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AMVS: PAST PROGRESS, FUTURE CHALLENGES

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Abstract

Forecast Sensitivity to Observations Impact (FSOI) show beneficial impact from atmospheric motion vectors (AMVs) at many NWP centres. In recent years, the Met Office has seen an increasing contribution from AMVs on this metric and since early 2015 the AMVs have been ranked third behind hyperspectral IR and microwave radiances, ahead of the conventional observations including radiosondes and aircraft.

This improvement comes from a combination of increased temporal and spatial coverage, improvements to the AMV derivation and their usage in NWP. If AMVs are to remain useful as forecasts and observing systems continue to improve it is critical we continue this progress. To achieve this we need to understand more about the characteristics of AMV data and their sources of error so we can improve their derivation, quality control and representation.

One idea is to make better use of the information available during the AMV derivation. In recent years there has been a move towards direct use of pixel-based cloud schemes developed by the cloud community. Many of these schemes provide estimates of height error and optimal estimation “cost” which can highlight where height assignment is more problematic and could be used for blacklisting and adjusting observation errors in NWP.

Another area of work relates to improving the use of AMVs for nowcasting and in high resolution models, particularly for the forecasting of high impact weather events. Current AMV products capture broad-scale to synoptic-scale flow. Looking at animations we can see information available on much smaller scales. This presents a challenge of how to extract and make best use of this information.

INTRODUCTION

Atmospheric motion vectors (AMVs) are produced by tracking clouds or areas of water vapour in consecutive satellite images and have been assimilated in Numerical Weather Prediction (NWP) models since the 1980s. In recent years the coverage (both areal and temporal) has improved, new derivation approaches have led to improved quality and usage in NWP has been developed, for example the introduction of situation-dependent error schemes (Forsythe & Saunders, 2008; Salonen & Bormann, 2012). Progress has been greatly helped by the good level of collaboration that exists between AMV producers and users.

In this paper we highlight the changes in data coverage, review results from Forecast Sensitivity to Observations Impact (FSOI) and data denial studies and look ahead to some future challenges.

AMV DATA COVERAGE

AMV data coverage has improved in recent years. Figure 1 shows the evolution in used data at the Met Office. In 2004 only data from the 5 main geostationary satellites were assimilated. In February 2005 AMVs from polar platforms were introduced into the global model, but this left a data gap around 50-65N/S as shown in the example from 2010. In the last few years, new datasets have been developed to help close the gap. In February 2015 we started assimilating EUMETSAT Metop winds derived using image pairs and multi-satellite winds known as Leo-Geo, produced at CIMSS (see also Warrick & Cotton, 2016). Both datasets provide improved coverage in these otherwise data sparse and meteorologically interesting regions. The example shown from 2016 demonstrates how these datasets have helped close the gap.

It is also worth noting that the number of winds assimilated has dramatically increased during this time, partly due to an increase in the number of AMVs produced, but also due to changes in the assimilation strategy to make more use of observations through the time window. The number of winds assimilated in 2016 is around 10 times the number assimilated in 2004.

