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Article

NWCSAF High Resolution Winds (NWC-GEO/HRW) stand-alone software for calculation of Atmospheric Motion Vectors and Trajectories

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Abstract:

The "NWCSAF High Resolution Winds (NWC/GEO-HRW)" software is developed by the EUMETSAT's "Satellite Application Facility on support to Nowcasting and very short range forecasting (NWCSAF)", inside its stand-alone software package for calculation of meteorological products with geostationary satellite data (NWC/GEO). The whole NWC/GEO software package can be obtained after registration at the NWCSAF Helpdesk, www.nwcsaf.org. It is easy to get, install and use. The code is easy to read and fully documented. And in the NWCSAF Helpdesk, users find support and help for its use.

"NWCSAF High Resolution Winds" provides a detailed calculation of Atmospheric Motion Vectors (AMVs) and Trajectories, locally and in near real time, using as input NWP model data and geostationary satellite image data. The latest version of the software, v2018, is able to process MSG, Himawari-8/9, GOES-N and GOES-R satellite series images, so that AMVs and Trajectories can be calculated all throughout the planet Earth with the same algorithm and quality.

In the "2014 and 2018 AMV Intercomparison Studies", "NWCSAF High Resolution Winds" has shown to be one of the two best AMV algorithms for both MSG and Himawari-8/9 satellites. And the "Coordination Group for Meteorological Satellites (CGMS)" has recognized in its "2012 Meeting Report": 1. "NWCSAF High Resolution Winds" fulfills the requirements to be a portable stand-alone AMV calculation software due to its easy installation and usability. 2. It has been successfully adapted by some CGMS members and serves as an important tool for development. It is modular, well documented, and well suited as stand-alone AMV software. 3. Although alternatives exist as portable stand-alone AMV calculation software, they are not as advanced in terms of documentation and do not have an existing Helpdesk.

Considering this, a full description and validation of the "NWCSAF/High Resolution Winds" is shown here for the first time in a peer-reviewed paper. The procedure to obtain the software for operational meteorology and research is also explained.

Keywords: Atmospheric Motion Vectors (AMVs); Trajectories; EUMETSAT; NWCSAF; AEMET; MSG; Himawari; GOES-N; GOES-R.

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1. Introduction

The "Satellite Application Facility on support to Nowcasting and Very short range forecasting (NWCSAF)" is a Consortium inside the EUMETSAT "Satellite Application Facility (SAF)" Network, conformed by five National Meteorological Services: AEMET/State Meteorological Agency of Spain, Météo France, ZAMG/Central Institute for Meteorology and Geodynamics of Austria, SMHI/Meteorological and Hydrological Institute of Sweden, and NMA/National Meteorological Administration of Romania.

Its main objective is to provide operational services to enhance the nowcasting and very short range weather forecasting (i.e., the weather forecasting up to a period of 12 hours [1]). This is achieved by developing and maintaining two stand-alone software packages, which calculate in near real time meteorological products from geostationary (NWC/GEO) and polar (NWC/PPS) satellite data, and by supporting its users on their production and application. As stand-alone software packages, they contain all the elements for the calculation of the meteorological products, without the need of any other external elements, beyond the corresponding input data.

The latest NWCSAF geostationary software package version (NWC/GEO v2018) calculates the following six types of meteorological products considering images of MSG, Himawari-8/9 and GOES-N and GOES-R satellite series (GOES-13 and subsequent ones), so covering the whole planet Earth in the areas which can be observed with geostationary satellites.

- Four cloud products: CMA/Cloud Mask, CT/Cloud Type, CTTH/Cloud Top Temperature, Height and Pressure, and CMIC/Cloud Microphysics. The last product provides the cloud phase, the cloud effective radius, the cloud optical thickness, and the liquid/ice water path.
- Two pairs of precipitation products: PC and PC-Ph/Precipitating Clouds (providing the probability of precipitation for a cloudy pixel), and CRR and CRR-Ph/Convective Rainfall Rate (providing instant and hourly values of precipitation, more suitably for convective clouds). In both pairs, the second product makes use of the CMIC/Cloud Microphysics product in its algorithm, while the first product does not make use of this information.
- Two convection products: CI/Convection Initiation (providing the probability for a cloudy pixel to become a thunderstorm within a forecast interval), and RDT/Rapid Developing Thunderstorms (tracking convective systems and monitoring them with many properties).
- One clear air product: iSHAI/imaging Satellite Humidity and Instability. This product provides for clear air pixels vertical profiles of humidity, temperature and ozone, precipitable water available in the total column and in three vertical layers, and several instability indices.
- Three conceptual model products: ASII/Automatic Satellite Image Interpretation, ASII-TF/ Tropopause Folding, and ASII-GW/Gravity waves. These products interpret the satellite image in terms of several conceptual models; the two last ones related to clear air turbulence.
- One extrapolation product: EXIM/Extrapolated Imagery. This product forecasts satellite imagery or other NWC/GEO products, considering kinematic extrapolation.
- One AMV product: HRW/High Resolution Winds. This product calculates Atmospheric Motion Vectors (AMVs) and Trajectories, through the displacement of cloudiness and humidity features in successive satellite images.

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A full description and validation of the “NWCSAF High Resolution Winds (NWC/GEO-HRW)” product (from now on, “HRW product”), included in “NWC/GEO v2018” software package, is shown in this paper. As already said, it provides detailed sets of “Atmospheric Motion Vectors” and “Trajectories” considering images of these four satellite series.

An “Atmospheric Motion Vector” (AMV) is the horizontal displacement between two Earth positions in two satellite images, of a square segment of n x n pixels called “tracer”. A “Trajectory” is the path defined by the displacement of the same tracer throughout several satellite images.

Examples of Atmospheric Motion Vectors (AMVs) and Trajectories obtained for a same slot with NWC/GEO-HRW algorithm are shown in **Figures 1 and 2**.

