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Using model cloud information to reassign low level AMVs for NWP

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Executive summary

Atmospheric Motion Vectors (AMVs) provide single-level wind estimates derived by tracking cloud features in image sequences from geostationary and polar orbiting satellites. They are established inputs to global as well as regional Numerical Weather Prediction (NWP) systems. Nevertheless, determining the heights of the winds as well as the assumption that clouds are passive tracers remain key sources of uncertainty in the use of AMVs. These aspects are often very difficult to examine, primarily due to a lack of independent wind observations over large parts of the oceanic regions, though the availability of Aeolus data has opened new possibilities in this respect. This report presents recent work focused on investigating possible height assignment issues in low level AMVs, particularly inspired by a study in the Indian Ocean which highlighted challenging regions for the assimilation of AMVs in tropical inversion regions. These regions are often associated with relatively sharp changes in the wind speed in the vertical, leading to a particular sensitivity to AMV height assignment errors.

Errors in the height assignment of low level AMVs are investigated using estimates of the cloud layer height provided by the ECMWF model. Analysis of background departure statistics (comparison of observations with the model background) showed that AMVs placed above the model cloud show larger deviations from the model fields compared to those placed unrealistically close to the surface. Reassigning the pressure of AMVs diagnosed above the model cloud layer to either the model cloud top, base or average pressure leads to improvements in Root Mean Square Vector Difference (RMSVD) and speed bias against the background wind fields. In assimilation experiments, reassigning the AMVs to either of these options resulted in positive impact on the vector wind field in the verification against own analysis. In the fit of independent observations to the model background, changes to conventional wind observations remained neutral however, positive signals were seen in Aeolus and scatterometer winds and in microwave imagers which are primarily sensitive to changes in the cloud. Overall, the reassignment to the cloud base or average pressure performed better than the cloud top in assimilation experiments. Combined with the results from the background departures, the option to reassign the heights of AMVs diagnosed above the model cloud to the average pressure of the cloud layer is recommended for future operational use.

1 Introduction

Atmospheric Motion Vectors (AMVs) derived by feature-tracking from sequences of satellite imagery form a key component of the global observing system and provide a significant contribution to Numerical Weather Prediction (NWP) (e.g. Forsythe et al. (2016)). Despite a long history of production (Menzel, 2000), there remain a number of difficult areas for AMV derivation such as those identified through regular analysis carried out by the NWP SAF (Satellite Application Facility for Numerical Weather Prediction) (`https://www.nwpsaf.eu/site/monitoring/winds-quality-evaluation/amv/amv-analysis-reports/`). Of the most recent issues highlighted, including a range of satellites and tropospheric layers, several were attributed to inaccurate height assignment (Cotton et al., 2020). Height assignment is considered to be one of the main error sources for AMVs e.g. (Velden and Bedka, 2009; Jung et al., 2010; Salonen et al., 2015) and has been a long standing area of research that has been undertaken by both the producers of the AMV product and those using the data in NWP. Assigning a representative height of the derived vectors has often been carried out by well established methods such as the CO_2 slicing or the water vapour intercept method (Nieman et al., 1997; Velden et al., 1998). Techniques have continued to evolve and recent years have seen a significant move towards using optimal estimation methods (Heidinger, 2013; Shimoji, 2014; Watts et al., 2011). These methods frequently aim to use the cloud top as the representative height of the wind although for low level winds, the cloud base is also occasionally used (Le Marshall et al., 1994). At ECMWF, AMVs continue to be interpreted as single-level wind estimates at the assigned height during assimilation when converting model variables to observation equivalents.

Recent work at ECMWF has pointed to two particular areas of interest in the height assignment of low level AMVs (assigned pressures $>$ 700hPa). The introduction of Meteosat-8 AMVs in the Indian Ocean (Lean and Bormann, 2018) revealed an issue with low level winds in the tropical Indian Ocean. A lack of variation of wind speed with height in the AMVs was found when compared to the model background, nearby radiosondes and Aeolus. The AMVs are on average faster than the equivalent model wind between around 700-850hPa which led to the hypothesis that some AMVs may be assigned heights that are too high. Secondly, during the assessment of Himawari-8 (Lean et al., 2016) it was noted that there were many winds that appeared unusually close to the surface. However, the data quality as assessed by background departure statistics was good and in fact the inclusion of these winds in assimilation had a positive impact. These two studies became the motivation to identify and if possible correct systematic height assignment errors with the aim to address two main questions:

1. Are some AMVs around 850-700hPa being placed too high?
2. Are some AMV heights unrealistically low?

In the present ECMWF system, low level AMVs are only assimilated over the ocean due to poor data quality close to the surface over the land, and as with all AMVs only those derived from cloudy targets are considered. None of the AMVs are subject to any bias correction prior to assimilation however, the quality control procedures are very strict with initial data selection (formerly known as blacklisting) and the first guess check removing a large percentage of data. For example, in the case of Meteosat-11 a typical cycle may remove 50-75% through data selection while 15-35% fail the first guess check. Situation dependent observation errors (Salonen and Bormann, 2013b) also provide a valuable method of accounting for uncertainties in the height assignment. However, if we are able to identify and suitably correct for systematic height errors there may be further benefit that we can extract from the observations. Accurate knowledge of the low level circulation is an integral part of NWP. Better use of AMVs may bring benefits such as forecast of the Indian Monsoon, where low level winds greatly influence India's climate (Neal et al., 2020), or the improved prediction of the transport of water vapour where the error in winds at 850hPa was identified as the main source of uncertainty (Lavers et al., 2018). While the focus in this report is on the low level winds, a successful method could be used in the future to explore other geographical regions and tropospheric layers.

There have been several studies in diagnosing and potentially correcting AMV height assignment errors. Folger (2016), for instance, derived height corrections based on collocations between AMVs and cloud information from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). In contrast, (Salonen and Bormann, 2016) investigated the possibility of correcting systematic height assignment biases based on best-fit pressure statistics (the model pressure that minimises the vector difference between the AMV and the model wind). While initial results showed promise in improving background departure statistics, assimilation experiments showed some concerning areas so the method was not pursued for operational use. Interpreting the AMV as a layer-average wind has also received attention over the years, in studies using collocations with other observations (Velden and Bedka, 2009; Folger, 2016) or background departure statistics (Salonen and Bormann, 2013a, 2015). The placement of such a layer relative to the originally assigned height remains a topic of debate, with studies typically suggesting a layer set below or centred at the assigned height.

In a simulation study, Hernandez-Carrascal and Bormann (2014) examined height assignment and layer averaging in relation to model clouds, using AMVs derived from simulated images. For low-level AMVs, they showed benefit from reassignment to the cloud layer-average pressure compared to the top or base of the model cloud. While they also found benefit from performing layer-averaging, treating the AMVs as a single-level wind at an adjusted pressure, guided by knowledge of the model clouds, was shown to attain a large fraction of the better agreement with model winds seen with a layer average. This suggests estimation of such a cloud-average pressure continues to be important.

In this report we will extend the idea of using model cloud information alongside other model variables to investigate the height assignment of the real AMVs. In moving away from a simulation framework, model clouds of course do not represent the "truth". However, recent work highlights that model clouds in background fields show a high degree of realism (Ahlgrimm et al., 2018; Ahlgrimm and Köhler, 2010). This is largely a result of improvements in model physics parameterisations, but also due to an increasing use of all-sky radiance assimilation, which takes into account model clouds during the assimilation process (e.g. Geer et al. (2017)). In addition, estimating the cloud base or vertical extent of a cloud from infrared radiance observations is difficult for low level clouds, providing further motivation to explore whether model cloud information can aid the height attribution of AMVs.

In this report we will start in section 2 with a brief review of the background and motivation for this investigation. Section 3 then explores the AMV data quality in relation to the model cloud. Section 4 considers the impact on background departure statistics of various height reassignment options using the model cloud information while section 5 presents their impact in assimilation experiments. Finally, in section 6 the results are summarised and future plans are discussed.

2 Background on identified height issues

2.1 Meteosat-8 in the tropical Indian Ocean

When assessing Meteosat-8 as the new provider of coverage over the Indian Ocean, a localised area of apparent degradation was seen in the tropical ocean (Lean and Bormann, 2018). Comparison with

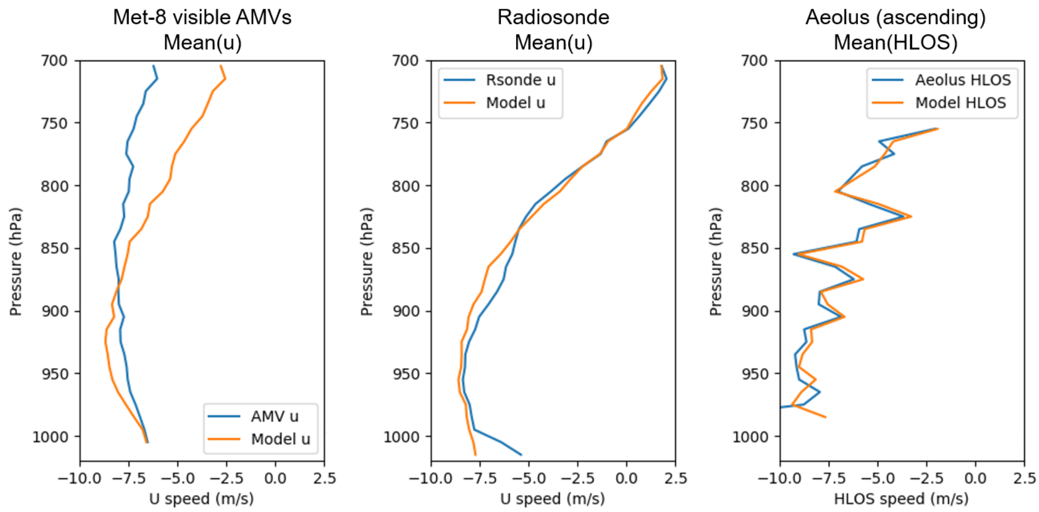

Figure 1: Comparisons of mean u-component for observations (blue) and ECMWF model background winds (orange) for 14th Sept - 13th Oct 2018 and over the area 50-100°E, 5-25°S for different observation types: a) Meteosat-8 visible AMVs actively used, b) radiosonde wind profile from Cocos Island c) Aeolus horizontal line-of-sight (HLOS) wind profile (actively used Aeolus winds, ascending orbits only, such that the HLOS wind is in a similar direction as the u-component)

average profiles of the wind from the model background (short range forecast from the previous 12 hour cycle) showed less variation of wind speed with height in the AMVs. Unfortunately, the area is sparsely covered by conventional wind observations but two nearby radiosondes gave support to the greater variation seen in the model. Since the study was carried out, we have had the launch of Aeolus in August 2018 which provides a valuable independent source of wind profiles over such data sparse ocean regions. Repeating the generation of average wind profiles over the Indian Ocean now reveal that Aeolus also supports the model variation (figure 1). Note that Aeolus will sample this region around a local time of 18:00 in the ascending part of the orbit whereas the visible AMVs averaged here are derived throughout the local daylight hours. The AMVs are on average faster than the equivalent model between around 700-850hPa leading to the hypothesis that some AMVs are placed too high.

