

Assimilation of Cross-track Infrared Sounder radiances at ECMWF

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1 Introduction

Cross-track Infrared Sounder (CrIS) is a Michelson interferometer providing radiance data on 1,305 channels in the wavenumber range $650\text{--}2550\text{ cm}^{-1}$. CrIS was launched into an afternoon orbit in October 2011 and it shares the Suomi-NPP satellite platform with the Advanced Technology Microwave Sounder (ATMS), Visible Infrared Radiometer Suite (VIIRS), and Ozone Mapping and Profiler Suite (OMPS). CrIS samples the infrared spectrum in three distinct bands with nominal spectral resolutions 0.625 , 1.25 , and 2.5 cm^{-1} in long-wave, mid-wave, and short-wave bands, respectively. The field-of-view (FOV) diameter is 13.5 km in nadir and global coverage is produced every 12 hours.

We aim at operational assimilation of CrIS radiances in the global Numerical Weather Prediction (NWP) system of the European Centre for Medium-range Weather Forecasts (ECMWF). Past experience gathered from experimental and operational assimilation of hyper-spectral radiances, including those from the Atmospheric Infrared Sounder (AIRS; McNally et al. (2006)) and Infrared Atmospheric Sounding Interferometer (IASI; Collard and McNally (2009)), is applied as far as possible: in experiments carried out so far, the assimilation of CrIS radiances is restricted to cloud-free channels over sea and sea ice, and the emphasis is put on efficient use of temperature sounding channels in the $15\mu\text{m CO}_2$ absorption band. In contrast to the operational assimilation of AIRS and IASI radiances, however, we deploy an aggressive approach by assimilating a large number of channels that are adjacent to each other in the observed infrared spectrum. Together with a relatively aggressive specification of observation error standard deviation this is hoped to compensate for the effect of poorer spectral resolution of CrIS instrument. A non-diagonal observation error covariance matrix is applied to account for the effect of the signal apodization.

This paper is structured as follows: we start by discussing the trade-off between instrument noise and spectral resolution in Section 2. Section 3 documents the baseline assimilation system that has produced a good impact on forecast system performance in recent experiments run using a slightly out-of-date version of the Integrated Forecasting System (IFS) at ECMWF. Section 4 describes further improvements to the assimilation system and results from experiments using the currently-operational version of the IFS. Planned future experiments are discussed in Section 5.

2 The effect of spectral resolution

In comparison with earlier hyper-spectral infrared sounders, the spectral resolution of CrIS is poorer, resulting in smoother radiance spectrum and reduced capability to resolve fine absorption lines. This has implications on vertical sounding properties. As demonstrated in Fig. 1, channel weighting functions of CrIS are more similar to each other than those of IASI. Noise characteristics being the same, the CrIS spectrum would contain less information. The vertical sounding capability is further degraded if apodized radiances are assimilated using a diagonal observation error covariance specification, as in this case one needs to limit the assimilation to every second or third spectral channel only.

Fortunately, the poorer spectral resolution of CrIS is mostly compensated by improved performance in terms of instrument noise level. The reduced noise level is clearly demonstrated in observation minus background departure statistics shown in Fig. 2. In theory, information retrievable from the “low-noise / low-resolution” spectrum of CrIS should be approximately similar to that retrievable from the “high-noise / high-resolution” spectrum of IASI, but taking advantage of the low noise levels in NWP context has proved more difficult than expected.