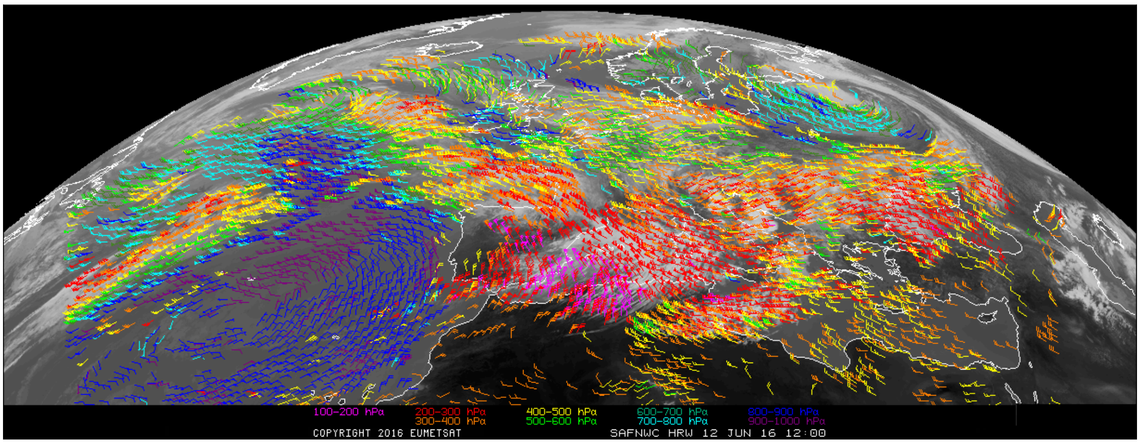

Figure 1: NWC/GEO-HRW output example of “Atmospheric Motion Vectors (AMVs)” in the European and Atlantic region, considering the default conditions for processing (12 June 2016, 12:00 UTC, MSG-3 satellite). Colour coding based on the AMV pressure

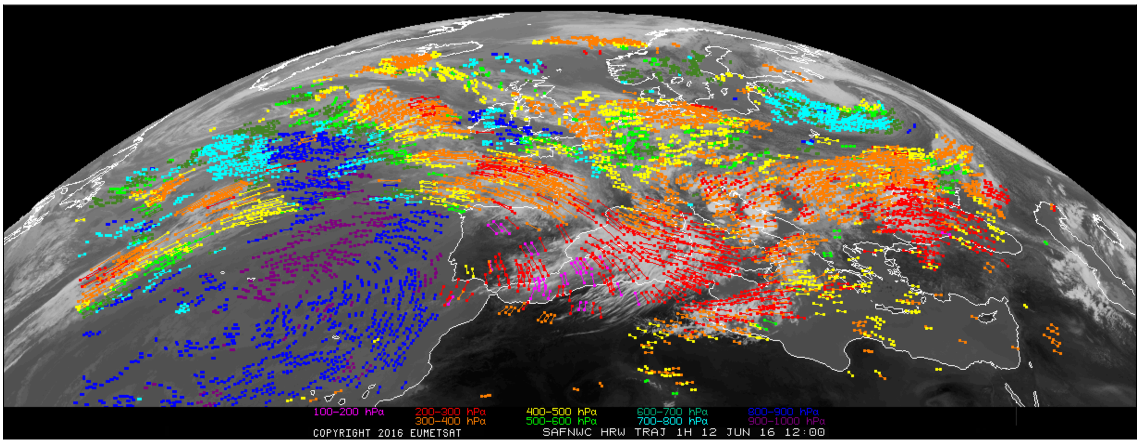

Figure 2: NWC/GEO-HRW output example of “1 hour Trajectories” in the European and Atlantic region, considering the default conditions for processing (12 June 2016, 12:00 UTC, MSG-3 satellite). Colour coding based on the AMV pressure

The tracer is defined through a specific cloudiness feature in visible, infrared or water vapour images (“cloudy tracer”), or through a specific humidity feature in cloudless areas in water vapour images (“clear air tracer”). The tracer has a fixed size in pixels. Tracers are identified in an initial image and tracked in a later image, so defining the AMV displacement between those images.

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HRW product includes pressure level information, which locates in the vertical dimension the calculated AMVs and Trajectories, and a quality control flagging, which gives an indication of the error in probabilistic terms, with auxiliary indicators about how the product was determined.

AMVs and Trajectories are calculated 24 hours a day, considering the displacement of tracers in:

- Up to seven MSG/SEVIRI channel images (HRVIS, VIS06, VIS08, IR108, IR120, WV62, WV73), every 15 minutes (in "Nominal scan mode") or 5 minutes (in "Rapid scan mode").
- Up to six Himawari-8/9/AHI channel images (VIS06, VIS08, IR112, WV62, WV70, WV74), every 10 minutes.
- Up to three GOES-N/IMAGER channel images (VIS07, IR107, WV65), every 15 minutes (in the Continental United States region) or 30 minutes (in the North America region).
- Up to six GOES-R/ABI channel images (VIS06, VIS08, IR112, WV62, WV70, WV74), every 10 or 15 minutes. The option for GOES-R satellites is implemented in a patch distributed for HRW v2018 product in the Autumn 2019.

AMVs are associated with the horizontal wind in the atmosphere. Exceptions exist to this, related generally to clouds which are blocked or whose flow is affected by orography, or to lee wave clouds with atmospheric stability near mountain ranges. But these exceptions are identified and discarded.

In order to forecast the weather, conventional observations are sparse whereas satellite based observations provide near global coverage at regular time intervals. This way, the derivation of AMVs from satellite images is an important source of global wind information, especially over the oceans and in remote continental areas.

Considering this, HRW product is useful in nowcasting applications, used in synergy with other data available to the forecaster. For example, in the monitoring of the general atmospheric flow, of small scale circulation and wind singularities, of convergence at low levels or divergence at the top of developed systems, and in the watch and warning of dangerous wind situations. It can also be used in the form of objectively derived fields, assimilated in numerical weather prediction (NWP) models together with many other data, or used as an input in analysis and forecast applications.

In case of interest on using NWC/GEO software package and HRW product, all National Meteorological Services within EUMETSAT Member and Cooperating States are automatically considered as potential NWCSAF users. All other organizations may also apply to become NWCSAF users, contacting through email at safnwchd@aemet.es. All applicants have become NWCSAF users without restrictions up to now.

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2. Materials and Methods

"NWCSAF High Resolution Winds (NWC/GEO-HRW)" product is designed in a modular way in the form of C and Fortran functions. These functions are available to the NWCSAF user, and are fully commented step by step, so that they are easy to understand. The whole process includes the following parts, explained in detail.