2.2 Himawari-8

The low level winds from Himawari-8 exhibit a large number of observations that are unusually close to the surface below 950hPa (illustrative example in figure 2) compared to the other geostationary satellites in operation (Lean et al., 2016). Although it was recognised that some of these heights may be unrealistic, background departure statistics still showed good data quality and assimilation experiments revealed positive impact on the low level wind fields - both using own analysis verification and on the fit of the model background (short-range forecast from the previous model cycle) to the independent scatterometer winds at the surface. The winds entered operational use with the aim to revisit the issue.

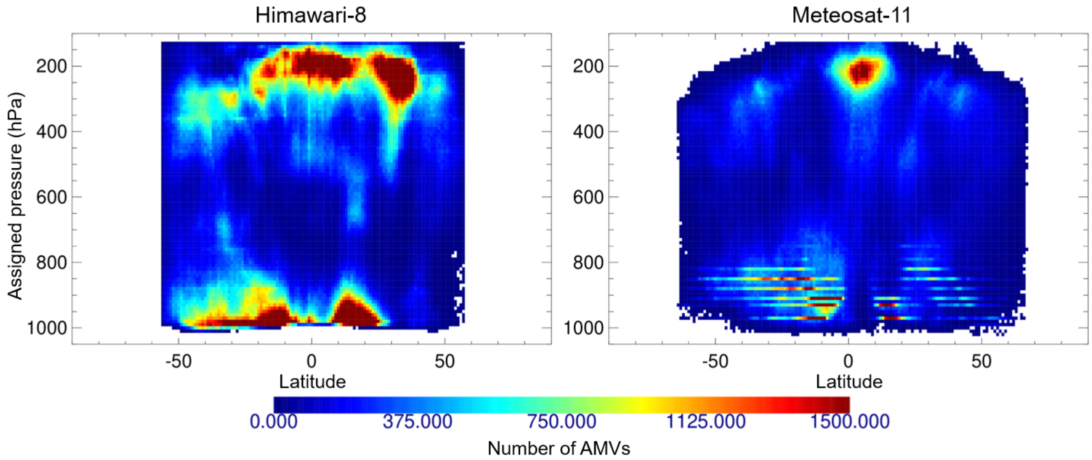

Figure 2: Zonal plot of the number of Himawari-8 (left) and Meteosat-11 (right) infrared AMVs for 1st-7th June 2020. No screening has been applied.

2.3 Speed bias relative to model boundary layer

Preliminary investigation explored separating the statistics of the AMVs using their position relative to the model boundary layer. This highlighted a difference in average speed bias between winds assigned within the boundary layer and those assigned above it. The depth of the boundary layer in the model is estimated using a threshold on the bulk Richardson number (Seidel et al., 2012) which is a measure of whether the air follows stable, laminar flow or is dynamically unstable and likely to become or remain turbulent. Figure 3 gives an example of the typical model boundary layer top across the globe. Over the tropical ocean values are often around 900-950hPa, rising to around 800hPa in the extra-tropics.

In mixed boundary layers, clouds tend to form towards the top of the boundary layer while fog may form in lower regions, particularly in the case of a stable layer (Hartmann, 2015). Considering the boundary layer heights in figure 3 it is therefore likely that many of the Himawari-8 winds derived at pressures $>$ 950hPa are unphysically low. Though this is a widespread issue for Himawari-8, other geostationary satellites also feature winds very close to the surface. For Meteosat-8 and Himawari-8 low level winds were collocated with model estimates of the boundary layer height. The model data was produced on a reduced resolution Gaussian grid at a resolution of N640 (16km) and at hourly intervals in very short range forecasts up to T+11 hours from each 00Z and 12Z cycle. AMVs were matched to the nearest grid point within 30 minutes of the observation. Some of the AMVs assigned very high pressures coincide with the locations of boundary layer tops that are also close to the surface. However, many more very low AMVs can be found across a much broader area, particularly in the case of Himawari-8 where there are occurrences across much of the disk. Figure 4 shows the average speed bias for winds assigned above or below the boundary layer top have a pronounced difference in the tropics. Here there is a slow speed bias for both satellites for the very low AMVs. Above the boundary layer top there is a fast speed bias which might be expected from the earlier analysis of Meteosat-8 in the Indian Ocean but hints at a wider problem. The contrast for the extra-tropics is not as strong and does not follow the same tropical pattern.

This initial exploration with use of the boundary layer lends support to earlier work that some AMVs are too close to the surface while others may be placed too high. In the case of the extra-tropics, where the contrast between being placed above or within the boundary layer is smaller , the boundary layer is

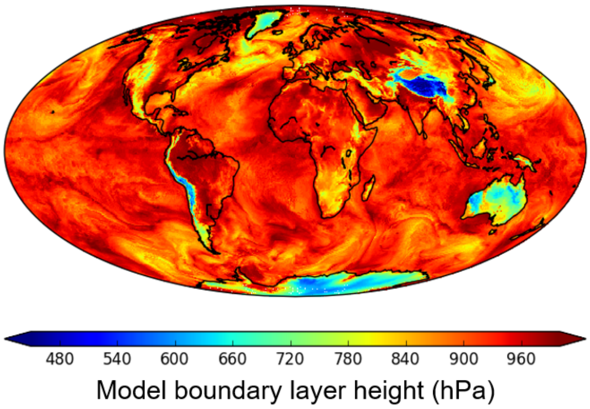

Figure 3: Typical height of model boundary top taken from 04Z on 4th Jan 2018

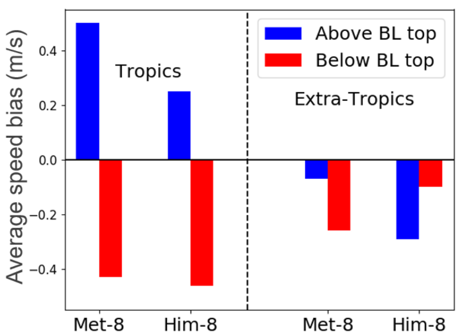

Figure 4: Average speed bias for low level infrared Meteosat-8 and Himawari-8 AMVs in the tropics (left) and extra-tropics (right) split by whether the assigned height was above (blue) or below (red) the collocated model boundary layer top. Data are for 3rd - 9th Jan 2018, data have been screened by quality indicator and first guess check and restricted to ocean only using land/sea mask where provided.

generally deeper so fewer AMVs are available between the boundary layer top and 700hPa. Diagnosis of the boundary layer height may also be subject to larger errors in unstable conditions (Lavers et al., 2019) such as the storm track regions. A correction for the unphysically low winds to the boundary layer top may hence be too crude, and less reliable in the extra-tropics, and it does not address the winds placed too high. To better understand the AMV errors and move towards a possible scheme for correcting the heights, we will instead consider a more detailed vertical structure of the atmosphere and establish the location of the model cloud.

3 AMV quality relative to model cloud

In the following, we will investigate background departure characteristics for low level AMVs in relation to the difference between the assigned pressure and the model cloud layer. The aim is to see to what extent the AMV height assignment is consistent with the model clouds, and whether background departure statistics indicate larger disagreements with the model winds in situations where there is larger disagreement between assigned height and the vertical positioning of the model clouds.

3.1 Estimating the cloud layer

The vertical extent of the model clouds is estimated from values of cloud liquid or ice water content and fractional cloud cover at the AMV location. The level of the cloud base is currently calculated in the Integrated Forecasting System (IFS) where the first model level above the surface satisfies the following criteria:

- Cloud liquid water (CLW) or cloud ice water (CIW) is greater than 10^{-6} kg/kg
- Cloud cover fraction is greater than 1%

In order to estimate the cloud layer for this study, vertical profiles of cloud variables are taken from the model backgrounds of research experiments which use a T_{Co}399 (25km) grid, 137 levels and provide data every 30 minutes for collocation with the AMVs. For each AMV, the model CLW/CIW and cloud cover profiles are checked at each model level against the criteria above starting from the surface. When at least three consecutive model levels meet the criteria and the cloud top is reached, the search stops and the layer top and base is recorded. Only low level clouds and AMVs (pressure $>$ 700hPa) are considered so it is possible that there may be a multi-layer cloud situation that is not detected or that the cloud in the model is at a lower pressure than 700hPa. The check for consecutive layers also means there is the possibility of missing thin cloud that exists on only one or two model levels. By requiring three levels the aim is to avoid noisy situations where the conditions are only marginally met for single levels. Model levels are closely spaced in the low troposphere for example ranging between around 20-100m apart below 900hPa for a standard atmosphere so this method still aims to capture relatively thin clouds. In the cases of Meteosat-8 and Himawari-8 around 85% of AMVs are matched with a model cloud.

3.2 Tropical Meteosat-8 AMVs

Statistics for the AMVs were calculated depending on the relative position to the model cloud top which reveals that the largest departures to the model background winds occur when AMVs are placed above the model cloud. Figure 5 confirms that the highest density of AMVs falls within the model cloud layer for both thick (layer depth > 100hPa) and thin cloud cases. This suggests considerable agreement between the cloud height assignment provided in the AMV product and the model clouds for a large proportion of cases. However, there are a significant number of AMVs above and below the model cloud, particularly in the thin cloud situations. The equivalent plots for the RMSVD shows for the AMVs above the model cloud top (with a relative position of < 0%) there are much higher values. Values for the AMVs placed below the model cloud (> 100%) show little change in RMSVD to those within the cloud. This suggests greater sensitivity to height assignment errors when the low level AMVs are placed too high compared to when they are assigned too close to the surface. While the visible channel winds are shown in this example, the infrared channel winds show similar characteristics.

Figure 5 also presents the AMV speed and the corresponding model background speed relative to the cloud layer. It is clear here, as noted in the average profiles earlier, that the model speeds exhibit a larger average wind shear with the most rapid change occurring within and above the top of the cloud. To explore this further, figure 6 shows individual example profiles of model variables collocated with tropical Meteosat-8 AMVs. The top row shows that the wind shear starts to increase above the boundary layer top with more rapid changes occurring between 850-750hPa. This means that the AMV assimilation is more sensitive to height errors in this region. Conversely, the AMVs that are too low will generally have smaller wind speed errors as a result of a height error. This corresponds to the smaller speed bias and stable RMSVD values compared to those above the cloud which implies that focusing on AMVs placed too high should be the greater priority. Figure 6 also illustrates how some of the higher AMVs are indeed faster than the model equivalent, whereas the AMV and model wind speeds match better around where the model cloud layer is (bottom left panel).

