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Prospects for improving AMV spatial coverage between geostationary and polar AMVs: LeoGeo and Dual-Sentinel

Francis Warrick and Niels Bormann

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Abstract

Historically there has been a gap in spatial coverage between AMVs provided from polar-orbiting satellites and geostationary satellites. In the use of AMVs at ECMWF, this has partly been filled with Dual-Metop AMVs from EUMETSAT and by accepting geostationary AMVs from higher zenith angles. Here we examine LeoGeo AMVs from CIMSS and Dual-Sentinel AMVs from EUMETSAT which both provide additional AMV data in the gap region. Our evaluation in the ECMWF system finds that the LeoGeo AMVs had very small background departure statistics but assimilation experiments showed some negative effects on the model geopotential height field. Dual-Sentinel AMVs showed similar departure statistics to the Dual-Metop AMVs, demonstrated a largely neutral result when assimilated in addition to Dual-Metop, and a positive result when assimilated in the absence of Dual-Metop.

1 Introduction

AMVs are usually derived by tracking features in either successive geostationary images or in the overlapping region of successive polar orbiter images. Historically, this has left a gap in the spatial coverage of AMVs around 50-60° latitude, between the geostationary and polar data.

In operational assimilation of AMVs at ECMWF, this gap is partly filled by the use of the EUMETSAT Dual-Metop AMVs, which track features between images from different Metop satellites. Operational assimilation started in 2016 following successful assimilation experiment results. The gap was further filled by relaxing the maximum zenith angle assimilated for geostationary AMVs from 60° to 64° [5].

Two new AMV datasets offer the possibility of further improving AMV coverage in the gap region. The first, Dual-Sentinel AMVs from EUMETSAT, track cloud features between pairs of Sentinel-3A and 3B SLSTR images. The second, LeoGeo AMVs provided by CIMSS[1] are derived by tracking features in composite geostationary-polar images that span the coverage gap.

This report describes, for each product, the quality of the data in terms of background departure statistics, details of assimilation experiments, and discussion of the experiment results.

2 Dual Sentinel-3 SLSTR AMVs

The derivation of this product is similar to EUMETSAT's Dual-Metop product, which uses image pairs from Metop-B and Metop-C (and Metop-A until 2021), but with one Sentinel-3A and one Sentinel-3B image [1]. The tracking is performed using SLSTR's 10.85 μm thermal infrared channel using only the instrument's nadir view, not the oblique view. There is no water vapour channel available on SLSTR or AVHRR. Visible imagery is available however this is not used due to poor contrast with snow and ice covered surfaces, height assignment difficulties and lack of sunlight (R. Borde, personal communication). As with other polar AMVs, model information must be used in the Dual-Sentinel tracking to predict where the tracer will have moved to. This is because, due to the longer time interval between overlapping polar images compared to overlapping geostationary images, the tracking solution is too ambiguous and likely to result in a false match if the search is not guided by model information. A quality indicator (QI) is provided with each wind vector, based on the consistency of the wind vectors derived from forward and reverse tracking between the image pair.

[1] Cooperative Institute for Meteorological Satellite Studies Space Science and Engineering Center / University of Wisconsin-Madison

The lack of a water vapour channel is a limitation for the height assignment as it means the water vapour intercept method cannot be used to avoid placing cirrus at too low a height. The height assignment method is generally the same as for Dual-Metop and includes a temperature inversion correction. The cross-correlation contribution (CCC) method is used to select pixels for the height assignment step based on their contribution to the tracking step.

A test dataset of Dual-Sentinel AMVs was provided by EUMETSAT. The data distribution follows a similar pattern for Dual-Sentinel and Dual-Metop (Figure 1). The main difference is the narrower swath width of the Sentinel-3 SLSTR instrument which is 1,420km [1] compared to Metop AVHRR's 2900km. This leads to a reduced density of data overall and limits AMV derivation in the tropics. This is also why only a dual Sentinel product is available, a single product is not viable due to the limited overlap between Sentinel-3A and 3B swaths. The nadir resolution of the 10.8 μm channel is the same on both SLSTR and AVHRR at 1 km. There are some strange features in the Sentinel data distribution, such as AMVs erroneously assigned a pressure of zero. Near the north pole there are some AMVs close to the surface with pressures greater than 950 hPa. This is known to be due to the different cloud masks available to SLSTR compared to AVHRR. To ensure all cloudy situations are tracked an SLSTR pixel is considered cloudy if any one of the cloud detection tests is passed (K. Barbieux, personal communication), whereas for AVHRR a majority of the tests must be cloudy. The order of the satellites used in the tracking affects the spatial coverage: A/B Dual-Sentinel coverage extends to the equator and has more data in the gap region than the B/A data, which just covers the polar regions.

Background departure statistics in terms of root-mean-square vector differences, as well as mean wind speed differences, are similar between the Dual-Metop and Dual-Sentinel products (Figures 2, 3). Both datasets show relatively large RMSVDs for AMVs below 900 hPa at northern mid and high latitudes, possibly a result of height assignment difficulties over very cold surfaces. As noted before, this affects more AMVs in the Sentinel-3 dataset at high latitudes due to the different use of the cloud mask noted earlier. The mean speed differences in the tropics, for pressure less than 400 hPa, are positive in both products, this has previously been linked to viewing tall clouds from high zenith angles [7] among other factors. In the main region of interest for these data (40-60°N/S, 400-700 hPa), the mean speed differences are similar in the southern hemisphere and slightly smaller in Dual-Sentinel in the northern hemisphere.

The Sentinel AMVs can be separated into those where the first image used in the tracking originates from Sentinel-A and those where it's from Sentinel-B. Over the latitudes covered by both, departure statistics were found to be similar between the two.

By comparing assigned AMV pressures to the model pressure at which the AMV-minus-model wind vector difference is minimised, we can estimate the quality of the AMV height assignment. Figure 4 shows that the best-fit pressure differences are slightly higher in the Dual-Sentinel AMVs than the Dual-Metop AMVs for the gap and polar regions. For the lowest-height Dual-Sentinel AMVs this is likely due to the cloud mask issue mentioned earlier. Although some of the best-fit pressure differences in Figure 4 are rather large, these uncertainties in the AMV height assignment can be compensated for in the AMV error scheme used in the IFS by assigning large height errors to such AMVs. The IFS AMV observation error scheme assigns a larger wind error when the local model wind shear is larger, since in these cases the negative consequences of an incorrect height assignment are more severe.

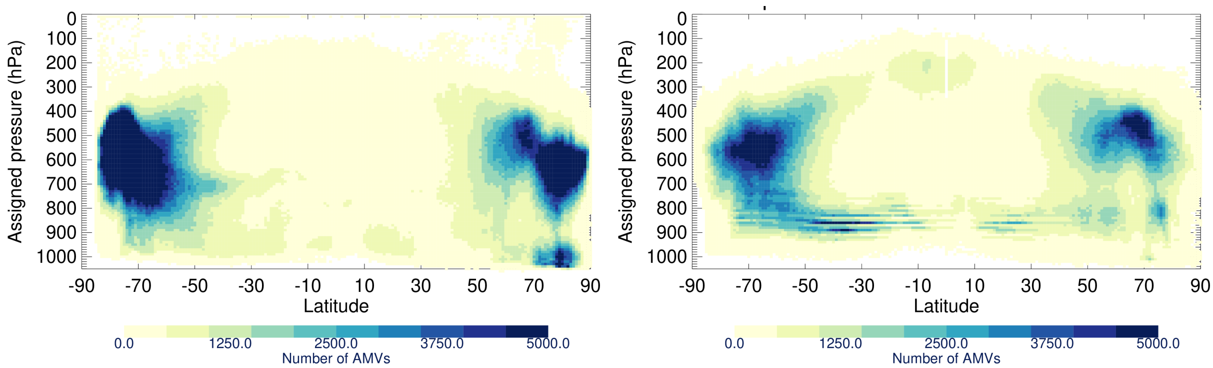

Figure 1: Distribution of Dual-Sentinel (left) and Dual-Metop AMVs (right), January 2021.

