Derivation of Wind Vectors from AVHRR/MetOp at EUMETSAT

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ABSTRACT

Atmospheric motion vectors (AMVs) are derived operationally at EUMETSAT from the AVHRR/3 instrument on the Polar System satellite MetOp-A since 2011. The launch of MetOp-B in 2012 allowed for doubling of the production of AMVs over the polar regions using both MetOp-A and MetOp-B satellite data. In addition to the single AVHRR polar wind product, in 2014 EUMETSAT developed a new global AVHRR wind product extracted from a pair of MetOp-A and MetOp-B images. This new product is extracted using the large overlap in the imagery data obtained from the tandem configuration of the two satellites on the same orbital plane but with a phase difference of about 50 min. The tandem configuration also provides the possibility to derive wind vectors over polar areas using a triplet of AVHRR images, keeping the same time period necessary to derive the single MetOp polar wind product but allowing for a temporal consistency check in the calculation of the AMV quality index. Three different AMV products are currently extracted from AVHRR imagery at EUMETSAT, using two or three images taken by one or two satellites having different coverage and time integration.

This paper describes the scientific concept of the AVHRR wind extraction algorithm developed at EUMETSAT and presents the performances of the various AVHRR wind products. Intercomparisons of these different products highlight the role of the temporal gap between the images used to extract the wind and the impact of the consistency check on the calculation of the quality index.

1. Introduction

Atmospheric motion vectors (AMVs) are derived from satellites by tracking clouds or water vapor features in consecutive satellite images. Because they constitute the only upper-level wind observations with good global coverage for the tropics, midlatitudes, and polar areas, especially over the large oceanic areas, the AMVs are continuously assimilated into numerical weather prediction (NWP) models to improve the forecast score. AMVs are extracted routinely by a number of meteorological satellite operators, such as the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), the Co-operative Institute for Meteorological Satellite Studies (CIMSS), the National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service (NOAA/NESDIS), the Korean Meteorological Administration (KMA), the Japan Meteorological Agency (JMA), the China Meteorological Administration (CMA), and the India Meteorological Department (IMD).

At EUMETSAT AMVs are derived operationally from Meteosat geostationary satellites and from the low-orbit MetOp satellites. AMVs are derived over polar regions using data from the Advanced Very High Resolution Radiometer (AVHRR/3) on board MetOp-A and MetOp-B, and processed in the EUMETSAT Polar System (EPS) ground segment (GS). The standard polar wind extraction method proposed by Turner and Warren (1989) and Key et al. (2003) uses image triplets for the tracking. The MetOp polar winds extracted at EUMETSAT rely only on image pairs, which results in the loss of the temporal consistency test between the two consecutive intermediate vectors obtained from image triplets. But the use of image pairs decreases the tracking time from 200 to 100 min and increases the overlap area,

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allowing wind retrievals down to 50° latitude north and south. The larger area covered by EUMETSAT MetOp polar winds helps fill the gap in wind observations from 55° to 70° latitude north and south between the coverage areas of geostationary and polar winds based on three successive orbits.

In 2012 EUMETSAT launched the MetOp-B satellite (engineering name MetOp-I or M01), which took over the primary operations on April 2013. The tandem configuration with MetOp-A and MetOp-B satellites in the same orbital plane provided an interesting opportunity to create AVHRR AMVs using the two MetOp satellites. Three different AVHRR wind products are derived by the same algorithm, using a pair or triplet of images from one or two MetOp satellites, and having different period reference and coverage (see Fig. 1; Table 1). These different products provide a unique opportunity to compare wind vectors extracted at the same location using different temporal gaps, different satellites, and different numbers of images. The first part of this paper describes the algorithm developed to extract all the AMV products from the AVHRR instruments at EUMETSAT. The second part presents a comparison of their respective performances, and it discusses the results as a function of the importance of the temporal gap between the images used for the tracking and the impact of the temporal consistency check used in the calculation of the quality index.

