Report on NOAA-20 ATMS and CrIS radiance data quality

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1. Introduction

JPSS-1 was launched on 18th November 2017 and renamed NOAA-20 once in orbit. Its payload consists of eight instruments including the Advanced Technology Microwave Sounder (ATMS) (Zhou et al., 2016) and a Cross-track Infrared Sounder (CrIS) (Han et al., 2013). It is the second in a series of five Joint Polar Satellite Systems (JPSS) US polar orbiting satellites to be launched between 2011 and 2031. All of these satellites will carry an ATMS and a CrIS instrument which contribute key atmospheric sounding components of the global satellite system and are operationally used at many NWP centres worldwide. The global data streams for evaluation started in March 2018 for ATMS and in May 2018 for CrIS.

In time ATMS will, effectively, replace the Advanced Microwave Sounding Units (AMSUs) and Microwave Humidity Sounder (MHS) carried onboard the US Polar Orbiting Environmental Satellite (POES) series (NOAA-15 to -19). The AMSU and MHS instruments onboard both the POES and the EUMETSAT Metop series have been shown to deliver significant benefit in many operational global and regional data assimilations systems worldwide (e.g. Joo et al, 2012). Likewise, data from the first ATMS instrument, carried on JPSS-0 which was renamed the Suomi National Polar-orbiting Partnership satellite (SNPP), launched on 28th October 2011 has been assimilated worldwide with significant impact on forecast quality (e.g. Doherty et al. 2015). ATMS will, therefore, form a key part of the global observing system and of data assimilation systems for the next two decades, and the current addition of another ATMS on NOAA-20 provides resilience for this important data stream.

CrIS is the first series of hyperspectral IR sounders to appear on an operational satellite series from the US and was first launched on SNPP in 2011. These hyperspectral IR measurements were building on experience with the Atmospheric InfraRed Sounder (AIRS; Chahine et al., 2006) on the Aqua satellite as an originally experimental system that has far outlived the specified design lifetime and is now commonly assimilated operationally by NWP centres. This was followed by the Infrared Atmospheric Sounding Interferometer (IASI) on the European Polar System Metop series. CrIS, also on the upcoming JPSS-X launches into the early 2030's, will carry on these high quality hyperspectral measurements started with AIRS and IASI. The instrumental design of CrIS is more akin to that of the IASI's although the spectral resolution is coarser and the spectral coverage is less continuous. Details on its initial assessment and assimilation performance using the Met Office system, where it is assimilated since 2013, were detailed in Smith et al (2015); the key findings were a small improvement in the forecast and a significantly improved fit to the model background for the already assimilated AIRS, IASI and MHS channels when the new CrIS data were introduced.

This report provides an initial quality assessment of the new ATMS and CrIS instruments on NOAA-20 from a NWP user perspective, and summarizes the results for technical data quality aspects complemented with some information on data use and impact from initial implementation trials. As this report is intended to document instrument quality with a focus on NWP applications, the evaluation is based on comparisons of observations to model equivalents from short-range forecasts and forward simulations using RTTOV (Saunders et al. 2013). The evaluation of ATMS and CrIS from NOAA-20 is done in comparison to data from the already flying ATMS and CrIS instruments on SNPP. Additionally, results for ATMS are compared to the corresponding channels from the well-established AMSU-A and MHS MW sounders on Metop-B/EUMETSAT and NOAA-19.

As quality assessments using model-based forward calculations are not independent of the NWP system used, the report is based on results from more than one centre with contributions from the Met Office and the DWD. These are summarized in the Data characterization Section 2. Additionally, the report provides in the Assimilation Experiments Section 3 a short overview of data implementation and quality selection decisions for assimilation trials and some forecast impact results.

2. Data Characterization

2.1 ATMS instrument characteristics and data processing

ATMS is similar to the AMSU/MHS instruments flown on NOAA-15 to -19 and Metop-A and -B. It has 22 channels: 5 sensitive to the surface (at 23, 31, 50, 51 and 89 GHz), 11 temperature sounding channels around the 50-60 GHz oxygen band and 6 moisture sounding channels around the 183 GHz water vapour band (Muth *et al*. 2004). ATMS has 96 footprints per scan line, each separated by 1.11°. The footprint size varies with channel. Channels 1 and 2 have a 5.2° beam width, channels 3-16 have a 2.2° beam width and channels 17-22 have a 1.1° beam width. This means that the lower frequency channels are at lower resolution and are highly oversampled.

The oversampling of the 50-60 GHz temperature sounding channels is associated with shorter integration times per footprint and results in higher radiometric noise values, relative to equivalent AMSU channels. Radiometric sensitivities, or noise, are currently significantly larger than forecast model errors expressed in observation space for key tropospheric temperature sounding channels (which are currently in the range 0.05-0.10 K). The radiometric performance of these microwave sounders is therefore critical in determining the impact on analysis and forecast accuracies (Bell *et al.,* 2010).

At the Met Office the ATOVS and AVHRR Pre-processing Package (AAPP) is used to remap the ATMS data to bring them close to AMSU noise performance and footprint size (NWP SAF, 2011a). The ATMS data assessed here have been manipulated to a beam width of 3.3° (apart from channels 1 and 2 for which the beam width is 4.8°) using Fourier techniques and have been re-sampled to give one field of view in three (i.e. 32 fields of view) across the scan. The data are also re-sampled at a rate of 1 in 3 in the along-track direction. This pre-processing allows the ATMS data to be processed following the method for AMSU/MHS. After remapping, SNPP and NOAA-20 ATMS temperature sounding data have similar noise values (NEΔTs) in the range 0.05 to 0.15 K (N. Atkinson, pers. Comm.).

At the DWD the ATMS pre-processing is done through the generic satellite pre-processor (satpp) used for all radiance input into the assimilation system. For ATMS, a pragmatic super-obbing approach is followed to achieve both a reduction in horizontal sampling and a reduction in noise. Currently, for channels 1-15, brightness temperatures are averaged within boxes of 3*3 FOVs (i.e. 3 neighbouring FOVs and 3 scanlines). The averaged brightness temperatures are assigned to the central FOV position and kept for further processing and ingest into the data assimilation. For the humidity sensitive channels in the 183 GHz band (channels 18-22), currently no averaging is done because sensitivity tests investigating different averaging in assimilation trial setups have not resulted in conclusive improvements.

At both centres, the ATMS data are received via EUMETCast in BUFR format, the BUFR files having been generated originally by NOAA. The NOAA-20 results presented in this report use brightness temperatures (corrected for antenna pattern) rather than antenna temperatures.

2.2 ATMS Monitoring results

Doherty *et al.* (2012) give details of data quality assessment for the first ATMS on SNPP. The main findings of the report were that SNPP ATMS data are of high quality and have low noise compared to AMSU after the pre-processing steps described in section 2.1. For this report, a similar analysis has been carried out for NOAA-20 ATMS at the Met Office and DWD. Comparisons of observations to the short range model background fields have been evaluated using RTTOV as forward operator (in version RTTOV 12.1 at the Met Office and at DWD). At DWD, the model background is a 3h forecast from the 3-hourly assimilation cycle run. At the Met Office, the background is a 3-9 hour forecast based on the 6-hourly 4DVar cycle. For the lower peaking channels 1-9, the statistics include only

FOVs that were selected as not contaminated by too high liquid water and/or rain contents and include only data over sea. The data selection follows the choices made for data used actively in the assimilation and are listed in detail in **Table 1** (for Met Office) and **Table 2** (for DWD), Section 3. The periods investigated cover one month (August 2018) for the Met Office and 3 months (mid-July to mid October 2018) for the DWD results.

At the Met Office satellite radiance measurements are corrected using observation biases derived from the variational bias correction (VarBC) scheme implemented in 2016 (Cameron and Bell, 2018). In this scheme the statistics of differences between the observations and background equivalents are estimated at each analysis step along with the estimated state; the bias correction process is adaptive rather than static, and adjusts the biases iteratively relative to the analysis (rather than the background) (Eyre, 2016). The DWD bias correction scheme applied is also adaptive, and adjusts the biases iteratively relative to –currently- the background fields.

Figure 1 shows the Met Office results as mean and standard deviation of both the uncorrected and the corrected difference from model background for both ATMS instruments and the corresponding channels from Metop-B and NOAA-19 AMSU instruments for the month of August 2018. **Figures 2** and **3** show the corresponding results for the DWD, but for all ATMS channels from 1-22, including also the water vapour sensitive channels along with the corresponding MHS channels from Metop-B and NOAA-19. The uncorrected biases of ATMS on NOAA-20 compare favourably with the other instruments for both the temperature and water vapour sounding channels. The biases based on the Met Office and DWD NWP systems display similar order of magnitude and sign and also mostly similar relative magnitudes between the different satellites for the channels 6-11. However, for channels 13-15 which are peaking high in the atmosphere, the biases seen at the Met Office and DWD have very different behaviour which can be attributed to NWP model differences and inherent systematic NWP model biases. For the water vapour channels 18-22 (see **Figure 2**), both in Met Office and DWD results, the bias level for ATMS/NOAA-20 is about 0.5-1 K colder than for ATMS/SNPP. The standard deviations for all channels of ATMS/NOAA-20 compare well with those of the instruments flying on the other satellites (bottom panels in **Figure 1** and **Figure 2**). As these globally computed standard deviations will depend on the biases in the model which often show a typical variation between latitude bands, a useful additional comparison is for standard deviations after the bias correction which very efficiently removes these systematic bias variations (remaining biases are below 0.05 K and below 0.02 K for channels 5-14). These standard deviations for bias corrected brightness temperatures are shown for DWD results in **Figure 3** and confirms quasi identical performance of ATMS on NOAA-20 and SNPP with slightly lower standard deviation for NOAA-20 in channels 6-15. **Figure 4** shows the comparison of warm and cold NEΔT counts for the SNPP and NOAA-20 ATMS channels averaged over the period 20/02/18 – 03/07/18 (N. Atkinson, pers. Comm.). Again, NOAA-20 and SNPP instruments show a similar quality with SNPP having slightly lower NEΔT across all channels. This fits and supports the previous results of comparisons with the NWP fields discussed above.

A feature which is normally accounted for in the bias correction schemes applied at NWP centres is a variation of bias over scan positions as displayed in **Figure 5** for selected channels of NOAA-20 in comparison to SNPP. Whilst some variation can be attributed to inaccuracies in the forward operator used, other contributions come from the instrument itself resulting for some channels in asymmetric behaviour across the scan (e.g. channel 1, 13 in **Figure 5**). The overall scan bias patterns for NOAA-20 and SNPP are very similar, whilst the magnitude of biases may be different.

The residual biases remaining after bias correction also compare well with SNPP ATMS as shown for an example for channel 10 in **Figure 6** from the routine monitoring of the Met Office operational system on 23/07/18. Note that, in the Met Office system, SNPP is given priority in the thinning, and, therefore, the NOAA-20 swath appears narrower in the geographical coverage plots. Detailed data analysis reveals that the NOAA-20 ATMS data quality is an improvement on SNPP because the striping is less pronounced, an artefact seen in the SNPP instrument's corrected minus background brightness temperature maps for tropospheric temperature sounding channels. This striping effect can be quantified by taking the ratio of the single-sample NEΔT of calibration views with the NEΔT that you would get after 3x3 averaging: the resulting ratio will be in the range 3 (if random noise dominates) to sqrt(3) (if low frequency noise dominates). Such analysis of NEΔT for the two ATMS instruments shows that the striping on NOAA-20 ATMS is much reduced compared to SNPP ATMS on all of the channels (N. Atkinson, pers. Comm.).

Another important quality aspect of the satellite radiances is their stability in time with respect to calibration and especially noise, although many of the bias correction methods typically used in NWP can adapt to a variation of bias in time as with VarBC. **Figures 7-9** show time series of mean and standard deviations of the uncorrected and corrected O-B's of ATMS channel from the Met Office system for the month of August, while **Figure 10** shows three months of mean uncorrected O-B's from the system at DWD. Time series of uncorrected O-B departures in **Figures 7-10** show that the globally averaged bias versus model fields is very stable in time for channels 5-13 showing the stability of the instrument with respect to a well-calibrated model. The variations for other channels visible in the time series and occurring on relatively short time scales are most likely to be attributed to changes in parts of the NWP model atmosphere which are poorly constrained by other observations and for which the model forecast state is inconsistent with the observations. These inconsistencies can arise from either model bias or observation bias in such poorly constrained portions of model atmospheres. A case in point is channel 14 which maintains a relatively large O-B even after bias correction (**Figure 8**, panel (d)). Examination of Met Office analysis departure statistics (not shown here) show that VarBC corrects the observations from this channel such that the forecast analysis departures are minimised which is the expected behaviour of VarBC. There is an ongoing residual O-B due to bias in the model background itself at this level. A similar behaviour is found for channel 13 of AMSU-A which has very similar spectral response. Thus, the measurement in this channel provides an increment at each assimilation cycle which brings the model state closer to the observations in this portion of the atmosphere that is poorly constrained by other measurements. Similar arguments can be made for the benefit of the humidity sounding channels 18-22 where O-B's are relatively large even after bias correction.

Figures 11 and **12** show global distributions of the mean uncorrected and corrected O-B's for ATMS Channel 7, respectively. The uncorrected O-B's in **Figure 11** show the latitudinal banding with cold biases in the northern half of the northern hemisphere and in a band around the 40° S with the rest of the globe biased warm. The histogram shows that the observations are on average 0.3 K cooler than the model equivalent observations. The corrected O-B's in Figure 12 show that VarBC effectively removes the mean bias but only reduces the standard deviation from 0.108 K to 0.095 K. The latitudinal banding has been removed but there is still patchy spatial noise in the corrected O-B's apparent in the plot.

2.3 CrIS instrument characteristics and data processing

A description of CrIS and its calibration can be found under e.g. https://jointmission.gsfc.nasa.gov/cris.html and Han et al. (2013) while further information on the data quality and its use in an operational NWP system is documented in e.g. in Smith *et al*. (2015) for the Met Office context. In short, CrIS is an infrared Fourier-transform interferometer similar to IASI with three frequency bands over which it measures 1305 channels at 0.625 cm^{-1} resolution in the longwave IR band (650 to 1095 cm^{-1}), 1.25 cm^{-1} resolution in the mid-wavelength IR band (1210 to 1750 cm^{-1}), and 2.5 cm^{-1} resolution in the short-wavelength IR band (2155 to 2550 cm^{-1}) for Nominal Spectral Resolution (NSR) and 0.625 cm^{-1} resolution for all bands at Full Spectral Resolution (FSR). It scans across track ±50° with respect to the nadir with 30 Earth scene views.