There are most likely several reasons why AMVs may be placed too high in some situations. One aspect is the handling of temperature inversions linked to the formation of cloud. An inversion correction is applied to Meteosat-8 (MSG Meteorological Products Extraction Facility Algorithm Specification Document, 2015), based on the temperature profile of a short-range ECMWF forecast, and Fig. 6 indeed includes some examples where temperature inversions are present in the model profiles. The current results may indicate some deficiencies with detecting or diagnosing the correct height of the inversion which may not be fully captured in the model profile or the coarser vertical representation used in the AMV processing[1]. While it would be possible to recalculate an inversion correction within the ECMWF observation processing using the higher resolution and latest model background information, we are here instead using the model cloud information directly, thus also capturing situations in which inversions may be weak or not fully resolved.

Multilayer clouds also present difficult situations for height assignment, in particular where optically thin high level cloud overlies low level cloud. In such cases the influence of the thin cloud in the pressure retrieval can cause the height of the low level cloud to be assigned too high. For example, Borde and Dubuisson (2010) suggest that multilayer clouds occur very frequently in tropical areas and using a CO_2 slicing method (which assumes a single layer cloud) revealed the height of the tracked low level cloud would often be somewhere between the two layers, ranging over several tens of hectopascals. Techniques to mitigate these issues include improving image pixel selection for the height assignment or using two-layer optimal analysis methods (Borde et al., 2014) however, multilayer cloud still remains a source of error in AMV height assignment (e.g. Heidinger and Li (2017); Cotton et al. (2020)). In using the model information, we have access to the whole vertical profile of cloud information leading to easier

[1] At present, processing for Meteosat-8 uses a 1°x1° grid and 30 vertical levels (MSG Meteorological Products Extraction Facility Algorithm Specification Document, 2015) which is much coarser than the 137 vertical levels in the model backgrounds used here.

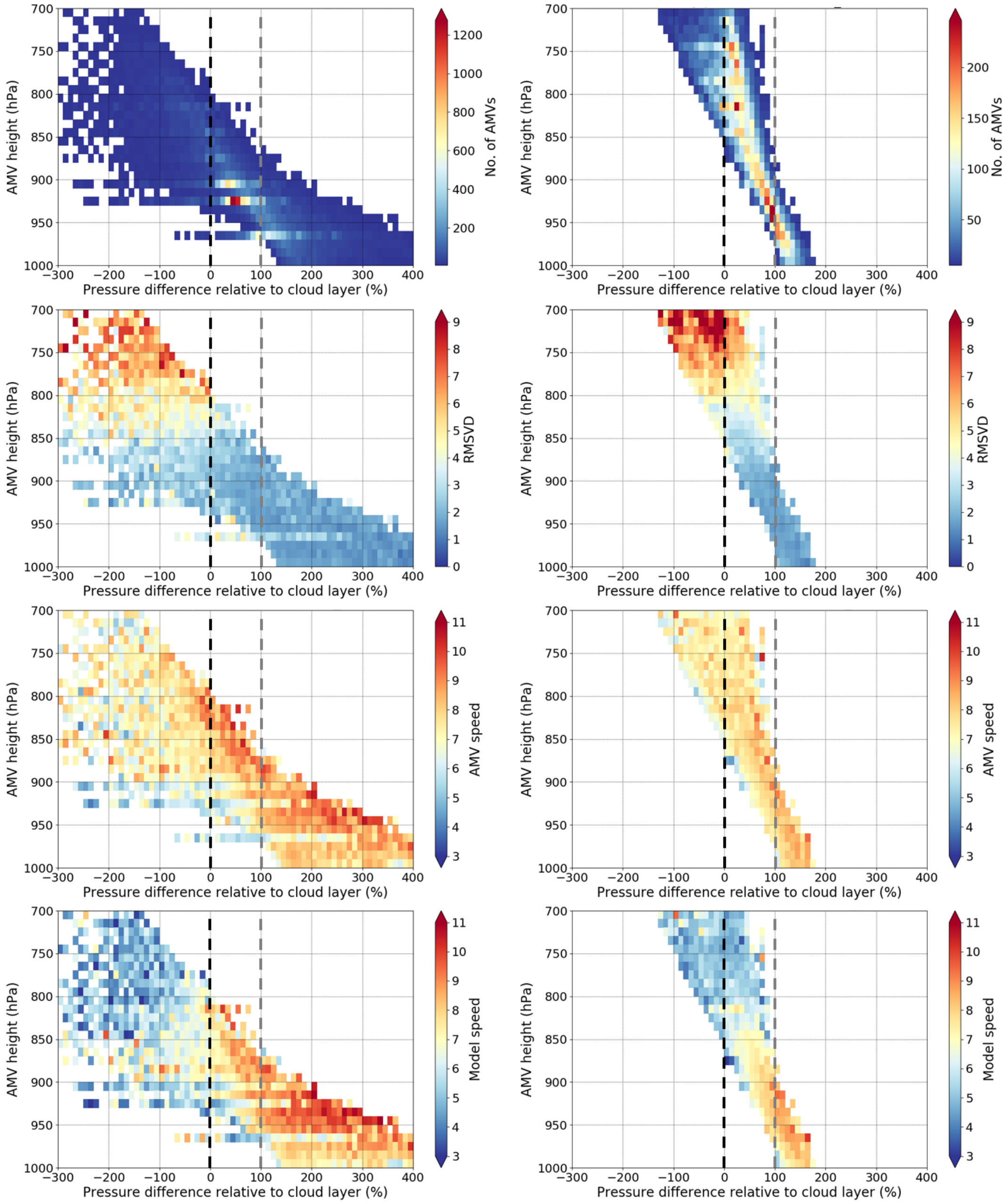

Figure 5: Histograms of the number of AMVs (top row), RMSVD (2nd row), AMV speed (3rd row) and model background speed at the assigned AMV pressure (bottom row) for low level visible Meteosat-8 AMVs in the tropics as a function of the difference between the model cloud top and the assigned AMV pressure (x-axis) and the assigned AMV pressure (y-axis). The x-axis scale is normalised by the thickness of the cloud layer, such that the black dotted line at 0% indicates the cloud top and the grey dotted line at 100% the cloud base. Cloud is split into thin layer (left column) and thick layer (right) where the threshold depth for thick cloud is 100hPa. Data are for 1st-5th Oct 2019 over sea, screened by the AMV quality indicator.

identification of the placement of the layers.

It should be noted here that the wind shear structure represented in the model is not free from error in certain situations either. For instance, Bechtold et al. (2012) highlights issues in low level winds particularly in the East tropical Pacific where there are potential errors in the cross equatorial flow. The model is shown to have difficulty with representing strong wind shear over strong sea surface temperature gradients but the AMVs at that time (GOES-13) also suffered from higher observation errors in the area of concern. However, the study concludes that there is uncertainty in quantifying the wind flow errors and coupled with the localised nature, the impact is expected to be small on the height reassignment carried out here. Sandu et al. (2020) meanwhile focuses on issues in the trade wind boundary layer where the zonal winds are found to accelerate in the first 12 hours of the forecast at the cloud base with the effects propagating downwards to directional and speed biases at the surface. However, the low level AMVs identified here as most detrimental are above the model cloud and therefore more often above the boundary layer. While investigating optimal vertical sampling for Aeolus, Houci (2016) assessed high resolution radiosonde data collocated with the ECMWF short-range forecast. The study showed that while the model has some difficulty to capture small scale vertical structures, there is good agreement in the horizontal wind across different geographical regions and heights. This is consistent with the results shown in figure 1 which demonstrated that for the Indian Ocean the average wind profile is in good agreement with Aeolus and the limited conventional data.

3.3 Extra-tropics and Himawari-8

Much of the behaviour seen for Meteosat-8 in the tropics also extends to the extra-tropics such as increasing RMSVD values particularly for AMVs placed above the cloud in both the thick and thin cloud situations (figure 7). The speed bias (not shown) also exhibits similar behaviour to the tropics where less variation in the AMVs compared to the model background results in larger biases above the cloud top placement. Further consideration of profiles such as those in figure 6 generated in the extra-tropical region (not shown) also display an increase in model wind shear above the boundary layer.

Other satellites and extra-tropical areas also show larger disagreements between AMVs and background equivalents when the low level AMVs are assigned above the model clouds, whereas assignment below the model clouds does not show elevated RMSVD values. While the distribution of AMVs can differ markedly (see, for instance, many more AMVs close to the surface for Himawari-8 compared to Meteosat-8 in Figure 8), the pattern of elevated RMSVD values when the AMVs are assigned above the model clouds tends to be broadly similar, particularly for thin cloud situations (e.g., 8). Similarly, example profiles for Himawari-8 also display a much lower amount of wind shear in the model below the boundary layer top suggesting that assignment too close to the surface does not translate to such a large error in speed, especially for cases of cloud within the boundary layer.

4 Benefits from height reassignment

In the previous section we have shown that there are some AMVs being assigned above the model cloud in layers of greater model wind shear where sensitivity to height errors is increased. Extending the analysis of Meteosat-8 beyond the localised area first identified in the tropical Indian Ocean indicates that this is a wider geographical issue and results from Himawari-8 suggest this problem may also impact other satellites. The investigation now turns to whether we can extract more positive impact from a different treatment of the AMVs, considering all the geostationary satellites, either through a height reassignment

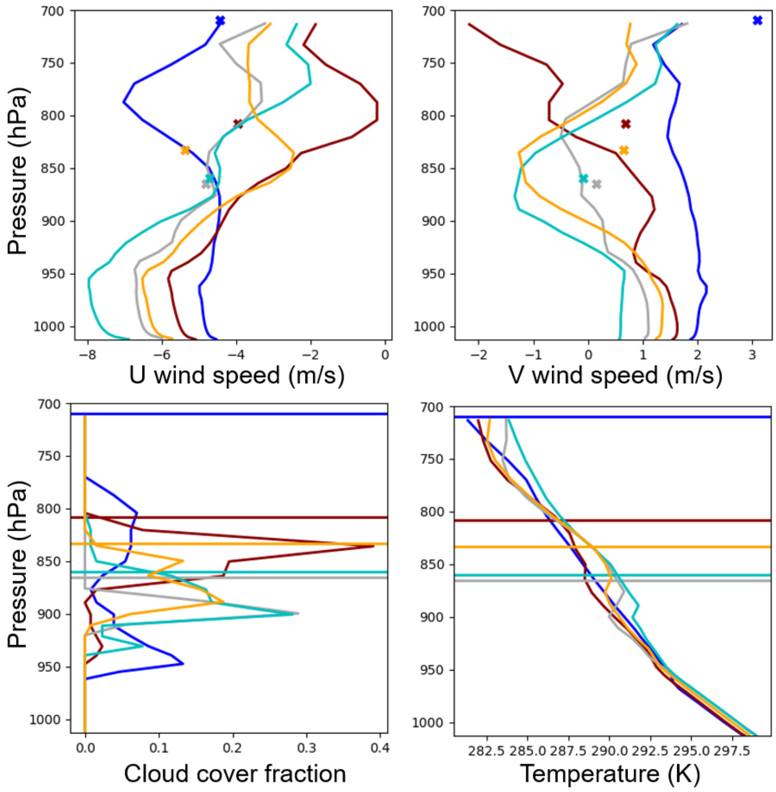

Figure 6: Example model profiles collocated with Meteosat-8 AMVs within a small box in the tropical Indian Ocean, 20-25°S, 65-70°E. Model U component (top right) and V component of wind speed (top left) with the AMV height and speed marked by cross, cloud cover (bottom left) and temperature (bottom right) with the AMV height marked by solid lines. Dotted lines indicate the corresponding model boundary layer top for each profile. Colours are used only to distinguish each AMV - model profile pairing. AMV data are for Meteosat-8 IR 5z 4th Jan 2018 and have been screened using quality indicator and first guess check.

