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Observation errors and their correlations for satellite radiances

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Observation errors and their correlations for satellite radiances

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The assumed observation errors for tropospheric channels from AMSU-A (Advanced Microwave Sounding Unit) have recently been reduced considerably in the ECMWF system, contributing to a significant positive forecast impact in Cy37r2 of the Integrated Forecasting System (IFS). With this change more weight is given to AMSU-A observations in the assimilation system. The rather simple adjustment has been prompted by a study into estimating observation errors and their correlations for most satellite radiances used in the ECMWF system. It was found that observation errors for AMSU-A show only weak correlations spatially or between channels, and the observation error is instead dominated by uncorrelated instrument noise. This suggested that the data could be used more aggressively than previously thought, even if we assume uncorrelated observation errors as is currently done in the ECMWF system.

For other instruments, such as IASI (Infrared Atmospheric Sounding Interferometer), the situation is more complex: while temperature-sounding channels mostly tend to behave in a similar way as those for AMSU-A, channels sensitive to water vapour or with strong surface contributions show considerable inter-channel or spatial error correlations.

This article summarises the observation error estimation and highlights some of the implications.

Observation errors – their role and how to estimate them

The assumed observation errors play an important role in the assimilation system, as together with the background errors they determine the weight given to an observation in the analysis. The observation errors should include an estimate of the error in the observation operator; this is the algorithm used to map the model fields to the observed quantity (i.e. for radiances a radiative transfer model).

For technical reasons, observation errors in today's assimilation systems are commonly assumed to be uncorrelated, so that the error in a radiance observation from one channel is assumed to be independent of (a) the error in a radiances observation from another channel on the same instrument and (b) the error in neighbouring observations. This assumption has long been questioned for satellite radiances, especially since the radiative transfer computations are expected to include errors that are similar between similar channels or neighbouring observations. For instance, the gas concentrations or channel characteristics assumed in the radiative transfer model might be slightly wrong, and this error will be the same between channels or neighbouring observations. To counteract some of the effects of neglecting observation error correlations, satellite radiances are commonly thinned spatially, and the assumed observation errors are inflated.

Estimating observation errors and their correlations is not straightforward. We do not know the 'truth' – we only have observations with measurement errors, radiative transfer models with radiative transfer errors, or forecasts and analyses with their associated errors. When we compare satellite radiances with model equivalents, the differences between the two quantities will be affected by all of these errors. However, over the years, several methods have been developed that allow us to estimate observation errors on the basis of differences between observations and first-guess or analysis equivalents. The first guess is the short-term forecast used in cycling assimilation systems. Differences between observations and first guess or analysis equivalents are usually referred to as departures, and they are routinely produced in assimilation systems

Based on a large sample of such departures, *Bormann & Bauer* (2010) estimated observation errors and their correlations for radiances used in the ECMWF system, employing three such error estimation methods (see Box A). None of the methods used is without flaws – all make some assumptions about the structure of the observation or background errors, and these assumptions are more or less valid depending on the observations in question. But it was found that the results were qualitatively quite similar for the three methods, giving additional confidence in the estimates. Here we highlight the results for AMSU-A and IASI, two of the most important satellite instruments currently in use.

Error estimation methods

A

Below is a summary of the three estimation methods used in *Bormann & Bauer* (2010) – the paper describes the assumptions and limitations in more detail.

Hollingsworth/Lönnberg method: The method assumes that errors in the observations (and the observation operator) are spatially uncorrelated. It has been used in the past to estimate background errors from radiosonde networks (*Hollingsworth & Lönnberg,* 1986). Observation errors can be estimated by using spatial covariances of first-guess departures and assuming that the spatially correlated part is due to errors in the first-guess. The method can only be used to estimate inter-channel error correlations, and it will give misleading results in the presence of significant spatial observation error correlations.

Background error method: The method assumes that the spatial structure of the background errors used in the ECMWF system is correctly modelled. Observation error covariances are estimated from spatial covariances of first-guess departures by subtracting a spatial background error covariance matrix mapped into radiance space, possibly scaled to be consistent with the first-guess departure covariances at longer separation distances.