NOAA-20 CrIS is only provided at FSR while SNPP CrIS was originally sampled at NSR and, while an FSR product for SNPP CrIS has been available since 2 November 2015, the Met Office and DWD, along with many other NWP centres, continue to only use SNPP data at NSR. Therefore, although there are plans to eventually assimilate NOAA-20 CrIS data at FSR, the initial assessments are performed using the NOAA-20 CrIS data at NSR.

At the Met Office, this NSR data is generated locally by reducing the effective optical path difference in a FFT of the FSR datastream on the mid-wavelength IR band and short-wavelength IR band. The initial data quality assessments are done for the 127 CrIS channels operationally assimilated at the Met Office: 74 temperature, 40 water vapour and 13 surface. The details of this channel selection can be found in Smith et al. (2015) and the spectral coverage of the channel set can be seen in **Figure 13**. The observation errors are kept consistent with those from SNPP CrIS data (0.2K plus instrument noise). Since Smith et al. (2015) was written seven channels have been removed to improve convergence in 4DVAR: two trace gas channels at 712-713 cm^{-1} and five UTLS humidity channels with wavenumbers between 1472 and 1734 cm^{-1}.

At DWD, the assessment is done using, for NOAA-20, the 431 channel FSR dataset that is distributed via EUMETCast. For SNPP, the current data processing is using the NSR datasets (as at the Met Office) providing a set of 399 channels. However, the initial assessment presented here covers only temperature sounding channels in the long-wave band where the FSR datasets have the same spectral resolution as the NSR datasets. The comparison is done for clear-sky scenes only and the McNally & Watts cloud detection scheme (2006) is used to flag for each FOV those channels that are likely to be cloud-affected. In order to have comparable results for the 431 channels FSR dataset for NOAA-20 and the 399 channels NSR dataset for Suomi-NPP only those channels that occur in both datasets were used in the McNally&Watts cloud detection and results are shown only for these common channels.

As with ATMS, CrIS data are received at both centres via EUMETCast, in BUFR format generated by NOAA. Hamming apodisation has been applied at the BUFR encoding stage. All spectral channels are included.

2.4 CrIS Monitoring results

The new CrIS data from NOAA-20 have been compared against simulated brightness temperatures based on short-range forecast fields (similar setup as for ATMS, see Section 2.2 for details). Statistics are computed using only data free from major sources of uncertainty, such as cloud or inaccurate surface emission values. The data selection at the Met Office includes data quality controlled for convergence issues and only includes channels used in the assimilation (see **Figure 13**). Data over land with elevation greater than 1000 m is discarded as well as channels which have significant impact from cloud. At DWD, only data over sea which are not flagged potentially cloudy by the McNally&Watts cloud detection scheme have been selected for these statistics. The statistics shown for both centres have been computed after application of bias correction. **Figure 14** shows the uncorrected (red) and corrected (green) O-B statistics of the Met Office for all measurements passing basic quality control tests on the 127 channels assimilated. Cases for cloud-affected scenes are likely to be included here but grossly erroneous data has been removed as only those soundings where some fraction of the channels has been involved in a 1DVAR retrieval which converges are shown. Note that VarBC only removes a small portion of the mean bias in these cases. **Figure 15** shows the same statistics for only those measurements over sea in the 650 to 950 cm^{-1} spectral region, which are key for temperature sounding that are passed to 4DVAR. Channels with greater than 5% vertical overlap with model cloud are further excluded here as well as those soundings which have significant corrected O-B’s, greater than 4 times the model covariance for that channel. For these assimilated soundings the bias correction brings the O-B’s to within 0.1 K for most channels. The O-B standard deviations for NOAA-20 CrIS data are very close in size to those derived from SNPP CrIS data, with a slight reduction seen in some channels (figure not shown). **Figure 16** shows the standard deviation of bias corrected O-B’s from the DWD monitoring for a four and a half months period (29 June to 15 October 2018). The mean residual biases (not shown) are below 0.03 K for channels 28 to 501 (corresponding to the wavenumber range 667-963 cm^{-1}) and then rise to be below 0.4-0.5 K for channels 565-654 (1002-1058 cm^{-1}). The results for the standard deviations are very similar in magnitude to the results obtained in the Met Office statistics for channels below 760 cm^{-1} (channel 177). Standard deviations then grow for the channels above 760 cm^{-1}, especially nearing 1060 cm^{-1}, comprising also channels sensitive to water vapour and the surface. The DWD results for this longer period show a slightly better performance of the NOAA-20 data compared to SNPP for the low wavenumbers (below 710 cm^{-1}, channel numbers up to 95) which is also visible in the Met Office results.

The time series of the mean (red) and standard deviation (green) of O-B's for Channels 1 and 82 is depicted in **Figure 17** where again the uncorrected values are shown in solid lines and the corrected values are shown with dashed lines. This shows the effect of VarBC in reducing the mean O-B as well as a very slight reduction in the standard deviation. Note that Channel 1 is a stratospheric temperature sounding channel with a Jacobian which peaks near 40 hPa while Channel 82 is a lower tropospheric sounding channel with sensitivity to both temperature and water vapour that peaks near 800 hPa. Thus Channel 82 is affected by cloud much more often than Channel 1 and the number of observations assimilated is much reduced in comparison (**Figure 17 (c)**). Note also that there was a data gap on the days of 21 to 23 August where the number of soundings was greatly reduced. The bias correction for Channel 1 is more stable during this period due to the smaller change in the uncorrected O-B's for that time. For both channels the magnitude of the trough in mean O-B at 21 August is reduced by VarBC.

Figure 18 shows the variation of mean global uncorrected O-B bias versus scan position based on the DWD statistics for a selection of CrIS channels from both satellites. The behaviour across the scan is predominantly symmetric for most channels with similar behaviour for NOAA-20 and SNPP. Channels above number 173 (757.5 cm^{-1}) show a less smooth behaviour across scan which is likely to be a product of instrumental artefacts or processing of the interferograms.

2.5 Data timeliness

The delay between observation time and data reception at NWP centres also influences the impact a data type can have for the assimilation as it determines the amount of data that can be used in an operational context. This is especially true for the main forecasts often having very stringent data cut-off times (e.g. 2h14 min for global forecasts at DWD and 3h at the Met Office, respectively), whilst the update assimilation cycle often runs in a more delayed mode and is less easily affected. **Figure 19** shows the timeliness for ATMS data received at DWD from NOAA-20 and SNPP for a monthly period 13 Nov to 13 Dec 2018. The histograms in the top panels show that the data from NOAA-20 arrive on average within 38 min. with 97.2% being in the archive within the first hour. For SNPP data the delay is larger with 1h26min. on average and only 6.6% within the first hour and 95.7% within 2 hours. Results for CrIS data are similar. Such a timeliness difference is also observed in the reception at the Met Office. The bottom panels show the stability of the reception and for both satellites the total number of data received as well as the number of data arriving within certain delay thresholds is very stable over time.

The likely reason for NOAA-20 data to be disseminated in a more timely way is the way the downlink is organised with NOAA-20 relying on two ground stations (Antarctic and over Svalbard; details at https://www.jpss.noaa.gov/news.html?110). This further enhances the usefulness of the new NOAA-20 data, as a timeliness of 40min. is much more likely to meet cut-off times even for regional modelling applications.

3. Assimilation experiments

This report contains results for trials introducing NOAA-20 ATMS carried out at both the Met Office and at DWD and NOAA-20 CrIS trials from the Met Office.

3.1 Met Office assimilation experiments

The Met Office trials for both ATMS and CrIS compared a low resolution version of the operational configuration of the model with (experiment) and without (control) the respective new instrument. The low resolution version was an uncoupled hybrid N320 UM, N108/N216 VAR and N216 ensemble.

To provide a sensible initial bias correction for NOAA-20 ATMS and CrIS, operational suites including the new data type only passively were run for two weeks to generate representative static bias correction files which were then used to generate initial bias coefficients for VarBC. To allow for initial adjustments within VarBC, the first 5 days of the assimilation experiments were ignored in the verification.

3.1.1 Met Office: ATMS assimilation experiments

A near real-time trial period was examined covering the period 25th April – 6th June 2018 (42 days). The NOAA-20 ATMS settings used in the trial were those currently used operationally for the SNPP instrument. The observation error for use in both 1D-Var and 4D-Var was calculated by scaling the SNPP ATMS values of the observation error covariance matrix, **R,** by the ratio of the noise given as ATMS pre-launch specification and the NEΔT for SNPP ATMS, except for the 183 GHz channels for which **R** was set to 4 K. **R** is assumed diagonal for ATMS in the Met Office system.

The ATMS channels used in the trials were 6-15 and 18-22. Surface sensitive channels were omitted. The quality control (QC) checks and thinning were identical to those used operationally for SNPP ATMS. Observations were thinned to a distance of 150 km with priority given to SNPP ATMS. **Table 1** summarises the channel selection for the trials. See Doherty *et al.*, (2012) for a detailed description of the cloud flags.

Table 1: ATMS channel selection at Met Office

Flag/ATMS channel	6	7	8	9	10	11	12	13	14	15	18	19	20	21	22
Clear	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Mwbcloudy	+	+	+	+	+	+	+	+	+	+				+	+
Mwcloudy		+	+	+	+	+	+	+	+	+		+	+	+	+
Rain					+	+	+	+	+	+					
Bennartz rain					+	+	+	+	+	+					
Sea	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Seaice	+	+	+	+	+	+	+	+	+	+					
Land		+	+	+	+	+	+	+	+	+					
Highland			+	+	+	+	+	+	+	+					
Mismatch			+	+	+	+	+	+	+	+					

There are four flags applied to screen out observations in the presence of deep cloud and precipitation as radiative transfer in these conditions is less reliable. These are termed 'rain', 'bennartzrain', 'mwbcloudy' and 'mwcloudy'. The 'rain' flag is a scattering test on the 89, 23 and 31 GHz channels, the 'bennartzrain' flag is an additional scattering index based on 89 and 150 GHz. The 'mwbcloudy' flag, also known as a cirrus cost test, uses the 183 GHz AMSU channels. The 'mwcloudy' test is carried out in AAPP and identifies areas of high liquid water path and categorises the most likely surface type for a field of view. All of these tests are described in more detail in Doherty et al. (2012).

High land is defined as land with model orography over 1000 m while mismatch is where the model and observation surface categorisation disagree, eg where they are on different scales near coastlines.

Trial verification results are shown in **Figures 20-21**. These plots show the results separated into latitude bands and analysed with respect to a range of forecast skill metrics. The trial is overall neutral in terms of the NWP index although the detailed picture is modestly positive, especially against analysis (+0.21%). Agreement with the ECMWF analysis is also improved (not shown).

Another way of assessing the impact of assimilating a new satellite observation is to examine the way in which the O-B statistics for other instruments changes with the addition of the new measurements. The main impact for the assimilation of NOAA-20 ATMS was a decrease in the standard deviation of the corrected O-B's for AMSU-A microwave temperature sounders and a slight increase in the standard deviation of the corrected O-B's for stratospheric temperature sounding channels of SNPP CrIS. This implies that assimilation of NOAA-20 ATMS pulled the analysis more towards the measurements of the microwave sounders and further away from the CrIS measurements. The addition of CrIS in addition to ATMS on NOAA-20 would likely counter this effect (trial not performed).

3.1.2 Met Office: CrIS assimilation experiments

An experimental forecasting suite with an operational configuration was used to assess the impact of NOAA-20 CrIS for the period of 18th May to 1st July 2018. The channel selection and observation errors used in assimilating NOAA-20 CrIS were consistent with those for SNPP CrIS data. The CrIS data from both satellite platforms was thinned together (one observation every 125 km in extratropics and every 154 km in the tropics), with no priority for either satellite. Observations were used over the land and the sea, but not over sea ice.

The impact of assimilating NOAA-20 CrIS on the forecasts is shown in terms of the change in root mean square error (RMSE) when verifying against analyses (**Figure 22**) and against observations (**Figure 23**). The overall results are neutral for both analyses (+0.07%) and surface observations (+0.02%) verification, with the strongest positive impact early in the forecast for NH geopotential height and temperature (eg. +2.8% and +1.4% against analyses at 250hPa at T+6 for height and temperature verification, respectively).

In the case of NOAA-20 impact of the assimilation on other instruments was found to be small with the main difference being a reduction in the number of SNPP CrIS observations assimilated because of NOAA-20 taking precedence in some cases as no priority was given to either satellite in the thinning. There was neutral impact on observations fit to background for MetOp-A and MetOp-B IASI, and SNPP ATMS.

3.2 DWD: ATMS Assimilation Experiments

At the DWD an assimilation experiment adding ATMS on NOAA-20 to the operational data setup (which includes ATMS on SNPP) was run covering the period 29 June to 14 September 2018. However, as the noise (diagnosed as standard deviation of O-B) of NOAA-20 ATMS was much worse than normal during the 2 July - 20 July 2018, only the period 20 July - 14 September 2018 was used in the verification. The observation errors were specified identically to the observation errors of ATMS on SNPP. The temperature sensitive channels were thinned to a distance of 160km. The ATMS channels are thinned together with the AMSU-A data, i.e. only one AMSU-A or ATMS observation for a given frequency is kept for assimilation in a 160km x 160km gridbox. Here, no priority is given to a particular instrument. The humidity sensitive channels are similarly thinned together with the MHS data. **Table 2** summarises the data selection criteria in the trial. Low peaking channels are not used in cloudy/rainy conditions based on a liquid water retrieval and threshold. Additionally, checks are done in the satellite radiance pre-processing based on scattering indices similar to bennartzrain and mwbcloudy used at the Met Office (see **Table 1**). Highland indicates orography above 1000m and data with a surface type mismatch between retrieval results (based on ATMS surface channels) and the model surface fields are also excluded. Of the five water vapour channels in the 183 GHz band only three (18, 20, 22) are currently used as inter-channel correlations of observation errors between the adjacent channels are not yet taken into account.