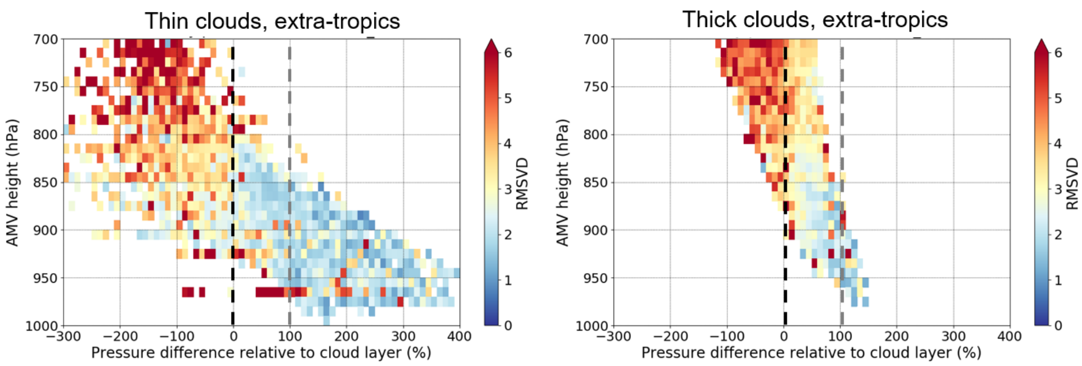

Figure 7: Values of the RMSVD as a function of the difference between the model cloud top and the assigned AMV pressure (x-axis) and the assigned AMV pressure (y-axis) for low level visible Meteosat-8 AMVs in the extra-tropics, similar to Fig. 5.

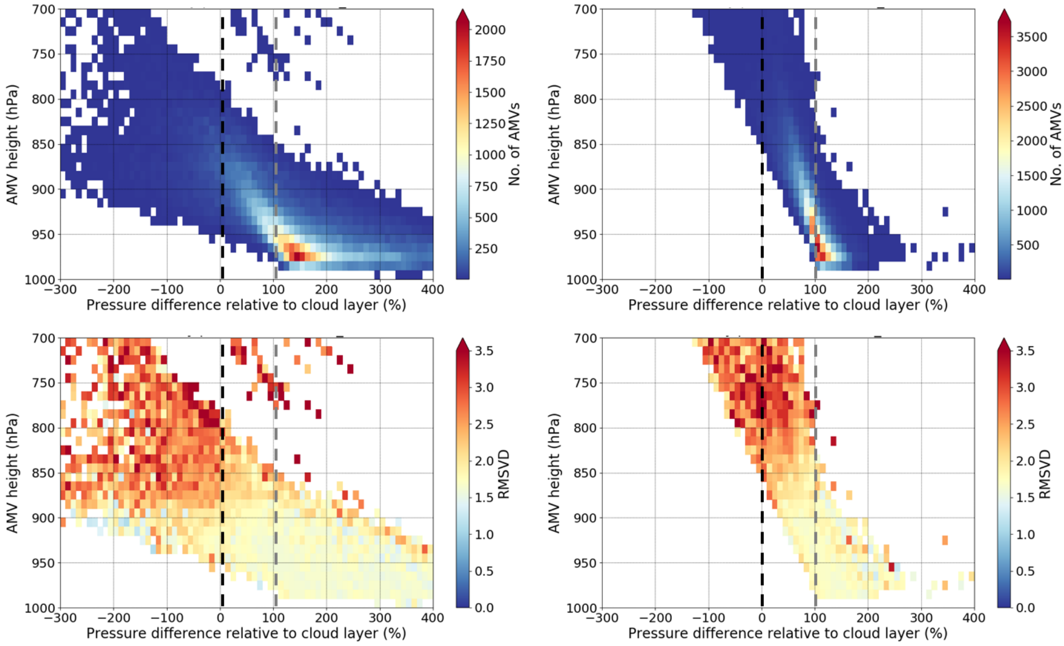

Figure 8: Values of the number of AMVs (top row) and RMSVD (bottom row) for low level visible Himawari-8 AMVs in the tropics, similar to Fig. 5.

or screening them entirely. AMVs assigned below the model clouds, and some even unphysically close to the surface, did not show similarly degraded statistics. In this case the benefits of a height correction would likely be difficult to quantify as this is a region more resilient to height errors. While it may be worth revisiting this is the future, the focus for the rest of this report will be to address AMVs assigned too high.

To study the effect of height reassignment on departure statistics, initial assimilation experiments were run which reassign the AMVs to selected levels given by the model clouds. These use the criteria for finding the cloud layer outlined in section 3.1, and reassign the heights of the AMVs if the original height of the AMV is:

- Above the top of the model background cloud
- Between 900 - 700hPa

A limit of 900 hPa was set after the analysis in section 3 found only a small number of AMVs that are assigned above the cloud but below 900hPa, and these showed little degradation in the statistics. Three different configurations allowed the affected AMVs to be reassigned consistently to either the cloud top, cloud base or to the middle of the cloud by using the average pressure of the layer. The AMVs are then subsequently subject to the normal processing and screening before assimilation. A further experiment was set up to identify the AMVs above the cloud but instead removed them from the assimilation. This experiment also provided the statistics for the AMVs at their originally assigned height. The experiments were run for three weeks in autumn (where some of the strongest impacts on the Indian Ocean had been noted in Lean and Bormann (2018)) starting 1st Oct 2018 and for a further three weeks in a spring period

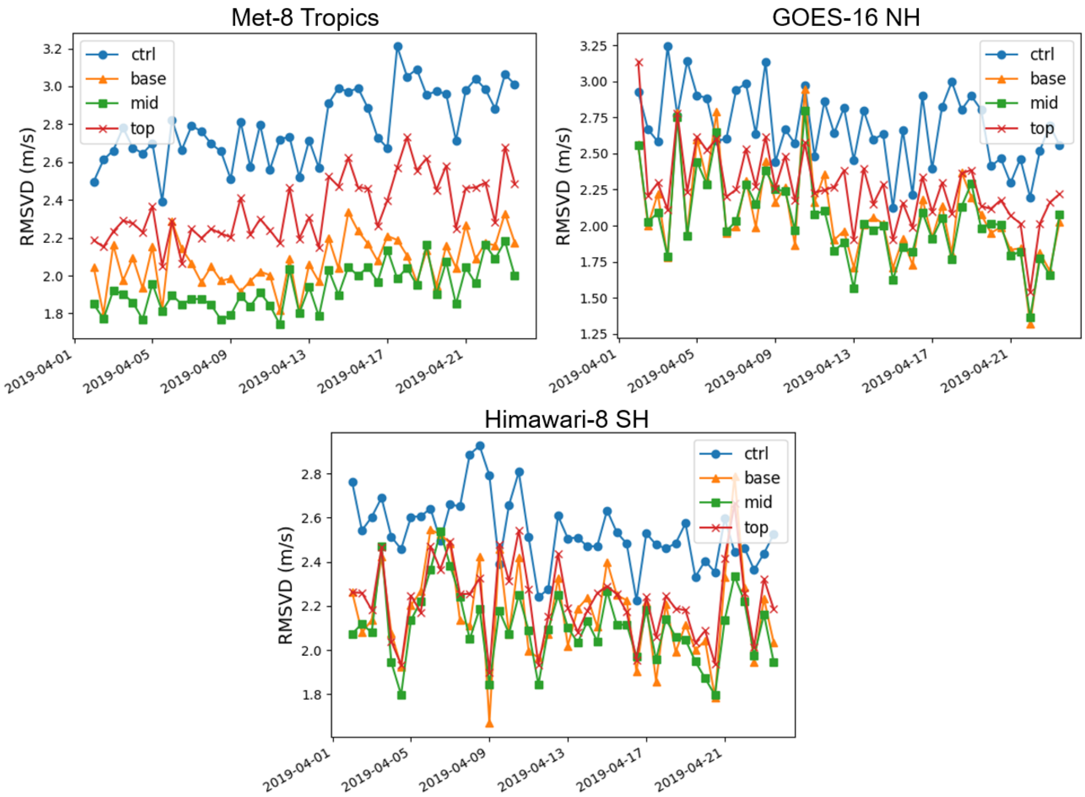

Figure 9: Time series for Meteosat-8 in the tropics (top left), GOES-16 in the northern hemisphere (top right) and Himawari-8 in the southern hemisphere (bottom) using only low level visible AMVs initially diagnosed as above the model cloud. The average RMSVD for each model cycle is calculated when the AMV is at the original height or reassigned to the cloud top, cloud base or average layer pressure of the cloud. Data are for 2nd - 23rd Apr 2019 and have been screened by first guess check.

starting 2nd April 2019. They use 12-h 4D-Var with a model resolution of $T_{Co}399$ (25km), and an final incremental analysis resolution of T_L255 (80km).

Using only the AMVs diagnosed for reassignment/rejection using the criteria above, the time series of the average RMSVD for each 12 hour model cycle (figure 9) show that values are significantly lower after the reassignment. A selection of satellites and regions of the disc are given here to represent the wider benefit of this correction. Moreover, reassignment resulted in a lower RMSVD on average for all five geostationary satellites in both the tropics and extra-tropics and autumn and spring periods. The only exception is Himawari-8 in the northern hemisphere where there is no clear reduction in the RMSVD. In the plots shown in figure 9, and more generally, reassignment to the average pressure of the cloud or the cloud base produced the lowest values. The improvement seen here in using the cloud layer average agrees with studies suggesting that a level within the cloud or use of a layer average is more representative e.g. Hernandez-Carrascal and Bormann (2014); Velden and Bedka (2009); Folger (2016).