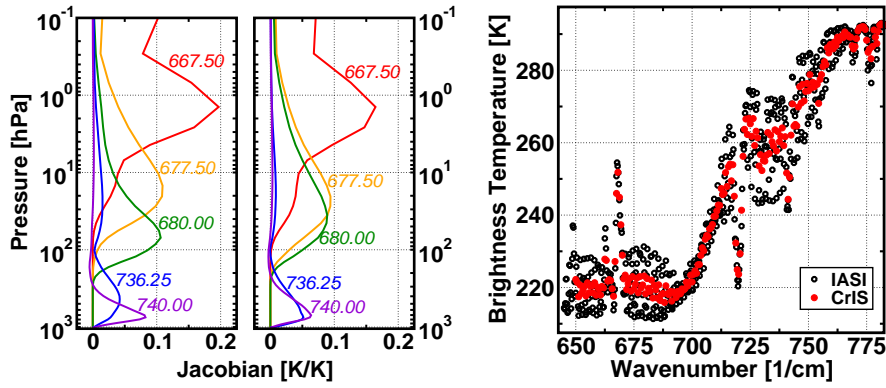


Fig. 1: (Left) Temperature Jacobians on selected IASI (left panel) and CrIS (right panel) channels in a tropical reference atmosphere. Central wavenumbers (in cm^{-1}) are indicated. (Right) Excerpts of IASI (black circles) and CrIS (red dots) long-wave spectra.

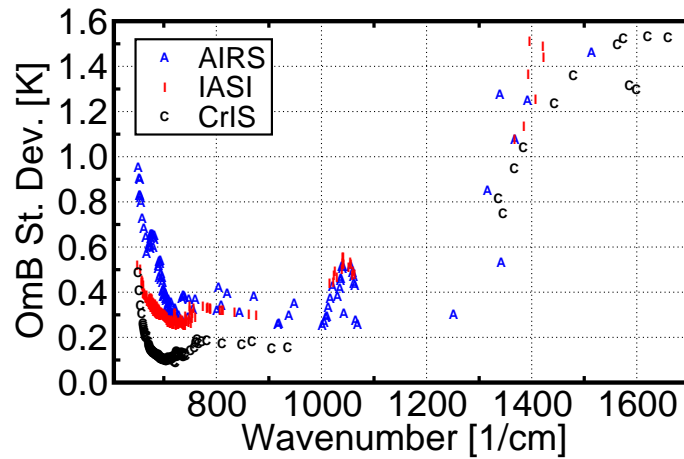


Fig. 2: Global standard deviation of brightness temperature background departure on selected AIRS (blue A's), IASI (red I's) and CrIS (black C's) channels.

3 Baseline configuration

Our approach to deal with the unique noise-resolution trade-off of CrIS is to maximize the retrieved vertical information by using almost all available channels between $670\text{--}730\text{ cm}^{-1}$. This is considered the most critical spectral range in NWP applications. Observation error covariance is specified aggressively. On the one hand this is done by setting error standard deviations lower than in the case of earlier infrared instruments (which is justified by the lower instrument noise levels). On the other hand, error correlation introduced during the signal apodization is explicitly taken into account. Such a specification for the error correlation is theoretically consistent with the Hamming apodization function. No other sources of observation error correlation are assumed to be present in this setup. Consequently, the observation error correlation is set to 0.625 (0.133) between each pair of channels adjacent (alternate) to each other in the observed spectrum.

Additionally, the baseline configuration for the assimilation of CrIS radiances includes the following specifications:

1. Pre-select the middle FOV (pixel 5) from each Field-of-Regard (FOR).
2. Assimilate 122 channels from the long-wave CO_2 absorption band (highlighted in red in Fig. 3).

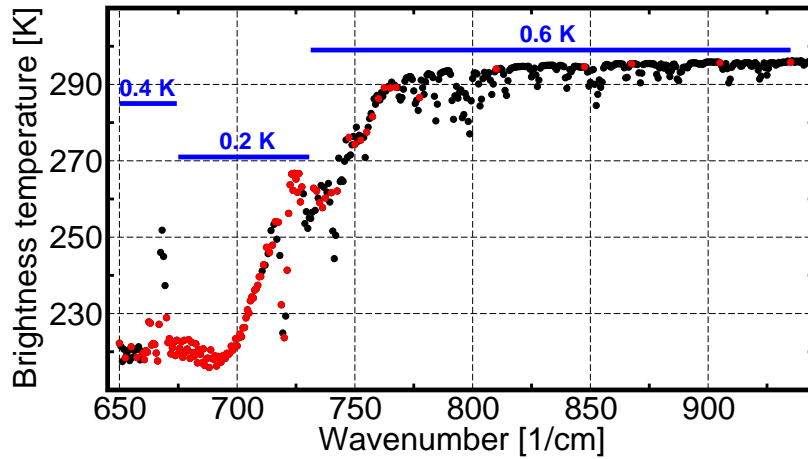


Fig. 3: Long-wave CrIS spectrum highlighting assimilated channels. Blue bars indicate the assumed observation error standard deviations.