Table 2: ATMS channel selection at DWD

Flag/ATMS channel	6	7	8	9	10	11	12	13	14	15	18	19	20	21	22
Clear	+	+	+	+	+	+	+	+	+	+	+		+		+
Cloudy/Rain					+	+	+	+	+	+					
Sea	+	+	+	+	+	+	+	+	+	+	+		+		+
Seaice					+	+	+	+	+	+					
Land					+	+	+	+	+	+					
Highland						+	+	+	+	+					
Mismatch					+	+	+	+	+	+					

The assimilation trial results are summarized in **Figure 24** showing the relative difference of rms errors between the experiment adding the new NOAA-20 ATMS and the reference not using NOAA-20 but only the ATMS/SNPP data. The overall experiment results are neutral to slightly positive for the key parameters geopotential, temperature, humidity and wind. Some slightly negative impact is observed, e.g. in the tropics. In the DWD system the higher atmospheric fields in the tropics often react very sensitively to the addition of new radiance data which trigger complex dynamic feedback mechanism between the temperature and wind fields which has previously been analysed using GPS RO data (Faulwetter, 2015). It does not, however, adversely impact the forecast results in other areas and results for the NH and SH are mostly positive. The fit of the short range forecasts (background) to other observation systems is also unchanged or slightly improved (not shown). This small beneficial impact corresponds to expectations when adding an additional instrument of a data type already assimilated, giving mainly a slight improvement in horizontal data coverage.

4. Conclusions

The quality of the NOAA-20 ATMS and CrIS observations has been assessed against simulated observations from background model fields, and compared against the same statistics for the currently assimilated SNPP ATMS and CrIS data. As data validation versus NWP model fields inherently also includes uncertainty due to the model this has been done for two model systems, from the Met Office and DWD. In general, results at both centres show that both ATMS and CrIS on NOAA-20 have characteristics and data quality similar to those on SNPP if not slightly better in some aspects.

NOAA-20 ATMS data are of very good quality generally. Biases and standard deviations of uncorrected and corrected data are similar, if not slightly smaller for the new ATMS instrument compared to ATMS on SNPP. Also, the scan bias patterns are very comparable. Close inspection of data along the overpass reveals that 'striping' which was detected for ATMS/NOAA-20 is not as strong in ATMS/SNPP data. Additionally, assimilation impact trials both at the Met Office and at DWD result in neutral to slightly positive impact despite the data covering largely the same geographical areas as the existing SNPP data so that the added data amounts are relatively small. The direct main benefit is to improve the resilience of the vital ATMS data, guarding against the possibility of failure of SNPP. Additionally, further work in tuning assimilation systems and increasing the data amounts used in various conditions will further enhance the impact

The NOAA-20 CrIS data are also of very similar quality to SNPP CrIS data with smaller or comparable O-B mean and standard deviation statistics. The global coverage after quality control procedures is improved by the inclusion of NOAA-20 CrIS. The forecast impact experiments at the Met Office show that the assimilation of NOAA-20 CrIS observations gives a generally neutral forecast impact, with the strongest positive impact seen early in the forecast for NH geopotential height and temperature. Also, there is a 2% improved fit of SNPP CrIS observations to background, but a 40% reduction in count number (because of the assimilation of additional CrIS data), and a neutral impact on observations fit to background for MetOp-A and MetOp-B IASI, and SNPP ATMS.

Data timeliness monitoring shows that the ATMS and CrIS data from NOAA-20 have shorter dissemination delays than the corresponding SNPP data, with about 97% arriving within the first hour after observation time. This makes them an extremely useful addition to the observing system suitable even for operational applications with more stringent cut-off times.

Current monitoring results for ATMS and CrIS on NOAA-20 are provided through the NWP SAF web site. For up to date statistics for timeliness as well as additional timeliness and data coverage plots, please consult https://www.nwpsaf.eu/site/monitoring/nrt-availability/ . Likewise, please refer to the near-real time data quality monitoring https://www.nwpsaf.eu/site/monitoring/nrt-monitoring/ for up to date data quality monitoring results versus different NWP models.

5. References

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6. Figures

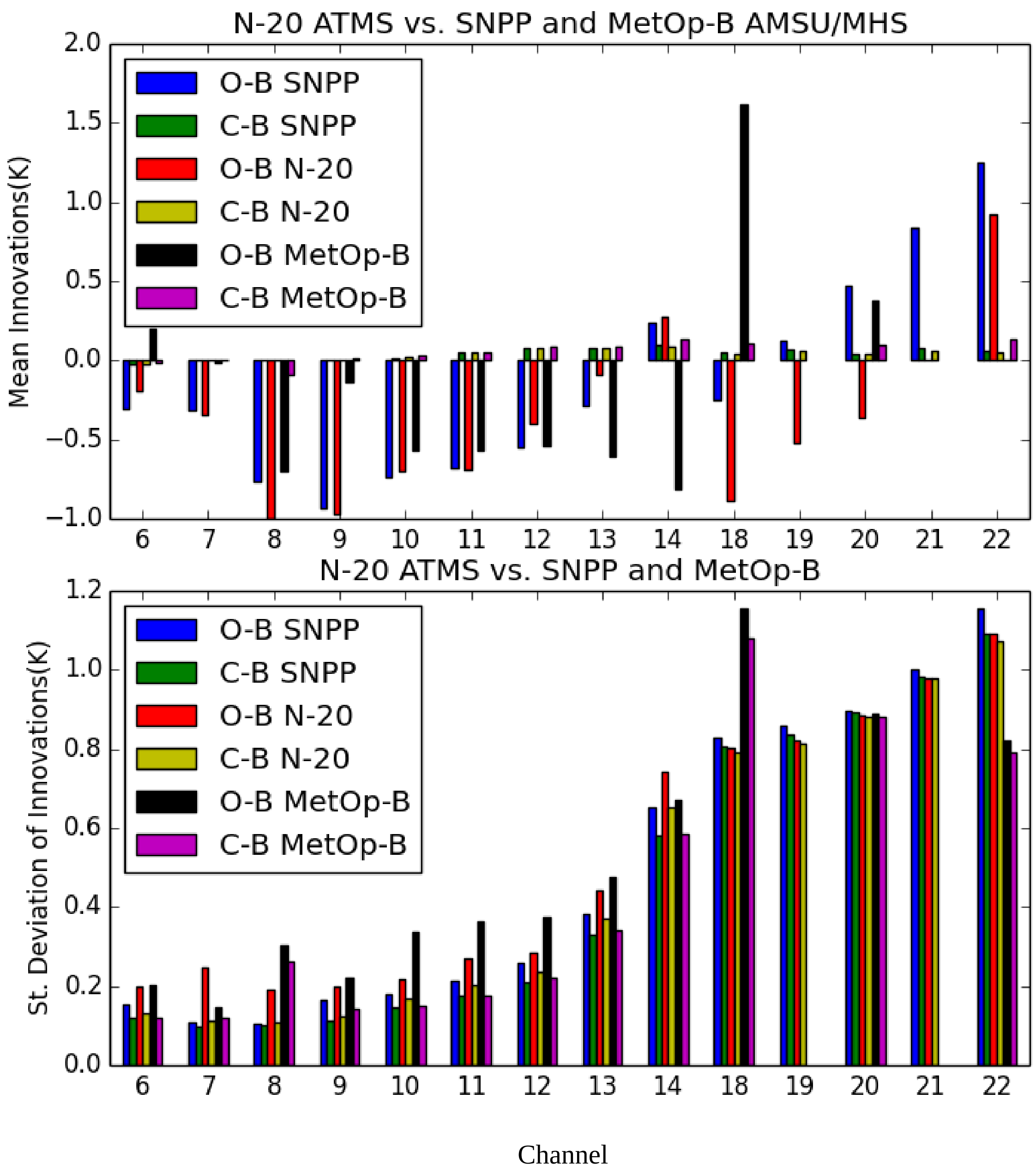

Figure 1: Met Office results for ATMS and AMSU-A mean (top) and standard deviation (bottom) of uncorrected and corrected departures O-B for August 2018 as global average.

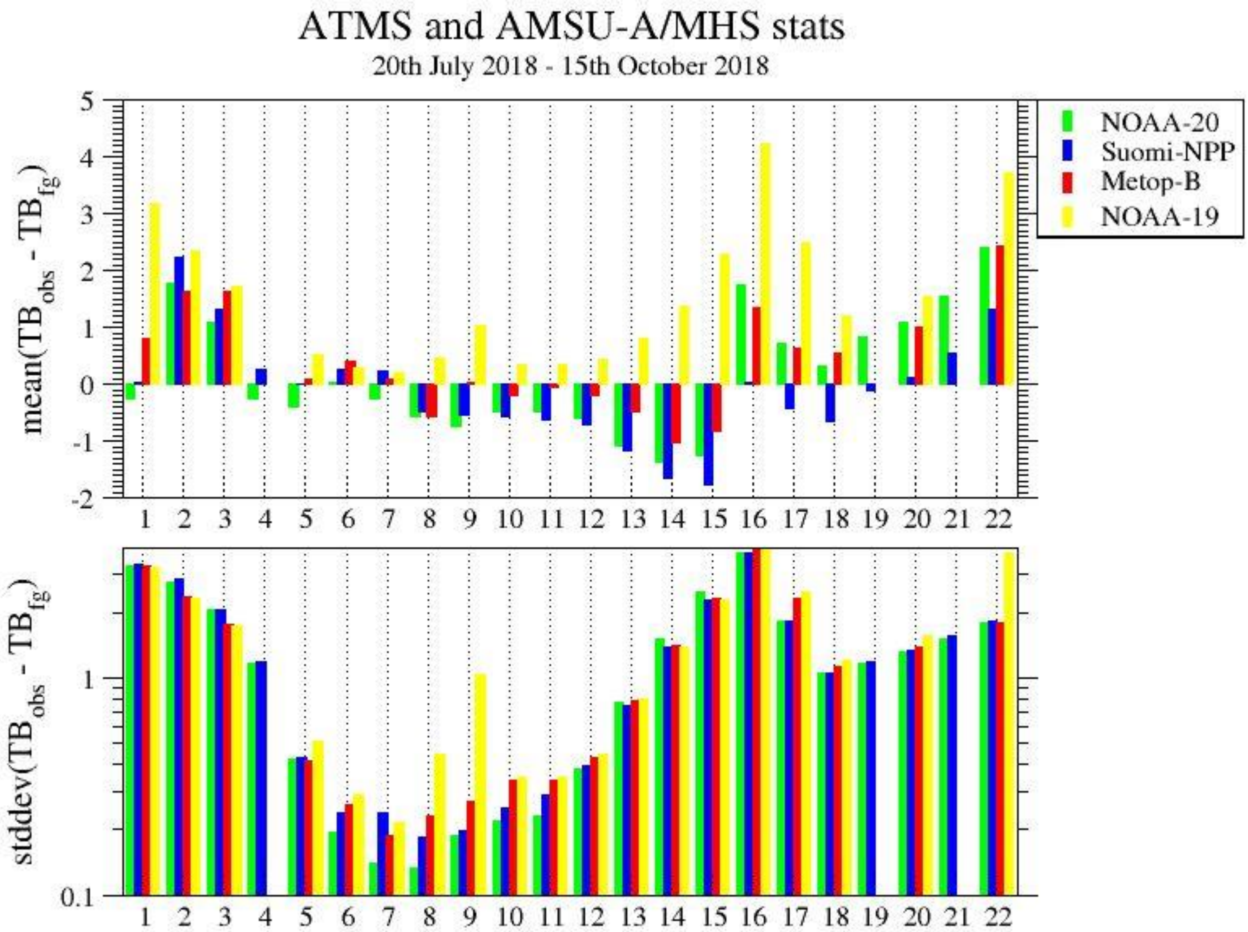

Figure 2: DWD results for ATMS and AMSU-A and MHS mean (top) and standard deviation (bottom) of uncorrected departures O-B for 20 July-15 October 2018 as global average. Green is NOAA-20 ATMS, blue is SNPP/JPSS0 ATMS, red is MetopB AMSU-A and MHS and yellow is NOAA-19 AMSU-A and MHS, as in Figure 1. MHS channels are compared to corresponding ATMS frequencies. Note that the y-scale for brightness temperature differences and standard deviations in [K] is logarithmic.

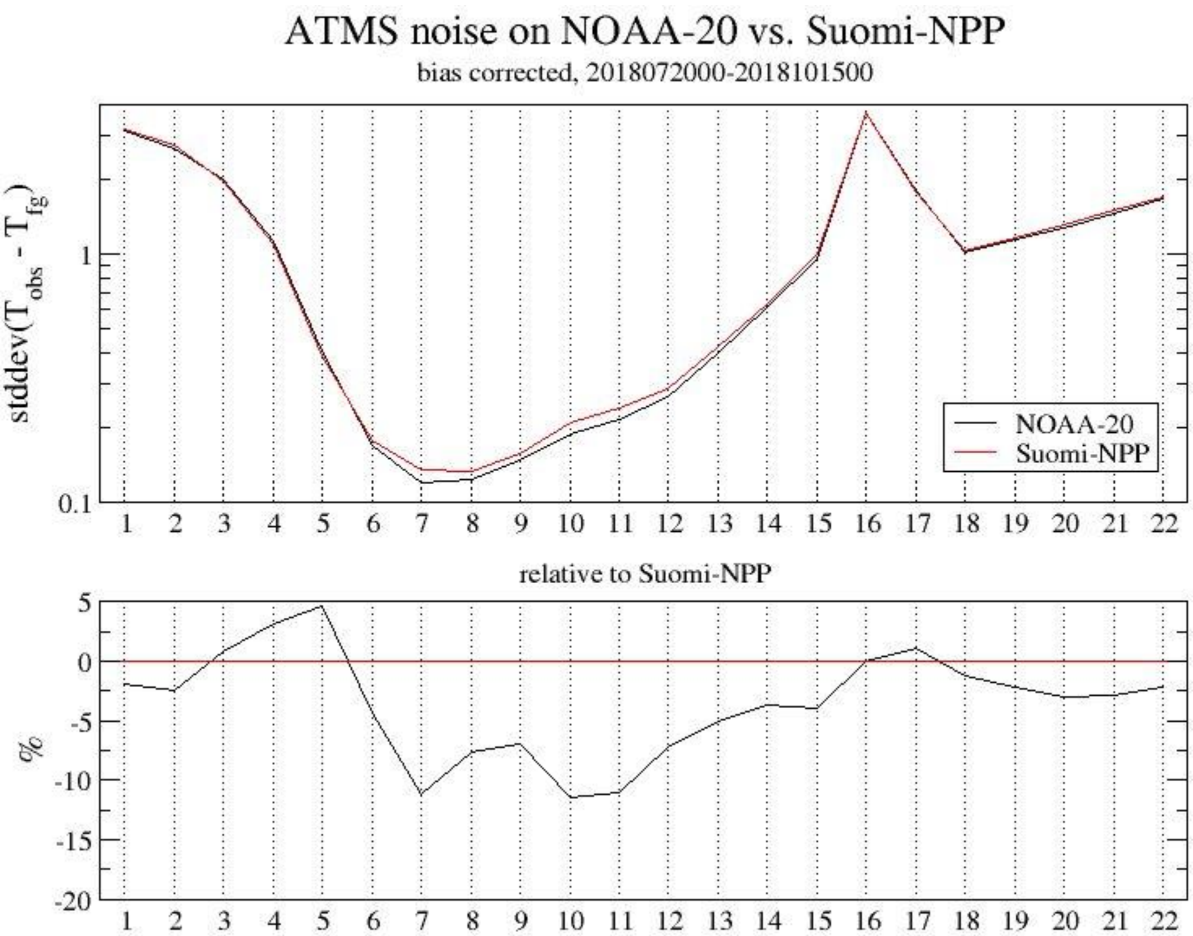

Figure 3: DWD results: ATMS standard deviation of bias corrected departures O(corrected)-B for 20 July-15 October 2018 for ATMS/SNPP (red) and ATMS/NOAA-20 (black). Top: Standard deviations in [K], bottom: difference of NOAA-20 and SNPP relative to SNPP in [%].