Examples of the corresponding changes in average speed bias are presented in figure 10. These show that in addition to reducing the RMSVD, it is also possible to improve the speed bias with the height reassignment. For example, the positive speed bias in the tropical Meteosat-8 AMVs becomes close to zero when the height is reassigned to the average pressure of the model cloud layer. While the improvement

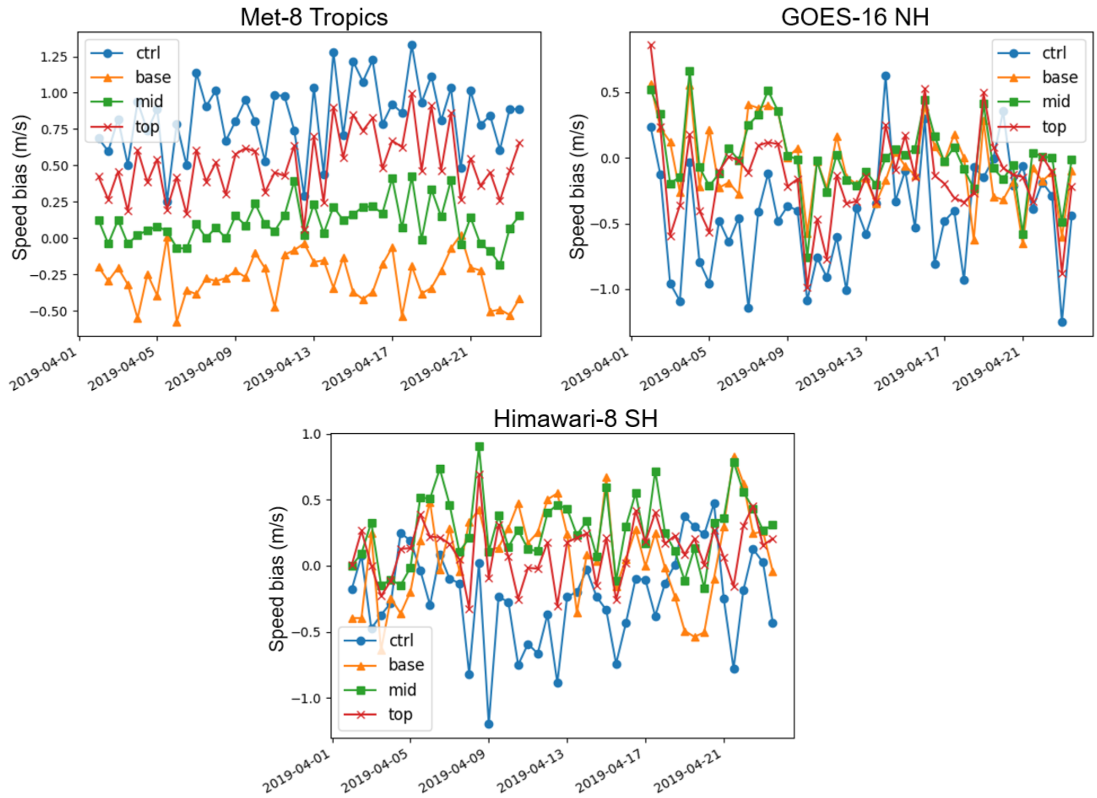

Figure 10: Time series for Meteosat-8 in the tropics (top left), GOES-16 in the northern hemisphere (top right) and Himawari-8 in the southern hemisphere (bottom) using only low level visible AMVs initially diagnosed as above the model cloud. The average speed bias for each model cycle is calculated when the AMV is at the original height or reassigned to the cloud top, cloud base or middle of the cloud. Data are for 2nd - 23rd Apr 2019 and have been screened by first guess check.

through reassignment is also observed more generally, unlike the RMSVD it is not always as obvious which of the three reassignment options has a larger advantage.

Returning to the area of the Indian Ocean (50-100°E, 5-25°S) that was a key motivation for this work, the average profiles of the U component of speed and the distribution of AMVs were generated again for the different height reassignment options. Here, only those observations that met the reassignment/screening criteria have been included in the statistics. Figure 11 shows the distribution of the AMVs shifting during the reassignment as expected with a change in the peak density of over 100hPa from the original height assignment to using the cloud base. In the corresponding plots of the bias in the U component, the negative bias that develops above around 850hPa is greatly reduced in the reassignment to the middle or base of the cloud, and there are far fewer AMVs that remain in the layer. However, there is a positive bias of around 1m/s emerging for those new heights at pressures $>$ 900hPa. Average background departures in these low level tropical regions for winds already assimilated at ECMWF are typically up to around 1m/s so this speed bias is not necessarily problematic. The V component bias above 850hPa (not shown), though a smaller magnitude of around 0.5m/s, is also further reduced with reassignment, particularly to the cloud middle.

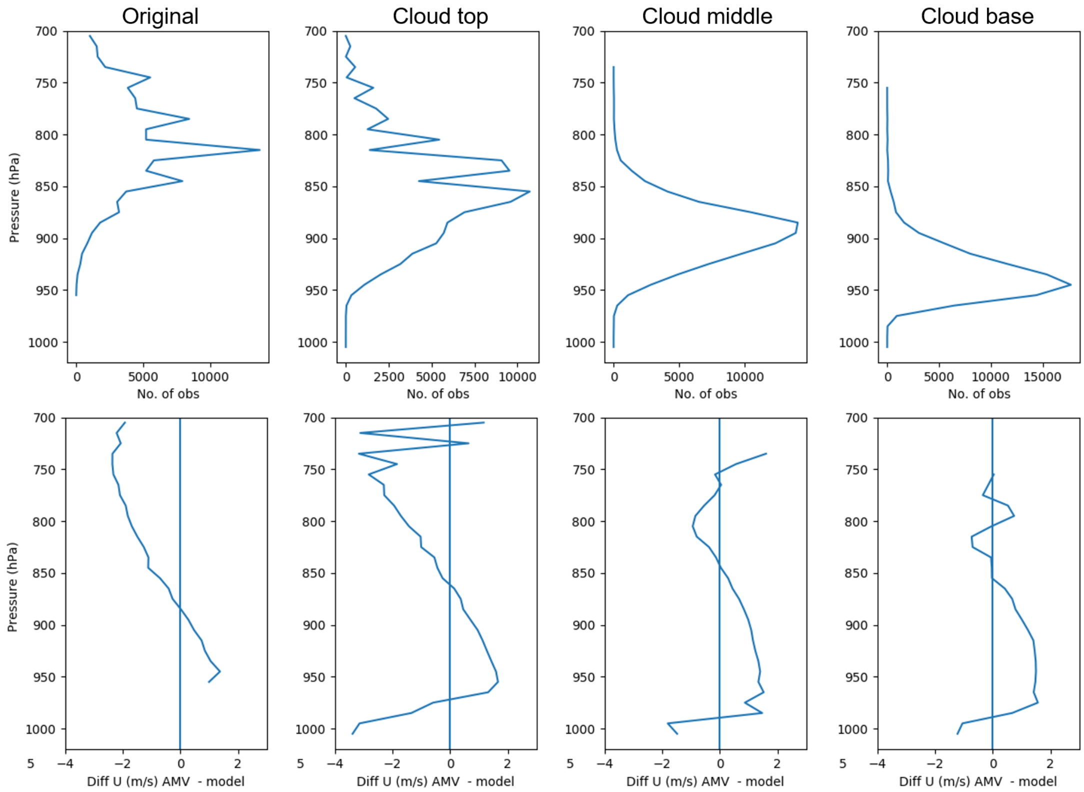

Figure 11: Meteosat-8 visible AMVs using (from left to right) the original height and reassigned height to top, average pressure or base of cloud compared with ECMWF model background wind. Top row: vertical distribution of AMVs. Bottom row: U component of wind. Data are for 1-31st Oct 2018, over the area 50-100°E, 5-25°S and have been screened by quality indicator and first guess check.

5 Assimilation experiments

Analysis of the low level AMVs using the model estimate of the cloud has identified possible detrimental impacts from the winds being assigned too high where regions of greater wind shear result in an increased sensitivity to height errors. Reassigning the height of the affected AMVs using the model cloud top, base or average pressure shows promising reductions in RMSVD and speed bias. The next step is to use assimilation experiments to examine whether these strategies have a positive impact on the forecast.

Two seasons were considered - 20th June - 30th Sept 2019 and 1st Dec 2019 - 31st Mar 2020 - providing over seven months of verification. All experiments run here use cycle 47r1 of the IFS , with a model resolution of $T_{Co}399$ (25km) and 137 levels in the vertical. All employ 12-hour 4D-Var with a final incremental analysis resolution of T_L255 (80km). The control experiment uses the original, unadjusted heights for all AMVs. Three experiments tested reassigning low-level AMVs from all five operationally used geostationary satellites to either the model cloud top, base or average pressure of the cloud, respectively. Reassignment for the polar satellites is not currently considered as quality control procedures currently remove all AMVs with assigned pressures greater than 700hPa. Criteria for which AMVs are reassigned are the same as those used in section 4 for the background departure analysis. Aside from the height reassignment, the processes of data selection, thinning and observation error calculation remains otherwise unchanged from the control. Note that the original height is used for the calculation of the situation-dependent observation errors. This is to investigate the height-assignment aspect in isolation, separate from implicit changes in the assigned observation errors. As the re-assignment tends to place the AMVs in regions of lower shear, the contribution in the observation error model relating to height assignment could instead be reduced, and this could be investigated further in the future.

Prior to running the experiments presented here, a further two seasons had also been completed using the previous model cycle, 46r1. In addition to evaluating the reassignment of the heights, a further configuration was considered which screened the affected AMVs to assess whether not using the data at all could instead be more beneficial. In the verification against own analysis, positive signals were present in a similar location but with a smaller magnitude to the experiments reassigning the heights. However, in the fit of independent conventional winds observations screening the AMVs showed a small signal of degradation in the southern hemisphere while there was also a negative signal in the tropical Aeolus winds not present in the reassignment experiments. Additionally, the reassignment appeared to perform slightly better than the screening option for instruments with cloud sensitivity. These experiments suggested that screening the winds does not perform as well as height reassignment and therefore this strategy was not pursued in the subsequent experiments described in more detail here.