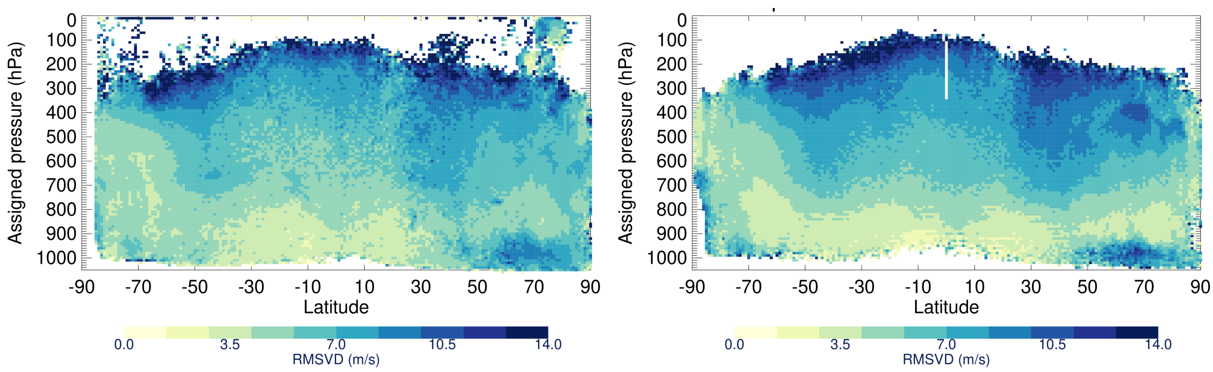

Figure 2: Root-mean-square vector difference of Dual-Sentinel (left) and Dual-Metop (right) AMVs versus ECMWF model backgrounds, January 2021.

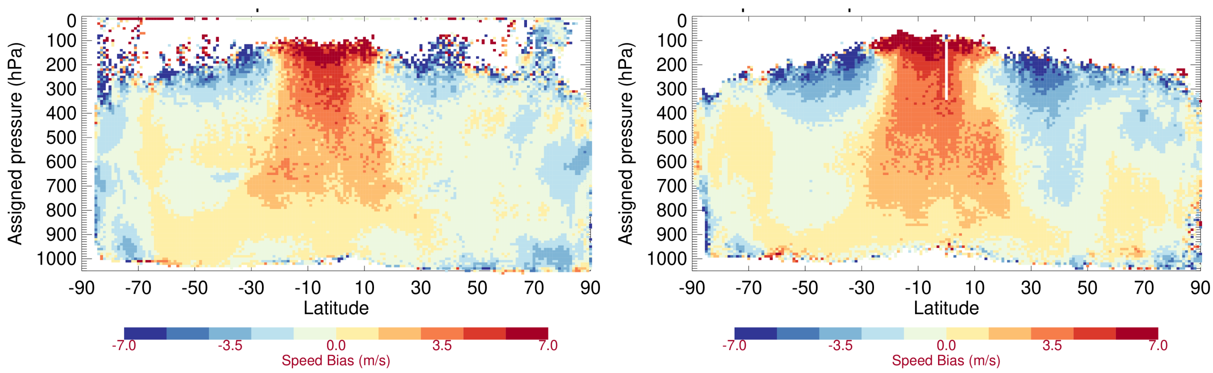

Figure 3: Mean observation-minus-background speed differences of Dual-Sentinel (left) and Dual-Metop (right) AMVs, January 2021.

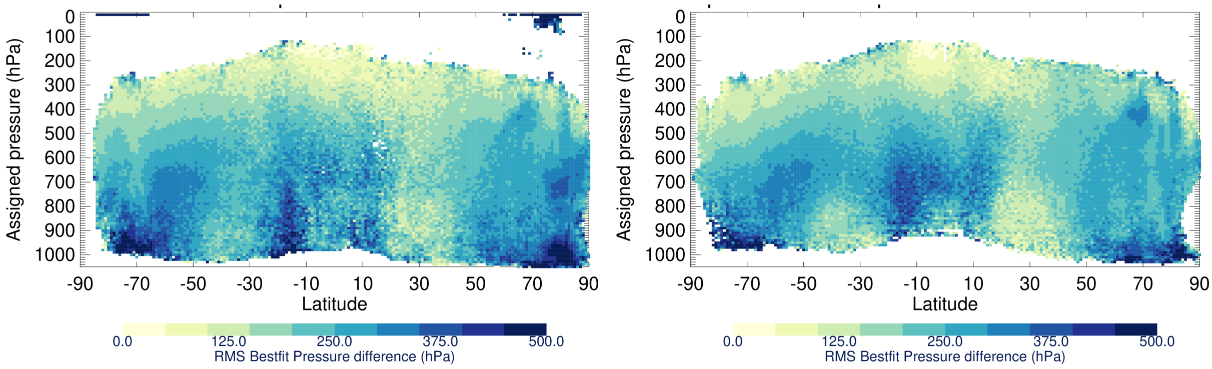

Figure 4: Root-mean-square difference of model best-fit pressures to AMV pressures for Dual-Sentinel (left) and Dual-Metop (right) AMVs, January 2021.

2.1 Assimilation Experiments Details

A set of assimilation experiments were run to test the impact on numerical weather prediction (NWP) forecasts of assimilating the Dual-Sentinel AMVs. They were assimilated using similar quality control to that used for other polar AMVs. This includes:

- Low-height rejection where polar AMVs have previously struggled with polar temperature inversions; this is applied for pressures greater than 700 hPa over sea and greater than 400 hPa over land. In the case of Dual-Sentinel this also helps by removing the near-surface AMVs in polar regions.
- All AMVs with pressures less than 100 hPa are rejected - so the ones supplied with zero pressure are not used.
- Filter the AMVs using the supplied forecast-independent quality indicator values to $>$ 60.
- Only using the Sentinel AMVs polewards of 40°. Equatorwards of 40° there is already good spatial coverage from geostationary AMVs. While Dual-Metop is only used in the 40-60° latitude bands so as not to overlap with the Single Metop AMV product, there is no Single-Sentinel product available due to the narrow swath, and so the Dual-Sentinel AMVs are assimilated all the way to the poles.

The Dual-Sentinel AMVs were also subject to other quality control steps that are applied to all AMVs. A major one is spatio-temporal thinning into 200 km, 50-175 hPa, 30 minute boxes. This is to mitigate the impact of correlated errors which are known to exist in AMVs but which are assumed to be zero in the data assimilation process. AMVs which deviate too strongly from the model background are rejected. AMV observation errors are assigned partly dynamically, based on the model wind shear at the AMV's location, and partly from static height and tracking error profiles [4]. The height and tracking errors used for Dual-Sentinel in these experiments are shown in Table 1 along with the Dual-Metop errors for comparison. The height errors are derived by calculating RMS best-fit pressure differences in 200 hPa layers. The tracking errors are derived from the RMS vector difference in 200 hPa layers, limited to the cases where the error due to height assignment is estimated to be small based on the model background profile. This is to separate the wind speed error from the tracking from the wind speed error due to height assignment.

	Pressure Errors (hPa)		Tracking errors (m/s)	
Pressure Range	Dual-Sentinel	Dual-Metop	Dual-Sentinel	Dual-Metop
0-200	250	80*	4.0	2.5*
200-400	140	160	4.5	4.0
400-600	200	205	3.2	4.0
600-800	250	245	3.0	3.0

*Table 1: Pressure and tracking errors assigned to the Dual-Metop and Dual-Sentinel. *default value, but very few winds this high.*

Experiment Name	Description
S3	Assimilates Dual-Sentinel AMVs in addition to the operational AMV assimilation usage, which includes Dual-Metop.
S3_ref	Reference experiment for **S3**: simply the operational AMV usage.
S3_iso	Assimilates Dual-Sentinel without Dual-Metop so that the impact of Dual-Sentinel AMVs can be seen in isolation
S3_iso_ref	reference for **S3_iso**: the operational AMV usage minus the Dual-Metop AMVs

Table 2: Description of Dual-Sentinel experiments.

The experiments were run for the periods 1 January - 31 March 2021 and 1 June to 31 August 2021. The experiments used the ECMWF IFS model, cycle 47R1.4, with an outer loop resolution of TCo 399 (nominally 25km), and four inner loops with the last of which is TL 255 resolution. Apart from the changes to AMV data selection, the experiments make use of the full observing system including microwave and infrared radiances, radio occultation data and conventional wind observations. Four experiments were run for these two seasons, they are described in Table 2

2.2 Assimilation Experiment Results

The Sentinel-3 and Metop satellites are in similar orbits, with the Metop satellites crossing the equator at 09:31 local time and the Sentinel-3 satellites at 10:00. Despite this, assimilation of Dual-Sentinel (**S3**) results in an increase of around 5-10% in the total number of AMVs assimilated at mid-level compared to **S3_ref**. Figure 5 shows an example of the extra coverage at around 25°E and 160°W in the 40-60° gap region, in addition to the extra coverage from 60°S to the South Pole, while Figure 6 shows that a large number of Sentinel AMVs are added in the 40-60° latitude bands without pushing out many Dual-Metop AMVs via thinning.