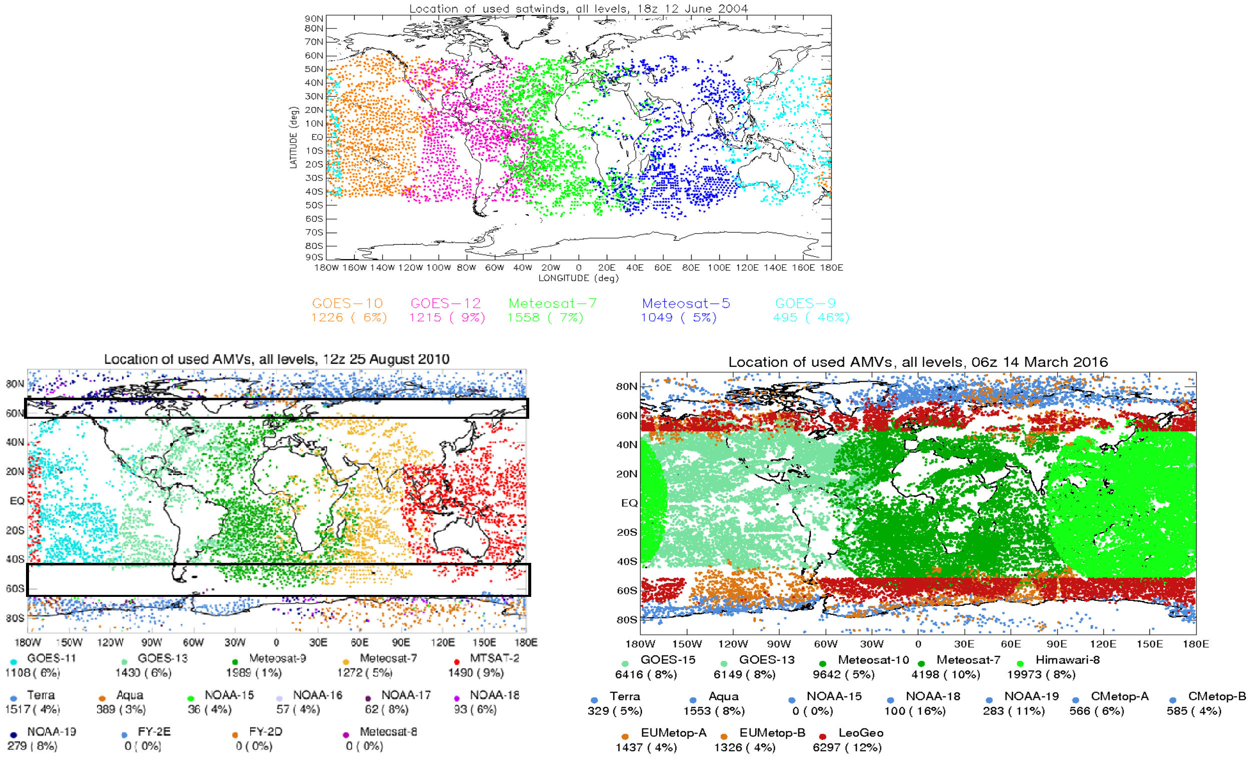


***Figure 1:* Data coverage plots showing the AMV usage in the Met Office global model for one run in (top) 2004, (left) 2010 and (right) 2016.**

Although great progress has been made there is room for improvement. There are data gaps within some runs of the NWP model and some of the polar and multi-satellite data arrive too late for the main forecast runs. The delay is due to a number of factors, but can be reduced markedly by using multiple downlink stations, using image pairs rather than image triplets and processing the data as soon as it becomes available. Figure 2 compares the delay for the LeoGeo winds produced from image triplets on a fixed schedule (average delay around 4.5 hours) to the EUMETSAT Metop AMVs produced using only 2 images (average delay around 1 hour). Although there may be some compromise in terms of quality and availability of QIs for quality control (traditional QI approach not possible), the EUMETSAT image pair winds are of good quality and have shown benefit in assimilation experiments. With this in mind it might be worth considering whether more of the polar or multi-satellite winds should be produced using image pairs. This will be particularly useful for assimilation in high resolution models, which often have much stricter cut-offs.