5.1 Impact on mean wind analyses

Figure 12 first shows the change in the mean low level wind analysis which reveals that the largest changes are confined within the tropics and over the ocean, and these are typically less than 0.2 m/s. While the example shown here uses reassignment to the average pressure of the cloud layer, similar patterns are seen in the other experiments although the change for using the cloud top is noticeably smaller in magnitude. The orange area of the U component in the tropical Indian Ocean to the east of Madagascar shows the slowing of the zonal winds in this region. The trade winds around the equatorial region generally have a westward direction so in other ocean basins the changes correspond to a mixture of slowing (red) or increasing (blue) the zonal component. For the V component, the dipole across the equator in the Atlantic and Pacific Oceans indicates a weakening of the convergence.

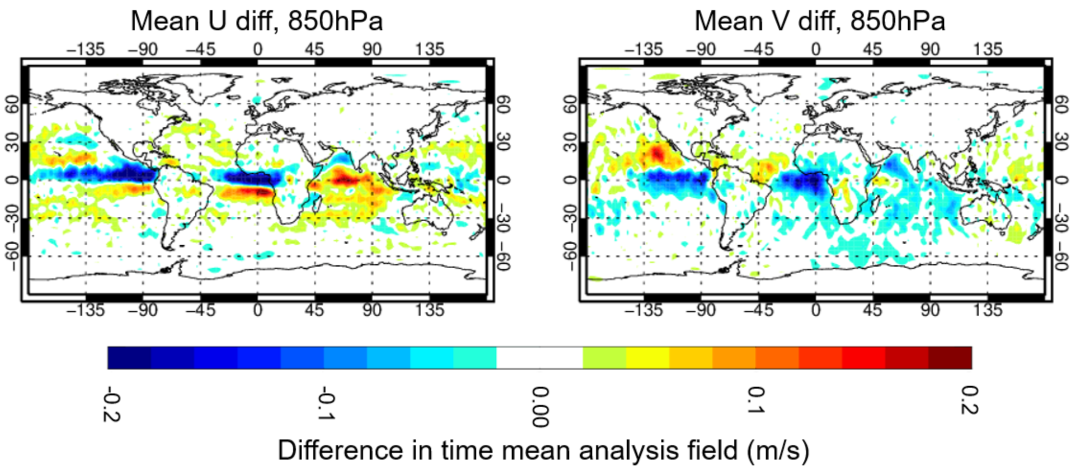

Figure 12: Mean change in the analysis wind field for the U (left) and V (right) component at 850hPa where AMVs identified as too high have been reassigned to middle of the model cloud. Average is over the period 20th June - 31st Sept 2019 and 1st Dec 2019 - 31st Mar 2020.

It has in the past been difficult to validate such changes to the mean wind analysis against other wind observations, though with the advent of Aeolus data the situation has improved. The change in the mean horizontal line-of-sight (HLOS) wind speed analysis departure (observation - analysis) in the tropics and extra-tropics (where the largest wind analysis changes occur) for Mie winds (scattering from clouds) in the 800-900hPa layer is illustrated in figure 13. Data from the ascending (local equator crossing time 18:00) and descending parts of the orbit have been separated. Encouragingly, the ascending part of the orbit shows support for the AMV change with areas of reduction in the analysis departure such as in the tropical Atlantic Ocean. The descending orbit data shows a more mixed picture and even conflicts with some of the ascending patterns where the change to the analysis departure has a different sign, for instance in the northern Indian Ocean. When considering the original pattern of analysis departures calculated using the control, there are differences in the HLOS wind speed bias sign and magnitude between the ascending/descending data. No orbital bias concerning the Aeolus instrument is known to affect the observations used here (pers. comm. M. Rennie, 2021) so this may be highlighting diurnal variation in the model or caused by changes in AMV usage between local daylight and night-time hours. Low level winds derived from the infrared channel in the tropics are screened leaving only visible winds and therefore no assimilated tropical low level AMVs used outside of local daylight hours. Importantly, the AMV reassignment is not showing any concerning degradation in either part of the orbit but clearer benefit in the Aeolus ascending phase may be as a result of more adjusted AMV data assimilated in the immediately preceding hours or better cloud representation in the model in the early evening.

As the changes are applied to the low level winds, it is also relevant to consider the impact on the surface winds measured by scatterometer data. Maps of the change in scatterometer speed bias (figure 14) show that the bias improves (blue colours indicate a smaller magnitude) particularly in the tropical regions just south of the equator. Similar results were seen in both seasons and ASCAT instruments.

Note that the change in the mean meridional component of the wind analysis is confined around 850hPa with little coherent change evident at the surface. Sandu et al. (2020) have highlighted that at the surface the equatorial convergence is not strong enough. Although this initially seems at odds with the changes caused by the AMV height reassignment, these two results are not incompatible - strong flow separation

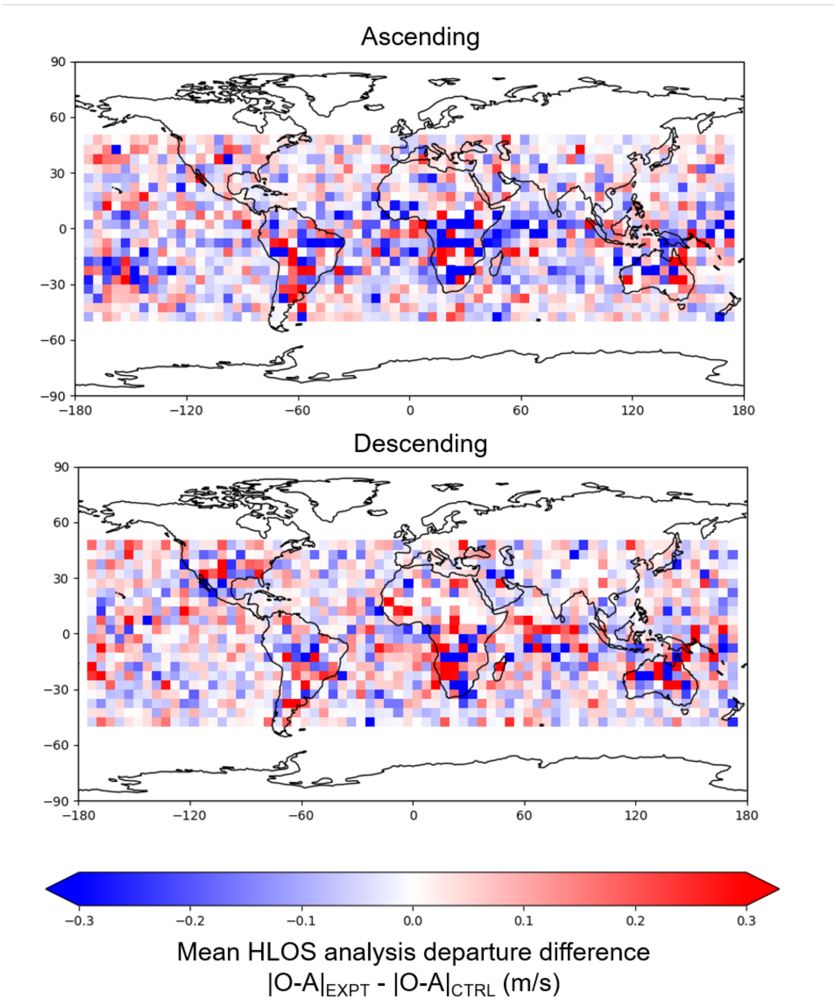

Figure 13: Maps of the change in Aeolus HLOS absolute value of analysis departure (observation - analysis) comparing an experiment where affected AMVs are reassigned to the average pressure of the cloud layer to the control with no change to the data use. Data are assimilated Mie winds only in the pressure layer 800-900hPa and split into ascending orbit (top panel) and descending orbit (bottom panel). Aeolus is used globally but to focus on areas of greatest wind analysis change, only the tropical and extra-tropical latitudes are shown here. Data are from 9th Jan - 31st Mar 2020. Blue colours indicate a smaller magnitude bias in the experiment.

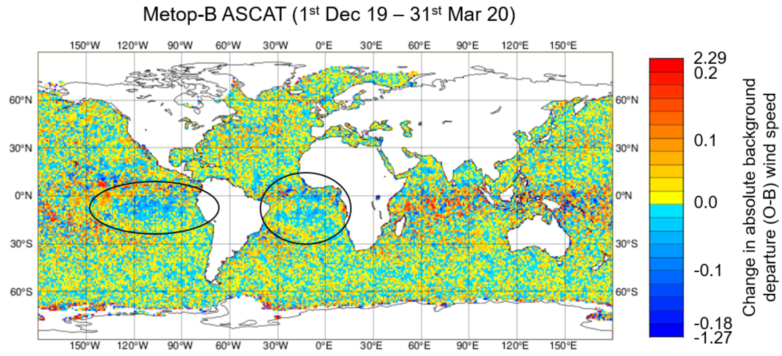

Figure 14: Maps of the change in Metop-B scatterometer speed bias comparing an experiment where affected AMVs are reassigned to the average pressure of the cloud layer to the control with no change to the data use. Data are from 1st Dec 2019 - 31st Mar 2020. Circles highlight areas of smaller magnitude bias in the experiment (blue colours).

between layers above and below 850hPa can allow different effects to take place. The interactions between changes in wind speed and heating or vertical mixing can be complex and nonlinear so the link between changes at the surface and at an altitude of around 1.5-2km are not straightforward. Sandu et al. (2020) also discuss the potential growth in error detected within stable trade wind regions within the first 12 hours of the forecast. The positive impact seen in the scatterometer speed bias suggest that where changes as a result of the AMVs do propagate to the surface, they are improving the model surface wind field in this very short-range forecast.

5.2 Forecast impact

The zonal plots of the verification against own analysis (figure 15) show that across the three experiment configurations there is a consistent reduction in the tropical vector wind error to day three of the forecast. This reflects the smaller background departures noted for AMVs earlier and shows a better consistency between the analyses and forecasts in the experiments with re-assignment. The improvements are significant with the reassignment to the cloud base and middle appearing to cover a slightly larger area in T+48 and T+72 than using the cloud top. Displaying the reduction on a map (for example figure 16) reveals that the improvement is spread across the different tropical ocean basins and not restricted to coverage of a subset of the geostationary satellites . Nevertheless, the signal is weaker under the disc of Himawari-8 in the western Pacific. Analysis in section 3.3 and 4 suggested that the issues for Himawari-8 may be less pronounced, consistent with this more neutral impact after reassignment. A small positive signal appears in the north polar region for the different reassignment options. The AMV heights are not adjusted in the polar regions so a direct source of this impact is not clear but a possible explanation could be that changes in the convergence in lower latitudes may sufficiently influence the large scale circulation to affect the polar regions. Additionally, there are small but significant reductions for the three experiments in the short-range forecast error for low level tropical humidity and temperature (figure 17). Note that forecast verification against operational analyses shows more neutral results.

To more closely assess the impact on the short-range forecast performance, we also consider whether the model background has been improved and therefore is in better agreement with other observations.