The forecast impact of adding the Sentinel-3 AMVs to the full observing systems is largely neutral in the short range forecasts, as can be seen in Figure 7 for both wind and geopotential forecasts although there are some small improvements to the wind field for the 12 and 24 hour forecasts. This is consistent with the finding that background fits to other assimilated observations are not significantly different for the **S3** and the **S3_ref** experiment (Figure 2.2), indicating a similar quality of the short-range forecast. However, Figure 7 also suggests some localised degradations for the geopotential forecast at day 4 and 5 around 40° South. These small degradations appear to be present in both seasons (Figure 8), with small variations in magnitude. The reason for these degradations is not clear; they are not concentrated in any particular region, and they are not present in the short-range forecast, making it difficult to pin down the origin. Longer experimentation may be useful to establish whether these are a robust signal.

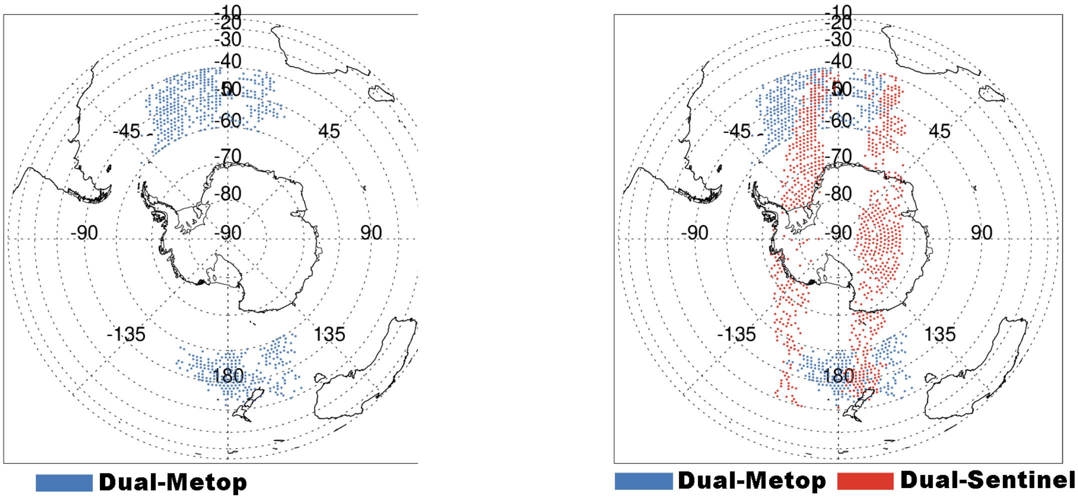

*Figure 5: Map of assimilated Dual-Sentinel and Dual-Metop AMVs for **S3_ref** (left) and **S3** (right), for times 0230-0330 UTC, 1-5 July 2021*

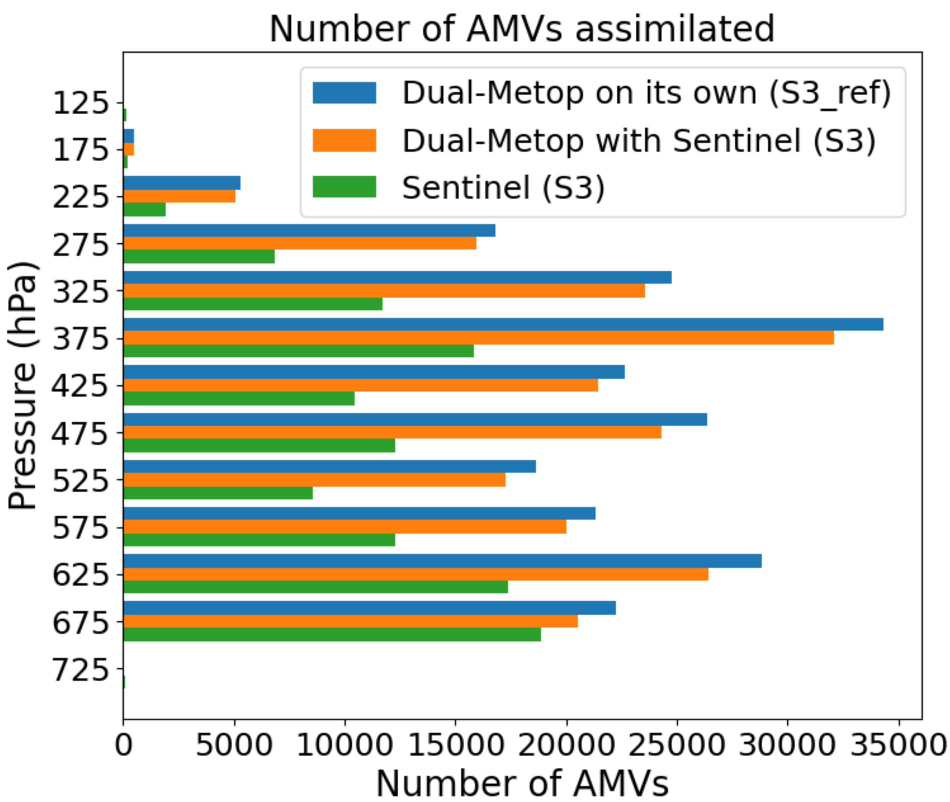

*Figure 6: Number of Dual-Sentinel AMVs assimilated in **S3** (green) at each height, along with the number of Dual-Metop AMVs assimilated in **S3** (orange) and **S3_ref** (blue). Data is for the 40-60° latitude bands, July 2021.*

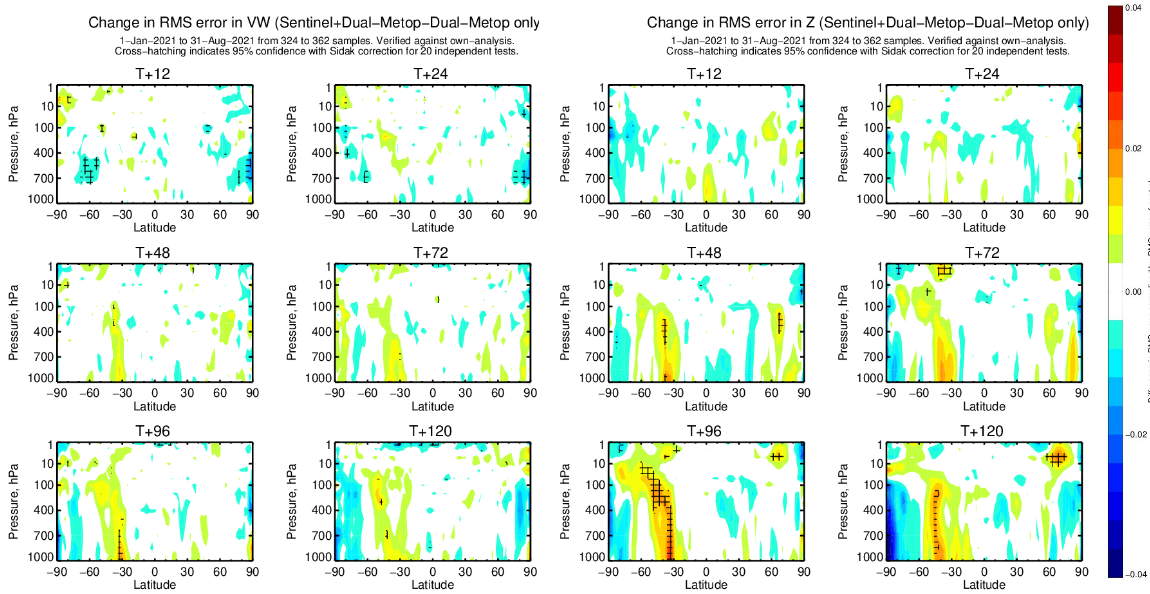

*Figure 7: Impact of **S3** versus **S3_ref**. Change in error forecast fields shown, verified against own analyses at a range of forecast lengths (in hours). The six plots on the left show the impact on the wind field, the six on the right the impact on the geopotential height fields. Cross-hatching indicates statistical significance.*