**Fig. 1.** Overlapping areas (darker gray color) where AVHRR wind products are extracted (examples of MetOp-A and MetOp-B orbits taken between 0746 and 1030 UTC 25 Nov 2015). (top left) Single MetOp wind product over North Pole, (top right) triplet mode over North Pole, and global AVHRR wind product coverage—(bottom left) on MSG disk area and (bottom right) over North Pole.
2. Description of the algorithm

The MetOp satellites are part of the EUMETSAT fleet of meteorological satellites, providing weather and climate data. The EPS program consists of a series of three polar-orbiting MetOp satellites that are planned for more than 14 years of operation (Klaes et al. 2007). The satellites MetOp-A (launched on 19 October 2006) and MetOp-B (launched on 17 September 2012) are in the same polar orbit at 0930 local solar time, equator crossing time, and descending node, and at an altitude of 817 km. The last satellite of the EPS program—MetOp-C—is due to be launched in 2018. The AVHRR/3 on board MetOp is an imager used for global monitoring of various meteorological quantities like sea surface temperature, cloud cover, ice, snow, and vegetation cover characteristics. The AVHRR/3 instrument is presently on board NOAA-15–19, MetOp-A, and MetOp-B satellites. It takes 2048 Earth views per scan and per channel, having a swath width of 2893 km and a pixel resolution of about 1.1 km at nadir. The AVHRR/3 instrument has six spectral channels ranged between 0.63 and 12 μm (see Table 2) but only five of them are recorded.

Polar winds are operationally produced by EUMETSAT from the infrared channel 4 of the MetOp AVHRR/3 instrument since 2011. Despite the differences in viewing geometry and temporal sampling between the polar-orbiting and the geostationary imagers, the AVHRR AMV algorithm is mainly based on the same cloud feature tracking methods used for geostationary satellites at EUMETSAT (Borde et al. 2014).

The current algorithm is deriving three different AVHRR wind products, using a pair or triplet of images and using one or two MetOp satellites. The single MetOp wind product, AMV_2S, is extracted over polar areas using two consecutive images of the same MetOp satellite. The temporal gap between the two consecutive images is approximately 100 min. This product is extracted operationally from the MetOp-A and MetOp-B satellites.

The global AVHRR wind product, AMV_2D, is extracted from a pair of consecutive AVHRR images taken by two different MetOp satellites (Borde et al. 2016). The temporal gap between the images is reduced to approximately 50 min and the extraction is done over the whole globe by two complementary products: one considering MetOp-A as the first image and MetOp-B as the second image of the pair (MetOp-A/MetOp-B), and another one considering MetOp-B as the first image and MetOp-A as the second image of the pair (MetOp-B/MetOp-A). This product is assimilated in the ECMWF NWP model since February 2016 between 40° and 60° latitude north and south (Salonen and Bormann 2016).

The triplet mode wind product, AMV_2T, is extracted over polar regions from a triplet of consecutive AVHRR images taken by two MetOp satellites (in sequence MetOp-A/MetOp-B/MetOp-A or sequence MetOp-B/MetOp-A/MetOp-B). Such a strategy allows us to consider a temporal consistency test between the two intermediate vectors in the calculation of the quality index (OI) of the final wind vectors. The temporal gap between two consecutive images is approximately 50 min, but the total tracking time necessary to extract the product is about 100 min. The chronogram of Fig. 2 summarizes the extraction of these different products from the two satellites. It can be noted that the 50-min temporal gap between the consecutive images used to extract the AMVs is similar for AMV_2D and AMV_2T, and that the total 100-min tracking period and the coverage are similar for AMV_2S and AMV_2T.

Whatever the product concerned, the following common steps are performed to derive one single vector displacement: target selection, derivation of target displacement, height assignment (HA), and automatic quality control (AQC). The cloud mask is used to define the suitability of the channel to provide good displacement vectors at all locations. The AMV extraction scheme uses the forecast temperature vertical profiles for HA from the ECMWF prediction model.

### Table 1. AVHRR wind products extracted at EUMETSAT.

<table>
<thead>
<tr>
<th>AVHRR wind products</th>
<th>No. of satellites used</th>
<th>No. of images used</th>
<th>Tracking time (−min)</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMV_2S</td>
<td>1</td>
<td>2</td>
<td>100</td>
<td>Polar areas</td>
</tr>
<tr>
<td>AMV_2D</td>
<td>2</td>
<td>2</td>
<td>50</td>
<td>Global</td>
</tr>
<tr>
<td>AMV_2T</td>
<td>2</td>
<td>3</td>
<td>100</td>
<td>Polar areas</td>
</tr>
</tbody>
</table>

### Table 2. Spectral Characteristics of AVHRR/3.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Central wavelength (μm)</th>
<th>Half-power points (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.630</td>
<td>0.580–0.680</td>
</tr>
<tr>
<td>2</td>
<td>0.865</td>
<td>0.725–1.000</td>
</tr>
<tr>
<td>3a</td>
<td>1.610</td>
<td>1.580–1.640</td>
</tr>
<tr>
<td>3b</td>
<td>3.740</td>
<td>3.550–3.930</td>
</tr>
<tr>
<td>4</td>
<td>10.800</td>
<td>10.300–11.300</td>
</tr>
<tr>
<td>5</td>
<td>12.000</td>
<td>11.500–12.500</td>
</tr>
</tbody>
</table>
should have enough variability to be clearly identified in the series of consecutive images, meaning that the target box contains a sufficient number of pixels (greater than 20) with high standard deviation.