2.1. Preprocessing

During the preprocessing, the following parameters are extracted for use by HRW product:

1) Reflectances (normalized taking into account the distance to the Sun) for all pixels in the processing region, in the visible images on which tracers are calculated and tracked.
2) Brightness temperatures for all pixels in the processing region, in the infrared and water vapour images on which tracers are calculated and tracked.
3) Radiances for all pixels in the processing region, in the images on which tracers are calculated and tracked, for MSG/IR108 and WV62, GOES-N/IR107 and WV65, or Himawari-8/9 or GOES-R/IR112 and WV62 satellite channels.
4) NWP profiles for all pixels in the processing region, considering the satellite lowest resolution, for the following variables: temperature forecast, geopotential forecast, wind component forecast and wind component analysis.
5) Latitudes and longitudes, and solar and satellite zenith angles, for all pixels in the processing region, in the images on which tracers are calculated and tracked (calculated by NWC/GEO).
6) NWC/GEO-CT Cloud Type, NWC/GEO-CTTH Cloud Top Temperature, Pressure and Height, and NWC/GEO-CMIC Cloud Phase, Liquid Water Path and Ice Water Path outputs, for all pixels in the processing region, in the image on which tracers are tracked.
7) High resolution global OSTIA data for Sea Surface Temperature and Local Estimated Error [19], obtainable such as described in [20]. Although not directly used by HRW product, it is used for the processing of the NWC/GEO-Cloud products.

Here, only the satellite data for the requested satellite channels, and the NWP temperature data with a minimum number of levels are mandatory (a configurable parameter with a default value of 4). All other data contribute to a higher number of AMVs and Trajectories and a better quality of the output data. The option to calculate AMVs and Trajectories without NWP data is not available, since the amount and quality of data provided would be significantly worse.

The satellite data are to be provided in full resolution uncompressed original SEVIRI/HRIT data (for MSG satellite series), AHI/HSD data (for Himawari-8/9 satellite series), IMAGER/GVAR data (for GOES-N satellite series) or ABI/NetCDF data (for GOES-R satellite series). For processing, the Normalized reflectances and Brightness temperatures from these satellite data are scaled to integer "brightness values" from 0 to 255 (inside an 8 bit data range), in so-called "N_Value matrices".

NWP data are to be provided with a horizontal resolution of at least 0.5°, and a temporal resolution of at most 6 hours (a time step of at most 3 hours is preferred). ECMWF NWP model is used as default option, but other NWP models have also been used by different NWCSAF users (being the most common MétéoFrance ARPEGE and NOAA/NCEP GFS NWP models). NWP data are then temporally interpolated at each image and spatially interpolated at each pixel in the processing region, for their use by HRW product.

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2.2. Tracer search

The process of HRW product starts with the calculation of “tracers” throughout the processing region in an initial image (as already said, square segments of n x n pixels, used as initial positions of an AMV and Trajectory, and identified by a specific cloudiness feature or humidity feature). The geographical region, and the latitude and longitude limits for the calculation of AMVs and Trajectories can be specified with configurable parameters.

With the default configuration, the definition of new “tracer locations” starts at the location of all “tracking centres” related to valid AMVs in the previous round, when they are available. A set of “persistent tracers” can so successively be defined and tracked in several images, and the progressive locations of the tracer throughout the time define “Trajectories”. For this, it is necessary that the conditions implied by the "tracer method" used for the determination of the tracer in the “initial image”, keep on being valid throughout all the images.

If no tracers are available for the calculation from a previous round of HRW product, the tracer calculation is the only process which is activated for the first image. Once tracers from a previous run identified as initial image are available and AMVs and Trajectories have been calculated, the following tracer calculation processes activate as the final step of each HRW product run.

Two computation methods are applied for the calculation of new tracers: “Gradient method” and “Tracer characteristics method”. Both define a tracer optimizing its location in the vicinity of the “starting locations” (defined at specific distances from each other). Gradient method is by far more efficient in computing terms. Tracer characteristics method is more specific: it defines more tracers in empty areas with a longer but still reasonable computing time.

These tracer computation methods are used one after the other in two different tracer selection strategies throughout the region: the “single scale procedure” (in which one scale of tracers is calculated), and the “two scale procedure” (in which two different scales of tracers are calculated: “basic scale” and “detailed scale”).

A single scale procedure calculating only basic tracers with a line and column tracer size of 24 pixels is proposed as default configuration. A tracer size of 24 pixels for basic tracers and 12 pixels for detailed tracers is proposed as baseline for the two scale procedure. The line and column tracer size in pixels can be defined through configurable parameters. However, HRW product is defined to work with square shaped tracers, so similar values for the line and column tracer size are kept for the processing.

These resolutions define different tracer scales between 48 to 96 km at subsatellite point (in the “basic lowest resolution image scale”) and 6 to 12 km at subsatellite point (in the “detailed highest resolution image scale”), with the high values related to GOES-N satellite series and the low values related to Himawari-8/9 and GOES-R satellite series. So, between “mesoscale ß” and “mesoscale γ” meteorological dimensions.

The nominal observation frequency of 10 to 30 minutes is enough to track the majority of features with these sizes, although in some cases like small cumulus over land, the lifecycle might be a bit short for this image frequency. The use of HRW product in “Rapid scan mode” with MSG satellites can improve the results with tracers of this small size.

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2.2.1. First tracer search method: Gradient method

Starting from the northwestern corner of the image in the processing region, "tracer locations" are defined with "Gradient method". This method is similar to the one defined by *Hayden & Merrill, 1988* [2]. It has the following steps:

- To look for a "brightness value" (identified as any of the pixel values of the corresponding "N_Value matrix", inside a "tracer candidate" located at a "starting location"), greater than 120 (in visible cases) or smaller than 240 (in the other cases). This parameter is configurable.
- To verify if a contrast exists between the maximum and minimum "brightness value" in the tracer candidate, greater than 60 (in visible cases) or greater than 48 (in the other cases). This parameter is also configurable.
- To compute inside the tracer candidate the value and location of the "maximum gradient" $|\Delta N\_Value(\Delta x) + \Delta N\_value(\Delta y)|$, where Δ means a distance of 5 pixels in both line and column directions. This maximum gradient cannot be located on the edges of the tracer candidate.