Desrozier diagnostic: The method is based on representing the assimilation system as a simple linear optimal estimation problem, and it assumes that the weights given to the observations in the assimilation system are consistent with true error covariances. In that case, simple equations for observation and background error covariances can be derived from covariances of first-guess and analysis departures (*Desroziers et al.*, 2005).

AMSU-A

One of the flagship satellite instruments for numerical weather prediction is AMSU-A. It is a 15-channel microwave radiometer that has provided the backbone for temperature soundings from space for more than a decade. Currently five of these instruments are assimilated in the ECMWF system, from the NOAA, MetOp and Aqua satellites. These observations are not as strongly affected by clouds as data from infrared instruments; therefore they provide some temperature-sounding capability in weak cloudy conditions.

The observation error covariance estimates for AMSU-A show surprising results for the error correlations. The estimates for error correlations between different channels are rather small (Figure 1), and while there are some spatial error correlations between closely-spaced observations, they tend to tail off to below 0.2 as long as the observations are separated by more than ~50–75 km (Figure 2). This compares to a thinning scale of 125 km used in the ECMWF system for AMSU-A observations. Consistent with the error correlation estimates, the estimates for the observation errors for most channels are close to the estimated instrument noise, i.e. the estimate of the random error provided by the data producers (Figure 3). The estimates of the observation errors are also much smaller than what was assumed in the ECMWF assimilation system.

The findings are surprising, as they seem to suggest that the radiative transfer error with its inter-channel and spatial correlations is rather small. This may be due to the high quality of the radiative transfer computations. But another factor is that the remaining radiative transfer errors for AMSU-A are likely to lead to large-scale, air-mass dependent biases, and these appear to be successfully taken out by the bias corrections routinely applied to these observations.

The fairly weak error correlations suggested that AMSU-A could be used more aggressively in the ECMWF system, even with the assumption of uncorrelated observation errors. We therefore performed assimilation trials in which either (a) the thinning scale was reduced to 60 km for channels 5–10 or (b) the assumed observation error for channels 5–10 was reduced (from 0.35 K to 0.20 K for channels 6–10 and from 0.35 K to 0.28 for channel 5), the values being inspired by the estimates provided in Figure 3. In each case the thinning scale or observation errors for the upper stratospheric AMSU-A channels was left unchanged, as a reduction led to problems in the assimilation due to instabilities of the tangent linear model in the stratosphere for high-resolution experiments.

The forecast impact of changing either the thinning scale or assumed error observation is very positive, leading to significant improvements up to forecast day 5–6 for most parameters. A combination of both approaches was also tested, but this did not show further benefits.

Due to the lower computational cost, the reduction of the observation errors has been implemented operationally in the latest cycle (Cy37r2), rather than the more costly reduction in the thinning. The positive impact of this change is illustrated by Figure 4 – this shows the normalised change to the root mean square forecast error of the 500 hPa geopotential height.

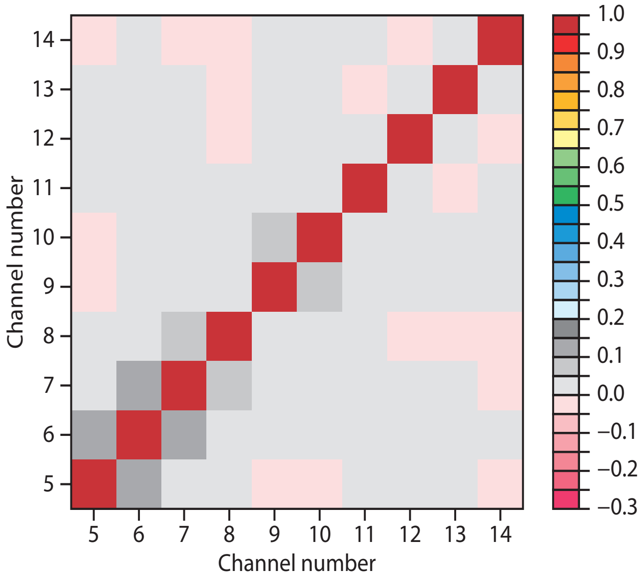

Figure 1 Estimates of the inter-channel error correlation matrix for the AMSU-A channels used at ECMWF. Channel 5 is the lowest sounding channel, peaking around 800 hPa, whereas other channels have their largest temperature sensitivity progressively higher in the atmosphere, with channel 14 peaking at around 2 hPa. The results were obtained with the Desroziers diagnostic.

