clear-sky radiances used in the ECMWF system. The assumed observation error covariances, together with assumed background error covariances, play an important role in determining the weight of a given observation in data assimilation systems. For technical or computational reasons, observation error covariance matrices used in data assimilation systems are mostly assumed to be diagonal. Estimation of observation errors is seen as a first step towards refining the observation error and thinning scale choices, or, alternatively, to provide input to take such error correlations explicitly into account in the assimilation. We have only space for a brief summary here; for more details the reader is referred to Bormann and Bauer (2010) and Bormann et al. (2010).

Data and methods

The statistics presented here are based on First Guess (FG) and analysis departures for pairs of observations for the respective instruments. The observations in each pair are required to be less than

1 h apart (i.e., within one orbit) and originate from the same instrument on the same satellite. The pairs of observations were binned by separation distance to calculate isotropic spatial covariance statistics as a function of separation distance. The results are based on data for the 21-day period 22 August – 11 September 2008. The assimilation experiment employed 4DVAR with a 12-hour observation window, a model resolution of T799 (~25 km), an incremental analysis resolution of T255 (~80 km), and 91 levels in the vertical up to 0.01 hPa. The experiment used a thinning scale of 60 km, approximately half the operational thinning scale.

The methods used to estimate the observation errors are the Hollingsworth/Lönnberg method (Hollingsworth and Lönnberg 1986), the consistency diagnostic provided by Desroziers et al. (2005), and a method based on subtracting a scaled version of the assumed background error, mapped into radiance space. The Hollingsworth/Lönnberg method assumes that true background errors are spatially correlated, whereas observation errors are not. It may therefore give misleading results for channels with significant spatial error correlations. The Desroziers diagnostic assumes that assimilation systems can be approximated by linear estimation theory; if the observation weights are consistent with true weights, a consistency diagnostic for the observation error covariance $\mathbf{R}$ and the background error covariance $\mathbf{B}$ in observation space is given by:

$$\tilde{\mathbf{R}} = E\left[\mathbf{d}_a\ \mathbf{d}_b^T\right]$$

$$\mathbf{H}\tilde{\mathbf{B}}\mathbf{H}^T = E\left[\mathbf{d}_b\ \mathbf{d}_b^T\right] - E\left[\mathbf{d}_a\ \mathbf{d}_b^T\right]$$

Here, $\mathbf{d}_b$ and $\mathbf{d}_a$ are FG- and analysis departures respectively, $\mathbf{H}$ the tangent linear of the observation operator and $E[]$ is the expectation operator. The last method uses a spatial representation of the FG error covariances in radiance space, calculated by randomisation from the assumed background errors. If these mapped background errors are too large compared to the FG-departure covariances, a scaling factor is introduced, using the assumption that background errors dominate FG departure covariances for longer separation distances. The method will be referred to as "background error method". All three methods assume no correlations between FG errors and observation errors.

The methods are based on spatial FG or analysis departure covariances, calculated from the database of pairs of observations introduced above. The departures are taken after the variational bias correction (e.g., Dee 2004). We only consider field-of-views (FOVs) for which all channels currently considered for assimilation are used in the assimilation system (i.e., are diagnosed cloud free). Further details on bias correction and the quality control, as well as the methods employed here and the assumptions inherent in these methods are given in Bormann and Bauer (2010) and Bormann et al. (2010).

Results

The observation error analysis has been performed for AMSU-A, HIRS, and MHS, as well as for AIRS and IASI. Here, we summarise only the results for AMSU-A and IASI over sea; for further details and results, the reader is referred to Bormann and Bauer (2010) and Bormann et al. (2010).

AMSU-A

Figure 1 shows estimates of the spatial error correlations for AMSU-A observations. The two estimates are fairly consistent and give relatively small spatial error correlations for AMSU-A for separations larger than the thinning scales currently used at ECMWF. For the current operational thinning scale of 125 km, the correlations are at or below 0.2 for all channels. Channels 5 and 6 have slightly higher correlations at shorter separation distances, but they are still relatively small (less than 0.3). Channels 5 and 6 have some sensitivity to the surface and to thick clouds and rain, and these aspects may lead to higher spatial error correlations, for instance, through the surface emission, undetected cloud or rain, or the quality control applied.