The altitude of the cloud feature present in the target box is estimated before tracking using the equivalent blackbody temperature of the 25% coldest cloudy pixels present in the target area and the corresponding forecast temperature profile. The ECMWF wind speed and direction from the 3-h forecast Integrated Forecasting System (IFS) model are interpolated to this altitude and are used to locate the search area in the previous image. The center of the search area in the previous image is set to the position where the feature in the initial image is expected to be found, assuming that the estimated NWP wind guess and altitude are correct. The effective size of the search area varies as a function of the wind guess speed in order to avoid the retrieval of unrealistic motions. The use of the wind guess for the tracking of AMVs has an impact on the AMV quality (Borde and García-Pereda 2014), especially when using small target boxes or long temporal gaps. However, because of the long temporal gaps between the image pairs from low-Earth-orbiting (LEO) satellites, leading to the possible large displacement of the feature in the next image, the use of the guess is required to maintain suitable computing time in an operational processing chain by keeping the search area size under a reasonable size (100 × 100).

4. Tracking

A classical cross-correlation method (Leese et al. 1971) is used for feature tracking in the AMV algorithm. The distance between the central locations of the target box in the image pair is converted to longitude and latitude positions, and “instantaneous” wind speed and direction are computed from these locations. Unfortunately, the temporal consistency test between the two consecutive intermediate vectors that are obtained from the use of image triplets cannot be done using only image pairs to derive the AMV_2S or AMV_2D wind vector. Therefore, a second “reverse” matching is done in the MetOp wind algorithm, to assess the quality of the first tracking. The target box used for this second matching process is the one identified in the second image of the pair at the end of the first matching. The search box is then located at the initial position of the target box in the first image. The wind speed and direction extracted by this reverse tracking are compared to the first wind speed and direction estimated by the first tracking in a vector consistency test (Holmlund 1998). A poor QI is set to the AMV when the two vectors are not in a good agreement, which means that the reverse tracking did not succeed in coming back to the initial position of the target box selected in the first image. Since three consecutive images are used for AMV_2T, a common temporal consistency check between the two intermediate vectors is applied in the calculation of the QI.

5. Height assignment

The level of the tropopause is determined using the forecast fields. According to the WMO (1957, p. 137), the tropopause is defined as “the lowest level at which the lapse-rate decreases to 2°C/km or less, provided that the average lapse-rate between this level and all higher levels within 2 km does not exceed 2°C/km.” Knowing the tropopause height, the altitude of the AMVs is set to an altitude between the ground and the tropopause, to avoid the possibility of getting wind vectors above the tropopause level.
The HA is done using the cross-correlation contribution (CCC) method (Borde and Oyama 2008; Borde et al. 2014), which keeps a direct link between the tracking step and the calculation of the AMV pressure using the individual contribution to the cross correlation of each pixel in the target box (Büche et al. 2006). The CCC method normally uses the cloud-top pressures (CTP) calculated for each cloudy pixel, but such a product does not exist for AVHRR on the EUMETSAT operational chain.

Therefore, the HA of the AMVs is estimated using the weighted average of the cloud-top equivalent blackbody temperature (EBBT) estimated using the CCC selection weighted average of the cloud-top equivalent blackbody AVHRR on the EUMETSAT operational chain.

The average radiance \( \bar{L} \) weighted by the individual contribution to the correlation coefficient \( CC_{ij} \) of the pixels considered is calculated following

\[
\bar{L} = \frac{\sum_{\text{cold branch}} CC_{ij} L_{ij}}{\sum_{\text{cold branch}} CC_{ij}} \quad (1)
\]

AMV pressure is calculated considering only the pixels that have radiance smaller than the average radiance within the target box and that have \( CC_{ij} \) greater than the mean \( \langle CC_{ij} \rangle \). However, when the target areas contain a very large and homogeneous cloudy layer, it can happen that none of coldest pixels have \( CC_{ij} \) greater than the average \( \langle CC_{ij} \rangle \). In such a case, all the pixels of the cold branch that have \( CC_{ij} \) greater than 0 are used to calculate the pressure. The corresponding EBBT of the cloud top is calculated from the weighted average \( \bar{L} \). The AMV pressure level \( P \) is then determined as the level where the EBBT of the cloud top fits the corresponding forecast temperature profile.