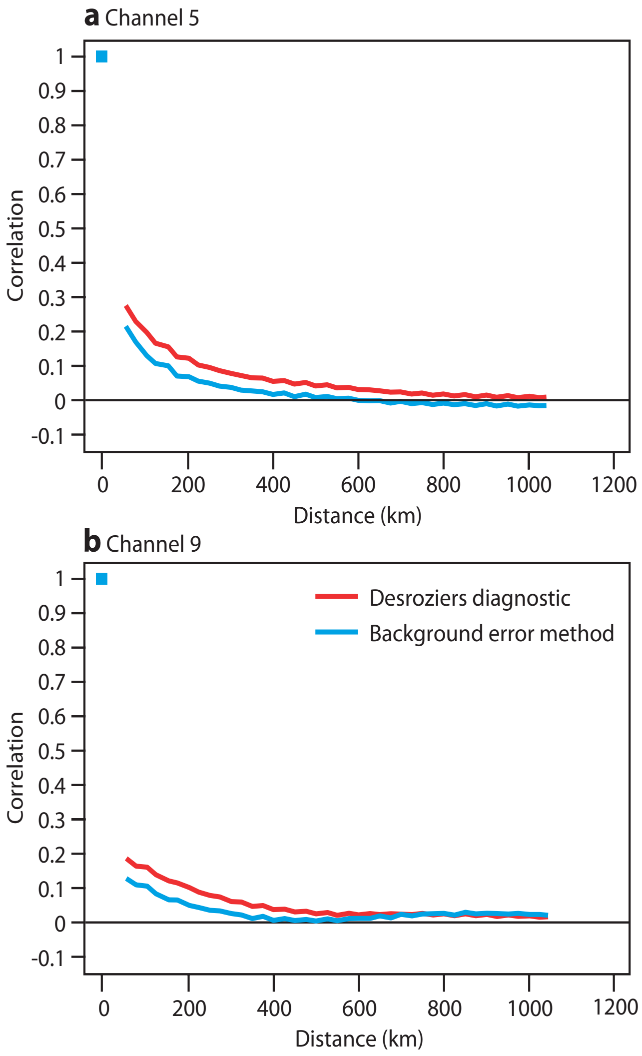

Figure 2 Estimates of the spatial error correlation matrix as a function of the separation distance between two observations for two typical AMSU-A channels: (a) channel 5 (peaking around 800 hPa) and (b) channel 9, peaking around 90 hPa. Results for two methods are shown: the Desroziers diagnostic and the background error method.

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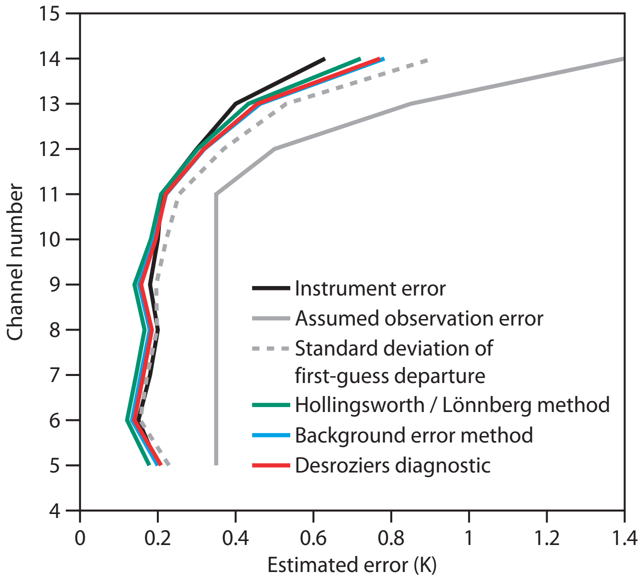

Figure 3 Estimates of the observation error (K) for the AMSU-A channels used in the ECMWF system. The coloured lines show the estimates from the three estimation methods used by *Bormann & Bauer* (2010) as indicated in the legend. Also shown are the instrument noise, the standard deviation of first-guess departures and observation error that has been assumed so far.