Estimates of observation errors from the three methods are in good agreement (Fig. 2), with values of less than 0.2 K for channels 5-10. For these channels, the estimates of the observation error are at or below the mean measured instrument noise. The finding that the values are at times below the

instrument noise is most likely due to sampling and quality control, although it could also indicate that the measured in-flight instrument noise is too large. The findings suggests that the radiative transfer error for these channels is relatively small, at least after applying the bias correction used in the ECMWF system. The three estimates of observation error are much smaller than what is currently assumed as observation error in the ECMWF assimilation system, typically by about 40 %.
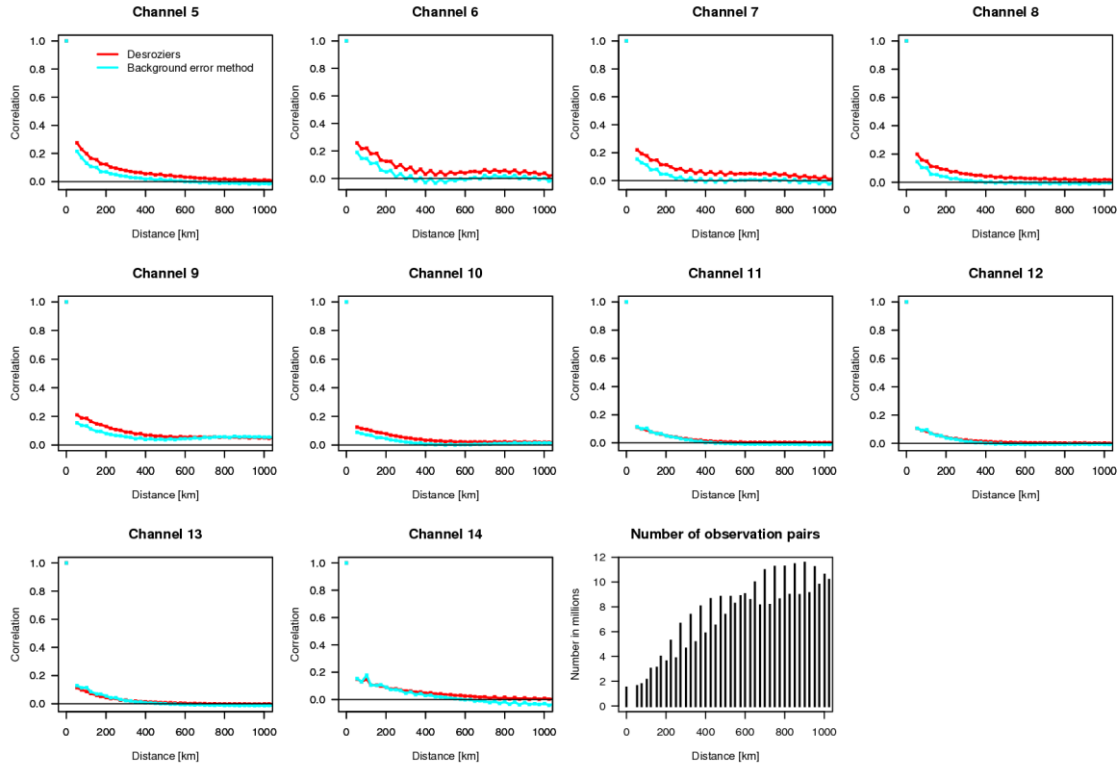