If all previous processes have been successful, a valid tracer is defined at the location of the maximum gradient. In the default configuration of HRW v2018 product, the starting location for the subsequent tracer is established by a "distance between tracers" of 24 km, or 12 km if the tracer is related to a "low or very low cloud". This way, the spatial separation of AMVs and Trajectories related to these low level cloud types is narrower than the one for the other ones. This has been a request of NWCSAF users to increase the proportion of AMVs located at low levels.

If one failure occurs in the definition of a tracer location with "Gradient method", the distance to the next possible tracer is reduced to a half. Two consecutive failures defining a tracer location identify a "coverage hole".

2.2.2. Second tracer search method: Tracer characteristics method

The centres of "coverage holes" are the "starting locations" for the tracer search in a second iteration with the "Tracer characteristics method". It is based on new development. It is useful especially in the visible cases, where many potential tracers can present fainter edges because of cloudiness at different levels, with a similar reflectance. The method evaluates "tracer candidates" at increasing distances from each coverage hole (every 3 lines and columns, up to a maximum distance of 12 pixels). Two tests are here applied in sequence, so that a valid tracer can be defined:

1) "Frontier definition in the "N_Value histogram test":

   It includes two parts, based on the histogram classification of the "brightness values" of the "N_Value matrix" pixels in a "tracer candidate". In the first part, a significant contrast in the brightness values is to be found through the centiles of the histogram (CENT_nn%):

   - CENT_10% > 0.
   - CENT_90% >= 114 (visible cases); CENT_10% <= 252 (other cases).
   - CENT_97%-CENT_03% >= 20 if CENT_97% >= 150; >= 30 if CENT_97% < 150 (visible cases).
   - CENT_97%-CENT_03% >= 30 if CENT_03% <= 180; >= 50 if CENT_03% > 180 (other cases).

   In the second part of this test, one significant minimum or "frontier" is to be found in the brightness value histogram for the tracer candidate. The frontier is defined as the location of the

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deepest minimum in the "N_value histogram", binned in groups of three "brightness values". This frontier defines then a group of "bright pixels" (brighter than the frontier) and a group of "dark pixels" (darker than the frontier).

2) "Big pixel brightness variability test":

The tracer candidate is now considered as a coarse structure of 4x4 "big pixels", to be classified according to the brightness values of the respective pixel population. Three classes are possible:

- CLASS_0: "dark big pixel" (< 30% of its pixels are "bright pixels").
- CLASS_2: "bright big pixel" (> 70% of its pixels are "bright pixels").
- CLASS_1: "undefined big pixel" (intermediate case).

It is requested to avoid ambiguous cases that both CLASS_0 and CLASS_2 appear at least once in the "4x4 big pixel matrix", while the incidence of CLASS_1 being less than twice the less frequent of the other ones.

The "4x4 big pixel matrix" is then checked for enough brightness variability. At least two CLASS_0 to CLASS_2 or CLASS_2 to CLASS_0 transitions must exist along three of the four main directions in the "4x4 big pixel matrix": rows, columns, ascending diagonal directions and descending diagonal directions. For this, all linear arrays are checked in the row and column directions, while only linear arrays with at least 3 elements are checked in the diagonal directions.

2.2.3. Condition on the tracer closeness

No tracer is retained if it is found too close to a previously computed one ("closeness threshold"). So, each time a tracer is computed all pixels located nearer than this closeness threshold are added to a "pixel exclusion matrix", and excluded as potential tracer locations.

An additional condition is verified, through which all pixels inside a tracer must have a satellite zenith angle (and a solar zenith angle in the case of visible channels) smaller than a maximum threshold (configurable parameters, 80° and 87° respectively). This guarantees that the illumination and satellite visualization conditions are good enough for the process.

2.2.4. Detailed tracers in the two scale procedure

The "Basic scale" in the "two scale procedure" works in a similar way than the procedure here described for the "single scale procedure", while additionally defining starting locations for the "Detailed scale", when one of following conditions are met:

- No "Basic tracer" has been found, but at the "tracer candidate" following condition occurs: CENT_97% > 102 (in visible cases) or CENT_03% < 204 (in the other cases). A "Detailed tracer unrelated to a Basic tracer" is so defined, with less demanding brightness thresholds.
- A "Wide basic tracer" has been found, in which CLASS_2 values appear in both first and last row or column of the "4x4 big pixel matrix", in the "Big pixel brightness variability test". In this case, four starting locations are defined for the "Detailed scale". Each of them is located at the corners of a "Detailed tracer" whose centre is the centre of the "Basic tracer".
- A "Narrow basic tracer" has been found, in which CLASS_2 values do not appear in both first and last row nor column of the "4x4 big pixel matrix", in the "big pixel brightness variability test". In this case, one starting location is defined for the "Detailed scale", whose centre is defined by the weighted location of the "big pixels" in the "4x4 big pixel matrix".

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Examples of AMVs related to different types of tracers for MSG satellite series, considering the "tracer method" and the "tracer type", are shown in **Figures 3 and 4**.

In **Figure 3**, "Basic AMVs" are shown considering the tracer method ("Gradient method" and "Tracer characteristics method").

In **Figure 4**, "Basic and Detailed AMVs" are shown considering the tracer type ("Basic tracers", "Detailed tracers unrelated to Basic tracers", "Detailed tracers related to wide basic tracers", and "Detailed tracers related to narrow basic tracers").