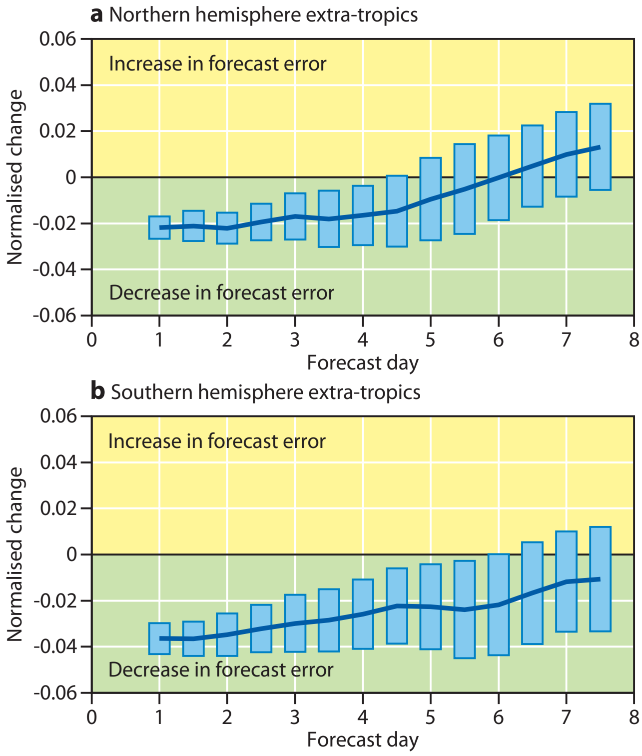

Figure 4 Forecast impact of reducing the observation error for AMSU-A observations for (a) northern hemisphere and (b) southern hemisphere extra-tropics. Shown is the normalised change to the root mean square of the forecast error of the 500 hPa geopotetial height as a function of forecast range. Negative values show a reduction of the forecast error as a result of the observation error reduction and hence a positive forecast impact. Error bars indicate statistical significance intervals. Results are from a trial with a total of 120 cases, for the periods 21 December 2009 to 31 January 2010 and 15 May 2010 to 31 July 2010.

IASI

Another important satellite sounding instrument is IASI, a hyperspectral infrared interferometer that provides measurements in 8,461 channels. At the time of writing, only one such instrument is flying in space, on the European MetOp-A platform, but further instruments are planned for the next few years. The ECMWF system uses up to 175 IASI channels, covering primarily the long-wave CO_2 temperature-sounding band. Infrared observations are much more affected by clouds than microwave ones, so only channels deemed clear from cloud, or totally overcast are currently assimilated in the ECMWF system.

The observation error covariance estimates for IASI tell a somewhat different story, as can be seen, for instance, in Figure 5. While the upper temperature sounding channels, displayed primarily in the lower left quarter of the figure, show similar characteristics as AMSU-A (i.e. with low inter-channel error correlations), other parts of the spectrum exhibit considerable inter-channel error correlations, as can be seen in the upper right quarter. These are channels affected by clouds, have a significant contribution from the surface ('window channels') or are sensitive to water vapour. For these channels, the observation error estimate is also considerably larger than the estimates for the instrument noise (Figure 6). It appears that either the radiative transfer error is larger or the bias correction less successful in compensating for it than for AMSU-A, or other aspects such as residual cloud contamination or representativeness play a role.

The error estimation study also highlighted other interesting aspects. For instance, neighbouring channels show rather high error correlations of around 0.6 (see circles in Figure 5). This is a result of the effect of apodisation, a convolution applied to IASI data aimed at compensating for some of the effects introduced by measuring a truncated interferogram. Although this characteristic is well known, it is reassuring that it shows up clearly in these observation error estimates.

Other characteristics of IASI data are less well known, but are highlighted through a further analysis of the observation error characteristics. For instance, for some channels, we found very small spatial observation error correlations that displayed a chess-board like pattern when displayed as a function of scan-line and scan-position difference (Figure 7). IASI scans the atmosphere across the satellite track, providing data for four pixels at 30 scan-positions for each scan-line. Considering just one of the four pixels, the finding suggests that part of the error is common to several observations with the sign of the error alternating with scan-position. The current explanation is that this is linked to an instrument feature, the so-called ghost-effect, a result of micro-vibrations of parts of the instrument. Although the error is negligible and of no concern for the assimilation of the data, the analysis illustrates the power of data assimilation systems to highlight minute features of satellite data.