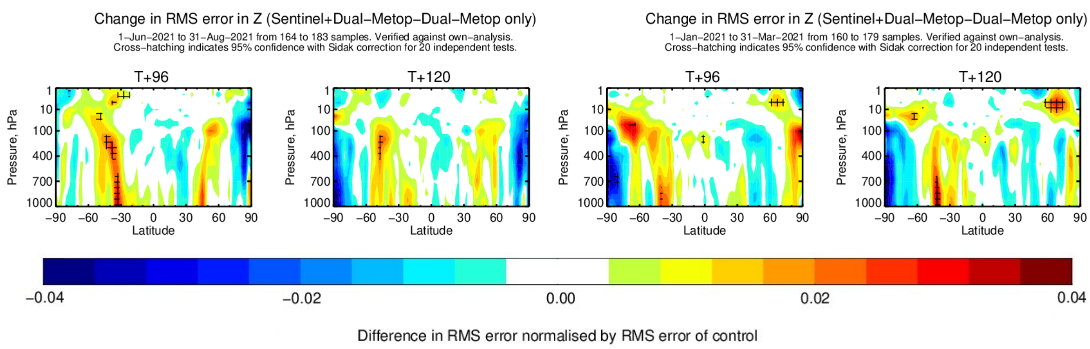

*Figure 8: Impact of **S3** versus **S3_ref** on geopotential field, split by season: January-March 2021 on the left, June-August 2021 on the right. Change in error forecast fields shown, verified against own analyses at a range of forecast lengths (in hours).*

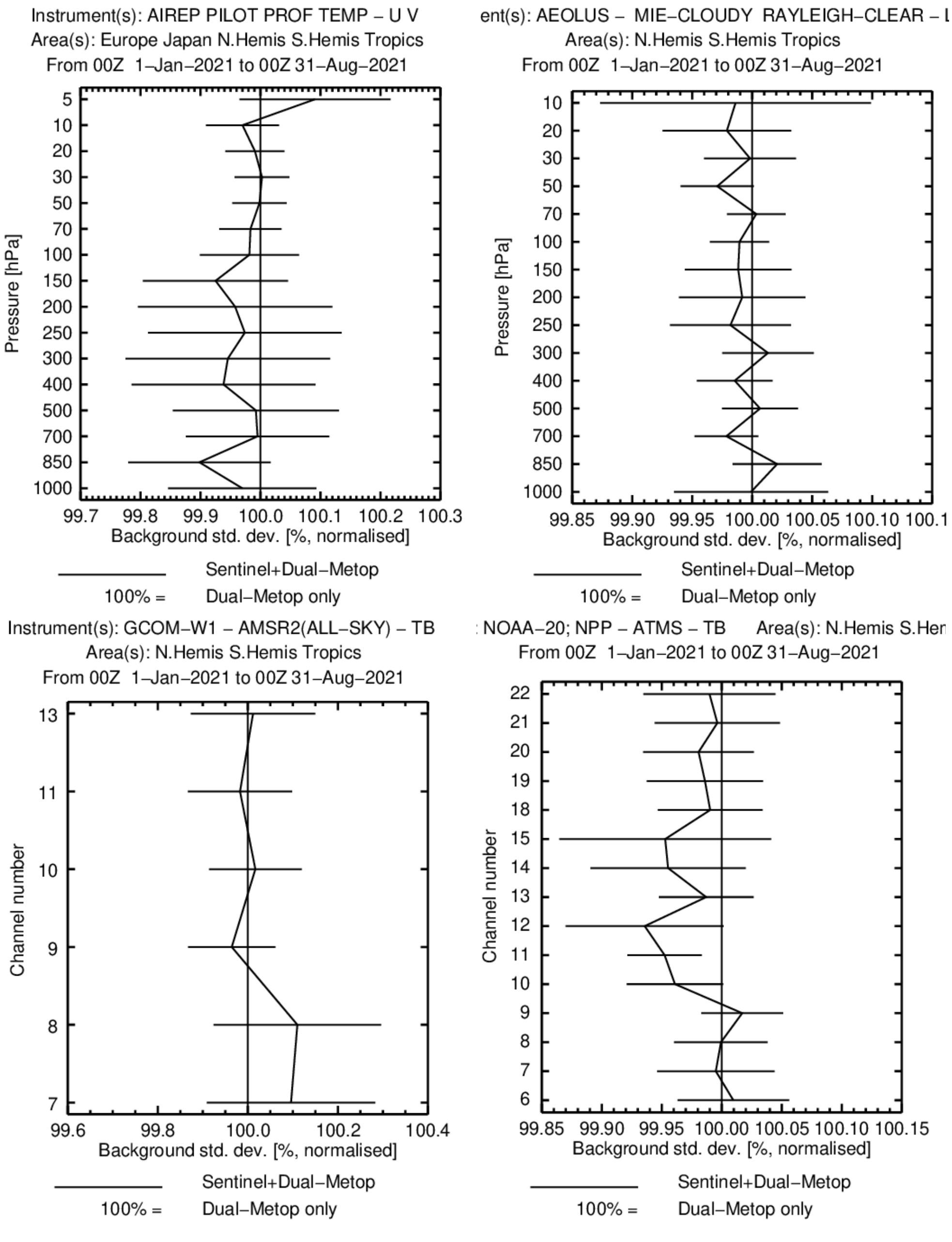

*Figure 9: Change in normalised standard deviation of model background fit-to-observations for **S3** vs **S3_ref**. Observation types are, clockwise from top-left, conventional wind observations, Aeolus winds, the microwave sounder ATMS, the microwave imager AMSR2*

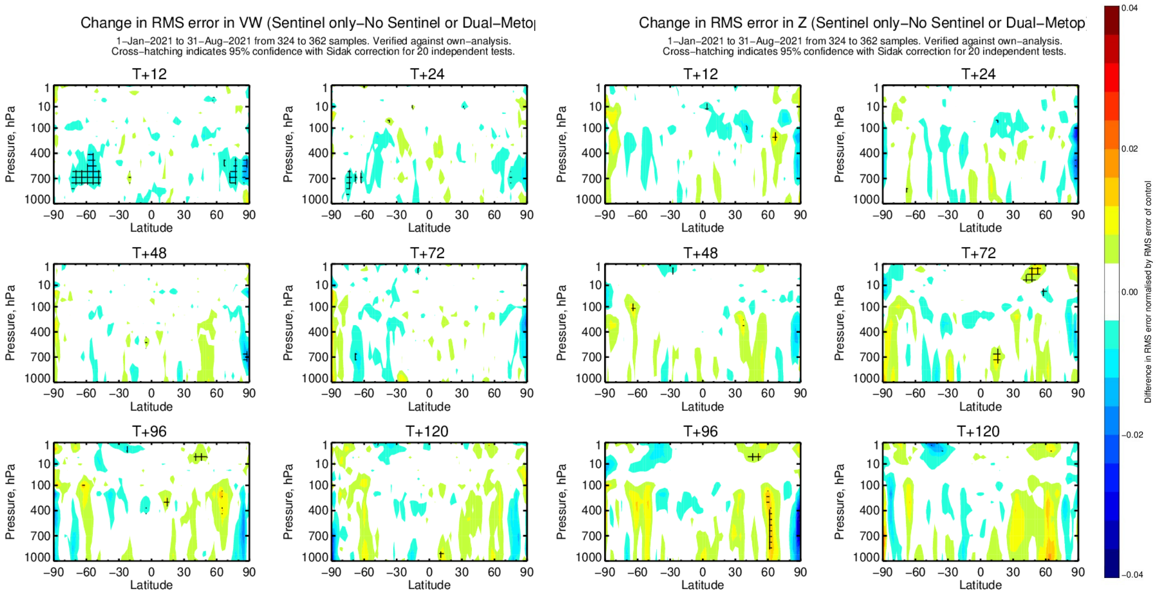

*Figure 10: Impact of **S3_iso** versus **S3_iso_ref**. Change in error forecast fields shown, verified against own analyses at a range of forecast lengths (in hours). The six plots on the left show the impact on the wind field, the six on the right the impact on the geopotential height fields. Cross-hatching indicates statistical significance.*

The impact of **S3_iso** versus **S3_iso_ref** is shown in Figure 10. The impact of Sentinel AMVs on the wind field is more clear in the absence of Dual-Metop, with some benefits seen out to 72 hours. The degradations in the geopotential field seen in Figure 7 are greatly reduced in Figure 10, while the forecast fit-to-observations results were mostly neutral again. These results show that Dual-Sentinel AMVs could improve forecast quality in a situation where Dual-Metop AMVs were unavailable, thereby adding resilience to the AMV observing system.