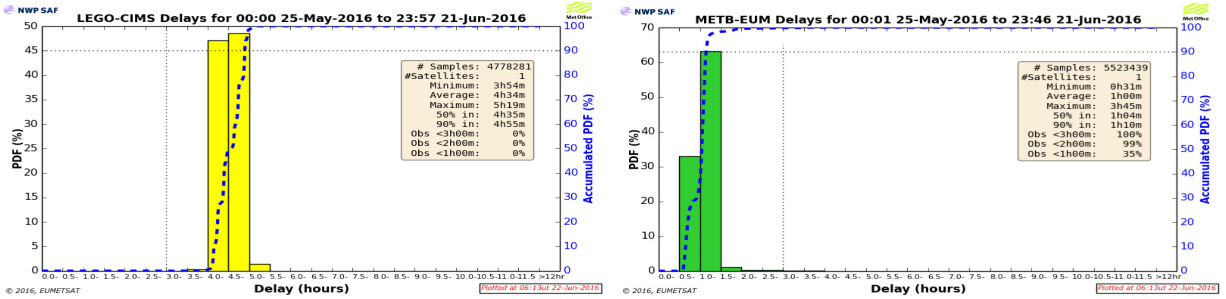
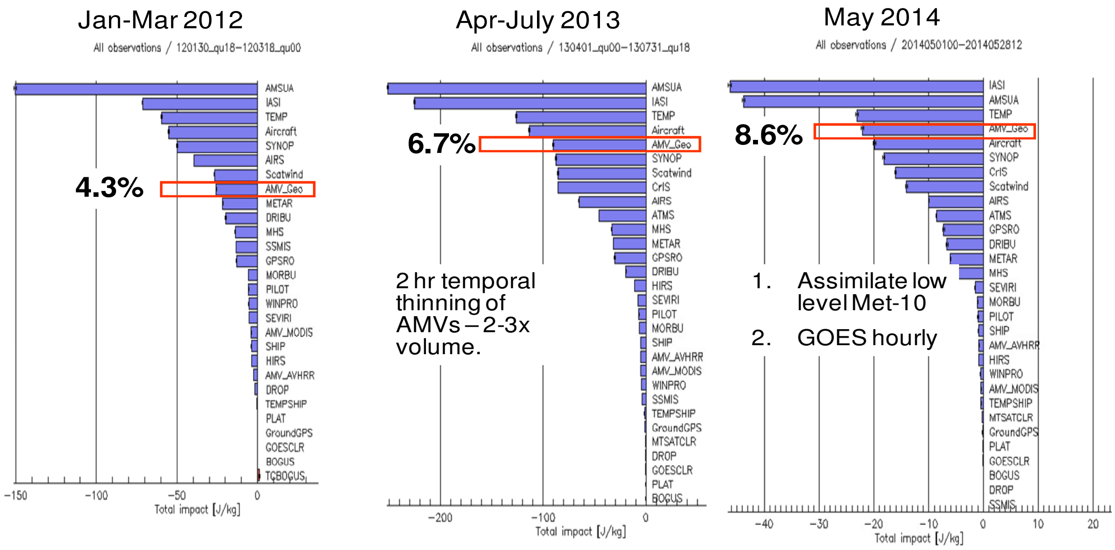


***Figure 2:* Plots showing the delay between observation time and receipt time for (left) the LeoGeo AMVs from CIMSS and (right) the Metop-B winds from EUMETSAT.**

While some improvement could be made to optimise the coverage in this gap region from greater use of image pairs and more optimal multi-satellite AMV production, there will always be a compromise in terms of spatial and temporal coverage and quality. An additional option that is worth mentioning is the use of satellites in highly eliptical orbit. This type of mission could provide improved spatial coverage, with good temporal resolution particularly over polar regions. The input imagery is homogeneous and use of image triplets could be retained for consistency checks. Two other key advantages would be improved timeliness of the data (particularly important for regional NWP) and more optimal image intervals for image tracking (more winds and of better quality). The more optimal image interval is a key strength and could reduce the reliance on NWP forecast information to guide the tracking step in the AMV derivation.

AMV IMPACT AND FSOI

Observation impacts on 24-hour forecast error reduction are evaluated using the adjoint-based Forecast Sensitivity to Observations (FSOI) method developed within the Met Office NWP system (Lorenc & Marriot, 2014), based on the method developed by Langland and Baker (2004). Figure 3 shows how the FSOI for AMVs at the Met Office has increased markedly, largely following increases in the number of winds assimilated (introduction of 2 hour temporal thinning, GOES hourly AMVs and the reintroduction of low level Meteosat-10 AMVs).


Jan-Mar 2012

Apr-July 2013

May 2014

4.3%

6.7%

8.6%

2 hr temporal thinning of AMVs – 2-3x volume.

1. Assimilate low level Met-10

2. GOES hourly

Figure 3: **Comparison of the of the observation impact of AMV_Geo with other observation types for periods in 2012 (left), 2013 (middle and 2014 (right).**

The trend has continued during the last 2 years and the AMVs have become established as the third highest rank dataset on this measure, behind the hyperspectral infrared and microwave radiances (Figure 4).