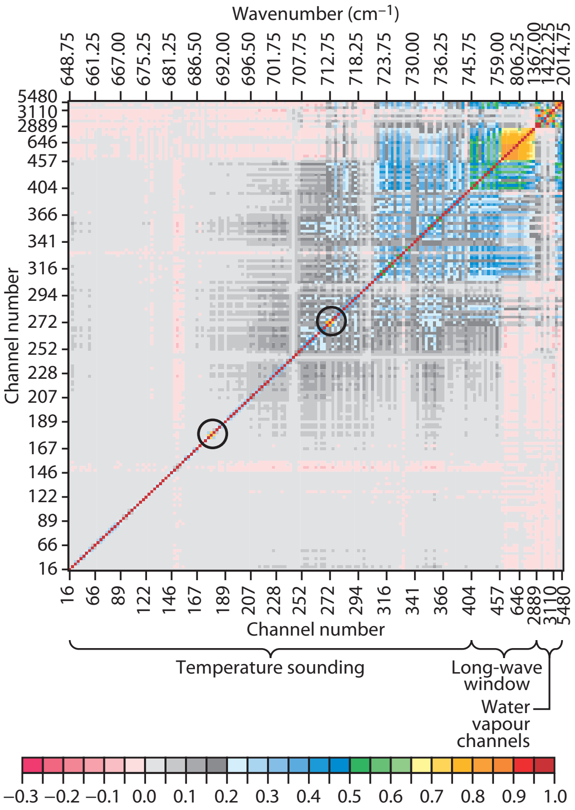

Figure 5 Estimates of the inter-channel error correlation matrix for the IASI channels used at ECMWF. The values are derived from spectra over sea for which all 175 channels used at ECMWF were diagnosed to be clear-sky. The lower axis gives the IASI channel number, whereas the upper axis gives the wavenumbers of the channels. The circles indicate two instances where neighbouring channels are selected, showing large error correlations arising from the apodisation.

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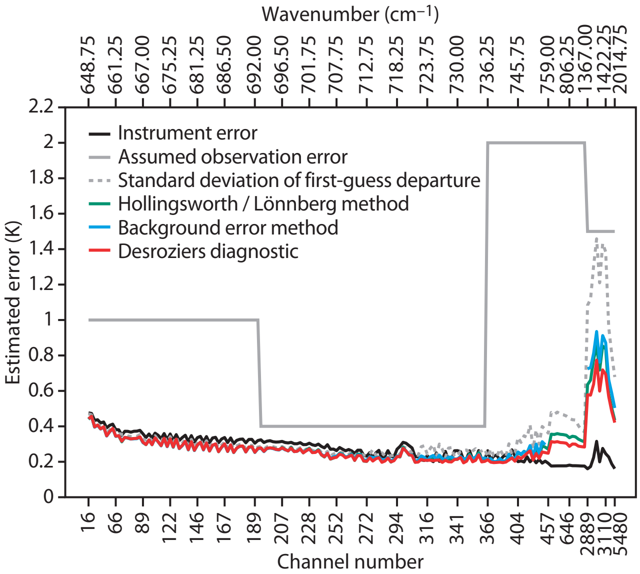

Figure 6 Estimates of the observation error (K) for the IASI channels used in the ECMWF system. The colour coding for the various lines is as described in Figure 3.