Figure 1: Estimates of spatial error correlations as a function of separation distance for NOAA-18 AMSU-A for the channels used at ECMWF. The estimates are based on Desroziers' diagnostic (red) and the background error method (cyan). The number of collocations as a function of separation distance is shown in the last panel.
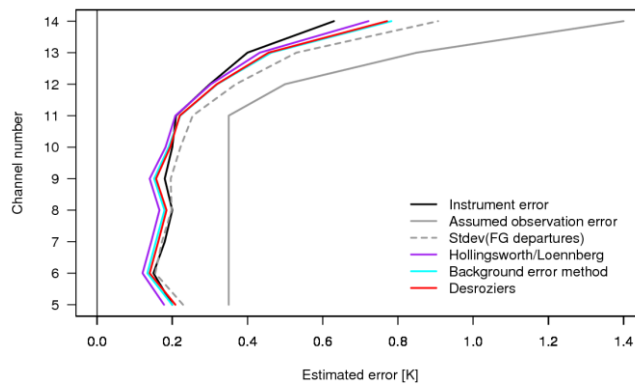

Figure 4: Estimates of observation errors for NOAA-18 AMSU-A channels used in the ECMWF system. The estimates are based on the measured in-flight instrument error (black), the observation error assumed in ECMWF's assimilation system (grey), the Hollingsworth/Lönnberg method (purple, calculated from the difference in FG-departure covariances at 0 km and 50 km separation), the background error method (cyan), and Desroziers' diagnostic (red). Also shown are the standard deviations of FG departures (dashed grey).

There is little evidence of inter-channel error correlations for AMSU-A (not shown). The three methods consistently give correlations of less than 0.2 between any channels. The largest error correlations are found for Desroziers' diagnostic, up to 0.13 between channels 5 and 6 and channels 6 and 7.

IASI

The same analysis has been performed for IASI. For temperature sounding channels and some window channels, the three methods show again good agreement. The observation error estimates for the stratospheric and upper tropospheric temperature sounding channels (~ up to channel 249) are close to or below the instrument noise (Fig. 3), show little spatial error correlations (Fig. 4) and negligible inter-channel error correlations (Fig. 5). The findings are similar for lower tropospheric temperature sounding channels (~ 252-445), except that the three methods consistently suggest the presence of some inter-channel error correlations.
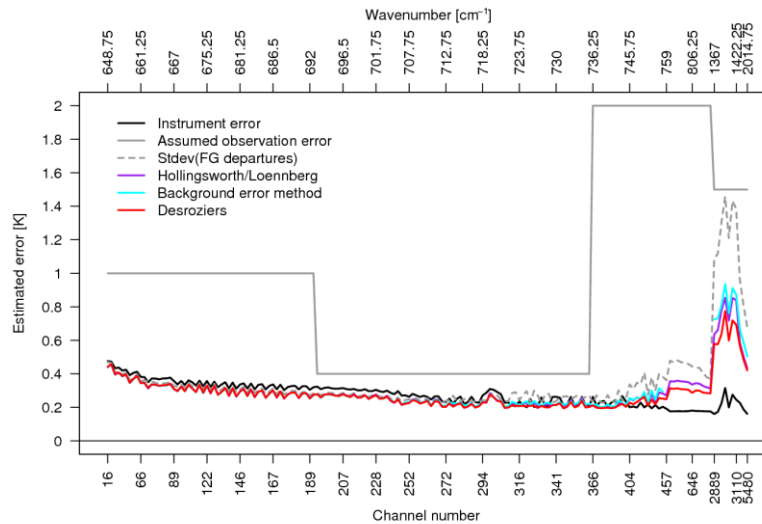