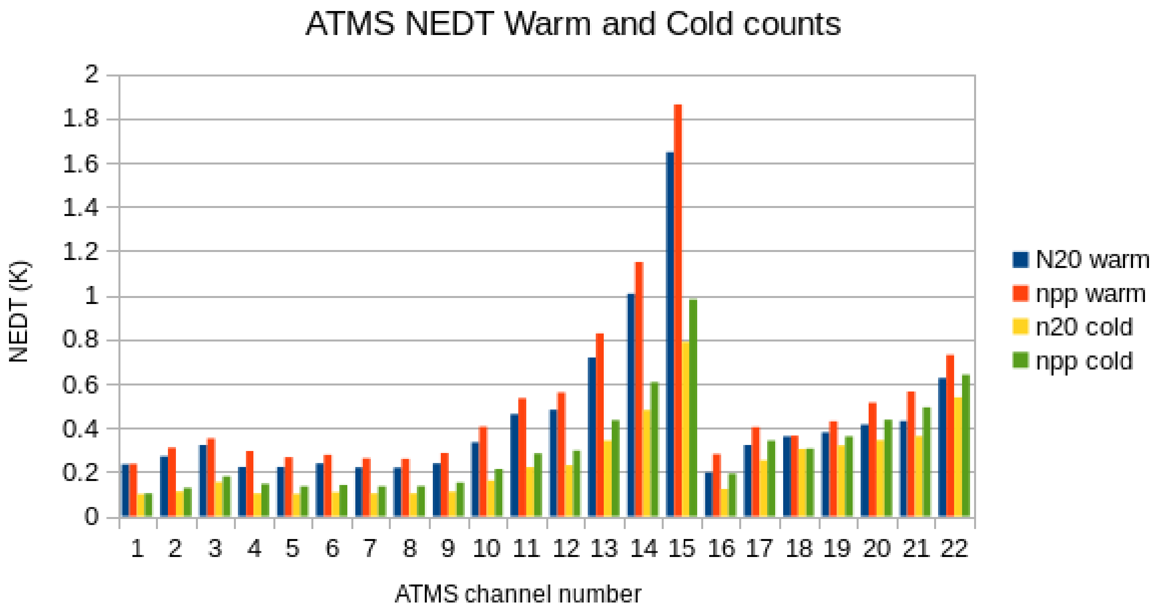

Figure 4*:* Noise characteristics for ATMS channels averaged over the period 20/02/18 – 03/07/18.

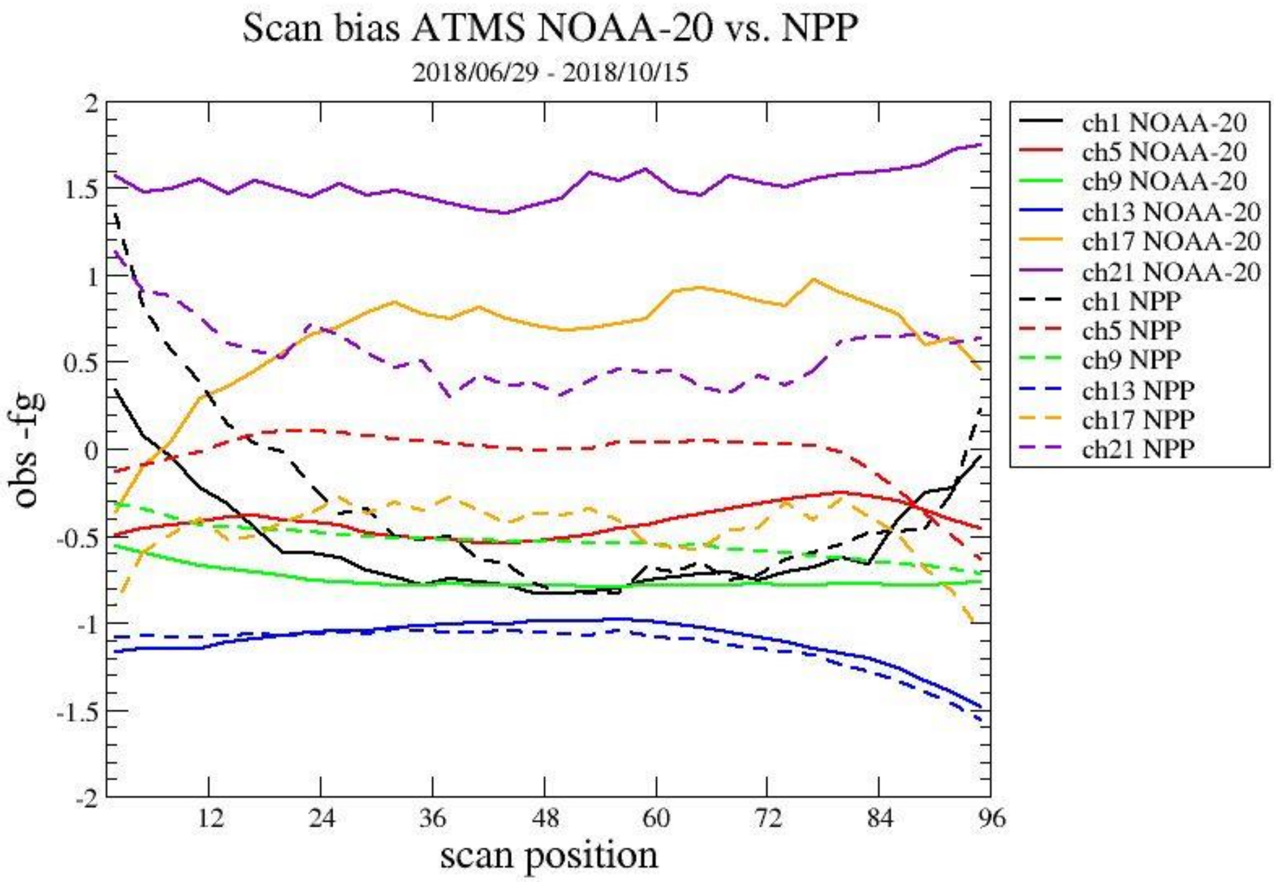

Figure 5: Global averages of observation minus background departures as a function of scan position for the period 20 July-15 October 2018 for ATMS/SNPP (dashed lines) and ATMS/NOAAN-20 (solid lies) for selected channels based on the DWD monitoring results.

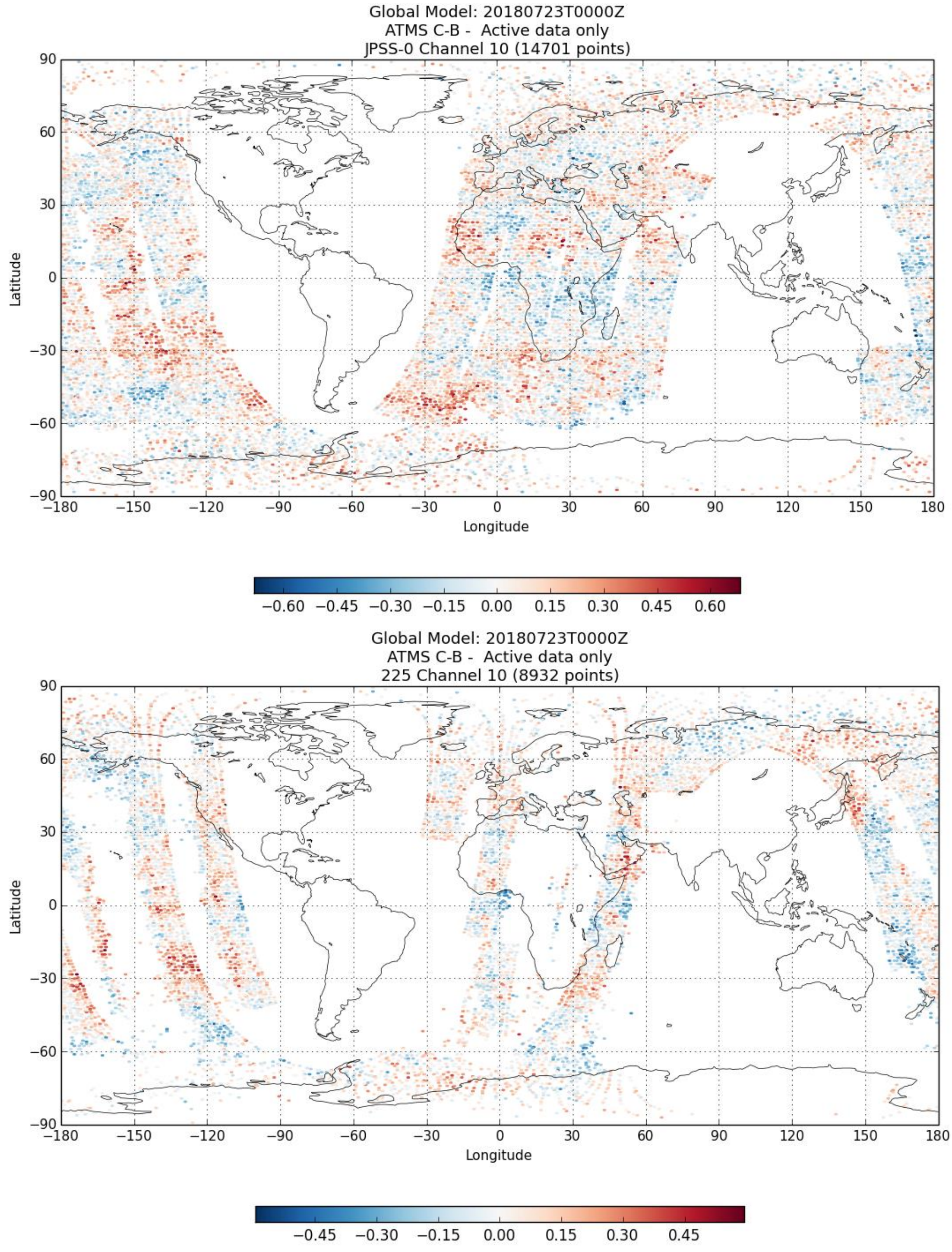

Figure 6: ATMS channel 10 (SNPP top and NOAA-20 bottom) C-B maps for the Met Office 0Z update run on 23rd Jun 2018.

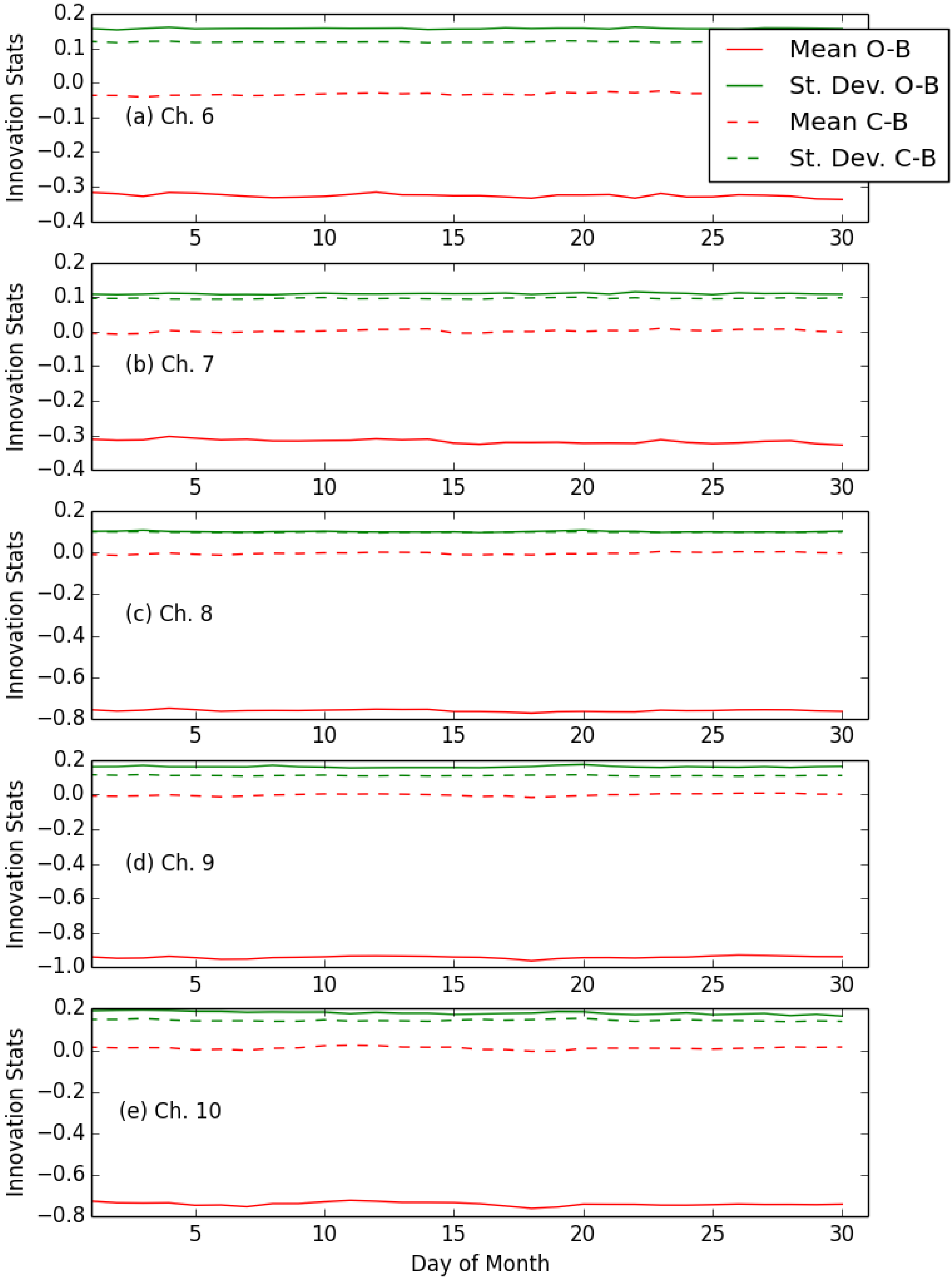

Figure 7: Timeseries of uncorrected and corrected mean and standard deviation of Met Office O-B's for NOAA-20 ATMS Channels 6 to 10 for the month of August 2018. Means and standard deviations are shown in red and green respectively, while the solid line represents the uncorrected values and the dashed line, the corrected values of O-B.