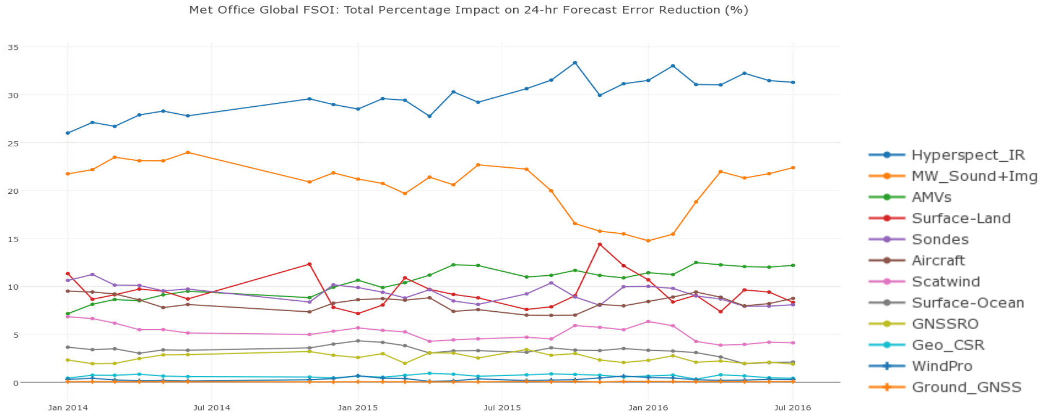


Figure 4: **Met Office global FSOI - time series of monthly total percentage impact on 24 hour forecast error reduction for a range of observation types (AMVs shown in green).**

It is encouraging that all AMV satellite-channel combinations show a beneficial impact (negative total impact in Figure 5). The largest contributions correspond to the datasets with the largest numbers of assimilated winds. If we look at the FSOI per observation the values are more comparable across the different datasets.

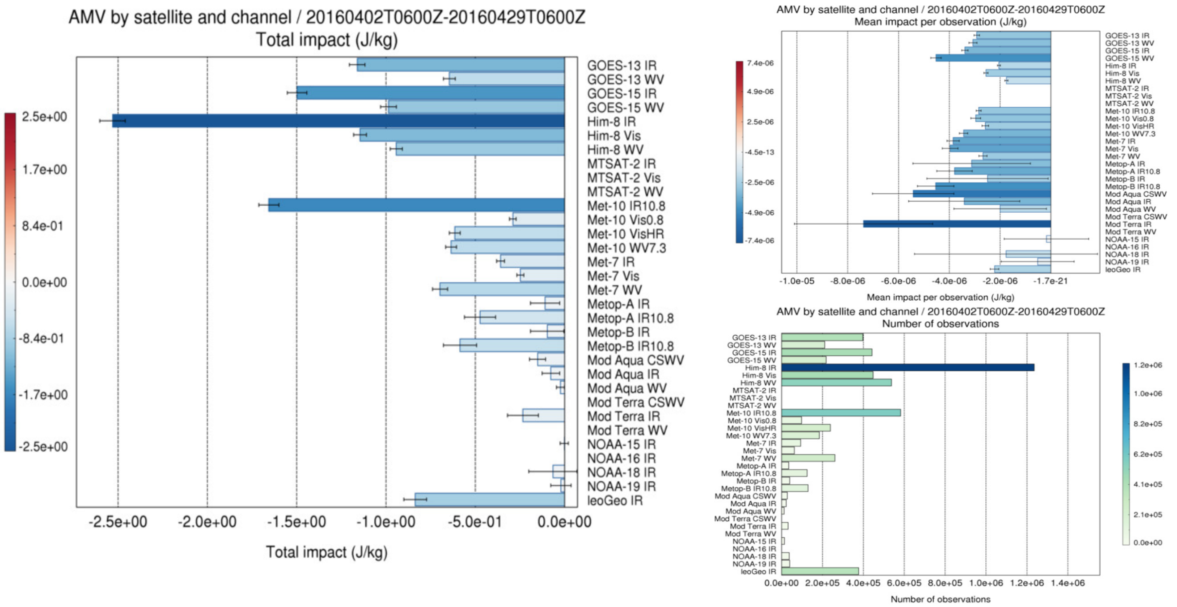


Figure 5: **Met Office global FSOI - total percentage impact on 24 hour forecast error reduction for different AMV satellite-channel combinations in June 2016 (left). Also shown are the mean impact per observation (top right) and the number of assimilated observation (bottom right).**

It is important to remember that the FSOI is only one measure which focuses on impact at T+24. To get a broader view of the impact we ran a series of data denial studies at the Met Office during 2016. The impact trials were run for the period 12 November 2015 to 15 January 2016 using a control which closely matches the global scientific configuration that became operational in March 2016 (parallel suite / PS 37), but at a reduced resolution of N320 (~40 km in mid-latitudes). Figure 6 shows the impact on RMS error for a range of forecast parameters (pressure at mean sea level, 500hPa geopotential height and winds at 850 hPa and 250 hPa) at different forecast lead time verified against ECMWF operational analyses for a subset of the data denial studies.