3. Set observation error standard deviations to 0.4 K, 0.2 K and 0.6 K on stratospheric-, tropospheric- and surface-sensitive channels, respectively (as shown in Fig. 3).
4. Only assimilate cloud-free channels over sea and sea ice. Identify and reject cloud-contaminated channels using the cloud detection scheme of McNally and Watts (2003).
5. Use RTTOV-10 for radiative transfer modelling.
6. Correct observation biases using a variational scheme with air-mass- and scan-angle-dependent predictors.
7. Only assimilate one FOV per thinning box (1.25° by 1.25°).

The baseline configuration has been applied in assimilation experiments using the previously operational version (Cy38r2) of the IFS. These experiments employ horizontal resolution T511 on 91 levels in vertical. Impact of adding CrIS radiance data on top of the full operational data usage in a 90-day experiment is shown in Fig. 4 in terms of global background fit to conventional and space-borne microwave radiance observations and in Figs. 5 and 6 in terms of medium-range forecast scores. The background fits suggest a modest improvement in radiosonde temperature in lower troposphere and mixed or slightly

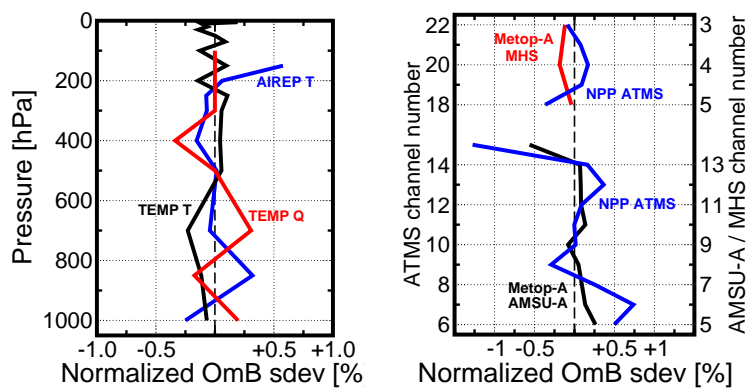


Fig. 4: Normalized global background departure standard deviations for some conventional (left) and space-borne microwave radiance (right) observations in a 90-day assimilation experiment. Negative values imply improved background fit when CrIS radiances are assimilated.

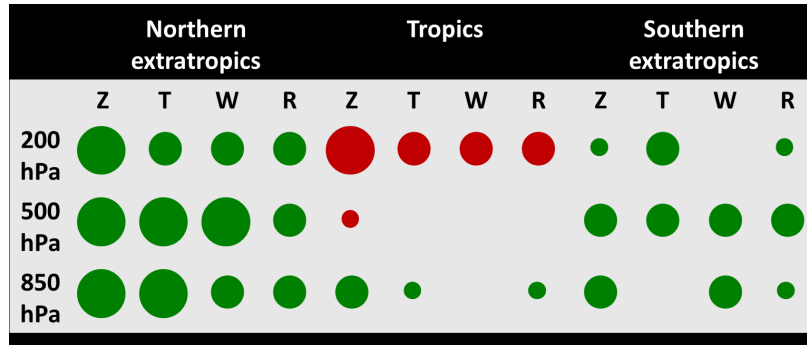


Fig. 5: Subjective visualization of the 3–7 day forecast impact from assimilating CrIS radiances. Z, T, W, and R refer to geopotential, temperature, vector wind, and relative humidity, respectively. Green (red) indicates positive (negative) impact. Dot size indicates the magnitude of the impact.