3 LeoGeo AMVs

The CIMSS LeoGeo AMVs fulfil a similar role to the EUMETSAT Dual-Metop and Dual-Sentinel AMVs, but use a different approach to observe the gap region. Where the EUMETSAT products are using images from pairs of the same satellite series for the tracking, at CIMSS, imagery from many polar and geostationary satellites [2] is used for tracking features in the gap region. This AMV product has been available for several years and has shown good forecast impact at other NWP centres including the Met Office [6]. The advantage of this approach, compared to the single-satellite AMVs already available from the contributing satellites, is to make it possible to derive more AMVs from polar imagery by filling the triplet with other polar imagery or geostationary imagery. In other words LeoGeo takes the advantage to spatial coverage seen with EUMETSAT's dual satellite Metop and Sentinel-3 AMVs and extends it to all available polar imagers and to geostationary imagers.

The tracking is performed in the infrared window channel using image triplets [3]. This channel is also used for the height assignment, by matching the coldest pixels to a model temperature profile. The temporal image spacing varies depending on the satellites used to form the image triplet.

[2] At December 2020 the satellites used were GOES-16, GOES-17, Himawari-8, NOAA-18, NOAA-19, Metop-A, Metop-B, Metop-C, Meteosat-11, Meteosat-8 (personal communication, D. Santek, CIMSS)

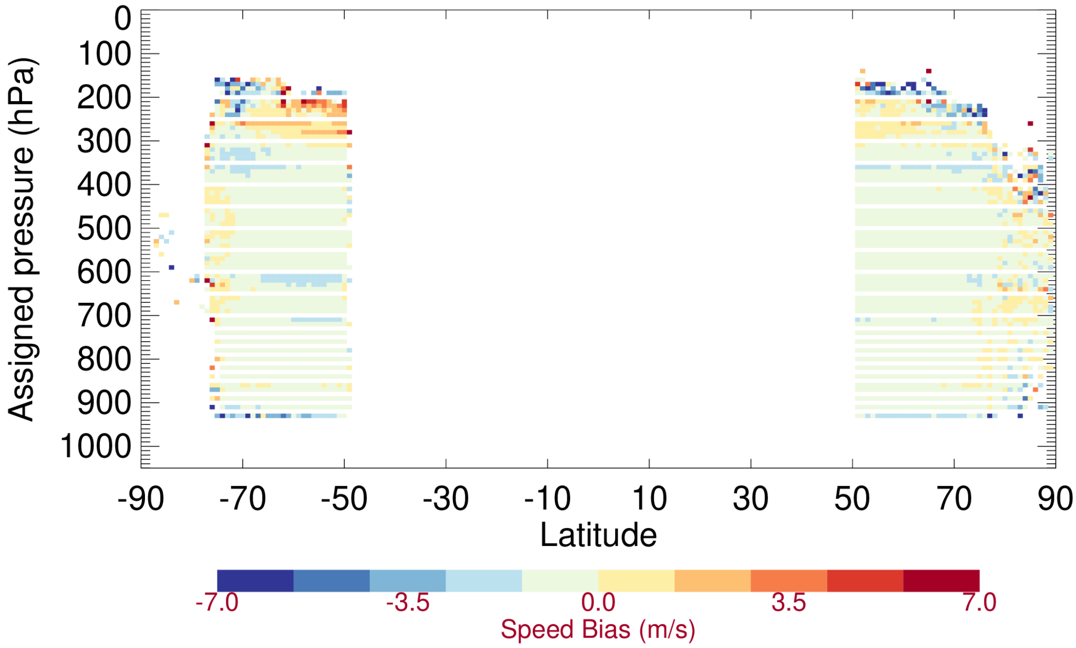

Figure 11: Mean LeoGeo AMV-minus-model speed difference for 1st Nov - 14th Dec 2020.

One weakness of the Leo-Geo product is that in many of the LeoGeo AMVs the contributing imagery comes from the same geostationary imager, essentially reusing the same information that is already assimilated in the IFS from single-satellite geostationary AMV products. Currently there is no way of identifying the contributing satellites for a particular LeoGeo AMV. Some dependence on NWP fields is normal for AMV height assignment, and the LeoGeo AMVs use a first-guess check to aid the tracking as other polar AMVs do. In addition, the LeoGeo derivation makes use of an 'autoeditor' which adjusts LeoGeo AMV speeds and pressures so that they better agree with a model background and nearby observations [2].

The background departure statistics of the LeoGeo AMVs, in terms of vector differences (Figure 12) are much smaller than we saw for Dual-Sentinel, while mean AMV-model speed differences (Figure 11) are small in the gap region. Best-fit pressure differences (Figure 14) are very small, especially compared to those we saw for the Metop and Sentinel products in Section 2. Smaller background departures are usually an indication of better quality AMVs. However, the size of the departures found for the LeoGeo AMVs is somewhat surprising in comparison to findings for other polar AMV datasets. It is likely at least partially the result of the use of the autoeditor in the processing, and it may be obtained at the expense of greater dependence on the short-range forecast used in the AMV processing.

LeoGeo provides a larger number of AMVs in the gap region than Dual-Sentinel. The distribution of LeoGeo AMVs (Figure 13) shows a different pattern to Dual-Sentinel AMVs despite observing at the same infrared wavelength and using a similar height assignment method. This may be due to the influence of the autoeditor, different choice of pixels used for tracking and height assignment and also due to observing features at a wider range of local times compared to the Dual-Sentinel and Dual-Metop AMVs.

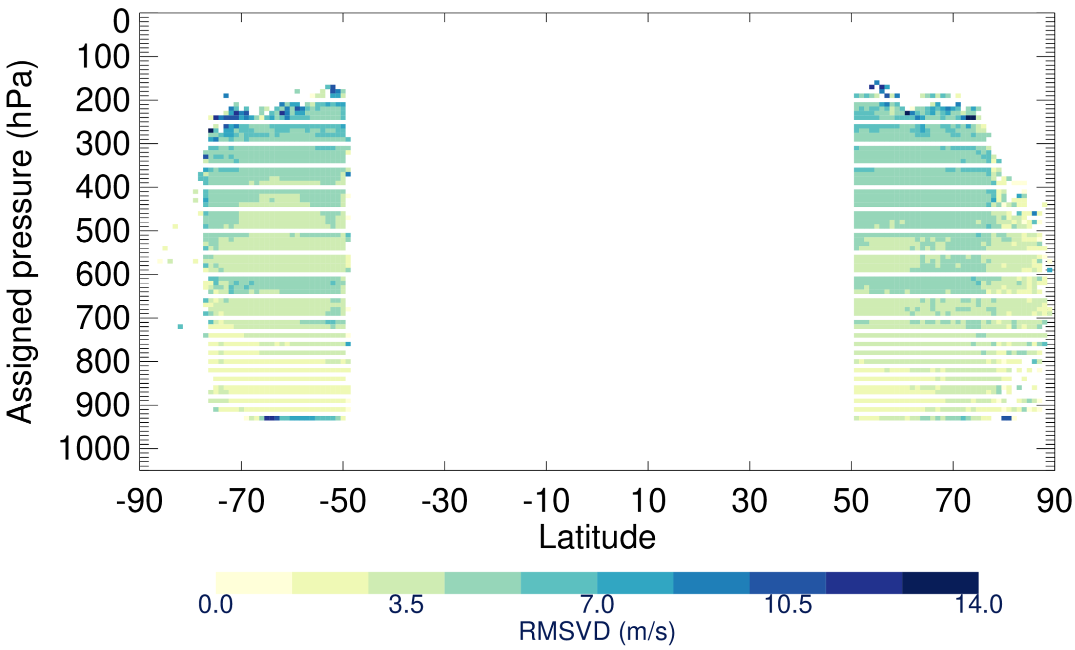

Figure 12: Root-mean-square vector difference of LeoGeo AMVs versus model background, 1st Nov - 14th Dec 2020.