A weighted radiance standard deviation \( L_{\text{sd}} \) is calculated using the same set of pixels. This standard deviation gives information on the variability that is present within the target box,

\[
L_{\text{sd}} = \text{SQRT}(L_{\text{var}}),
\]

where

\[
L_{\text{var}} = \frac{\sum_{\text{cold branch}} CC_{ij}(L_{ij} - \bar{L})^2}{\sum_{\text{cold branch}} CC_{ij}} \quad (2)
\]

Corresponding EBBT and pressure standard deviations are derived from \( L_{\text{sd}} \). The pressure standard deviation \( P_{\text{sd}} \) (hPa) is associated with the AMV pressure in the output file.

In the HA process, the algorithm checks whether a temperature inversion exists in the corresponding forecast profiles interpolated at the AMV location and the pressure of the AMV is then set to the bottom of the inversion layer. This process is commonly used for AMVs extracted from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on the Meteosat Second Generation (MSG) satellite and is known to improve the quality of the AMVs at low levels.

None of the semitransparent correction methods usually applied in geostationary AMV algorithms, like the water vapor intercept method (Schmetz et al. 1993) or the \( CO_2 \) slicing method (Menzel et al. 1983), can be used because there are no appropriate water vapor or \( CO_2 \) channels on AVHRR. The presence of the Infrared Atmospheric Sounding Interferometer (IASI) instrument on the same MetOp satellite (August et al. 2012) provides the possibility to use the IASI cloud-top pressure product to set the dual MetOp wind pressures. However, the coarse resolution of IASI footprints does not cover the whole area seen by the AVHRR instrument. So, the feature tracked by the AMV algorithm does not always collocate with an IASI footprint, and this may be a source of error when using the IASI cloud-top height (CTH) product to set the AMV pressure. So, the algorithm first checks to confirm the center of the feature tracked is inside the footprint of an IASI pixel; this minimizes the risk of error when using IASI to set the AMV pressure. The location of the feature tracked is determined by using the individual pixel contributions to the correlation process of the CCC method (Borde et al. 2014) applied to latitude and longitude. The EBBT method described above is used when the feature tracked is found outside an IASI footprint.

6. Automatic quality control

The automatic quality control of AVHRR winds considers the same consistency tests commonly used for the Meteosat First and Second Generation AMV extraction algorithms (Holmlund 1998). Spatial consistency, temporal consistency, and forecast consistency checks provide individual normalized output values between 0 and 1, such that they can be linearly combined to obtain a final quality index attached to each vectors and disseminated with the AMV product. The final quality index that includes a forecast consistency check is noted as QI; the index that is model independent is noted as QIX. The final AMV speed and direction are those derived from the first pair of
images. The reference image for the time, for the estimation of the position, and for the HA is the first image of this pair (i.e., the last one taken by the instrument due to backward tracking). Then, the final location of the AMV used for comparison against forecast fields corresponds to the location of the feature tracked in the reference image, corrected for parallax error using the view angle and the final pressure of the AMV.

7. Performances and comparison of the various AVHRR wind products

All three products are extracted over polar areas, which allow for a direct comparison of their respective performances against forecast fields and provide an opportunity to explain the differences observed between each other as a function of the settings used for the extraction. The main differences during the extraction process between AMV_2S and AMV_2T are the use of a single satellite, and a temporal gap of 100 min between the images for AMV_2S, and the use of two satellites leading to the halved temporal gap of ~50 min for AMV_2T. Assuming that the images taken by two AVHRR instruments have very similar characteristics, the direct comparison of these two products illustrates the impact of the temporal gap on the AMV derivation.

AMV_2T is extracted using three images having approximately 50-min temporal gap between each image pair. A comparison of these winds against AMV_2S winds extracted at the same place during the same time period illustrates the benefit of using three images for the AMV extraction and the impact of using a temporal consistency test in the calculation of the QI. The final wind speeds and directions of both the AMV_2D and AMV_2T products are extracted using 50-min temporal gaps. The difference between the two products comes from the use of a temporal consistency test in the calculation of the QI for the AMV_2T product.