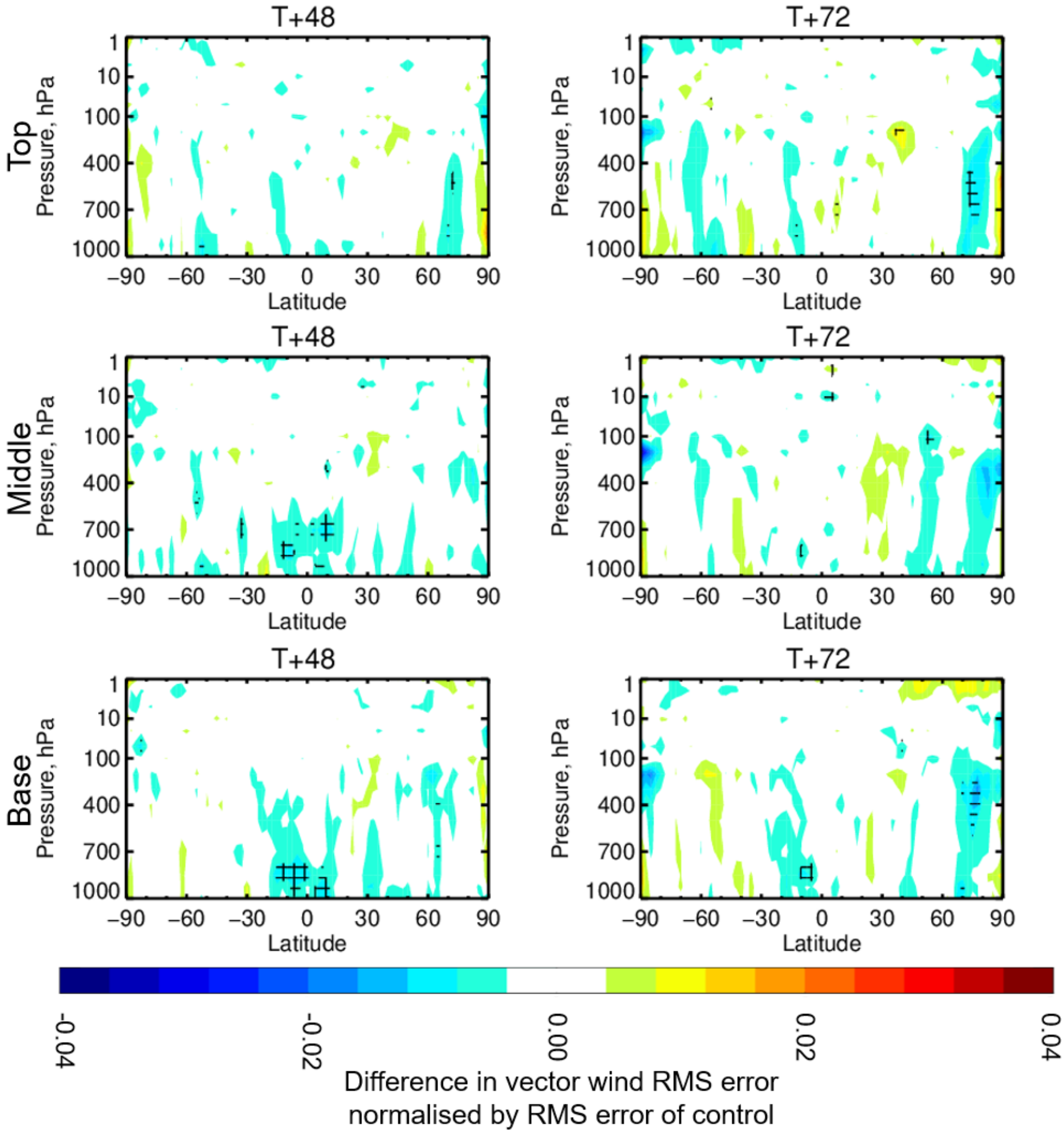

Figure 15: Zonal plots of the change in vector wind RMS error verified against own analysis for 48 and 72 hour lead times comparing experiments where affected AMVs are reassigned to the cloud top, average pressure or base to the control with no change to the data use. Data are from 20th June - 31st Sept 2019 and 1st Dec 2019 - 31st Mar 2020. Black hatched lines indicate significance at the 95% level.

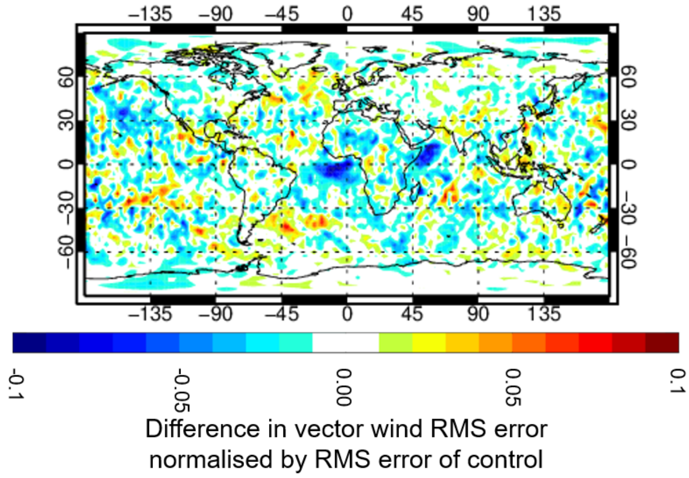

Figure 16: Map of the change in vector wind RMS error verified against own analysis at 850hPa for 48 hour lead time comparing an experiment where affected AMVs are reassigned to the middle of the cloud to the control with no change to the data use. Data are from 20th June - 31st Sept 2019 and 1st Dec 2019 - 31st Mar 2020.

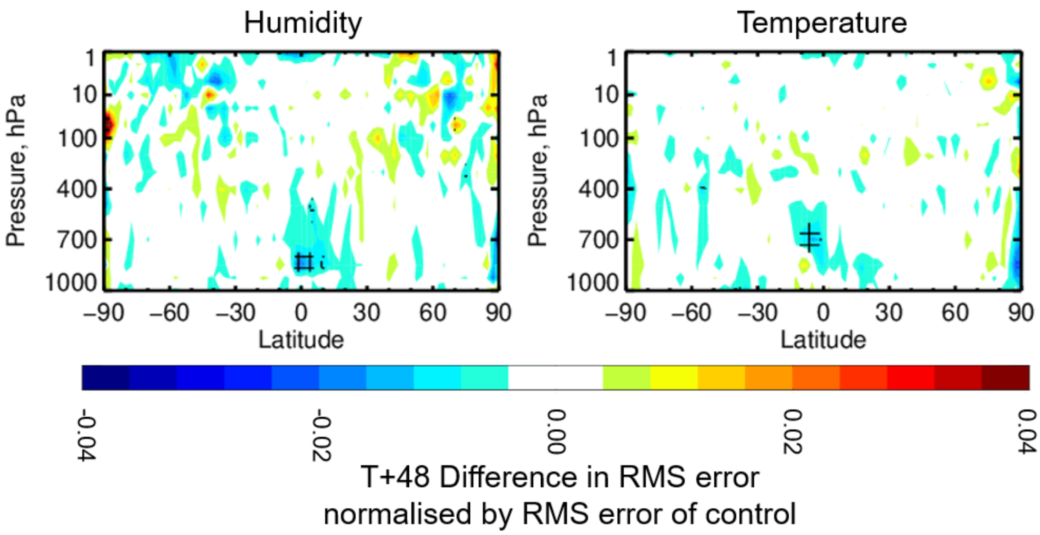

Figure 17: Zonal plots of the change in humidity (right) and temperature (left) RMS error verified against own analysis for 48 hour lead time comparing an experiment where affected AMVs are reassigned to the middle of the cloud to the control with no change to the data use. Data are from 20th June - 31st Sept 2019 and 1st Dec 2019 - 31st Mar 2020.

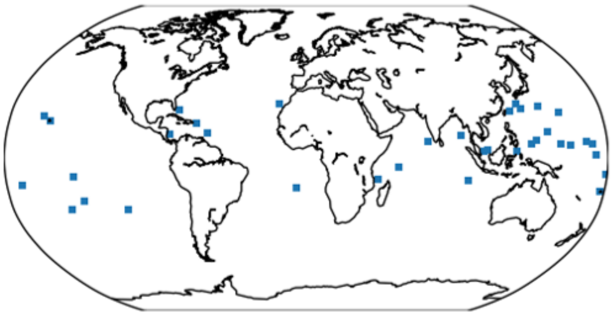

Figure 18: Locations of radiosonde sites chosen to verify the impact of height reassignment seen mainly in the tropical ocean.

Use of conventional observations is difficult as the impact is mainly over ocean (as shown in figure 16) where data is very sparse. However, Aeolus provides sampling of the affected regions, and was included in the assimilation from 9 January 2020, consistent with its operational use at ECMWF. While the signal is relatively small, Aeolus shows a statistically significant reduction in the standard deviation of background departures around 850 hPa for the re-assignment to the model cloud top or the cloud average pressure (figure 20). This further confirms a small improvement in the short-range forecasts. Verification against radiosonde wind observations is less conclusive. A subset of conventional data sites was selected, using small island stations, to try to focus on the tropical ocean with the largest changes in forecast scores (figure 18). The changes in standard deviation of first guess fit to the wind speed (figure 19) suggest largely neutral impacts for the lower levels. There is a small signal of degradation around 200hPa for the base and middle of the cloud reassignment where the uncertainty bars show it has just reached significance. This is well above the levels directly affected by the height re-assignment, and there is no indication of degradation in analysis-based forecast scores at these levels. The signal is also not repeated in the reassignment to cloud top and was not seen in earlier 46r1 experiments. It is hence likely that this is not fully representative of the wider region, as the sampling is still very sparse and unevenly distributed around the tropics as illustrated in figure 18.

Other observations that are more indirectly linked to the changes in the wind field also suggest some small benefits for the short-range forecasts. Improvements are also seen in the fit of the microwave imager Special Sensor Microwave Imager/Sounder (SSMI/S) with positive signals not quite reaching significance in Advanced Microwave Scanning Radiometer 2 (AMSR2). Used in an all-sky framework, these instruments are particularly sensitive to changes in cloud (figure 21). Similar results were also seen in the earlier 46r1 experiments. This lends support to the changes in the strength of the tropical convergence noted earlier. Humidity sounding instruments however generally showed neutral changes. The positive impacts in the verification presented here give further confidence that the change to the AMVs can improve the region around 850hPa that it directly affects while not exacerbating near surface wind biases.