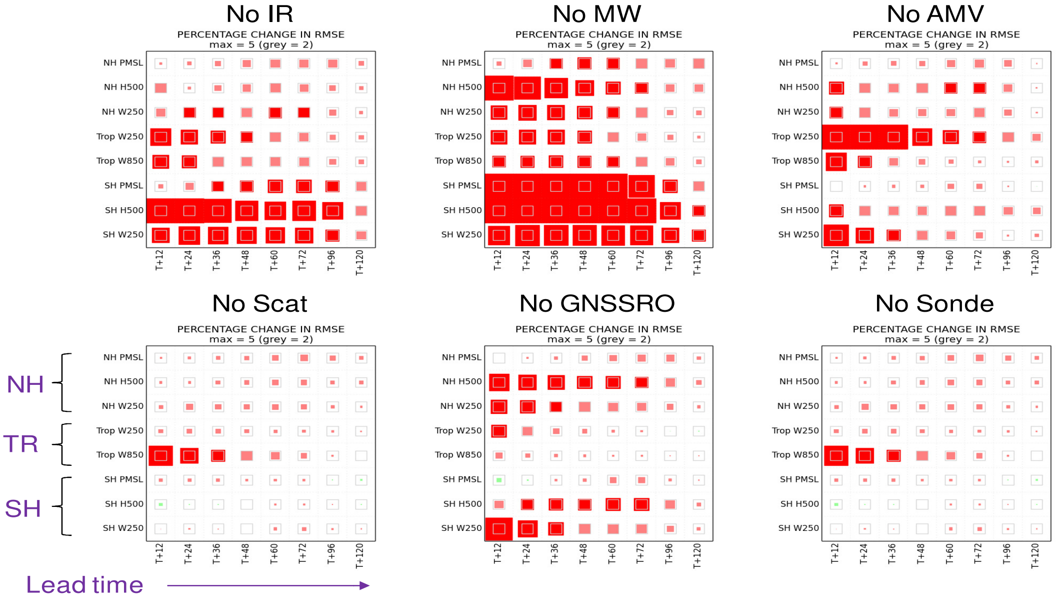


Figure 6: **Percentage change in forecast RMS error (trial minus control) for various data denial trials verified against independent ECMWF analyses. Green squares indicate a positive impact from denying the observations (reduction in error) and red squares indicate a negative impact (increase in error). The size of the squares is scaled to the size of the RMS change with a maximum of 5% filling the square box.**

Red indicates an increase in the RMS error when the observation types are removed from the operational baseline. As expected the biggest impacts are seen when the infrared (IR) or microwave (MW) radiance datasets are removed, but AMVs show a significant detrimental impact, particularly on the tropical wind fields and at shorter range in the extra-tropics.

The AMV denial trial also showed degraded fits of the background to other observations, including the humidity sensitive hyperspectral IR and microwave radiance channels and tropospheric temperature sensitive hyperspectral IR channels (Figure 7).

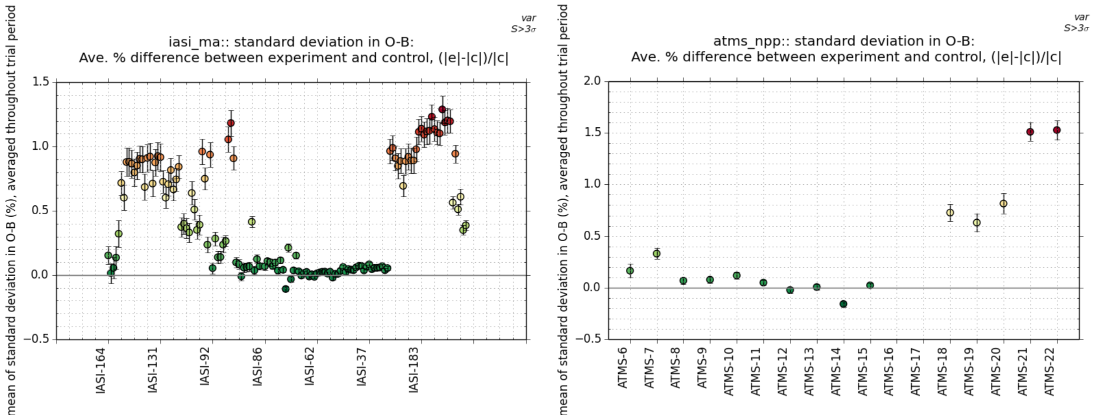


Figure 7: **Percentage change in standard deviation of O-B for (left) Metop-A IASI channels and (right) NPP ATMS in the AMV denial trial relative to a control based on the PS37 operational baseline.**