Figure 3 presents the performances of AVHRR wind products extracted over a northern high-latitude region and over a southern high-latitude region during the period from 1 July 2016 to 31 August 2016. Plots show the total amount of AVHRR winds and the performance of the AVHRR wind product against corresponding forecast fields: speed biases and root-mean-square vector difference (RMSVD). The amount of AMV_2S and AMV_2T winds extracted are very similar and are much smaller than the amount of AMV_2D winds extracted during the same period over the same area. This difference is mainly due to the larger overlapping area considered for the extraction of AMV_2D winds, as illustrated in Fig. 1.

The percentage of good winds (QI > 60) is about 56% for AMV_2D extracted over Northern Hemisphere high latitude (NHL) and 63% over Southern Hemisphere high latitude (SHL). This percentage is slightly smaller for the AMV_2S product (52% and 58%, respectively), and it drops to 32% and 40%, respectively, for the AMV_2T product. So, the use of the temporal consistency test in the calculation of the QI reduces by 25%–30% the amount of winds that have a QI > 60 and that are potentially useful for assimilation in NWP models.

The difference in the percentage of good-quality winds between AMV_2S and AMV_2D extraction comes from the different temporal gap used, 100 and 50 min, respectively. The longer the temporal gap between the two images, the more difficult the matching.

The time series of speed biases and the root-mean-square (RMS) vector difference against forecast (FC) fields of the three products are plotted in Fig. 3. Over NHL the average speed biases are about +0.25 m s\(^{-1}\) for AMV_2S, 0.35 m s\(^{-1}\) for AMV_2D, and 0.35 m s\(^{-1}\) for AMV_2T over the months of July and August 2016. Over SHL they are about +0.10, −0.15, and −0.10 m s\(^{-1}\) for the AMV_2S, AMV_2D, and AMV_2T products, respectively. The time series show that both the speed biases and RMSVD may vary daily as a function of weather situations, but the same trends remain between the three products. As the final AMV_2T product corresponds to the intermediate vector extracted using the second pair of images, it is identical to the AMV_2D product extracted at the same location. So, the two products have quite similar speed bias statistics against FC fields over time.

Vertical distributions of the three products (QI > 60) over NHL and SHL are shown in the left column of Figs. 4a and 4b for the months of February and August 2016, respectively, to illustrate a winter and summer example over each pole. Thanks to a larger extraction area, the AMV_2D production is slightly larger for the whole profiles. The distributions present two peaks around 500 and 850 hPa, and most of the AMVs are extracted in the 600–400-hPa layer for the three products. The AMV_2S and AMV_2T distributions are very close together at low levels, illustrating that the largest loss of good-quality AMV_2T winds is done at midlevels within the 700–400-hPa layer. The mean speed profiles show that AMV_2D and AMV_2T winds are very similar and generally slightly faster than AMV_2S winds, especially in the higher levels of the troposphere above 600 hPa.
The mean vector difference (MVD) and speed biases statistics vertical distributions are plotted in the right column of Figs. 4a and 4b. The corresponding statistics for Figs. 4a and 4b presented in Tables 3a and 3b are split by layers (high levels: $P < 400$ hPa, midlevels $400 < P < 700$ hPa, and low levels $700$ hPa < $P$). The three products have similar speed biases along the complete vertical profile, being small and positive below 450 hPa, and slightly negative above 450 hPa. If the AMV_2S product has frequently a slightly larger speed bias, then the speed bias differences noted are not statistically significant. It must be noted that the statistics in Figs. 3, 4a, and 4b and Tables 3a and 3b are not normalized by the average speed, so the magnitude of the RMSVD, the MVD, and the biases depends also on the absolute values of the speeds: the smaller the speeds, the smaller the biases.

The RMSVD against FC fields are larger for the AMV_2D product than for the AMV_2S and AMV_2T.
products over the whole time series in Fig. 3. The AMV_2T product has statistically significant smaller RMSVD than the two other products. The same trend can be observed for the complete vertical distribution of the MVD in Figs. 4a and 4b and Tables 3a and 3b.