Figure 3: Estimates of observation errors for IASI channels used in the ECMWF system. The estimates are based on the measured in-flight instrument error (black, converted to brightness temperature errors using the US Standard Atmosphere), the assumed observation error (solid grey), the Hollingsworth/Lönnberg method (purple, based on subtracting the FG-departure covariances for the 50 km separation bin from the FG-departure variances at zero separation), the background error method (cyan), and Desroziers' diagnostic (red). For some channels, results from the background error method are not shown due to failure of the method (see text for further details). Also shown are the standard deviations of FG-departures (dashed grey). The lower x-axis gives the channel numbers for selected channels (linear in the channel index), whereas the upper x-axis shows wavenumbers for the corresponding channels.
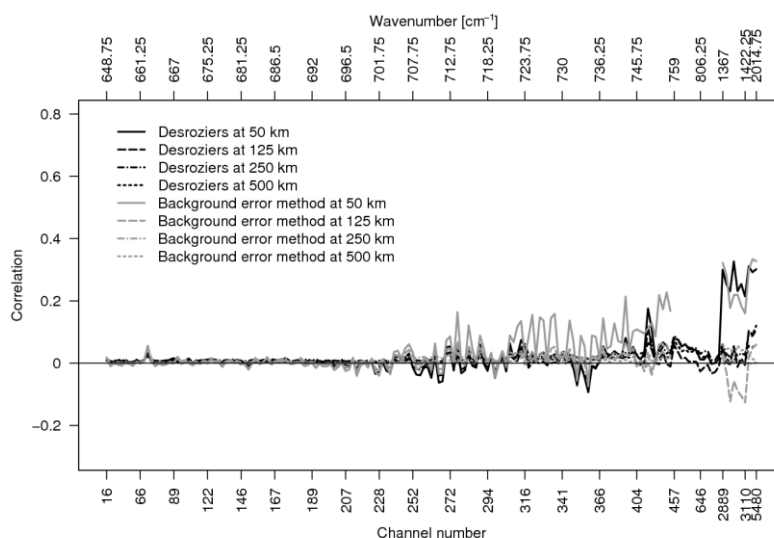

Figure 4: Estimates of spatial observation error correlations for IASI for selected spatial separation distance. Black lines give estimates from Desroziers' diagnostic, grey lines from the background error method. Different line styles separate the selected separation distances as provided in the legend.

In contrast, the longwave window channels (~457-921) exhibit somewhat different characteristics. For these channels the background error method fails due to limitations in the modelling of the background errors for the skin temperature, and only the remaining two methods can be used. These suggest observation errors that are 1.5-3 times the instrument noise (Fig. 3), with some spatial error correlations that tail off fairly sharply with separation distance (Fig. 4). Most striking, however, are the rather strong inter-channel error correlations (Fig. 5), with typical values in the range of 0.65-0.9. The longwave window channels also show some error correlations with the lower tropospheric temperature sounding channels in the longwave. Residual cloud contamination is a likely candidate to introduce inter-channel error correlations for these channels.
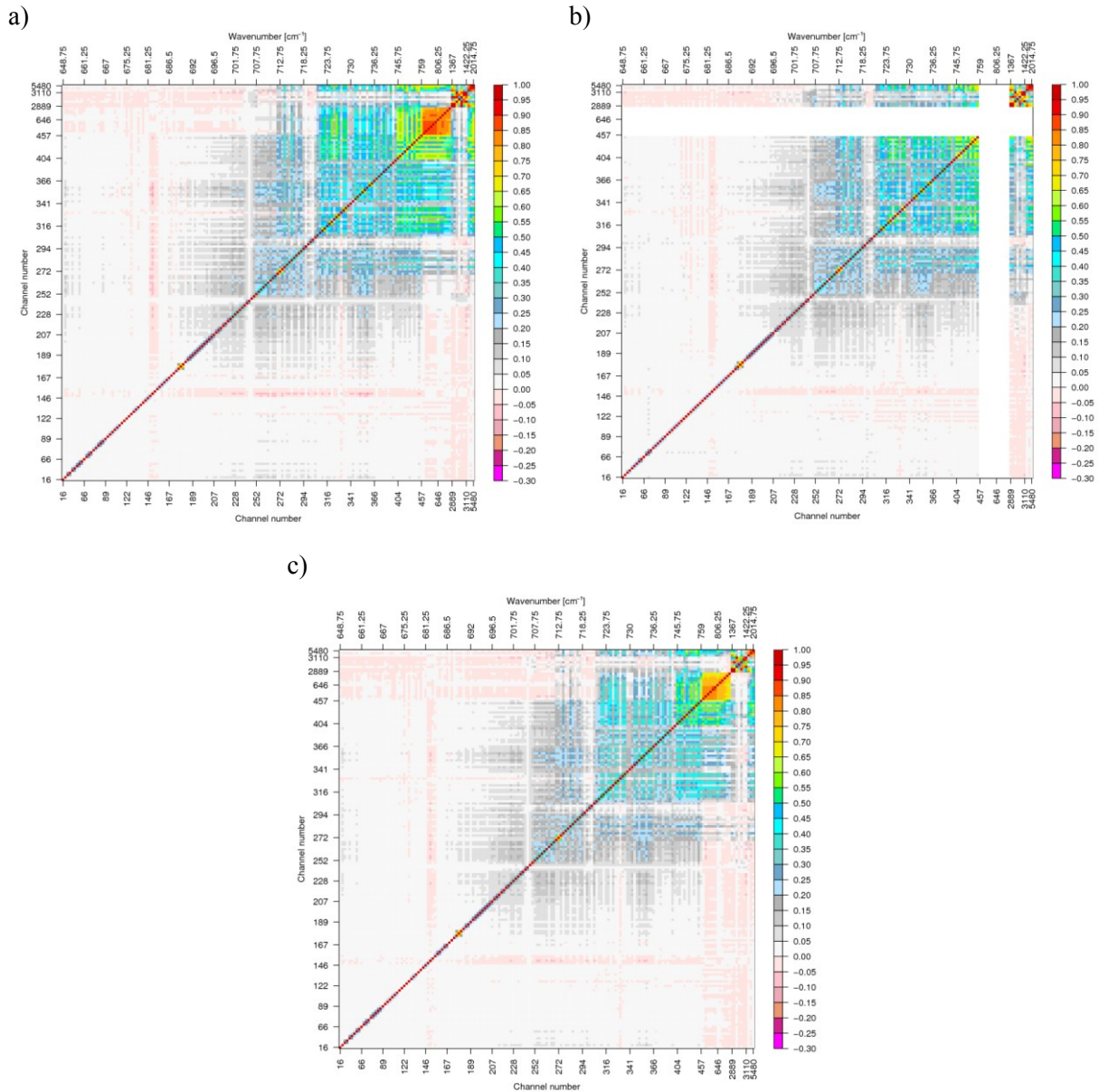
a)