FUTURE CHALLENGES

Improving the data quality and representation of errors

As forecasts and observing systems continue to improve, it is critical we continue to improve the quality of the AMV products and their usage.

In some NWP systems AMV observation errors vary only with pressure. However, we know the errors vary widely dependent on the navigation, tracking, radiance biases, forecast data, radiative transfer models, the passive tracer assumption, the validity of treating as a wind at a specific height and the list could go on. Improving our understanding of the sources of error should enable improved quality control and representation of the errors in NWP. This is one of the key aims of the NWP SAF AMV monitoring available from https://nwpsaf.eu/site/monitoring/winds-quality-evaluation/amv/.

For most AMV products the main source of error is thought to be from the height assignment step. This is likely to be more of a problem in regions of high wind shear, where an error in the height could introduce a large vector error. As an example if a wind is assigned 80 hPa too low or too high in a region of strong shear the resultant vector error could be more than 10 m/s. One option to allow for this is to generate individual observation errors for each wind using information on the quality of the AMV vector and height assignment (Forsythe and Saunders 2008). If we assume the AMV vector and height errors are independent (reasonable assumption), the total AMV error can be calculated by combining the vector error with the error in vector due to the height error. The latter can be calculated using the model background wind profile and an estimate of the height error. With this approach, the same height error will yield a bigger observation error in regions of high vertical wind shear, allowing us to down-weight winds where a height error would be problematic and to give greater weight where the height assignment is less critical. The inputs required for this approach are estimates of the error in the height assignment and in the u and v wind components. Some benefits have been seen with this approach in assimilation experiments at the Met Office and ECMWF (Forsythe & Saunders, 2008; Salonen & Bormann, 2012).

Currently height errors used in the individual observation error schemes are based on statistics comparing AMV assigned heights to model best-fit pressure (e.g. Salonen et al. 2014) and at the Met Office the u and v errors are set based on the QI values. However it is possible that information from the derivation could be used to improve these estimates and also to improve the blacklisting. A key effort is ongoing in the International Winds Working Group to define a new BUFR sequence to include additional information from the tracking and height assignment which we hope will prove useful for identifying the more reliable data and screening out those in which we have less confidence.

Estimating the height errors from the derivation is helped by recent progress towards direct use of pixel-based cloud schemes developed by the cloud community. This is an encouraging step allowing the AMV products to directly benefit from expertise in the cloud community, including new techniques to allow for multi-layer cloud (e.g. Watts et al. 2011) and better handling of heights of cloud edges (e.g. Heidinger 2014). Many of these schemes also provide estimates of height error and cost from the optimal estimation. These values may provide some information on where height assignment is more problematic and could be used for blacklisting and adjusting observation errors in NWP. Additional information from the tracking step (for example from the correlation surface) may prove beneficial for better estimating the u and v errors.

NESDIS have provided test data from their GOES-R derivation, including some additional information which might be of use for NWP. Figure 8 shows an example of the impact on O-B statistics of applying a blacklisting threshold using the optical depth (bottom plot after optical depth > 0.75 applied). Although this reduces the number of winds available to the assimilation, the coverage is still good. The overall standard deviation improves from 5.37 to 4.74 m/s and the fast bias, particularly in the tropics is significantly reduced. Further results of the NESDIS test data are provided in Warrick & Cotton (2016).