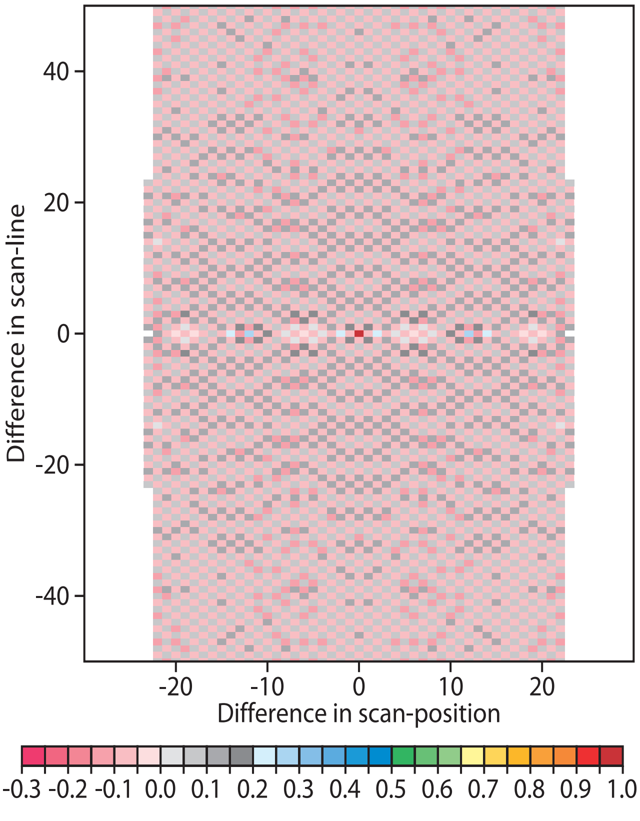

Figure 7 Estimates of the spatial observation error correlation for IASI channel 380, as a function of the difference in scan-lines and AMSU-A scan-position between the two observations.

Other instruments

We performed the same analysis of observation errors for radiances from all main satellite instruments currently used in the ECMWF system, with consistent findings across all of them. Water vapour channels or channels with strong surface contributions show considerable inter-channel or spatial error correlations. We found the largest spatial error correlations for humidity-sensitive microwave radiances, for which spatial correlations can be larger than 0.2 for separations larger than 100 km. Microwave imager radiances in cloudy or rainy regions show particularly strong error correlations. However, for the humidity-sensitive radiances, the estimation of observation errors is also more difficult, as some of the assumptions made in the estimation methods are more stretched.

The effect of observation error correlations

Given the finding of significant error correlations for some of the radiance observations, the question arises: what does it mean for data assimilation if two observations have a significant error correlation?

Let us consider two observations that have a significant positive error correlation and the same observation error. This means that, compared to the case of uncorrelated errors, for a given situation it is statistically (a) more likely that the true errors for both observations are similar (e.g. they have the same sign and comparable magnitude) and (b) less likely that the true errors are different (e.g. they have the opposite sign, but comparable magnitude). Consequently, an assimilation system that takes these error correlations into account will respond differently to the presented observations, depending on the differences between the first guess and the observations.

- If the two observations differ in a similar way from the first guess, the assimilation system will put less weight on the observations compared to the system that ignores such error correlations. This is because similar differences are more likely for observations with correlated errors, so it is more likely that the error is due to an error in the observations.
- If the two observations differ in a different way from the first guess (e.g. opposite signs of departures), the assimilation system will put more weight on these observations compared to a system that ignores the observation error correlations. This is because different errors are less likely for the correlated observations, so the departures are more likely to indicate an error in the first guess.

This behaviour can also be demonstrated for IASI in a real assimilation system. To do so, we investigated what happens when a single IASI spectrum is included in an assimilation system that either ignores inter-channel error correlations or takes these into account. We investigated several selected cases in which all IASI channels that are usually considered for assimilation were diagnosed as cloud-free. In each of these experiments no other observations were assimilated, in order to study the influence of the observation error correlations for IASI in isolation. When error correlations are taken into account, the observation error correlation matrix used was the one shown in Figure 5, and the observation error (from the diagonal of the observation error covariance matrix) was kept the same as when uncorrelated errors are used. Results from two cases will now be presented.

Figure 8 shows the departures for the assimilated IASI channels for the first case. Here, most departures for the lower-peaking temperature sounding channels have the same sign. This suggests that the first-guess is too warm or that there may be residual cloud contamination even though the observations are assumed to be clear-sky.

Figure 9 shows profiles of the increments of temperature and specific humidity that result from assimilating this spectrum with or without taking error correlations into account. Increments are the adjustments made to the first guess as a result of assimilating the observations, and the size of the increments reflects the weight given to the observations in the assimilation. The figure shows that these adjustments are smaller when the inter-channel error correlations are taken into account for this case. The reason is that now the assimilation system knows that the errors in the observations are not independent, and the consistently negative departures are likely to be a reflection of such errors in the observations. As a result, the assimilation system puts less weight on the observations compared to when the observation errors are assumed to be independent.