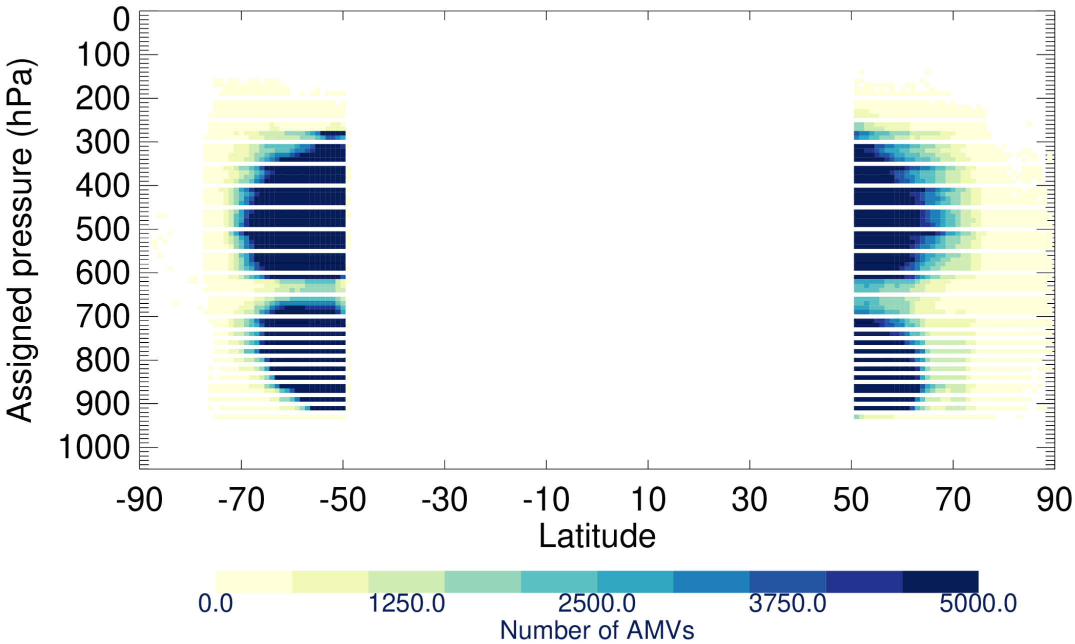

Figure 13: Zonal distribution of LeoGeo AMVs, 1st Nov - 14th Dec 2020.

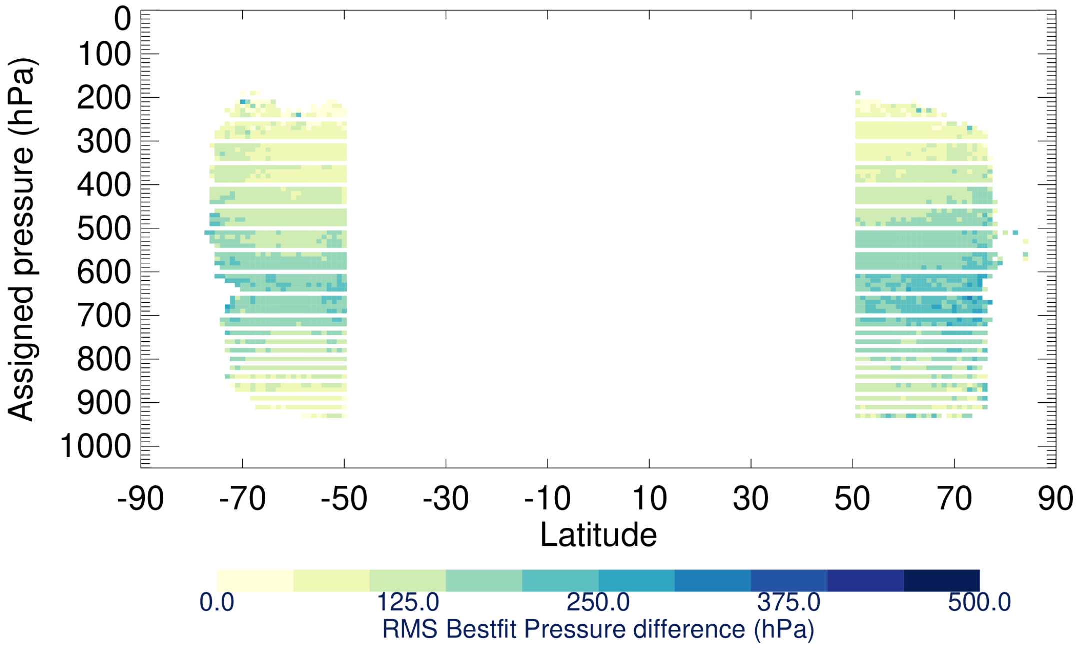

Figure 14: Root-mean-square AMV minus best-fit pressure differences for January 2021.

	Pressure Errors (hPa)		Tracking errors (m/s)	
Pressure Range	LeoGeo	Dual-Metop	LeoGeo	Dual-Metop
0-200	100	80*	4.0	2.5*
200-400	090	160	3.2	4.0
400-600	135	205	3.0	4.0
600-800	190	245	2.5	3.0

*Table 3: Pressure and tracking errors assigned to the LeoGeo and Dual-Metop AMVs. *default value, very few winds this high at latitudes used.*

3.1 Assimilation Experiment Details

Assimilation experiments were run covering 1st June - 31st August 2020 and 15th November 2020 to 14th February 2021. The IFS cycle, resolution, use of other observing systems and general AMV quality control was the same for the following experiments as it was for the Dual-Sentinel experiments described in 2.1.

Many of the Leo-Geo AMVs are derived entirely from geostationary imagery. Since AMVs from this imagery are already assimilated via the dedicated AMV product for each geostationary satellite, we prefer not to assimilate such AMVs so as to avoid assimilating the same information twice and thus giving too much weight to the AMVs in the data assimilation process. To avoid this, we gave LeoGeo AMVs a reduced thinning score [3] to ensure that the assimilation always chooses the main polar or geostationary AMV product if it is present in the same thinning box. To reduce cases where a LeoGeo AMV and a geostationary or polar AMV are tracking the same feature, but assigned to a different vertical thinning

[3] In the IFS code, the thinning score for AMVs is 100 minus the quality indicator value supplied with the AMV, the AMV with the lowest thinning score in the box is selected. LeoGeo AMVs were given a score of 1000 minus quality indicator.

box [4] and both assimilated, we only assimilate the LeoGeo AMVs in the 55-65°N/S latitude bands.

Three assimilation experiments were run: the **Control** experiment uses the full set of observations as in the operational ECMWF system at the time. The **LeoGeo_1** experiment is the same as the **Control**, but with the LeoGeo AMVs added. This experiment uses the tracking and height errors given in Table 3. These are relatively small compared to Dual-Metop, as a consequence of the small LeoGeo departure statistics. Other quality control measures are the same as used for other polar AMVs including the pressure-based data rejections described in Section 2.1. Only LeoGeo AMVs with a quality indicator greater than 50 were assimilated. A further experiment, **LeoGeo_2**, assimilates the LeoGeo AMVs with the same height and tracking errors as the Dual-Metop AMVs. This experiment tests the sensitivity of the results to the assignment of the observation errors. The use of larger errors will downweight the LeoGeo winds compared to **LeoGeo_1**, an ad-hoc attempt at counteracting the suspected larger NWP-dependence of the LeoGeo AMVs.

3.2 Assimilation Experiment Results & Discussion

The impact on the forecast wind fields of assimilating the LeoGeo AMVs is shown in Figure 15 when verified against the operational analysis. The impact appears largely neutral, with a small improvement at T+120 over the southern hemisphere for **LeoGeo_1** which is reduced in the **LeoGeo_2** experiment. In contrast, for geopotential height forecasts there is a significant increase in the root-mean square error (RMSE) over the south polar region up to day 1 when verified against the operational analysis (Figure 16). This feature is only partly reduced by the increased LeoGeo observation errors used in **LeoGeo_2**, and it is particularly strong for the southern hemisphere winter season (not shown). The increase in RMSE is strongly dependent on the verifying analysis used: When each experiment is verified against its own analysis instead, there is a reduction of the RMSE over the same region. This most likely reflects a considerable model bias in the region for the winter months. The presence of this model bias can be seen in Figure 17, which shows the mean difference between the day-5 forecast and the analysis. This shows that during southern hemisphere summer there is a positive geopotential bias in the model at the same latitudes of the southern hemisphere where we saw a negative impact on the geopotential field in Figure 16. Figure 18 shows that in the same region there is an increase in the mean geopotential in the LeoGeo experiments. It appears that the assimilation of the LeoGeo AMVs is exacerbating an existing model bias, which leads to a reduction in RMSE when verified against own analysis, but an increase in RMSE when verified against operations.