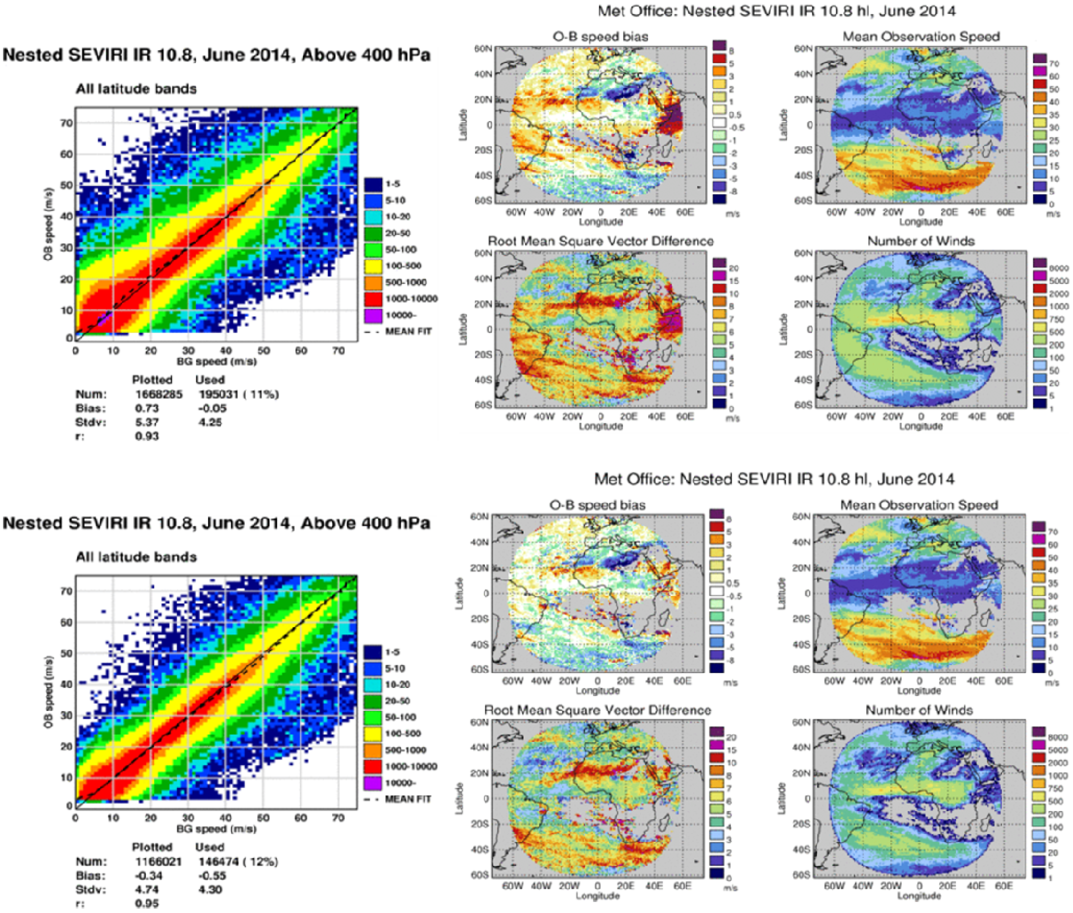


Figure 8: **O-B speed histogram and O-B statistics map plots for SEVIRI infrared AMVs above 400 hPa using the GOES-R derivation. Top: full dataset, bottom: after optical depth > 0.75 is applied.**

The challenges of high resolution

Current AMV products capture broad-scale to synoptic-scale flow. Looking at animations we can see information available on much smaller scales. Can we use this information to improve nowcasting and high resolution models, particularly for forecasting of high impact weather events?

At the moment it is unclear. There are a number of difficulties to overcome with both the AMV derivation and assimilation. In order to produce AMVs representative of smaller scale features of the flow we need to use smaller target boxes (probably 5-10 pixels in dimension) and shorter image intervals (5-10 min). However, the smaller number of pixels in the target makes it harder to find a unique solution and tends to result in a large number of invalid vectors. To address this, we need to focus on filtering out the poorly resolved cases (e.g. using information from the correlation surface) or using a clustering scheme (as applied in the GOES-R nested tracking, Bresky et al 2012) or finding another way to better constrain the tracking (e.g. Shimoji 2014). Other considerations for the AMV derivation include: greater sensitivity to registration errors, inability to resolve the slower winds with shorter image intervals and the need to find alternatives to the current QIs, which tend to penalise spatially varying accelerating wind features.