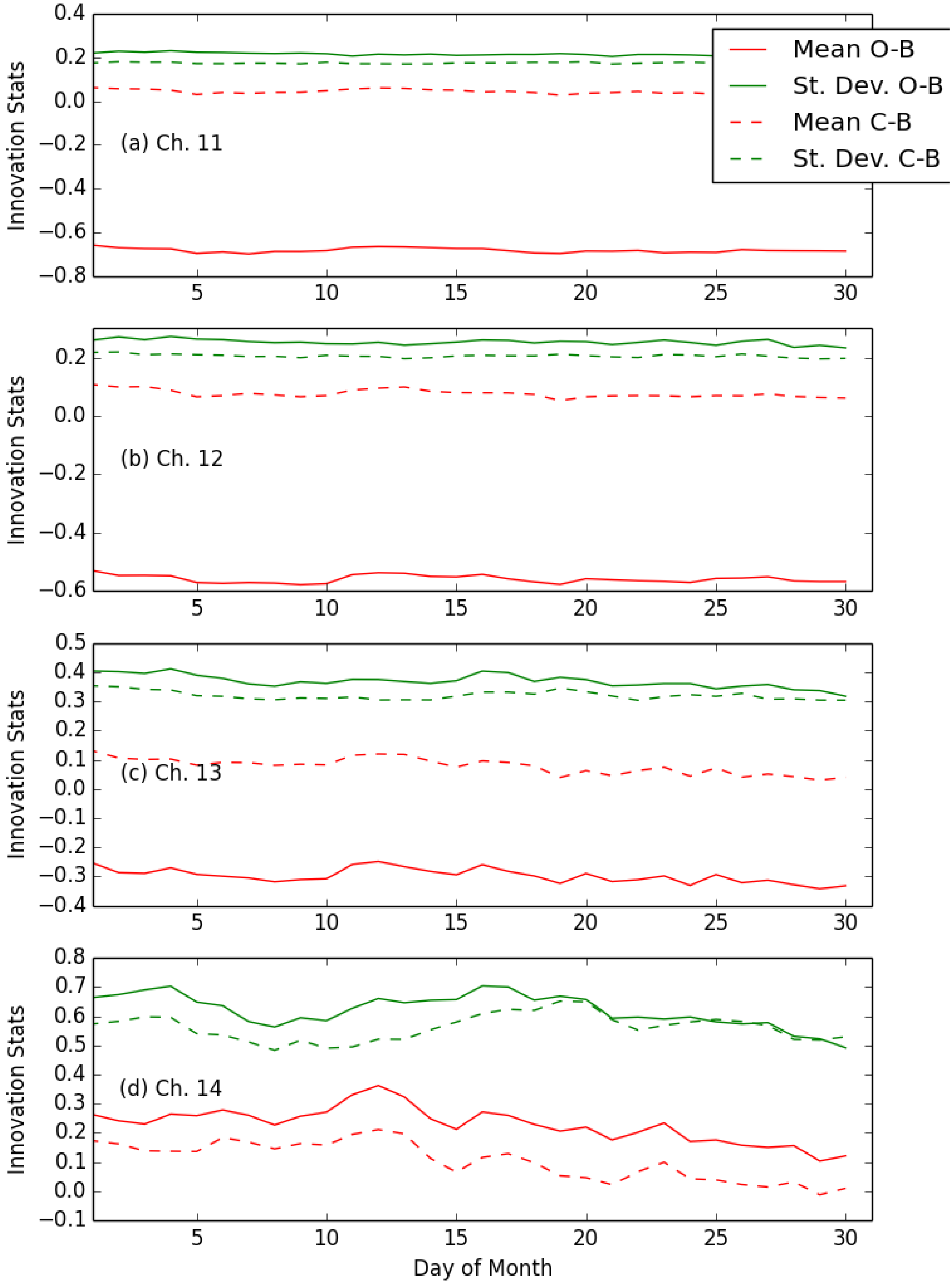

Figure 8: As Figure 7 but for Channels 11-14.

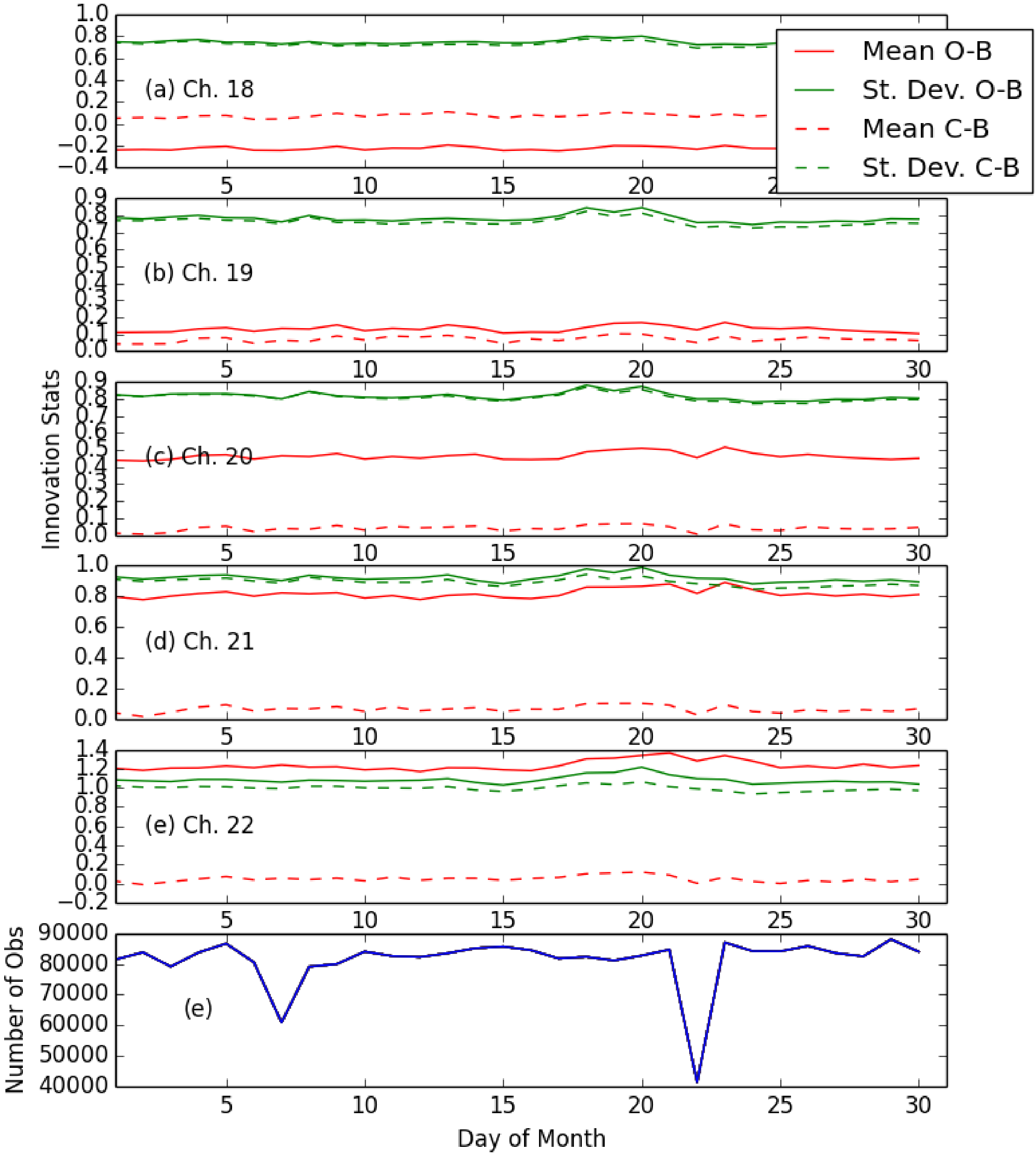

Figure 9: As Figure 7 but for Channels 18-22. Panel (e) shows the number of observations assimilated.

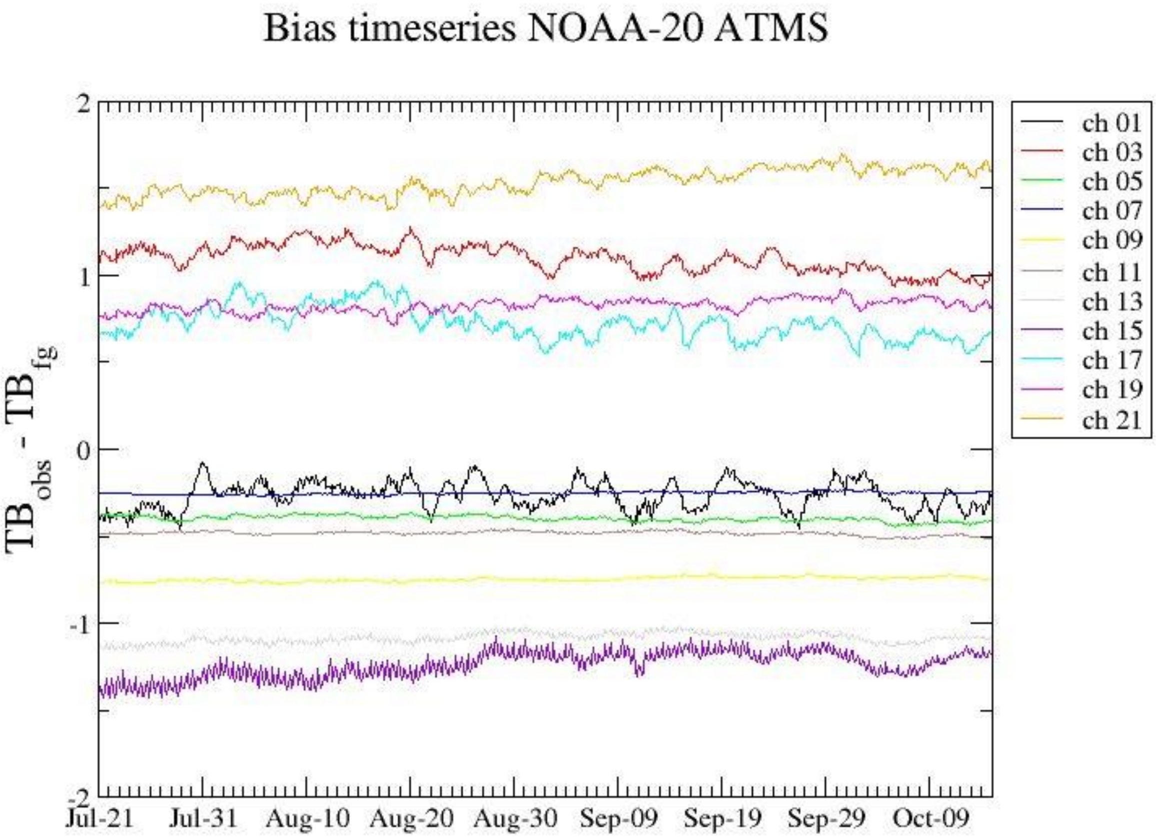

Figure 10: Timeseries of daily and globally averaged mean differences of uncorrected brightness temperatures versus background (O-B) in [K] for the period 20 July to 15 October 2018 from the DWD monitoring for selected channels.