But the opposite can happen as well: in the second case, the departures vary significantly around zero between channels (Figure 10). Here, the increments are actually larger when observation error correlations are taken into account (Figure 11), consistent with the considerations above for the two-observation case.

We can compare this behaviour with the commonly used approach of using inflated but uncorrelated observation errors. This approach will have a similar effect of reducing the increments as shown in the first case, as less weight is given to the observations. But it will also reduce the increments in the second case, and thus do the opposite of what is observed when error correlations are taken into account. So an error inflation will not have the same effect as taking the error correlation into account.

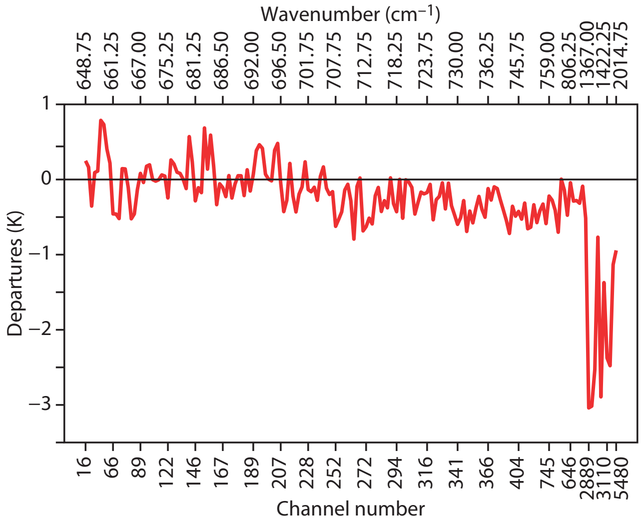

Figure 8 Departures (i.e. difference between observations and first guess) for the first case of single-IASI spectrum experiments.

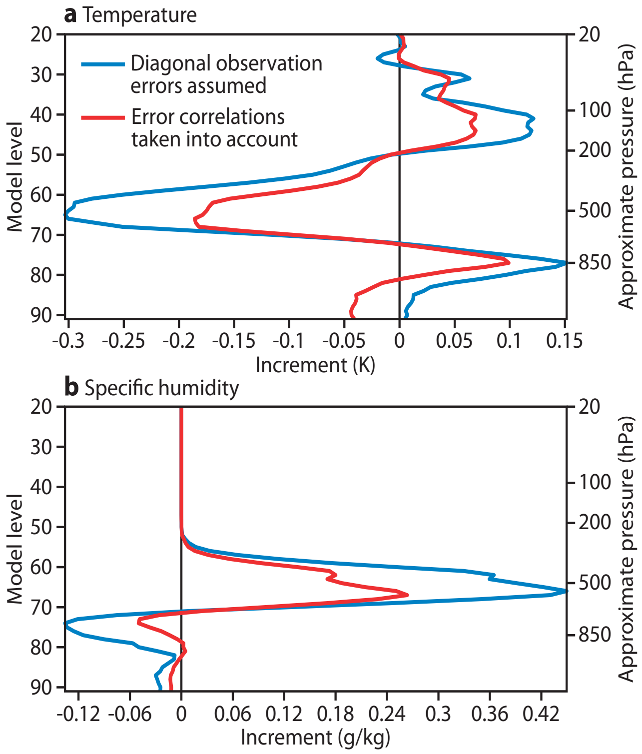

Figure 9 Profile of the increments (i.e. differences between the analysis and the first guess) of (a) temperature and (b) specific humidity at the location of the assimilated IASI spectrum for the first case of single-IASI spectrum experiments. The blue line shows results from the experiment that assumes diagonal observation errors, whereas the red line shows results from the experiment that takes the error correlations into account.