The use of a temporal consistency test in the QI calculation of the AMV_2T product dramatically reduces the number of AMVs that have a high QI, but it makes the dataset smaller and more homogeneous, which reduces the speed bias and MVD against FC fields. It is difficult to explain why the AMV_2S product has a smaller RMSVD and MVD than the AMV_2D product, as it is derived using a longer temporal gap of 100 min instead of 50 min for the AMV_2D product. Indeed, we could expect intuitively to have better accuracy due to a less noisy tracking using a shorter temporal gap. As already mentioned above for the biases, the AMV_2S product tends to extract slower AMVs, which slightly reduces the magnitude of the absolute values of the RMSVD. However, the main reason must be found from the algorithm and from the relative error of the speed. The speed $v = x/t$ being related to a motion $x$ that has been done during a period $t$, the relative speed error is then expressed as follows:

$$\frac{\Delta v}{v} = \frac{\Delta x}{x} + \frac{\Delta t}{t},$$

where $\Delta v$, $\Delta x$, and $\Delta t$ are the errors related to the speed, to the displacement, and to time, respectively. The error $\Delta x$ is linked to the uncertainties coming from the imagery, like the rectification accuracy, and from the tracking and matching processes. This error
is similar for all the AVHRR wind products whatever the AVHRR image used to derive the wind vectors. The error $\Delta t$ relates to the uncertainty of the time attached to the image used. This error is very small, and the relative error $\Delta t/t$ becomes negligible in Eq. (3) when $\Delta t$ is divided by about 3000 s for the AMV_2D and AMV_2T products, and by 6000 s for the AMV_2S product. Assuming that the same speed $v$ must be retrieved by the AMV_2S and AMV_2D products at the same location and at the same time, the temporal gap being double for the AMV_2S product, the displacement of the cloud feature $x$ is then expected to be twice longer for the AMV_2S product than for the AMV_2D product. Finally, the relative speed error $\Delta v/v$ is mathematically expected to be nearly twice larger for AMV_2D than for the AMV_2S product, just because the imagery used for AMV extraction is the same for the two products and because the temporal gap is divided by two. This is an important aspect, which increases the noise ratio in the whole AMV extraction process and which impacts the magnitude of the RMSVD. It must be considered more carefully in the analysis of the statistics in the future, not only for AVHRR wind products, but also for comparison of AMVs extracted from normal scan imagery with the AMVs extracted from rapid scan imagery. Rapid scan AMVs are extracted using the same images but shorter temporal gaps, increasing the noise ratio of the AMV extraction, resulting in increased RMSVD values.

In summary all three products show good performances against FC fields having quite small biases and RMSVD values. Borde et al. (2016) have shown that the performance of the AMV_2D product is even slightly better than that of the collocated Meteosat-7 and Meteosat-10 AMVs in the Northern and Southern Hemispheres at high and midlevels. Such a
result is a good quality check because the Meteosat-7 and Meteosat-10 AMV products have been used and evaluated in NWP for a long time and are known to be reliable products. These results are also in good agreement with the exhaustive comparison of the AMV_2D product against geostationary AMVs from GOES-15 (135°W), GOES-13 (75°W), Meteosat-10 (0°), Meteosat-7 (57.3°E), and MTSAT-2 (145°E), as well as polar-orbiter AMVs from MODIS and MISR (both on the Terra satellite), presented by Horváth et al. (2014). The results of this initial study have been recently confirmed using the latest version of the AVHRR AMV extraction algorithm presented in this paper, and completed by comparisons against radiosonde observations and model winds from the ERA-Interim (Horváth 2016). The AMV_2T product is slightly better quality than the AMV_2S and AMV_2D products, but the amount of AMVs available for assimilation (QI 60) in NWP models is 30% smaller than the other two products.

### Table 3a. Performances against FC of the three AVHRR wind products extracted over NHL (top) and SHL (bottom) for February 2016. Low (below 700 hPa), Mid (between 400 and 700 hPa) and High (above 400 hPa) numbers are given in percentage of the total number of winds extracted (All).

#### NHL February 2016

<table>
<thead>
<tr>
<th>AMV_2S</th>
<th>AMV_2D</th>
<th>AMV_2T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>Speed (m s(^{-1}))</td>
<td>Bias (m s(^{-1}))</td>
</tr>
<tr>
<td>All</td>
<td>1 035 829</td>
<td>15.8</td>
</tr>
<tr>
<td>Low</td>
<td>22%</td>
<td>11.41</td>
</tr>
<tr>
<td>Mid</td>
<td>65%</td>
<td>15.73</td>
</tr>
<tr>
<td>High</td>
<td>13%</td>
<td>24.2</td>
</tr>
</tbody>
</table>