b)

c)

Figure 5: Estimates for inter-channel error correlations for the AIRS channels used in the ECMWF system, based on the Hollingsworth/Lönnberg method (a), the background error method (b), and the Desroziers diagnostic (c).

The remaining 10 channels are water vapour channels and they show quite different characteristics. Here, the three methods give estimates for the observation errors that are 3-4 times above the instrument noise (Fig. 3), with some spatial (Fig. 4) and in particular inter-channel error correlations (Fig. 5). For the water vapour channels, the three methods show the largest disagreement in the observation error estimates, reflecting that it is more difficult to estimate observation errors for water vapour channels on the basis of FG and analysis departures. This is primarily because the background

errors in radiance space are relatively larger, with shorter spatial correlation scales, making it more difficult to separate observation and background error influences.

For all channels, the effect of apodisation can also clearly be seen in non-zero error correlations for the first off-diagonal elements, in particular for two cases where neighbouring channels are used, leading to inter-channel error correlations of about 0.7 (Fig. 5).

Application in assimilation experiments

The findings of the observation error covariance study are now being used to provide guidance to refine thinning scales or observation error covariance settings in the ECMWF system. Due to other sub-optimalities in the system (e.g., residual observation or model biases, sub-optimal background error specifications, sub-optimal observation screening, etc), we do not expect that the results are directly applicable in an assimilation system, so some adjustments to the above estimates are expected to be necessary.

AMSU-A

For AMSU-A, the lack of spatial or inter-channel error correlations suggests that the data could be used more aggressively, either through a reduction in the observation error or through a reduction in the thinning scale. The latter was tested in assimilation trials over two seasons (December 2008/January 2009 and June/July 2009), using ECMWF's 12-hour 4DVAR system with a T511 (~40 km) model resolution and an incremental analysis resolution of T159 (~80 km). Two experiments were run for each period: the first one used the full observing system as used in operations, with spatial thinning for AMSU-A at 125 km; the second experiment was identical to the first, except that the spatial thinning for AMSU-A was set to 62.5 km.