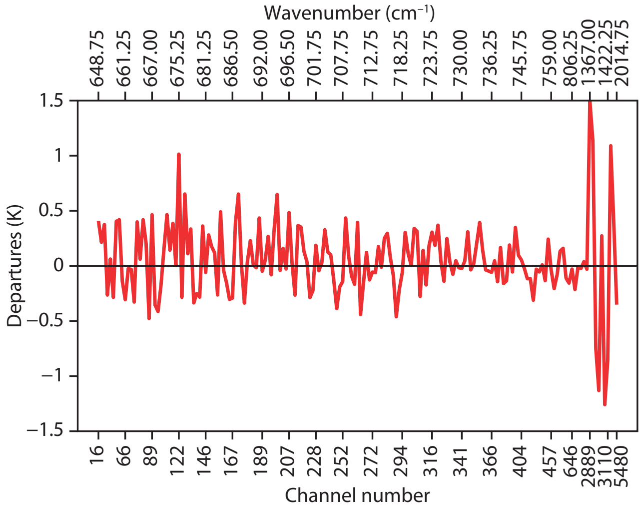

Figure 10 Departures (i.e. difference between observations and first guess) for the second case of single-IASI spectrum experiments.

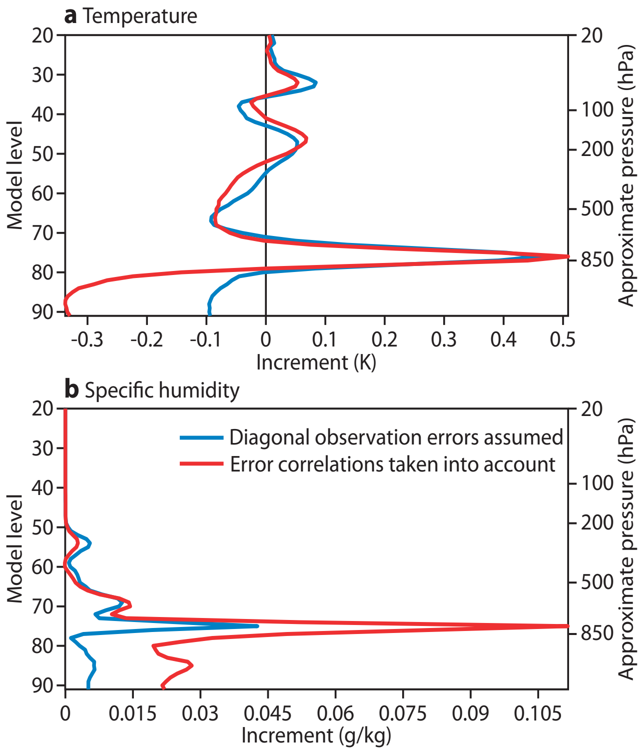

Figure 11 Profile of the increments (i.e. differences between the analysis and the first guess) of (a) temperature and (b) specific humidity at the location of the assimilated IASI spectrum for the second case of single-IASI spectrum experiments. The blue line shows results from the experiment that assumes diagonal observation errors, whereas the red line shows results from the experiment that takes the error correlations into account.

Future

Taking inter-channel or spatial error correlations into account in the assimilation system is an area of active research at ECMWF and elsewhere. While it is clear that neglecting error correlations may lead to a sub-optimal weighting of observations, it is less clear how well we need to model the observation error correlations in order to see a clear benefit over assuming diagonal, possibly inflated observation errors. In addition, observation errors and their correlations are likely to be partly situation-dependent, especially for instruments like IASI, where residual cloud-contamination is thought to be one of the reasons for the presence of inter-channel error correlations. Further work in this direction is required. As the experience with AMSU-A shows, an optimised weighting of observations can lead to rather significant forecast improvements.

Further reading

Bormann, N. & **P. Bauer,** 2010: Estimates of spatial and inter-channel observation error characteristics for current sounder radiances for NWP, part I: Methods and application to ATOVS data. *Q. J. R.Meteorol. Soc.*, **136**, 1036–1050.

Bormann, N., A. Collard & **P. Bauer,** 2010: Estimates of spatial and inter-channel observation-error characteristics for current sounder radiances for numerical weather prediction. II: Application to AIRS and IASI data. *Q. J. R.Meteorol. Soc.*, **136**, 1051–1063.

Desroziers, G., L. Berre, B. Chapnik & **P. Poli,** 2005: Diagnosis of observation background and analysis-error statistics in observation space. *Q. J. R. Meteorol. Soc.*, **131**, 3385–3396.

Hollingsworth, A. & **P. Lönnberg,** 1986: The statistical structure of short-range forecast errors as determined from radiosonde data. Part I: The wind field. *Tellus*, **38A**, 111–136.

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