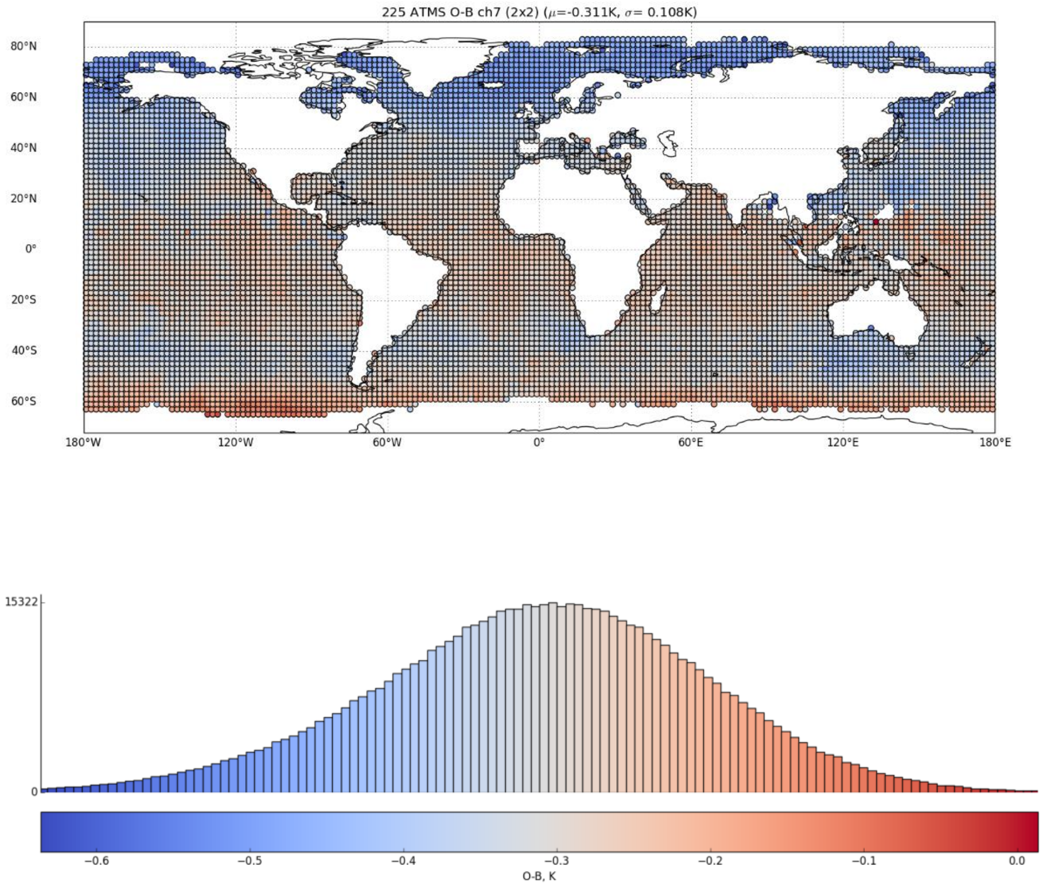

Figure 11: Met Office mean uncorrected O-B for the month of August 2018 for NOAA-20 ATMS Channel 7. Spatial means are aggregated on a 2° by 2° grid. The histogram and the colour scale are shown in the bottom panel.

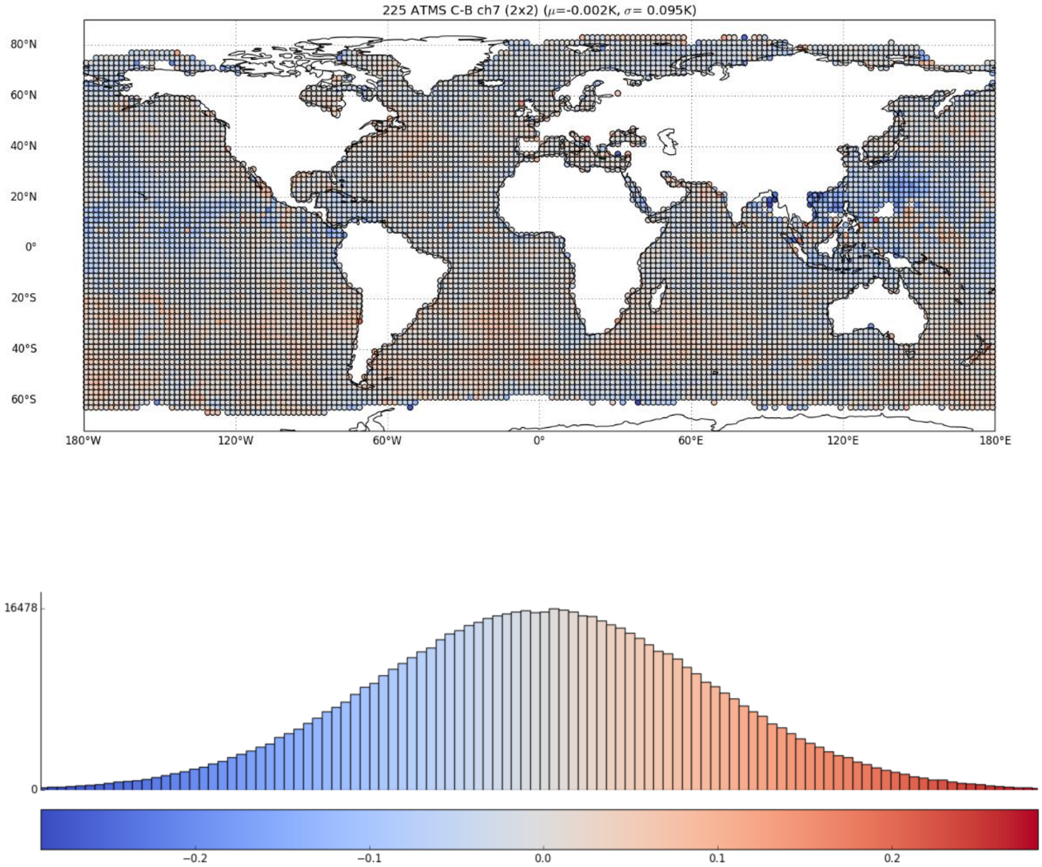

Figure 12: As Figure 11 but for corrected O-B's.

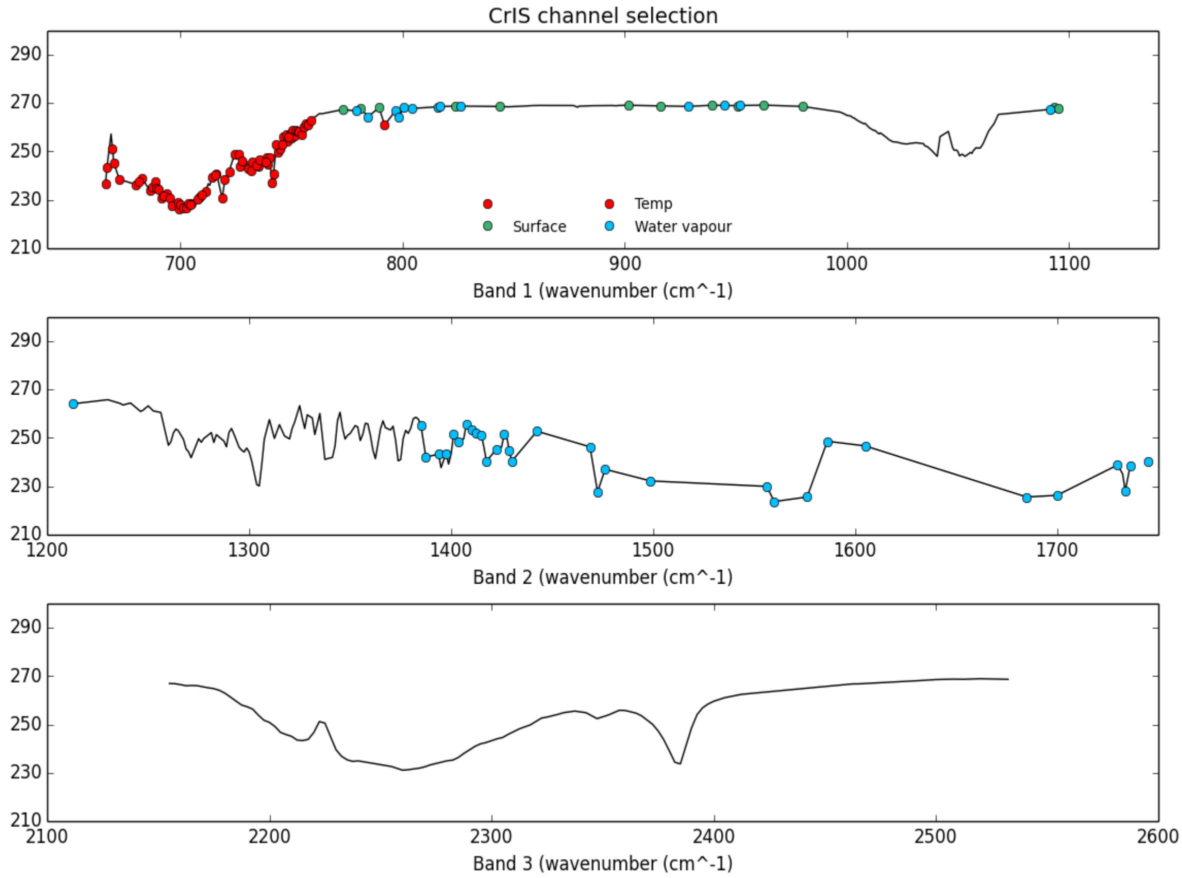

Figure 13: Typical CrIS spectrum with channel selection (127 channels) at the Met Office: 74 temperature (red), 40 water vapour (blue) and 13 surface channels (green).

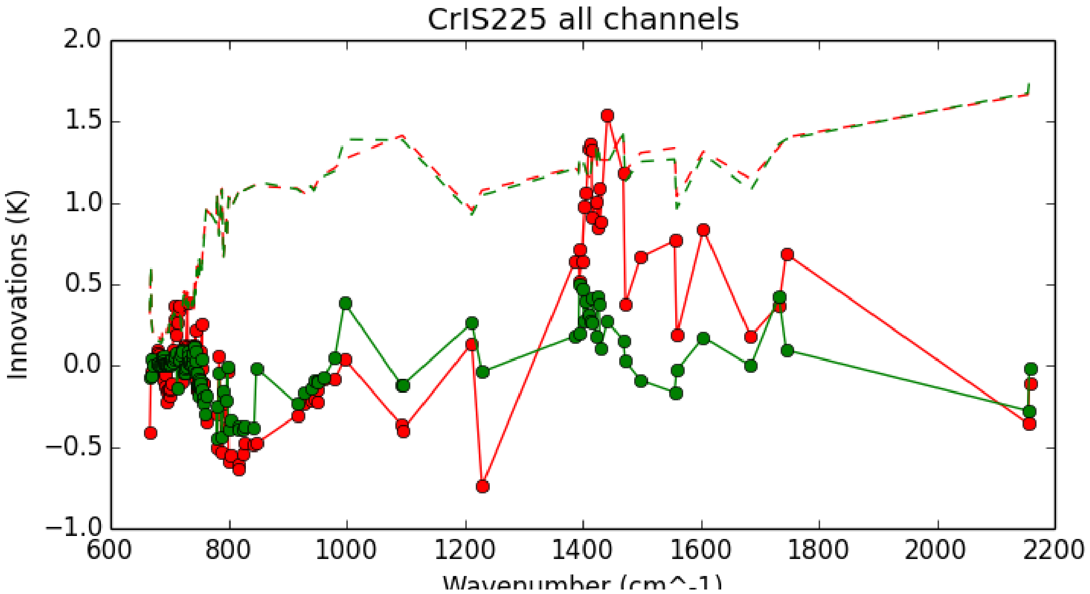

Figure 14: Mean (solid) and standard deviation (dashed) O-B (corrected in green and uncorrected in red) for NOAA-20 CrIS from the Met Office's operational system.

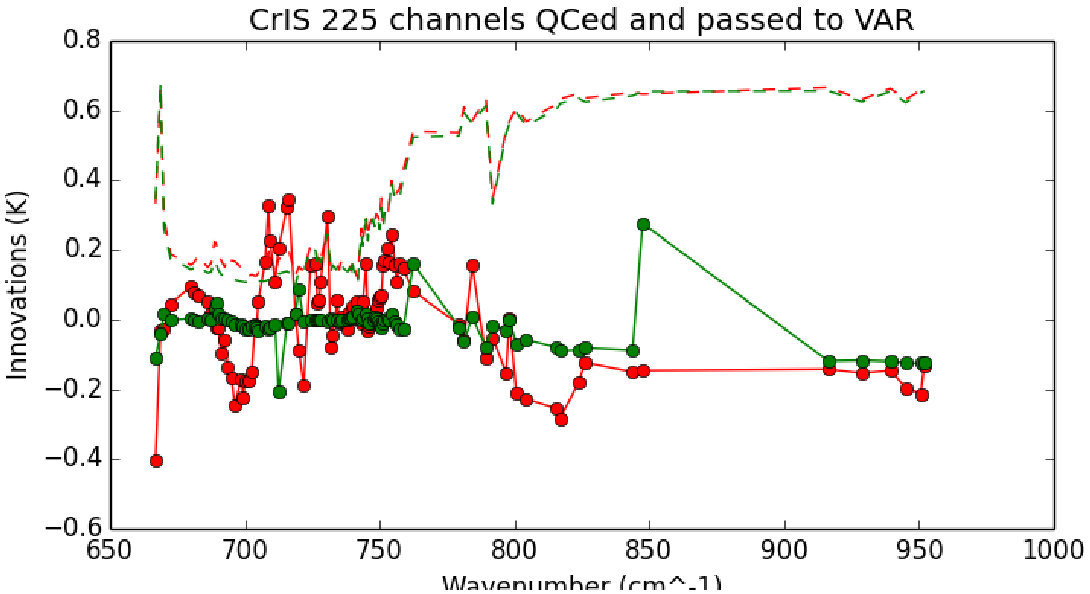

Figure 15: Mean and standard deviation O-B (corrected in green and uncorrected in red) for NOAA-20 CrIS from the Met Office's operational system after quality control.