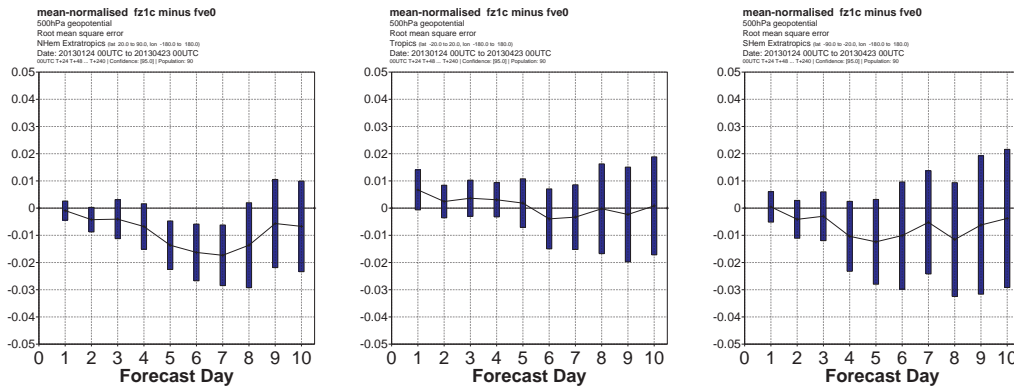


Fig. 6: Control-normalized root-mean-squared error in 500 hPa geopotential forecast in the Northern extratropics (left), Tropics (middle) and Southern extratropics (right) as a function of forecast lead time in a 90-day assimilation experiment. Negative values imply forecast improvement from adding CrIS radiances. Bars indicate the 95% confidence intervals.

negative impacts on other parameters. However, the forecast impact appears to be consistently positive in both the Northern and Southern extratropics and negative only in the tropical upper troposphere. Unfortunately, the positive forecast impact from the baseline configuration has not been reproduced in recent assimilation experiments based on newer IFS version (Cy40r1) run in higher horizontal and vertical resolution.

4 Refinements on top of the baseline configuration

Given that there is only little evidence of improved background fit to independent observations when the baseline configuration is applied and that it has proved difficult to reproduce the positive forecast impact in an up-to-date assimilation system, it appears necessary to further refine and improve the treatment of CrIS radiance data before operational implementation can be considered. Short assimilation experiments suggest improved forecast system performance when the following modifications are made on top of the baseline configuration:

1. Pre-select the warmest FOV out of pixels 2, 4, 6, and 8 of each FOR, as determined from observed radiance on a window channel.

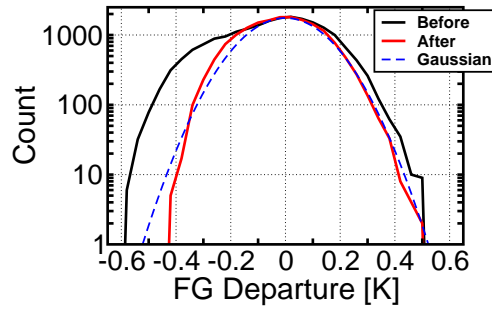


Fig. 7: Frequency distribution of background departure on a mid-tropospheric sounding channel before (black) and after (red) the cloud detection re-tuning.

2. Add 12 channels in the water vapour absorption band (i.e., mid-wave band) to the assimilation system.
3. Remove humidity-sensitive channels in the long-wave CO₂ absorption band from the assimilation.
4. Relax specified observation error standard deviation to 0.5 K, 0.3 K and 1.2 K on stratospheric-, tropospheric- and surface-sensitive channels, respectively.

More importantly, increased care is taken of identifying cloud-contaminated data. In our experiments, the cloud detection is based on the scheme proposed by McNally and Watts (2003), which looks for radiative effect of cloud in a set of vertically-ranked brightness temperature background departures. The scheme includes several parameters allowing one to make the use of radiance data more aggressive or conservative as desired. As the scheme is only based on background departure information and therefore sensitive to background errors, it is inevitable that some clear data will be incorrectly flagged cloud-contaminated (false alarms) and vice versa (misses). An optimal balance needs to be found between false alarms and misses in order to maximize the performance of the assimilation system. The previously-applied tuning of the cloud detection is found to overlook the effect of the low instrument noise, making the scheme overly aggressive and missing too many clouds. Consequently, the assimilation system is found to benefit from making the cloud detection increasingly stringent. This is revealed by improved symmetry in background departure histograms, as demonstrated in Fig. 7 for a case of a mid-tropospheric temperature sounding channel.