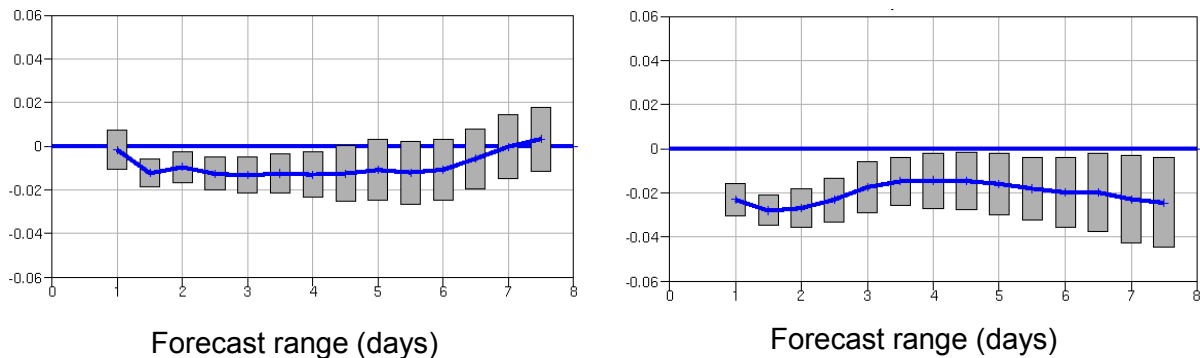Forecast range (days)   Forecast range (days)

Fig. 6: Normalised difference in the root mean square forecast error for the 500 hPa geopotential between the experiment with halved thinning scale for AMSU-A and the control, as a function of forecast range. Negative values indicate a reduction in the forecast error in the experiment with the halved thinning scale, as verified against the operational analysis. Grey bars indicate 90% confidence intervals. Left: Northern Hemisphere; right: Southern Hemisphere. Results for the two study periods have been combined (123 cases).

Halving the thinning scale results in a highly significant positive forecast impact, particularly over the first four days and for the 500 hPa geopotential (Fig. 6). The impact is larger for the summer hemisphere (not shown). Halving the thinning scale means the number of used AMSU-A data is increased by roughly a factor of 3.7, such that around 72 % of the considered AMSU-A FOVs are assimilated.

IASI

For IASI, the observation error estimates indicate considerable inter-channel error correlations for some channels, and it therefore seems appropriate to investigate the impact of taking such error correlations into account in the assimilation system. Mathematically, this involves an inversion of the non-diagonal observation error covariance matrix. In practice, the explicit inversion is avoided and

instead performed implicitly by using an efficient Cholesky decomposition. Here we present some preliminary results from experiments that compare the use of a diagonal and non-diagonal observation error correlation matrices.

Three experiments have been performed for the period July/August 2009, using ECMWF's 12-hour 4DVAR system with a T511 (~40 km) model resolution and an incremental analysis resolution of T159 (~80 km). The control uses the standard operational observation error specification (Fig. 3) with a diagonal error correlation matrix. EXP1 still uses a diagonal observation error correlation matrix, but observation errors set to 2.5 times the values of the Desroziers estimate for IASI's temperature-sounding channels and old observation errors for all other channels. EXP2 uses the same observation errors as EXP1, but an error correlation matrix as estimated by the Desroziers method for all channels.