5.3 Discussion and interaction with new moist physics

The experiments have shown promising results for the height reassignment of the low level winds diagnosed above the model cloud. The results discussed here focus on using the currently operational IFS version, cycle 47r1 however, as mentioned earlier, initial experiments used the previous cycle 46r1. En-

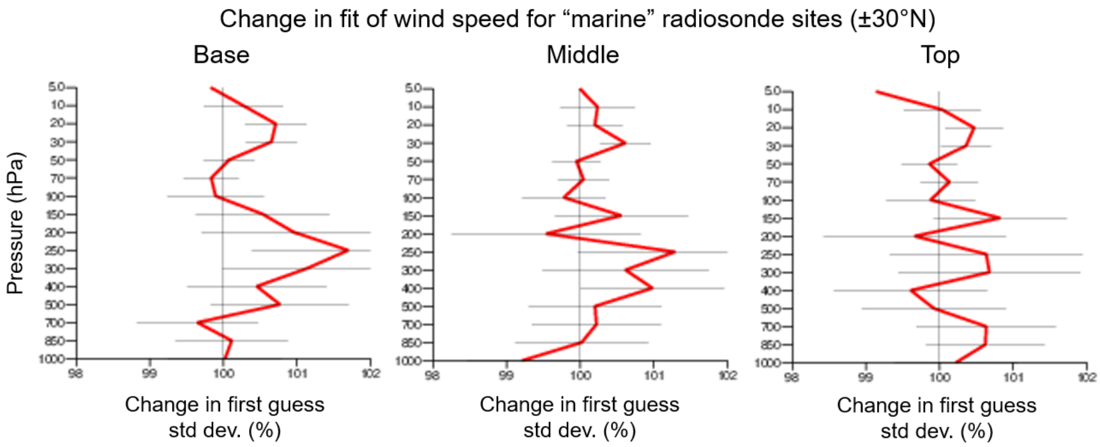

Figure 19: Change in the standard deviation of the first guess wind speed of the marine radiosondes (latitude ± 30°N) for all experiments reassigning heights of affected AMVs to the cloud base (left), average pressure (middle) and top (right) compared to the control with no change to the data use. Data are from 20th June - 31st Sept 2019 and 1st Dec 2019 - 31st Mar 2020.

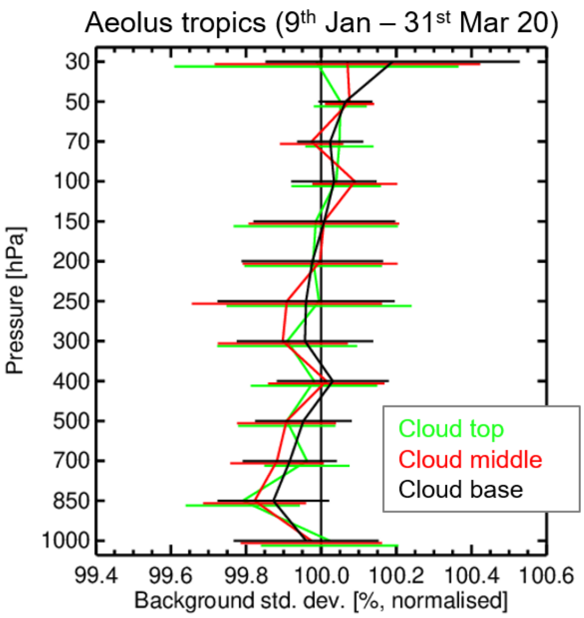

Figure 20: Change in the first guess standard deviation fit of the model background to Aeolus HLOS winds (cloudy Mie and clear sky Rayleigh scattered situations) for the experiments where affected AMVs are reassigned using the model cloud compared to the control. Data are from 9th Jan - 31st March 2020 after Aeolus entered operational assimilation.

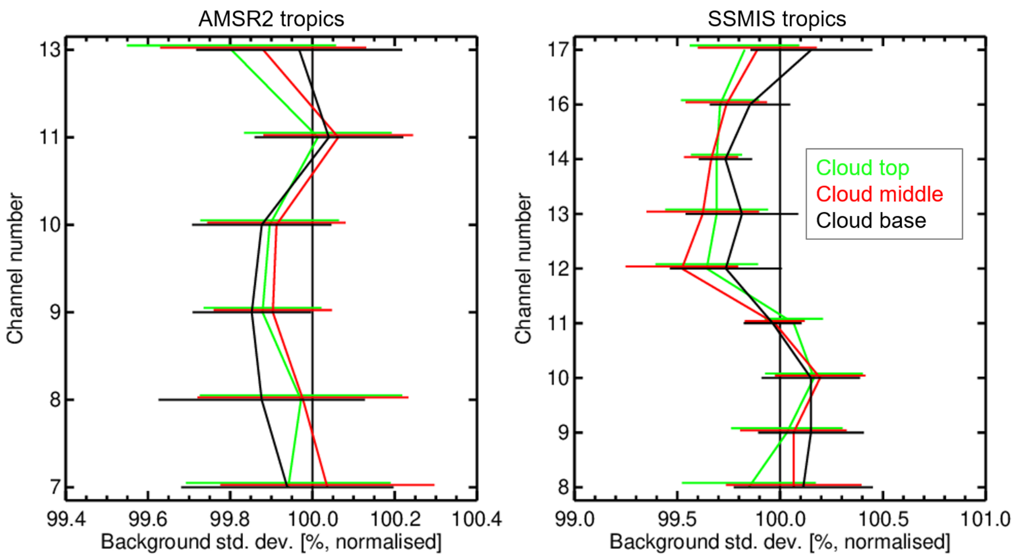

Figure 21: Change in the standard deviation of the first guess brightness temperatures of the AMSR2 and SSMI/S imagers over the tropics (latitude ± 20°N) for all experiments reassigning heights or screening affected AMVs compared to the control with no change to the data use. Data are from 1st Oct 2018 - 31st Jan 2019 and 2nd Apr -31st Aug 2019.

couragingly, many of the positive impacts seen here were present in both adding reassurance of a robust signal. Across both sets of experiments, the reassignment to cloud base or average pressure appeared slightly more favourable than the cloud top. Earlier investigation using background departures showed use of the average pressure as consistently performing best in the reduction of RMSVD. Combined with the experiment results, the average pressure of the cloud layer is recommended for future operational use.

There is a major upgrade to the moist physics scheme in development at ECMWF intended for operational use as part of the next IFS upgrade (Bechtold et al., 2020). One of the key aims of these changes will be to improve the representation of low level cloud. A more accurate cloud distribution would be beneficial for the AMV height reassignment. To make sure of the compatibility with the AMV change, a short, one-month experiment was run which tested the AMV change in addition to the most up to date version of the moist physics upgrade (small refinements were still ongoing at the time of testing). Reassuringly, similar positive impacts seen in the experimentation presented here are retained although the short time period meant signals had not often reached significance.

6 Summary

Earlier work at ECMWF has highlighted potential height assignment issues in the low level AMVs, particularly in the Indian Ocean and for Himawari-8. The data quality of the AMVs was assessed as a function of the AMV height relative to the cloud layer placement estimated by the forecast model. This revealed that AMVs diagnosed above the model cloud height estimate generally exhibited larger RMSVD and speed bias values. A tendency for greater wind shear above the model cloud means there is more sensitivity to height assignment errors in this region. For AMVs close to the surface and below the model cloud, data quality remained stable which may be related to little wind shear. The choice was made to focus on the AMVs potentially placed too high where larger wind shear means height assignment error may be more damaging in the assimilation. Reassigning the height of affected AMVs to either the model cloud top, base or average pressure generally improved the RMSVD and speed bias with the average cloud pressure often performing best. Extending the analysis to other geostationary satellites also revealed that the positive impact of reassignment of the background departures was widespread in satellite and geographical area.

Assimilation experiments showed positive impacts from using any of the three options of reassigning AMVs diagnosed above the model cloud to the cloud top, base or average pressure. A further experiment tested simply the screening out affected winds however, results were not as positive and in the case of conventional winds and Aeolus even showed some negative signals. Verification against own analysis showed reductions in vector wind error around the tropics when the height reassignment was active. Impacts on the conventional observations were largely neutral but coverage is sparse over the ocean where the change is largest. Encouragingly, both Aeolus and scatterometer observations showed better agreement with the model background in the tropics. Changes in the mean wind analysis showed a weakening of the equatorial convergence at 850hPa which was supported by improvements in the fit of cloud sensitive observations such as from SSMI/S. While signals were consistent across the different height reassignment options, use of cloud base or average pressure generally showed greater positive impacts than the cloud top.

Taking into consideration both the model background statistics and assimilation experiments, reassigning to the average pressure of the cloud layer is planned for operational use from cycle 47r3 onwards. The change means that the operational AMV usage becomes sensitive to the representation of clouds in the forecast model and hence to developments for the cloud physics parameterisations or assimilation of cloud-affected observations. As the representation of model clouds improves further, so should the use of the low-level AMVs. To this end, testing with a forthcoming upgrade to the moist physics processes, which aims to improve the low level cloud representation, has already suggested that these impacts should be retained and the changes will be compatible.

In this work we have shown benefit based on the current operational system however, there is uncertainty as to how well the use of this technique could be extended back in time in a reanalysis context. AMVs are available as early as the 1970s but the model cloud fields may be less accurate, especially due to the otherwise sparse satellite data usage. For now, use of the height reassignment is recommended to be restricted to recent years when the observing system contains a much higher volume and range of data, including key satellite instruments such as microwave imagers used in an all sky capacity. Based on these considerations, we suggest applying the reassignment from 2010 onwards, but confirming this initial choice is left for future work.

We have used model estimates of cloud here to perform the correction to the AMV heights focusing on an area where there are clearly elevated RMSVD and speed bias values. In these regions of greater wind shear, height errors in these observations are likely to have a more detrimental impact. The present work may allow further developments in this respect: for instance, the exclusion of low-level infrared AMVs in the tropics could be revisited, as the height reassignment may address problems for these AMVs encountered earlier. This could lead to substantial increase in the use of low level AMVs in these areas. The present study has also shown that model cloud fields provide useful information for effective investigations of AMV height errors, especially over ocean areas lacking other wind observations. This could be extended in the future to analyse mid-/upper-tropospheric winds, and possibly lead to further improvement of the use of AMVs in areas with height assignment difficulties.

Understanding the physical reasons for incorrect height assignment and correcting for these errors at source in the initial derivation of the wind would also be desirable in the long term. A transition, currently underway, to a new format of the files disseminated by AMV producers will allow more information about the derivation process, including cloud parameters and uncertainties, to be available in the future. This is anticipated to provide more opportunities to probe AMV issues and potentially improve quality control or observation error formulation. In addition, the recent launch of Aeolus provides a very valuable source of wind profile information which can be used to better characterise these height assignment uncertainties.

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