Impact of assimilating CrIS radiances on top of the operationally-used data in a 50-day experiment based on the currently-operational IFS cycle (Cy40r1) is shown in Fig. 8 in terms of global background departure standard deviation for conventional and space-borne microwave radiance data. While there is a

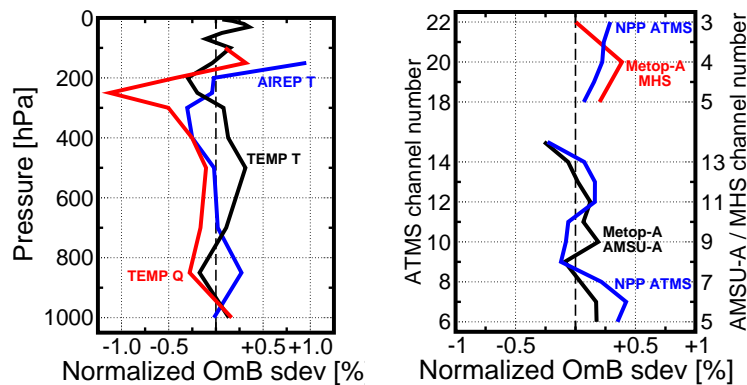


Fig. 8: As Fig. 4, but for a 50-day experiment in a more up-to-date assimilation system.

relatively strong positive impact on background fit to radiosonde humidity data in the upper troposphere, the impact on other parameters remains neutral or negative in this experiment. Furthermore, no consistent positive forecast impact can be reported here.

5 The way forward

Despite the improved cloud detection and more sophisticated FOV and channel selection procedures, assimilating CrIS radiances in the currently-operational IFS setup has still not been found to produce a consistently positive impact as verified using independent observation departure statistics and forecast scores. It is speculated that once AIRS is currently providing high-quality infrared information in the afternoon orbit, there is little room for additional benefit from assimilating CrIS radiances with nearly-identical observing geometry in a similar orbit. To test this hypothesis, assimilation of CrIS radiances will next be experimented in a degraded system where AIRS radiances are not used. If adding CrIS in such a degraded system demonstrates a good impact, the option of replacing AIRS by CrIS in the operational assimilation at ECMWF will be considered. This can be justified as AIRS is not expected to continue providing useful data for many more years into the future.

Remarkably, the aggressive setup including the use of a large number of adjacent channels and a non-diagonal observation error covariance matrix has produced a good forecast impact in one assimilation experiment only. Furthermore, even in the most successful experiment, independent observation departure statistics provide little support to conclude that forecast system performance was actually improved. Therefore, additional experiments will be run using simpler methodology including diagonal observation error covariance matrix and avoiding the use of spectrally-adjacent channel pairs (implying a considerably reduced count of actively-assimilated channels). Of course, such an approach was tried in the past without noticeable success, but it is worth revisiting now as the recent improvements can be applied in such a framework and they might have potential to change the outcome.

In the more distant future, we will consider accounting for inter-channel error correlations other than those introduced during the signal apodization. As demonstrated in Fig. 9, diagnostic methods suggest presence of strong observation error correlations shared by surface-sensitive channels on the one hand and by humidity-sensitive channels on the other. Appearance of the inter-channel error correlations is qualitatively similar to those diagnosed earlier for AIRS and IASI (see, e.g., Bormann et al. (2009)), although the correlations diagnosed for CrIS are stronger. The origin of these error correlations is not fully understood. Additionally, the assimilation of CrIS radiances is planned to be improved by the use of stratospheric-peaking channels over land and by better cloud detection that makes use of collocated imager information and not only background departures on CrIS channels.