Forecast scores for the three experiments suggest a mainly neutral impact from updating the observation errors for the temperature-sounding channels with a diagonal observation error correlation matrix (Fig. 7a,b). However, some positive impact can be seen from additionally taking the error correlations into account (Fig. 7c,d), and these appear statistically significant around day 4-6. Further analysis and experimentation for different seasons is needed to confirm these encouraging results.
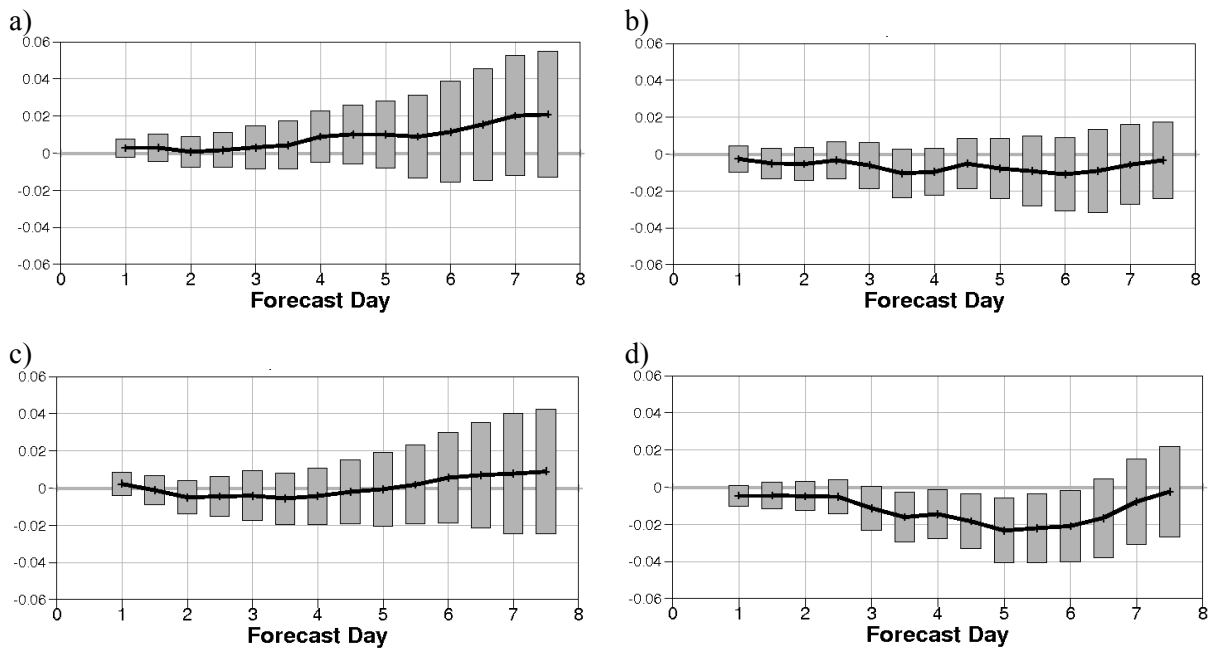
a)

b)

c)

d)

Fig. 7: a) Normalised difference in the root mean square forecast error for the 500 hPa geopotential between EXP1 and the control experiment for the Northern Hemisphere, as a function of forecast range. Negative values indicate a reduction in the forecast error in EXP1, as verified against the experiment's own analysis. Grey bars indicate 90% confidence intervals. b) As a), but for the Southern Hemisphere. c) As a), but for EXP2 instead of EXP1. d) As c), but for the Southern Hemisphere. Results are based on 54 cases.

Conclusions

In this paper we summarised findings for observation error covariance estimation based on three methods, and first applications of these findings in a data assimilation system. More details on the observation error estimation can be found in Bormann and Bauer (2010) and Bormann et al. (2010). The main findings are:

- There is little indication for inter-channel or spatial error correlations for the AMSU-A channels currently used in the assimilation system, and the estimates for the observation errors are close to the instrument noise. The findings suggest that a more aggressive use of AMSU-A data should be possible in the ECMWF system, and experiments with halving the thinning scale for AMSU-A indeed show a statistically significantly positive forecast impact.

- Most longwave temperature-sounding channels for IASI show small inter-channel or spatial error correlations and observation error estimates close to the instrument noise. Small inter-channel error correlations exist for the lower tropospheric temperature-sounding channels, and these rise to values of 0.6-0.9 for the longwave window channels. Water vapour channels also exhibit considerable inter-channel and some spatial error correlations. Experiments with taking error correlations for IASI into account in the assimilation indicate encouraging results that deserve further study.

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