To avoid the issue with the verifying analysis, Figure 19 presents standard deviations of background departures for other assimilated observations over the southern hemisphere. These are mostly neutral, though a few mid-tropospheric temperature and humidity channels from ATMS show some small degradations that are borderline statistically significant (channels 8, 9 and 19). While it is a faint signal, it suggests that short-range forecasts are slightly degraded with the assimilation of AMVs. The slight degradations are somewhat mitigated by the larger observation errors used in **LeoGeo_2**, but not improved completely.

As the forecast impact of the LeoGeo AMVs appears overall mixed, various investigations were carried out to further understand the behaviour seen. The direction bias of the LeoGeo AMVs compared to the model background was examined, but was not clearly more consistent than that of the Dual-Metop AMVs. The assimilation of the Dual-Metop AMVs over similar periods has a slight positive impact and does not appear to exacerbate a model bias. This finding may indicate that the Dual-Metop AMVs

[4] Thinning box dimensions are 200 km by 200 km by 50-175 hPa

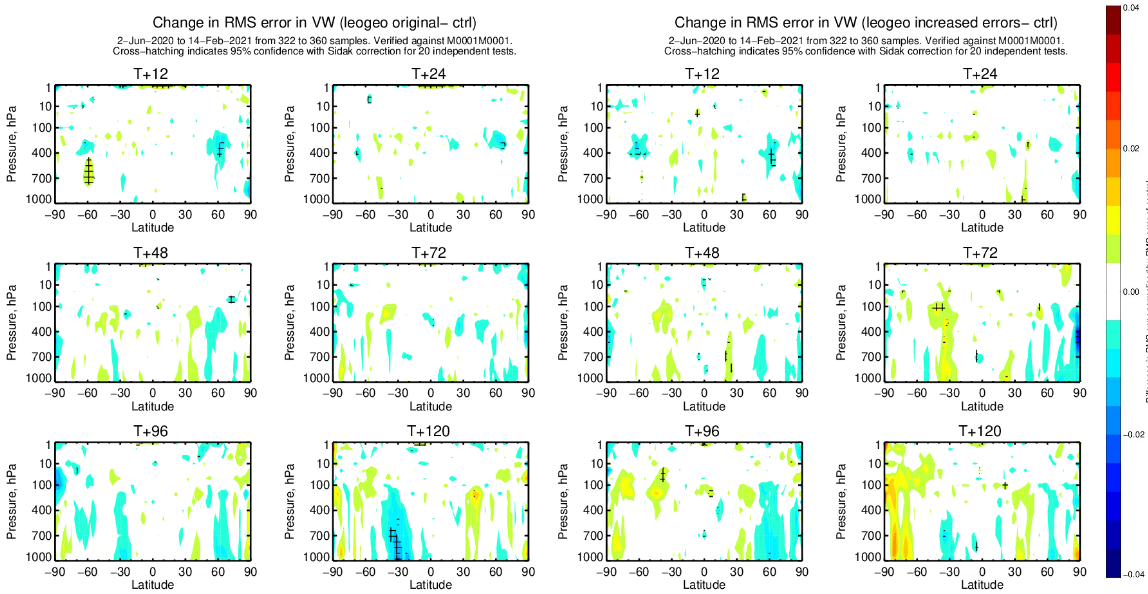

*Figure 15: Impact of LeoGeo AMVs on forecast wind error, verified against operational ECMWF analyses at a range of forecast lengths (in hours). The six plots on the left are for **LeoGeo_1**, the six on the right show are for **LeoGeo_2**. Cross-hatching indicates statistical significance.*

are in fact correcting a model bias while the LeoGeo AMVs exacerbate it. One possibility why the LeoGeo AMVs could be more prone to exacerbating the model bias may be the greater dependence on a short-range forecast noted earlier. Since the ECMWF short-range forecast is not used in the derivation of the LeoGeo AMVs this explanation would, however, require that the NWP forecast used in the winds derivation has a similar structure as that from the ECMWF system.

4 Conclusions

An assessment of Dual-Sentinel AMV background departures for January-August 2021 showed the data is good quality, similar to that of the Dual-Metop AMVs. Assimilation experiments using this test data showed a largely neutral impact on forecast quality, though there was a clear positive impact when Dual-Sentinel was assimilated in the absence of Dual-Metop. This suggests that Dual-Sentinel could add resilience to the AMV observing system and would be beneficial if Dual-Metop becomes unavailable in the future.

The LeoGeo AMVs agreed very closely with the model wind field. Assimilation experiments using these AMVs showed some minor benefits to the model wind field but also some serious degradations to the geopotential height field. It seems likely that the LeoGeo AMVs are reinforcing an existing model bias, especially in the December 2020 - February 2021 season. This dataset would be worth revisiting if the derivation was changed to the nested tracking scheme used for NOAA AMVs, and if the contributing satellites could be identified within the data so that the single-satellite AMVs could filtered out more easily.

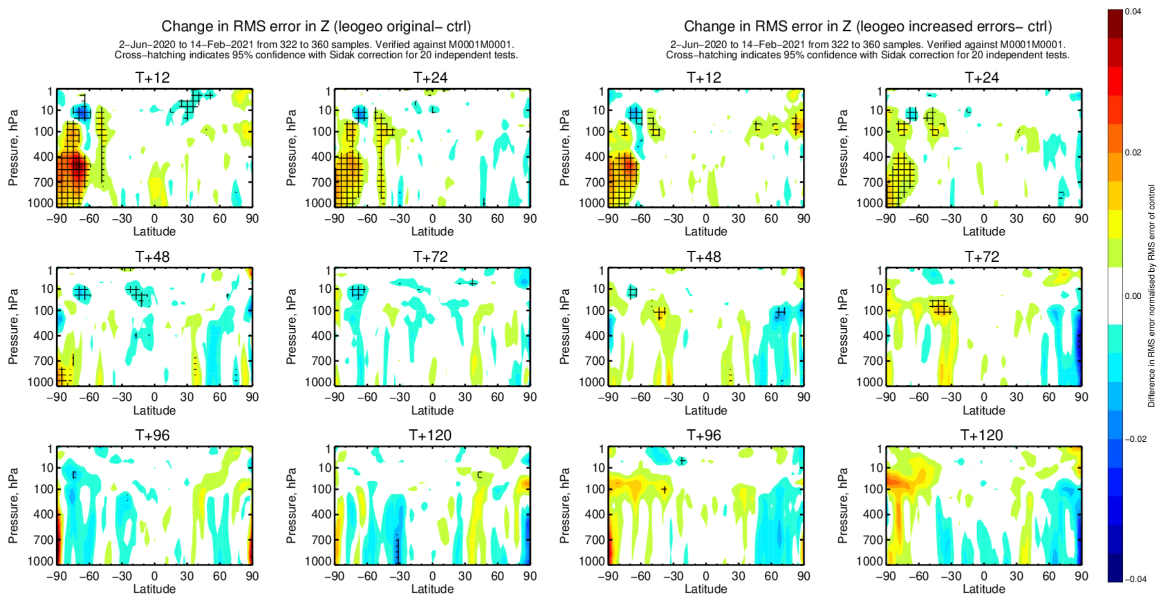

Figure 16: Impact of LeoGeo AMVs on forecast geopotential height error, verified against operational ECMWF analyses at a range of forecast lengths (in hours). The six plots on the left show the impact of ***LeoGeo_1****, the six on the right show the impact* ***LeoGeo_2****. Cross-hatching indicates statistical significance.*