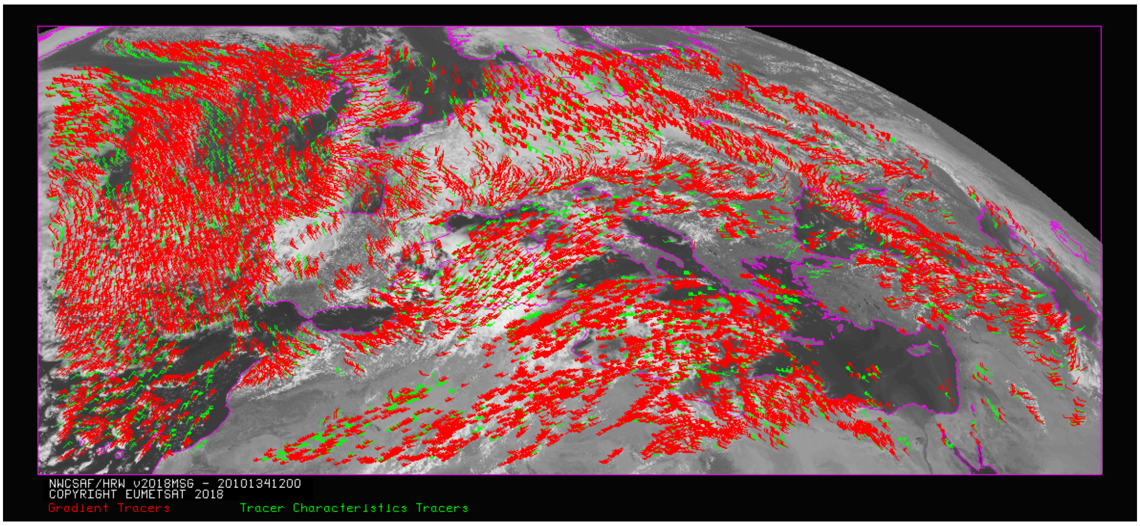

Figure 3: "Basic scale AMVs" (in red and green, considering the Tracer calculation method used for their extraction), in a single scale NWC/GEO-HRW example for the European and Mediterranean region, with the default conditions for MSG satellites (14 May 2010 12:00 UTC, MSG2 satellite)

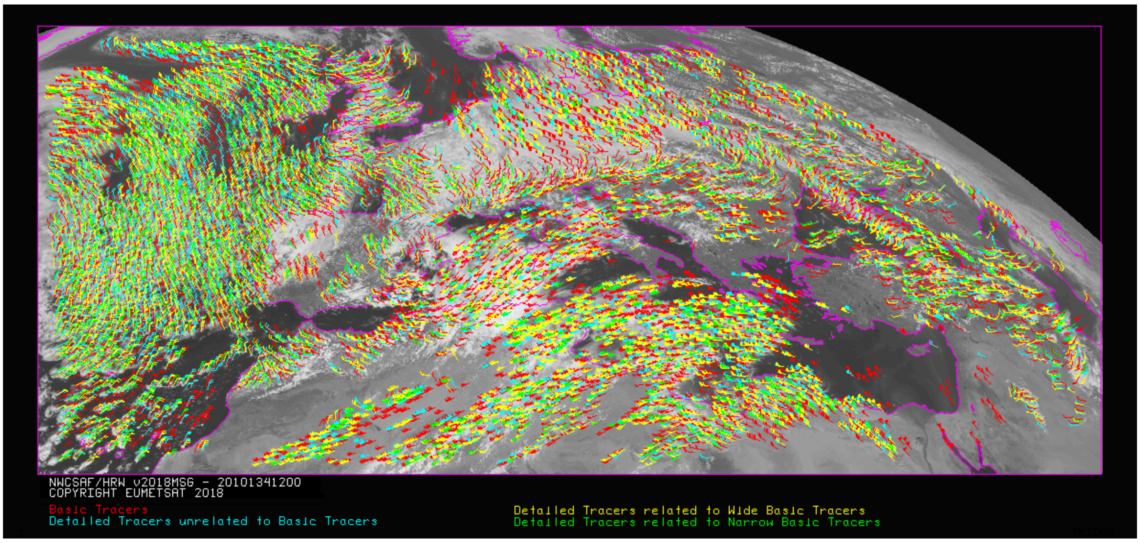

Figure 4: "Basic scale AMVs" (in red), and "Detailed scale AMVs" (in yellow, green and blue, considering their relationship with the Basic scale AMVs), in a two scale NWC/GEO-HRW example for the European and Mediterranean region, with the default conditions for MSG satellites (14 May 2010 12:00 UTC, MSG2 satellite)

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2.3. Tracer tracking

The "tracking" process looks for the location of a tracer computed in an initial image, inside a portion of a later image ("tracking area"). The process performs a pixel by pixel comparison between the tracer "brightness values" and those of a square segment of the same size ("tracking candidate"), repeatedly moving this tracking candidate throughout the tracking area.

For a tracking candidate (i,j) inside this tracking area, the algorithm used for the tracking process is one of the well-known methods:

- "Euclidean distance", in which the sum $LPij = \Sigma\Sigma(T - S)^2$ is calculated. T and S correspond to the "brightness values" for the tracer and the tracking candidate pixels at corresponding locations. The best tracking locations are defined through the minimum values of the sum LPij. This method is for example also used by NOAA operational AMV algorithm, as defined in [21].
- "Cross correlation", in which the normalized correlation value $CCij = COV_{T,S}/(\sigma_T \cdot \sigma_S)$ is calculated (default option for the processing). T and S correspond again to the "brightness values" for the tracer and the tracking candidate pixels at corresponding locations; COV is the covariance and σ is the standard deviation of these "brightness values" for the tracer and the tracking candidate. The best tracking locations are defined through the maximum values of the correlation CCij. This method is for example also used by EUMETSAT, JMA, KMA, and CPTEC/INPE operational AMV algorithms, as defined in [21].

The centre of the tracking area can preliminarily be defined through a "wind guess" obtained from the NWP forecast of the rectangular wind components, interpolated to the tracer location and level. This permits to reduce the tracking area size and the running time of HRW product.

However, HRW product has been optimized not to use this wind guess as default option, so reducing the dependence of the calculated AMVs from any NWP model used (although the running time is two to three times longer).

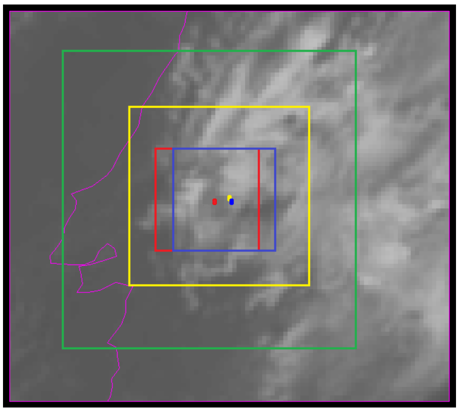

Figure 5: A low resolution tracer for 16 December 2009 11:45 UTC (red square, with its centre in the red mark), the location of its centre defined by NWP wind guess at 12:00 UTC (yellow mark), and its true tracking centre at 12:00 UTC defined by HRW product (blue mark), for an example case of AMVs with MSG2 satellite. The yellow square (with its centre at the position defined by the NWP wind guess at 12:00 UTC) corresponds to the "tracking area" using the wind guess for its definition. The green square (with its centre at the position of the tracer at 11:45 UTC) corresponds to the "tracking area" not using the wind guess for its definition. The larger size of the tracking area when the wind guess has not been used is to be noticed, which causes a longer time for the running of HRW product, but at the same time reduces the dependence from the NWP model

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The line and column size in pixels of the tracking area is calculated so that it is able to detect displacements of the tracer of at least 272 km/h in any direction, when the wind guess is not used in the definition of the tracking area. This parameter is configurable.