#### SHL February 2016

<table>
<thead>
<tr>
<th>AMV_2S</th>
<th>AMV_2D</th>
<th>AMV_2T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>Speed (m s(^{-1}))</td>
<td>Bias (m s(^{-1}))</td>
</tr>
<tr>
<td>All</td>
<td>1 302 232</td>
<td>15.64</td>
</tr>
<tr>
<td>Low</td>
<td>26%</td>
<td>12.88</td>
</tr>
<tr>
<td>Mid</td>
<td>64%</td>
<td>14.9</td>
</tr>
<tr>
<td>High</td>
<td>10%</td>
<td>27.06</td>
</tr>
</tbody>
</table>

### Table 3b. Same as Table 3a, but for August 2016.

#### NHL August 2016

<table>
<thead>
<tr>
<th>AMV_2S</th>
<th>AMV_2D</th>
<th>AMV_2T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>Speed (m s(^{-1}))</td>
<td>Bias (m s(^{-1}))</td>
</tr>
<tr>
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<td>22.1</td>
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</table>

#### SHL August 2016

<table>
<thead>
<tr>
<th>AMV_2S</th>
<th>AMV_2D</th>
<th>AMV_2T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>Speed (m s(^{-1}))</td>
<td>Bias (m s(^{-1}))</td>
</tr>
<tr>
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<td>18.07</td>
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<tr>
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</tr>
<tr>
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<tr>
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<td>28%</td>
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A strong seasonal cycle is present in Arctic cloud cover, with summer cloudier than winter. Eastman (2009) showed that this cycle is primarily attributable to low stratiform cloud cover (stratus, stratocumulus, and fog), presenting a dramatic rise from April to May and a slower decline in autumn. This cycle appears linked to the Arctic geography and so to the landmasses and oceanic regions. The summer and winter cloudiness difference is well illustrated in Fig. 5, which represents the average cloudiness over the Arctic as seen by the AVHRR/MetOp-A overpasses for the first 10 days of February 2016 and the first 10 days of August 2016. Figure 6 shows that this seasonal cycle is consequently well reflected in AMV_2S wind production over the Arctic during the period 1 April 2015–31 December 2016. About 50% more AMVs are produced from June to October than during the other months, because more clouds are present for tracking. This strong cycle is specific to the Arctic and does not appear over the Antarctic for which the AMV production is more stable during the same period.

However, the poor performance of the cloud mask scheme presently available on the EUMETSAT operational AVHRR chain (EUMETSAT 2013) and used in AVHRR wind extraction also creates some differences between summer and winter. The simple thresholding methods used for pixel identification prevent clear separation of the cloud pixels from ice or snow in polar regions. So, the amount of pixels identified as cloudy is much larger during daytime than during nighttime; consequently, the number of AMVs produced is different during the polar day and polar night seasons.

Figure 7 shows the AMV speeds (QIx > 60) extracted over NHL and SHL for AMV_2S, AMV_2T, and AMV_2D on 27 June 2015. The coverage is somewhat similar for the AMV_2S and AMV_2T products, and better populated for the AMV_2D product—especially at lower latitudes. The same trends and large-scale features are detected by all the products, like the fast speeds (>60 m s⁻¹) of the polar jet over SHL. However, the AMV_2D product better characterizes them both in the density of AMVs and in coverage. The AMV_2S product detects fewer fast speeds than the two other AVHRR AMV products. This is explained by the longer temporal gap between the two images used to extract AMV_2S winds, 100 min, instead of 50 min for the two other products. The use of long temporal gaps prevents the extraction of fast winds from LEO satellites because the feature identified in the first image has moved outside the area seen in the second image due to the limited field of view. So, the target box selected in the first image cannot be matched in the second image. This problem is less critical with geostationary satellites that observe the full disk at every slot. The faster winds that can be extracted from LEO satellites are then directly linked to the size of the field of view, the size of the overlapping area between the consecutive images, and to the temporal gap used to detect the winds. Too small a field and/or too long a temporal gap prevents the extraction of fast winds from the imagery.

Clouds may evolve quickly in the troposphere, appearing and disappearing due to both small- and large-scale phenomena, and constantly changing their shape. To be tracked accurately in consecutive images,
a cloud must keep the same characteristics over the entire tracking period. So, a cloud that has a lifetime of about 1 h can be tracked only by the AMV_2D algorithm and not by using the tracking period of 100 min of the AMV_2S and AMV_2T products. García-Pereda and Borde (2014) discussed the relationships between the tracer size, the temporal gap between consecutive images, the size and lifetime of the feature tracked, and the quality of the tracking in the High Resolution Winds AMV extraction software [Satellite Application Facility on Support to Nowcasting and Very Short Range Forecasting (NWC SAF)/MSG High Resolution Winds (HRW)]. They showed that larger tracer sizes reveal the motion of larger-scale features that have a longer lifetime and that can be tracked over a longer period. The relationships between all these criteria are complicated and the use of long temporal gaps tends to select the motion of larger-scale features that do not change very much their shape and texture. This also means that the size of the target box used to extract the winds must be adapted to the selection of such features in order to optimize AMV retrievals.