For NWP there are additional considerations. In NWP smaller scales tend to change fast and represent only modest energy conversion. The quantity and coverage of observations required to initialise and evolve these scales is a daunting challenge. Inadequate coverage could compromise the analysis of the larger scales. Also AMVs have correlated errors in space and time. To alleviate problems, data is thinned (or superobbed) and errors are inflated. But if we thin too much, we will lose the mesoscale information of interest. Efforts continue in this area at a number of centres and an IWWG web page has been put together to help foster collaboration.

Looking ahead to geostationary hyperspectral IR sounders

With AMVs, winds are inferred from the motion of features within the imagery. An alternative approach, made possible by the development of 4D assimilation systems in the 2000s, is to assimilate the thinned radiances directly and obtain wind information through tracer advection (e.g. Peubey and McNally 2009). Figure 9 illustrates these 2 approaches.

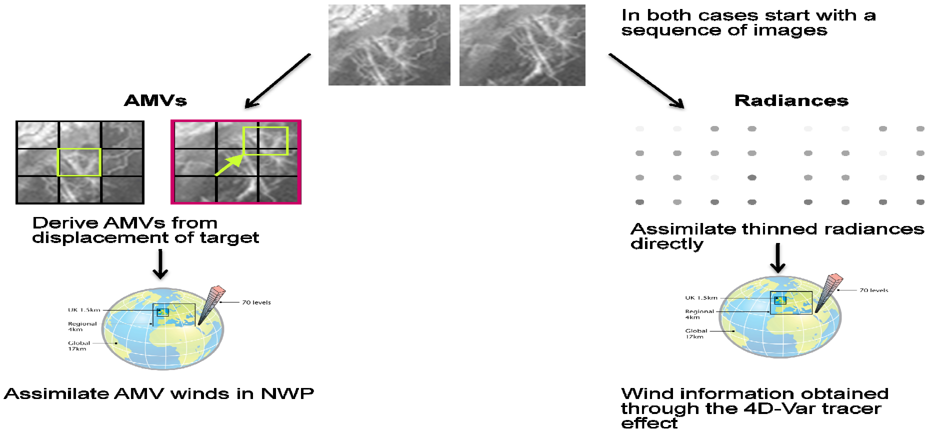


***Figure 9:* An illustration of the two routes to obtaining wind information in NWP from sequences of satellite imagery.**

It is attractive to consider extracting wind information in the assimilation system from direct radiance assimilation, allowing for development and dynamical coupling of features. Assimilation of clear sky radiances already shows improvement to wind analyses and these are largely used instead of clear sky AMVs. However, a number of challenges remain in cloudy regions:

1. Highly non-linear operators with respect to cloud variables
2. Requires adequate representation of model cloud – errors with mismatched cloud locations between models and observations
3. Handling of multi-layer cloud
4. Need more situation-dependent and cloud-specific background error formulations
5. Resolution of analysis in space and time and spatial and temporal density of assimilated radiance data – suggest only extract broad-scale motion.
6. Choice of data assimilation methodology – demonstrated in 4D-Var, but not yet proven in 4D ensemble approaches.

The question of radiance assimilation versus AMV derivation and assimilation is particularly relevant to plans for extracting wind information from geostationary hyperspectral IR sounders e.g. MTG-IRS. It is not yet clear which approach will be best. A novel approach to AMV derivation was developed at CIMSS (Velden et al. 2004) and explored further by Stewart (2013). They use sounder data to derive moisture analyses on different levels and produce wind profiles by applying AMV tracking techniques to these sequences of moisture analyses. The approach has been demonstrated with simulated data, considering both clear and cloudy regions. Whether the wind information comes from this novel twist on AMV derivation or direct radiance assimilation, there is potential to get improved vertical resolution (similar to existing hyperspectral sounders on polar platforms), but at the better temporal resolution possible from a geostationary platform.

This may go some way towards meeting the requirement of the Global Observing System for good horizontal, vertical and temporal coverage of the winds, supporting other missions such as Doppler Wind Lidar (e.g. Rennie, 2014).

SUMMARY

AMVs are an important part of the observing system, which can be seen in both FSOI results and data denial studies. A number of challenges remain to ensure maximum benefits can be obtained from this data type in the future. This will involve producers and users working together to improve the quality of the data, the information provided to the users and the quality control and assimilation. Other areas of development relate to maximising the benefit of AMVs in high resolution NWP models and realising the benefits of future geostationary hyperspectral sounders like MTG-IRS for improving model wind fields.

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