6 Conclusions

As compared with earlier hyper-spectral sounders, CrIS radiances are affected by a unique trade-off between noise characteristics and spectral resolution. Experience from the operational assimilation of AIRS and IASI radiances is therefore found insufficient, albeit useful, to facilitate successful assimilation of CrIS radiances.

Emphasis is put on strong exploitation of cloud-free sounding channels in the 15 μm CO₂ absorption band. Despite little improvement is gained in background fit to independent observations, a positive medium-range forecast impact is found in both the Northern and Southern extratropics, when CrIS radiances are assimilated into the previously-operational IFS version at ECMWF. However, similar level of impact has not been produced using the currently-operational IFS version, even when new developments in the cloud detection and data selection are applied.

The work towards understanding the nature and impact of CrIS radiance data in the ECMWF 4D-Var system will be continued. As a next step, parallel assimilation experiments will be run including CrIS radiances only in the absence of AIRS radiances (and vice versa), as it is speculated that assimilating hyperspectral radiances from the two sounders with nearly-identical orbits might diminish the benefit

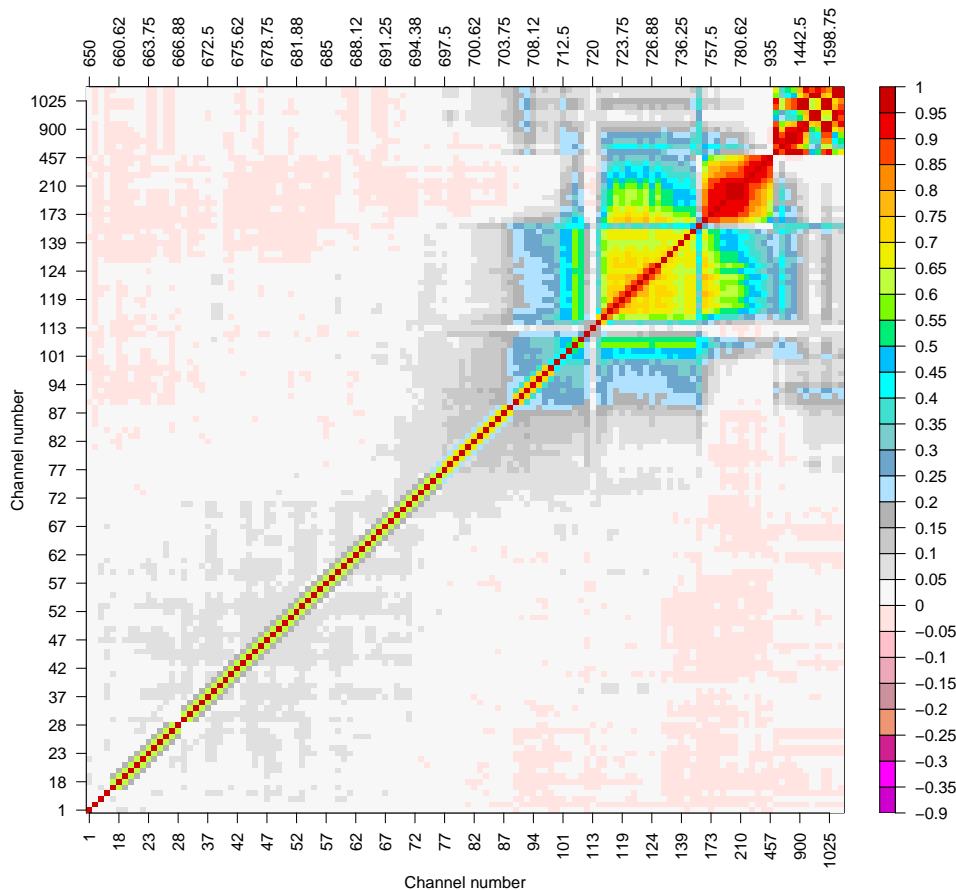


Fig. 9: Inter-channel observation error correlations as diagnosed using the Hollingsworth-Lönnerberg method in a selection of 128 CrIS channels.

attributed to individual sounder. Furthermore, a simpler approach to the assimilation, including the use of a diagonal observation error covariance and a lower number of active channels, will be reconsidered.

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