Figure 8 shows the zonal distributions of speeds, speed biases, and RMSVD versus pressure for AMV_2T winds extracted on 27 June 2015. A substantial amount of winds are still detected at 50°–40° latitudes, where AMVs extracted by geostationary satellites are commonly available for assimilation in NWP models. The fast winds of the polar jet (>60 m s⁻¹) are well described near 60° latitude south, at a pressure close to 300 hPa. This retrieval matches very well with the average location and altitude of this synoptic-scale phenomenon in June. The speed biases and RMSVD are small but slightly larger at high altitudes and in the polar jet areas.

8. Discussion

This paper describes the algorithm recently developed at EUMETSAT to extract various AMV products operationally from the AVHRR instrument. It presents the characteristics of the three extracted products and shows their performances against forecast fields. These products are extracted using two or three consecutive images taken by one or two MetOp satellites. All three products are extracted over the polar areas, which allow for a comparison between each other. The differences noted in terms of AMV production or performances against corresponding forecast fields have been analyzed considering the role of the temporal gaps between the consecutive images and the use of a temporal consistency test in the calculation of the QI.

The results presented above clearly show that good-quality winds can be extracted considering only pairs of images instead of the triplets that are commonly used in other AMV extraction algorithms developed for geostationary and polar satellites. The atmospheric characteristics retrieved from the algorithm and the speed biases against FC fields are similar for all three AVHRR wind products considered in this study. However, the use of three images and a temporal consistency test in
the calculation of the QI slightly improves AMV_2T product performance, mainly reducing the RMSVD against FC fields. But the use of this test also greatly reduces the amount of good-quality AMV_2T winds available for assimilation in NWP models. Further discussions with AMV users will be necessary to define a good trade between these two aspects for optimal use of AMVs in NWP models.

Results illustrate the role of the temporal gap between the consecutive images used in the AMV extraction.
Because the field of view seen from LEO satellites is limited, the features that move very fast cannot be tracked using long temporal gaps between the image pairs. Therefore, the shorter temporal gaps of the AMV_2D and AMV_2T products allow for the extraction of more fast winds than the AMV_2S product, and they better characterize the polar jets. Using the same imagery and shorter temporal gaps has also been shown to increase RMSVD values by increasing the relative speed errors in the extraction process. This feature should be considered more carefully in the analysis of the results in the future, especially when comparison statistics are done using rapid scan imagery.

The nominal situation at EUMETSAT is to have one satellite EPS MetOp operational, not two in opposite phases in orbit. This means that the AMV production and midterm stability of the products are ensured contractually only for the AMV_2S product, which is extracted using only one MetOp satellite. The production, the coverage, and the quality of the AMV_2D and AMV_2T products should be obviously impacted by the end-of-life scenario of MetOp-A, which should be moved on its orbit in 2017, until the launch of MetOp-C, presently foreseen in 2018. This makes difficult the definition of the best strategy for the assimilation of these products in NWP models. However, the results presented in this paper clearly show the benefits to having two AVHRR instruments flying in opposite phases in the same orbit, allowing for global coverage extraction of AMVs with the AMV_2D product, and better characterizing the polar jets phenomena between 50° and 70° latitude. This may be an argument to be considered for the specification of future LEO satellite programs, and it may noted that the orbit of the Joint Polar Satellite System JPSS-1 satellite is planned to be in tandem configuration with the Suomi National Polar-Orbiting Partnership (SNPP), similar to the MetOp configuration.

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REFERENCES


FIG. 8. Zonal distribution of (top) AMV_2T speeds, (middle) speed bias, (bottom) and RMSVD vs pressure for winds extracted on 27 Jun 2015 (QIx > 60). Dot size relates to the density of the AMVs extracted, and the color scale corresponds to the wind speed (m s\(^{-1}\)) for the top panel, to the speed bias (m s\(^{-1}\)) for the middle panel, and to the RMSVD (m s\(^{-1}\)) for the bottom panel.