When the wind guess is used, the parameter is to be understood as the difference in speed with respect to that of the NWP wind guess that HRW product is at least able to detect.

To avoid the computation of LPij or CCij in all (i,j) locations of the tracking area, a gradual approach is performed in four iterations, based on the idea that the Euclidean distance and the Correlation change slowly, such as shown by *Xu & Zhang, 1996* [3].

In a first iteration, a pixel computation GAP = 8 is applied: LPij or CCij is evaluated only at (1,1),(1,9),…(9,1),(9,9),… pixel locations inside the tracking area. The four locations with the best values of LPij or CCij are retained for the following iteration. In the second, third and fourth iterations, LPij or CCij are only evaluated if possible at four locations around each one of the four best locations retained in the previous iteration, defined by (imax ± GAP, jmax ± GAP), for which GAP reduces to a half in each one of the iterations until having the value of 1.

After all four iterations, the three "tracking centres" with the best Euclidean distance or Correlation values are retained. With Cross correlation, it is also requested that the best correlation value is at least greater than 80% (50% for GOES-N satellites).

Finally, in the default configuration, the line/column and latitude/longitude location of the three best tracking centres is refined through second order interpolation with "subpixel tracking" process. Here, considering for example a tracking case with Cross correlation, being POS_{INT} and POS_{REAL} the line/column location of the tracking centre before and after this subpixel tracking, and CC_{-1}, CC_{+1}, CC the correlation values one position up/left from, down/right from, and at the tracking centre:

$$POS_{REAL} = POS_{INT} + (CC_{-1} - CC_{+1}) / 2(CC_{-1} + CC_{+1} - 2CC).$$

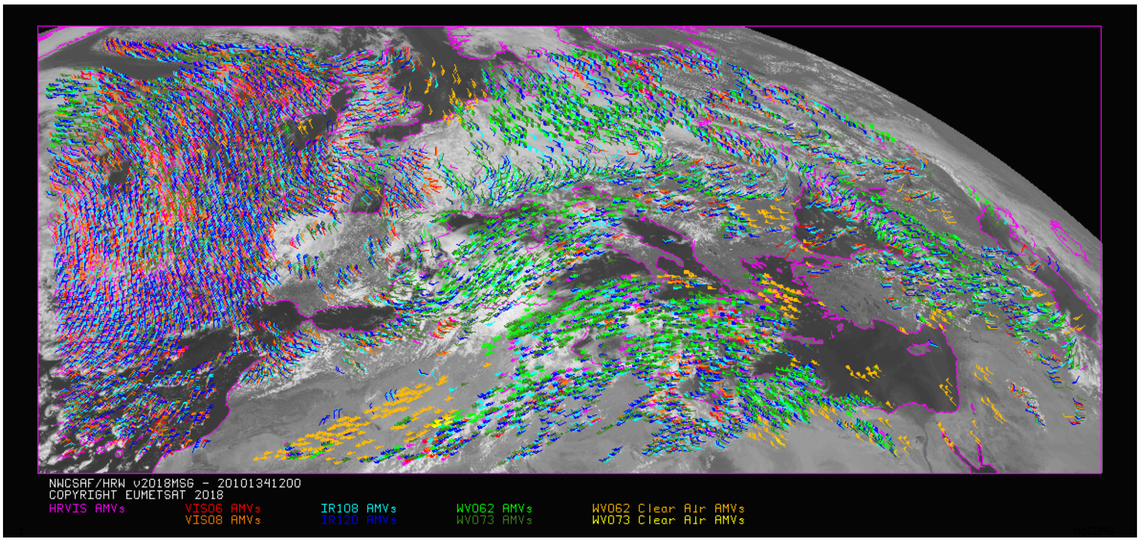

Figure 6: AMVs considering the satellite channel used for the AMV calculation, in a NWC/GEO-HRW example for the European and Mediterranean region, with the default conditions for MSG satellites (14 May 2010, 12:00 UTC, MSG2 satellite)

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2.4. "EBBT (Effective black-body brightness temperature)" height assignment

"EBBT (Effective black-body brightness temperature)" height assignment was the first option implemented in HRW product. Although not used anymore in the default configuration, it is still available in the HRW code. The method is still used by other AMV operational algorithms partially or with variations (with the main exception of JMA, as defined in [21]). However, in general in the latest years, it is being replaced by other more sophisticated methods in all AMV processing centres.

The height assignment is based on the brightness temperature of the tracer pixels for the infrared and water vapour channels. MSG/IR108, GOES-N/IR107, Himawari-8/9 or GOES-R/IR112 brightness temperatures are used for the visible channels. With this:

- A "Cloud top temperature" is computed through the coldest class of the brightness temperature histogram with at least 3 pixels, after histogram smoothing.
- A "Cloud representative temperature" is computed with $T_C + 1.2\sigma_C$ (visible cases), and T_C (other cases), where T_C is the mean value and σ_C the standard deviation of the brightness temperature.

A conversion of these temperature values to pressure values ("Cloud top pressure" and "Cloud representative pressure") is then done through interpolation inside the nearest NWP temperature forecast profile. If NWC/GEO-CT Cloud Type product output is available, it is read to define the "AMV cloud type", and which of the calculated pressure values is used as "AMV pressure".

Some tracers are also eliminated depending on the AMV cloud type value and the satellite channel with which they have been calculated. These cases are identified as empty cells in **Table 1**, and are related to tracers in visible and infrared channels with less than a 2.5% of cloudy pixels, fractional clouds, and cloud types for which the validation statistics are significantly worse. In the rest of cases, the AMV cloud type and the AMV pressure are also defined such as shown in **Table 1**.