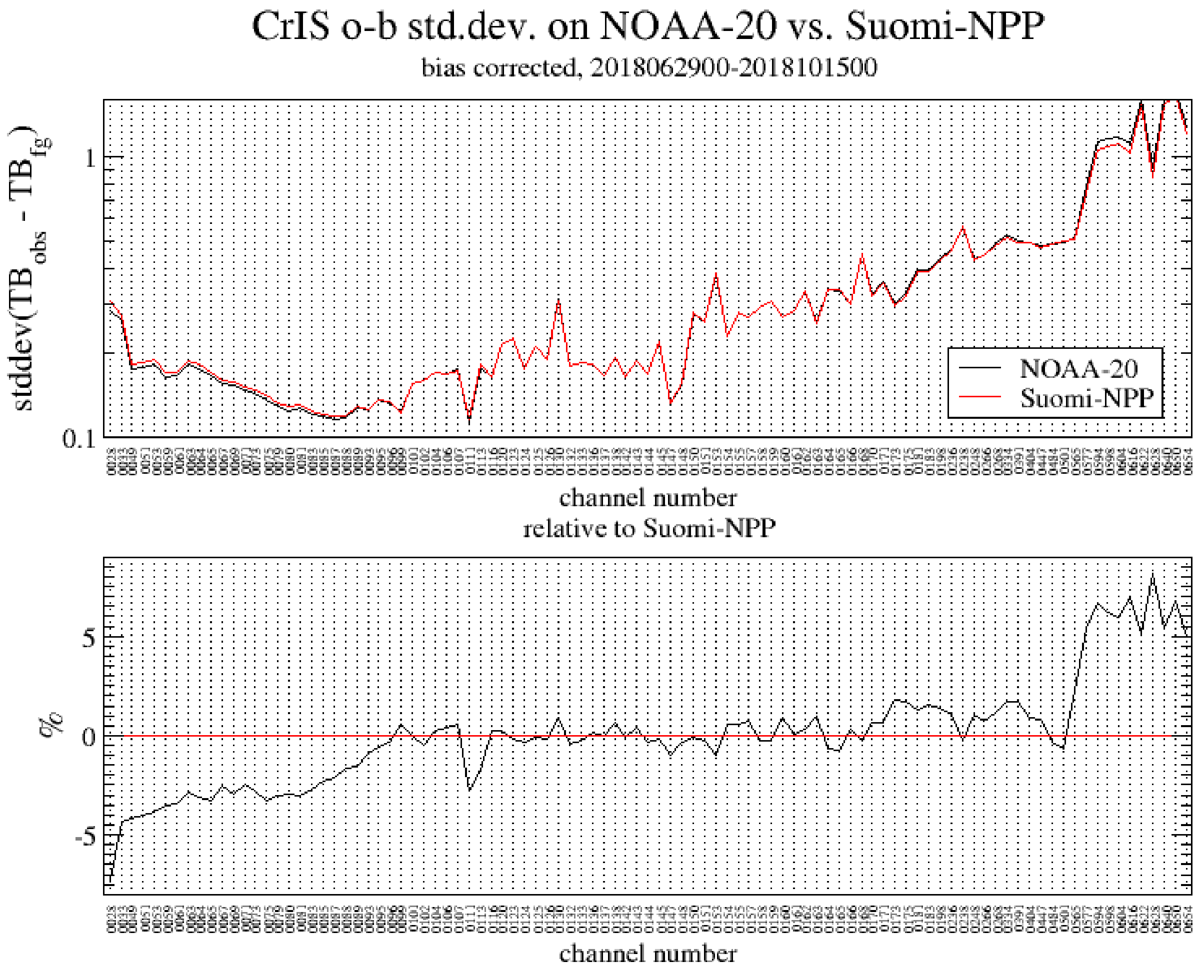

Figure 16: DWD results of CrIS monitoring showing the standard deviation of bias corrected departures O(corrected)-B for 20 July-15 October 2018 for SNPP (red) and NOAA-20 (black). Top: Standard deviations in [K], bottom: difference of CrIS/NOAA-20 and CrIS/SNPP relative to CrIS/SNPP in [%]. The spectral wavenumber range corresponding to the indicated channel numbers extends from 666.9 cm-1 to 1058.1 cm-1.

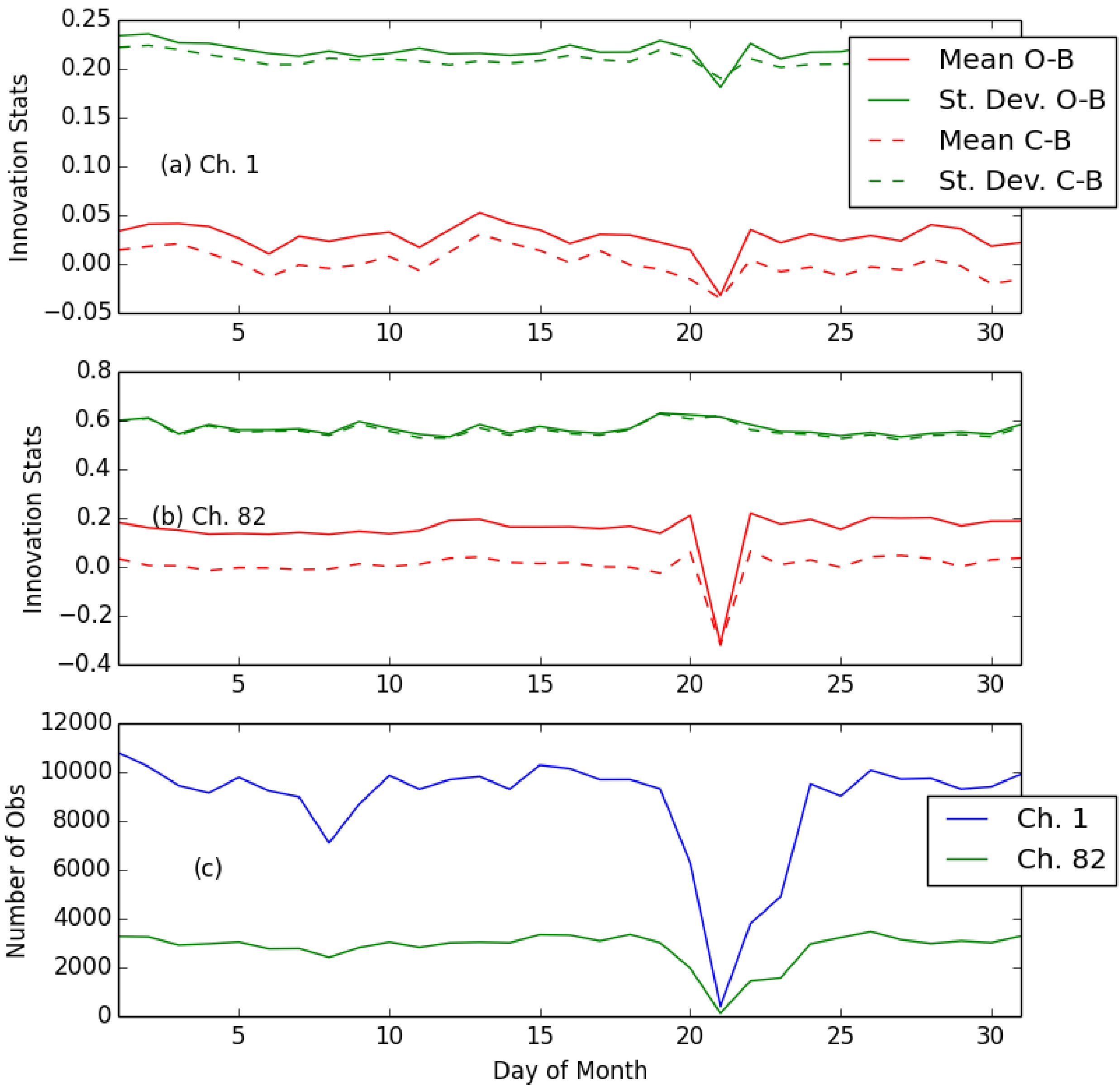

Figure 17: Met Office time series of global O-B's for CrIS channels 1 and 82 for the month of August 2018.

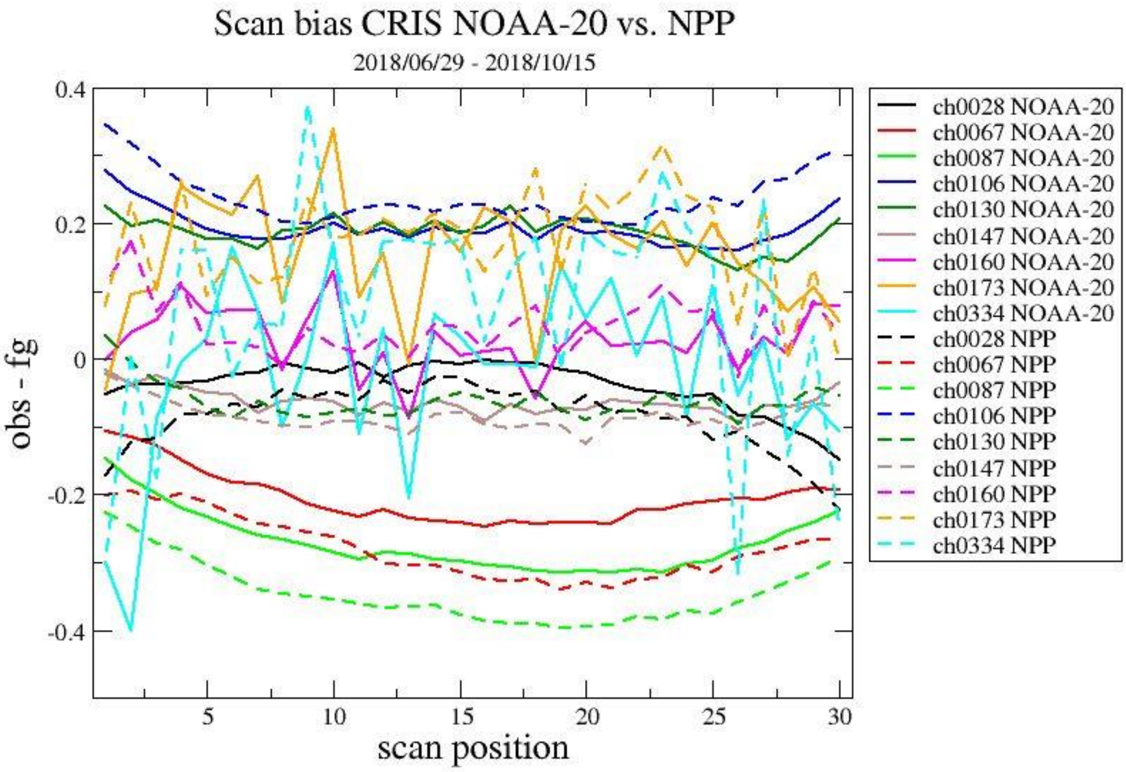

Figure 18: Averages of globally averaged departures O-B as a function of scan position for the period 29 June-15 October 2018 for CrIS/SNPP (dashed lines) and CrIS/NOAA-20 (solid lies) for selected channels based on the DWD monitoring results.

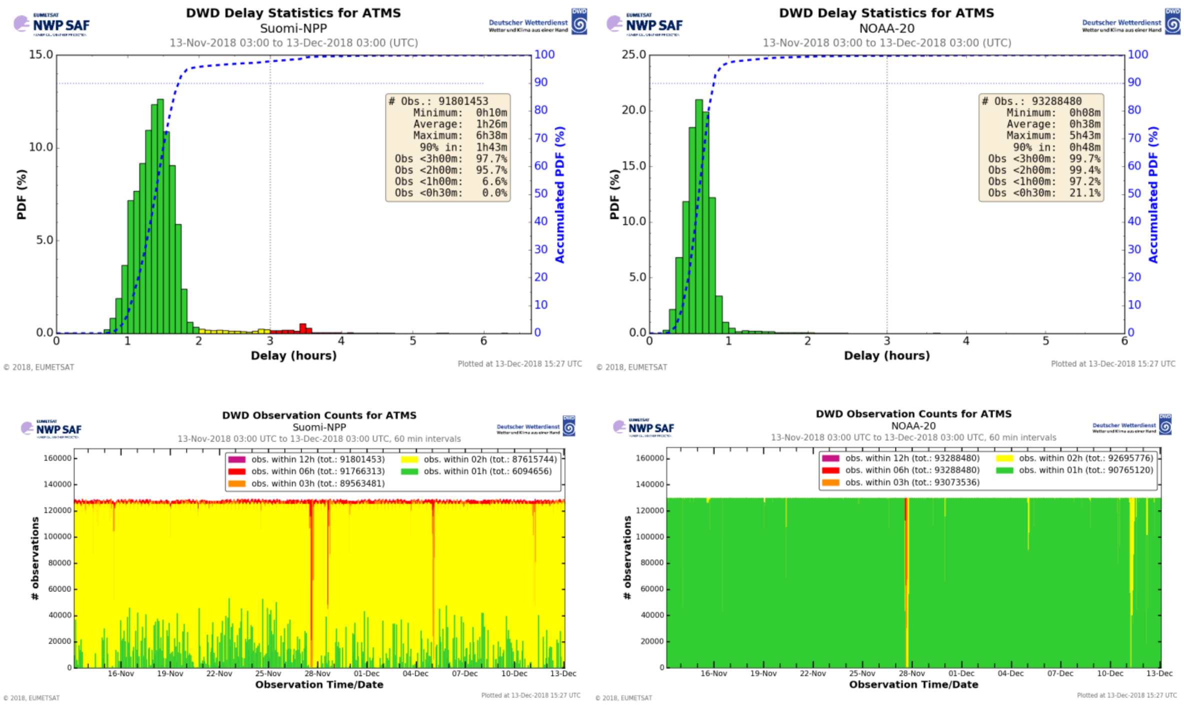

Figure 19: Timeliness statistics for ATMS on SNPP (left panels) and NOAA-20 (right panels) for the one month period 13 November to 13 December 2018 from DWD monitoring. Top panels: Normalized histograms of number of data arriving as a function of time delay (difference between observation time and archive entry time). Bottom panels: Timeseries of number of data arriving with a delay lower than selected timeliness thresholds (1, 2, 3, 6, 12 hours); the total number of data arriving within the thresholds over the monthly period are given as nmbers.