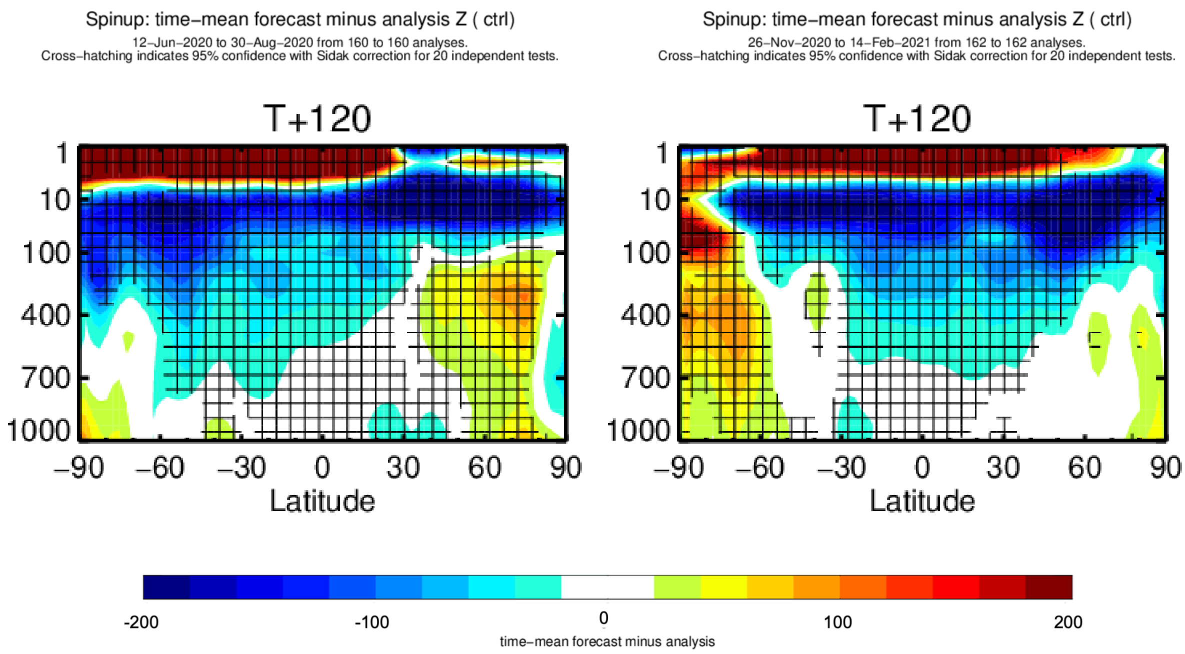

Figure 17: Zonal plots of forecast geopotential error of 5-day forecasts verified against own analyses, corresponding to the two LeoGeo experiment seasons: June-August 2020 (left), December 2020 - February 2021 (right)

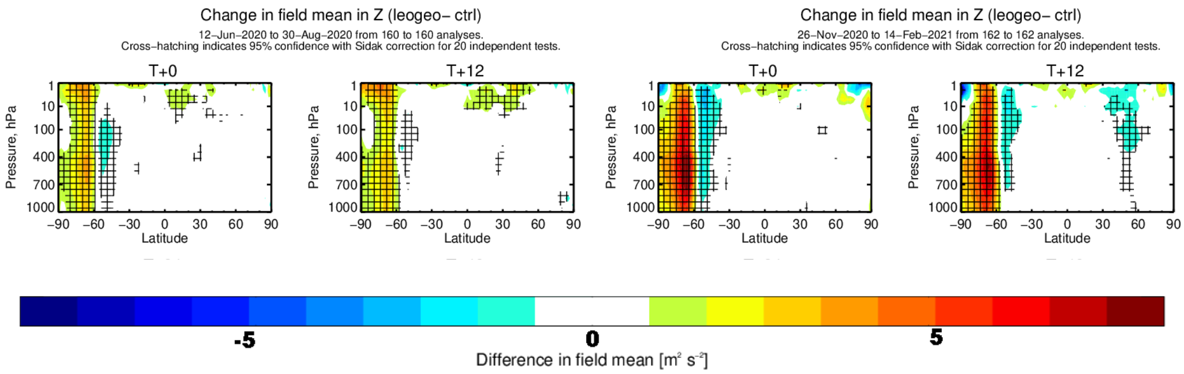

*Figure 18: Mean change in model geopotential fields for the two **LeoGeo_1** experiment seasons: June-August 2020 (left), November 2020 - February 2021 (right).*

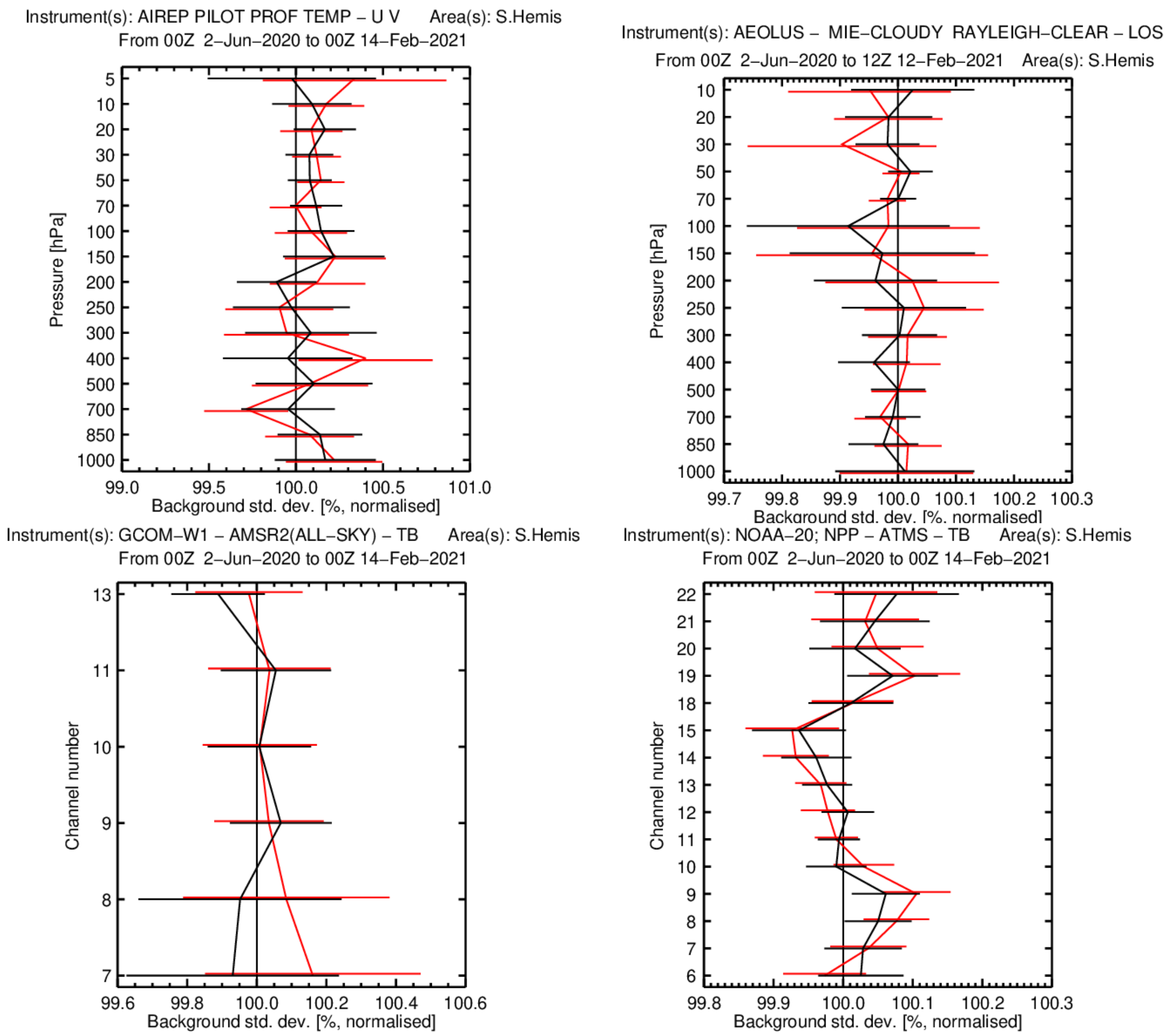

*Figure 19: Change in normalised standard deviation of model background fit-to-observations for **LeoGeo_1** and **LeoGeo_2** versus operations, 20-90°S. 100% = operations. Observation types are, clockwise from top-left, conventional wind observations, Aeolus winds, the microwave sounder ATMS, the microwave imager AMSR2.*

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