Table 1: AMV filtering related to the "AMV cloud types" (in rows) and the satellite channels used for the AMV calculation (in columns), and consideration of the "Cloud top pressure (T)" or "Cloud representative pressure (R)" in the EBBT height assignment method for the "AMV pressure"

MSG channel	**HR VIS**		**VIS 06**	**VIS 08**	**IR 108**	**IR 120**	**WV 62**		**WV 73**
GOES-N channel	**VIS 07**				**IR 107**		**WV 65**		
Himawari-8/9 or GOES-R channel	**VIS 06**	**VIS 08**			**IR 112**		**WV 62**	**WV 70**	**WV 74**
01/02 Cloud free land/sea							T	T	T
03/04 Land/sea contaminated by ice							T	T	T
05/06 Very low/low cumulus/stratus	R	R	R	R	R	R		R	R
07 Medium cumulus/stratus	R	R	R	R	R	R		R	R
08/09 High/Very high cumulus/status	R	R			R	R	R	R	R
10 Fractional clouds									
11 High semitransp. thin					T	T	T	T	T
12 High semitransp. meanly thick	T	T			T	T	T	T	T
13 High semitransp. thick	R	R			R	R	R	R	R
14/15 High semitransp over cloud/ice					T	T	R	R	R
21 Multiple cloud types	R	R			R	R	R	R	R
22 Multiple clear air types							T	T	T
23 Mixed cloudy/clear air types	R	R			R	R	R	R	R
31/255 Unprocessed cloud type	R	R	R	R	R	R	R	R	R

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2.5. "CCC (Cross Correlation Contribution) method" height assignment (Cloudy cases)

"CCC (Cross Correlation Contribution) method" height assignment is used as default option in HRW product. This method was developed by *Borde & Oyama, 2008* [4], and is also used by several other operational AMV algorithms (EUMETSAT and KMA, as defined in [21]).

It requires the use of Cross correlation as tracking method, and the calculation of NWC/GEO-CT Cloud Type and CTTH Cloud Top Temperature and Pressure outputs for the image in which tracers are tracked, before the running of HRW product. If these outputs are not available, HRW product skips this method and uses the AMV pressure and AMV temperature values provided by "EBBT height assignment method".

In case the wind guess was used for the definition of the tracking area, the AMV pressure and AMV temperature values calculated by CCC height assignment method replace the values calculated previously by EBBT height assignment method.

CCC method has the advantage of including in the height assignment all procedures included in NWC/GEO-Cloud products for the identification of clouds and calculation of the cloud top pressure [16, 17, 18], and which are common methods used by other AMV producers, including:

- Opaque cloud top pressure retrieval considering infrared window channels, with simulation of radiances with RTTOV radiative transfer model, and possibility of thermal inversion processing.
- Semitransparent cloud top pressure retrieval with the radiance ratioing method and the infrared window/water vapour intercept method, considering water vapour and carbon dioxide channels.

CCC method defines the AMV pressure and the AMV temperature considering only the pressure and temperature of the pixels contributing most to the Cross correlation between the tracer in the initial image and the tracking centre in the final image.

For this, the "partial contribution to the correlation (CC_{ij})" for each pixel inside the tracer and the tracking centre is used. It is defined by the following formula, in which respectively for the tracer and the tracking centre Tij/Sij are again the "brightness values" for each pixel, T_M/S_M are the mean values and σ_T/σ_S the standard deviations of these "brightness values", and NUM is the total number of pixels inside the tracer or tracking centre:

$$CCij = (Tij - T_M)\ (Sij - S_M)\ /\ NUM \cdot \sigma_T \cdot \sigma_S.$$

The graph "Normalized reflectance(Partial contribution to the correlation)" for the visible channels, or the graph "Brightness temperature(Partial contribution to the correlation)" for the infrared/water vapour channels has in general the shape of the letter "C", as shown by the lower graphs in **Figure 7**. The left one corresponds to a MSG/VIS08 case, and the right one to a MSG/IR108 case. In this letter "C", the largest "partial contribution to the correlation" is given by the brightest and darkest pixels (for the visible channels), and by the warmest and coldest pixels (for the infrared/water vapour channels).

The AMV pressure and AMV temperature are calculated considering only the pixels whose partial contribution to the correlation is higher than a "CCC calculation threshold" inside the bright branch of the "Normalized reflectance(Partial contribution to the correlation)" graph in the visible cases. In the infrared and water vapour cloudy cases, it considers only the pixels whose partial contribution to the correlation is higher than the "CCC calculation threshold" inside the cold branch

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of the "Brightness temperature(Partial contribution to the correlation)" graph. The "CCC calculation threshold" is defined as the mean partial contribution to correlation, or zero if so no pixels are kept.

Considering this, the "AMV pressure (P_{ccc})" and "AMV temperature (T_{ccc})" are calculated considering the partial contribution to the correlation (CCij), the CTTH Cloud Top Pressure (CTPij) and the Cloud Top Temperature (CTTij) outputs for the pixels defined before inside the "tracking centre", with the formulae:

$$P_{ccc} = \Sigma(CCij \cdot CTPij) / \Sigma CCij$$

$$T_{ccc} = \Sigma(CCij \cdot CTTij) / \Sigma CCij$$

The procedure is repeated for the up to three tracking centres defined for each tracer. If the "parallax correction" is considered later in **Chapter 2.8** for the position of the tracer/tracking centre, a similar calculation is done for the "AMV height (H_{ccc})", considering the Cloud Top Height (CTHij) and the equivalent formula:

$$H_{ccc} = \Sigma(CCij \cdot CTHij) / \Sigma CCij$$

The "AMV cloud type" is calculated as the one with the highest sum of partial contributions to the correlation. The "AMV pressure error (ΔP_{ccc})" is finally calculated with the formula:

$$\Delta P_{ccc} = (\Sigma(CCij \cdot CTPij^2)/\Sigma CCij - P_{ccc}^2)^{1/2},$$

which can be useful as a Quality control parameter for the filtering of AMVs and Trajectories. Here, a maximum AMV pressure error is defined with a configurable parameter (with a default value of 150 hPa).

Images in **Figure 7** show in detail two examples of the running of "CCC method" (as already said, for a MSG/VIS08 AMV on the left side, and a MSG/IR108 AMV on the right side).