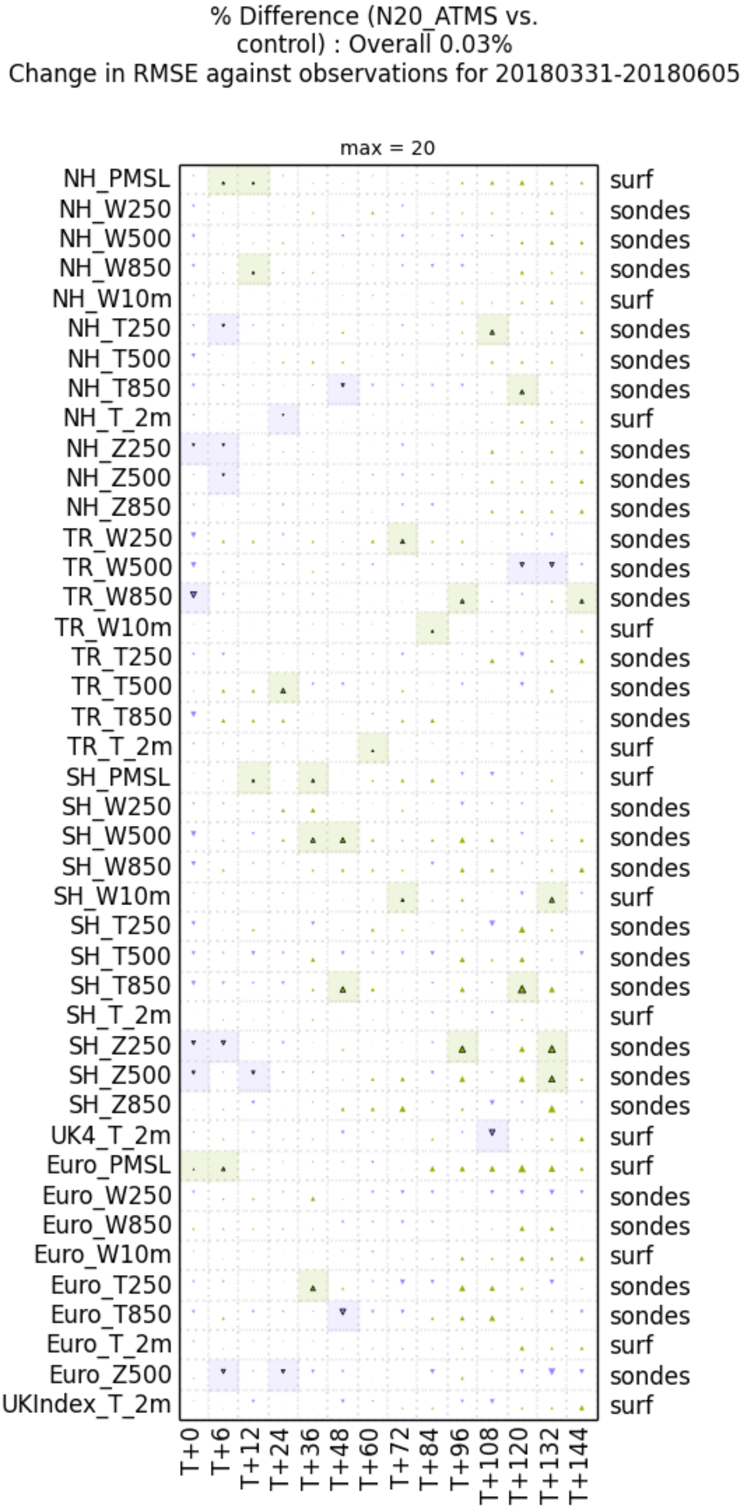

Figure 20: Results from ATMS/NOAA-20 data impact trial at Met Office showing mean RMS change and change in weighted skill for observations for the near real-time trial with the addition of NOAA-20 ATMS (25 April – 6 June 2018).

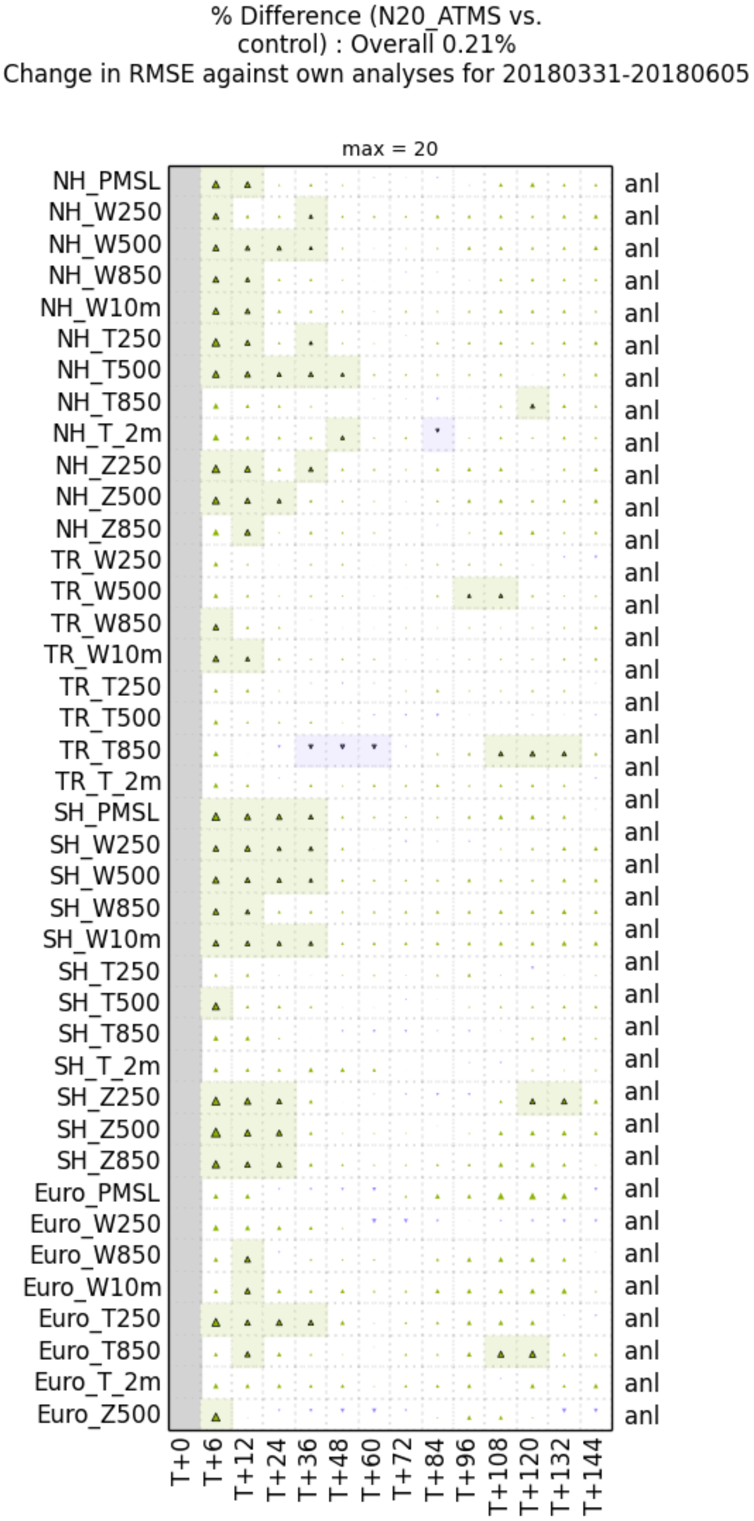

Figure 21: Results from ATMS/NOAA-20 data impact trial at Met Office showing mean RMS change and change in weighted skill for own analysis for the near real-time trial trial with the addition of NOAA-20 ATMS (25 April – 6 June 2018).

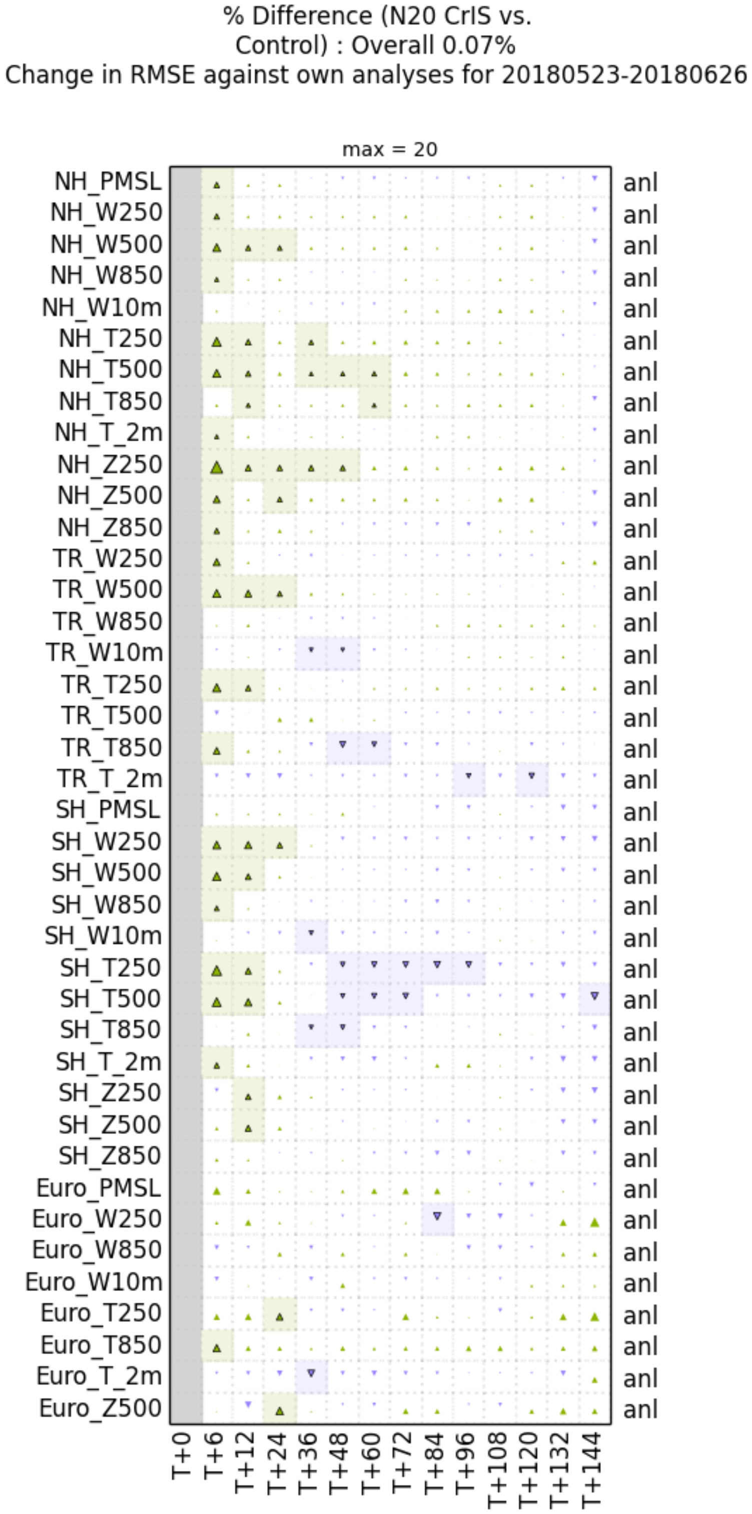

Figure 22. Results from CrIS/NOAA-20 data impact trial at Met Office showing mean RMS change and change in weighted skill against own analysis for the near real-time trial of the introduction of NOAA-20 CrIS (18 May - 1 July 2018).

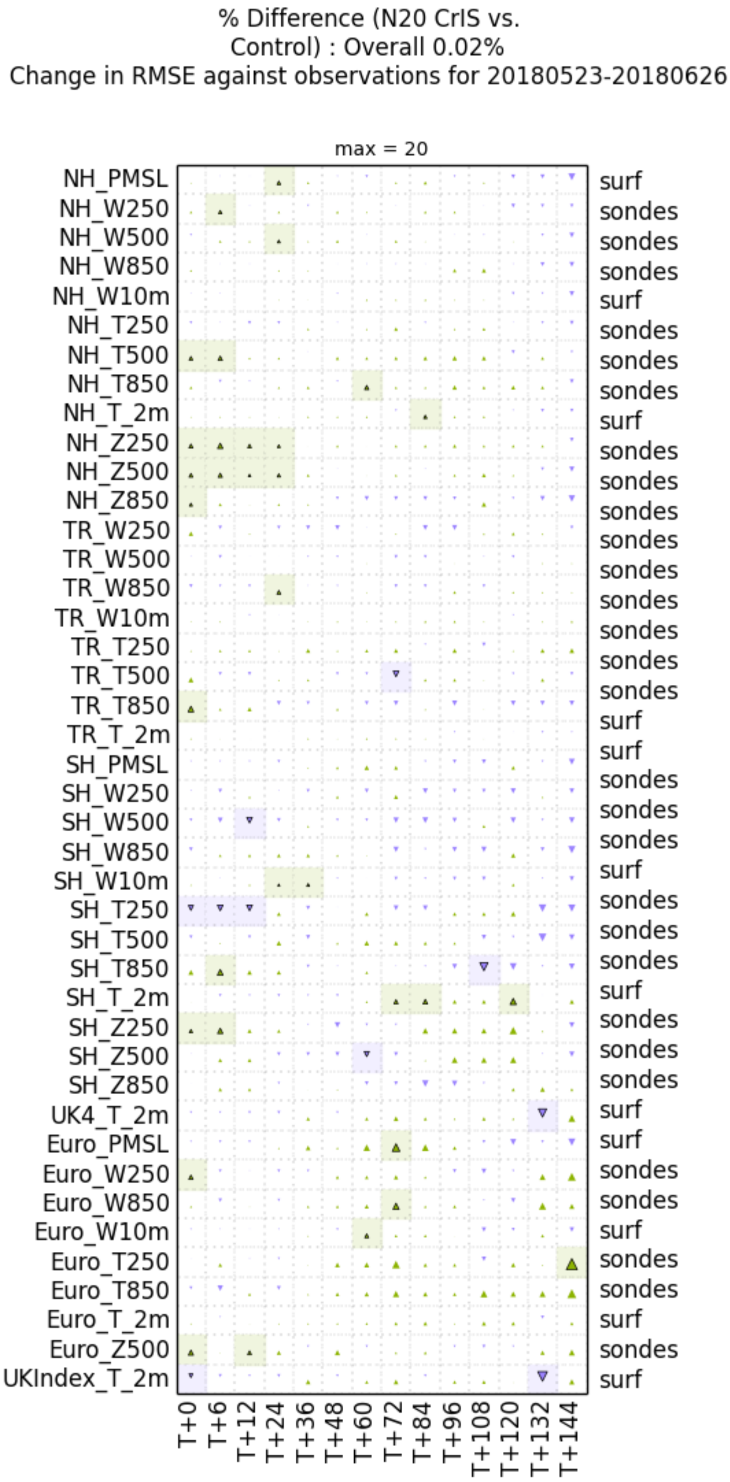

Figure 23. Results from CrIS/NOAA-20 data impact trial at Met Office showing mean RMS change and change in weighted skill against observations for the near real-time trial of the introduction of NOAA-20 CrIS (18 May - 1 July 2018).

Figure 24. Summary of assimilation results for the experiment adding ATMS/NOAA-20 data (Exp 10616) to the reference setup (Exp 10615) including only ATMS/SNPP data from DWD trial. The scores shown are differences of rms (forecast versus own analyses) relative to the reference as mean profiles versus forecast time (ranging from 24-168 hours) for different parameters (columns) and areas (rows) averaged over the period 20 July – 10 September 2018.