In the first row of the images, the "N_value matrices" for the tracer pixels in the initial image, and for its tracking centre pixels in the later image are shown. Comparing the images, it is visually clear that the same object is being observed in both cases, in spite of the evolution shown in a period of 15 minutes.

In the second row, the NWC/GEO-CT Cloud type and CTTH Cloud Top Pressure related to the tracking centre pixels are shown. In the third row, the "partial contributions to the correlation" for the tracking centre pixels are shown: on the left considering all pixels and on the right considering only those pixels defined as valid by the "CCC calculation threshold" (which in these cases is the "mean contribution to the correlation").

As already explained, the last row of the images shows respectively the "Normalized reflectance(Pixel correlation contribution)" graph and the "Brightness temperature(Pixel correlation contribution)" graph for these cases, with the "CCC calculation threshold" defined by the method as a vertical purple line. Only those pixels having a value inside the blue boxes of these graphs are used in the calculations of P_{ccc} and ΔP_{ccc}.

In the MSG/VIS08 example on the left, these pixels correspond to the very low and low cloud in the right part of the tracking centre, defining values of P_{ccc} = 834 hPa and ΔP_{ccc} = 27 hPa. In the MSG/IR108 case on the right, these pixels correspond to the high cloud in the upper right corner of the tracking centre, defining values of P_{ccc} = 286 hPa and ΔP_{ccc} = 24 hPa.

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With the default configuration of HRW product, the displacement of the AMV between the tracer and the tracking centre locations is not considered between the centres of these tracer and tracking centre, but between the "weighted locations" defined with similar formulae (where Xij and Yij correspond to the line and column position of each pixel inside the tracer and tracking centre):

$$X_{CCC} = \Sigma(CCij \cdot Xij) / \Sigma CCij.$$

$$Y_{CCC} = \Sigma(CCij \cdot Yij) / \Sigma CCij.$$

The weighted locations relate the displacement of the AMVs and Trajectories to the displacement of the part of the tracer with the "largest contribution to the cross correlation". These weighted locations are identified in **Figure 7** as red crosses.

When trajectories are calculated, tracking consecutively during several images the same tracer, the calculation of these weighted locations occurs only for the first AMV in the trajectory, and keeps the same value during all the time the Trajectory is alive. This way, spatial discontinuities in the trajectory are avoided.

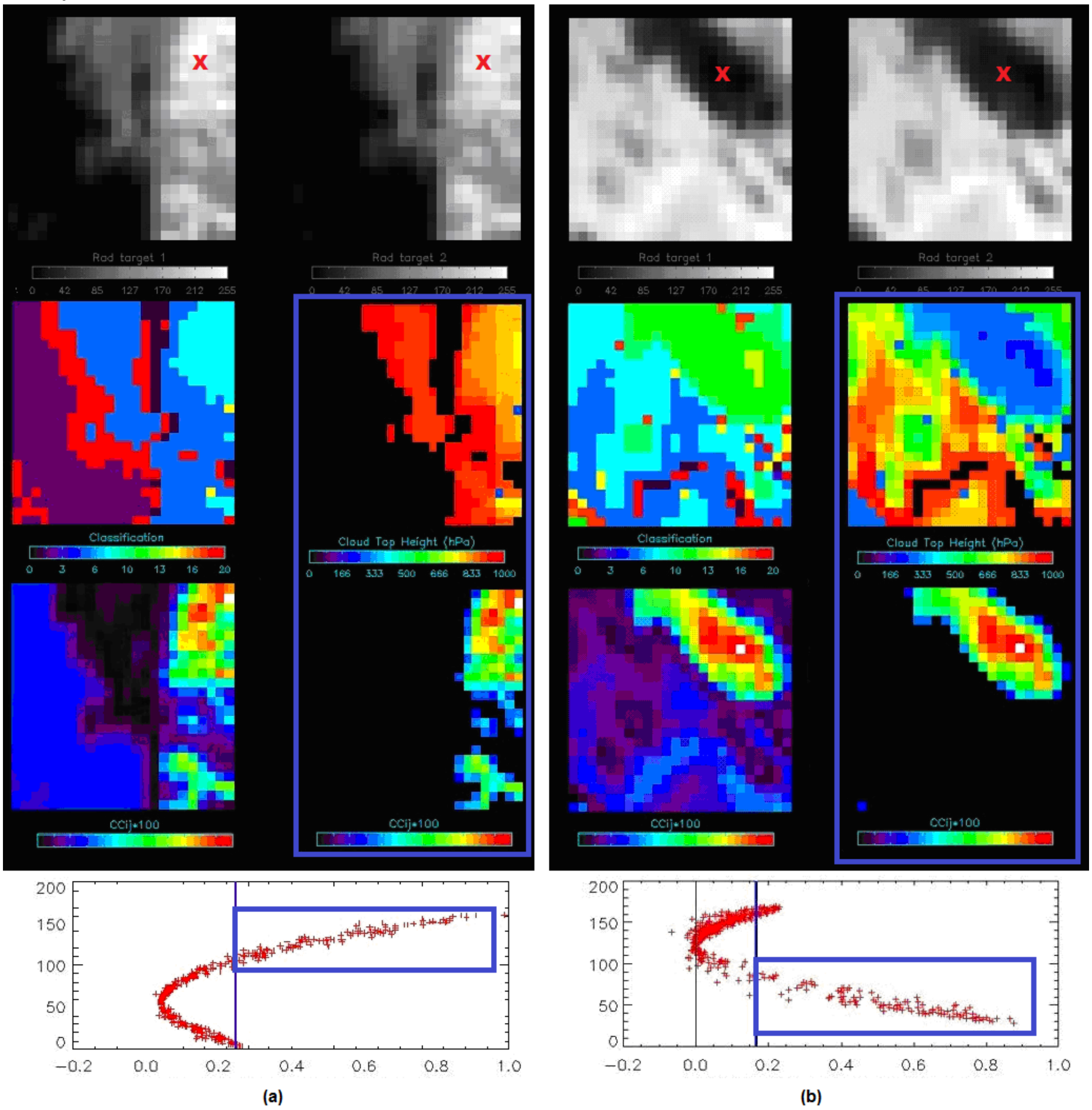

Figure 7: Matrices and graphs used in the calculation of "CCC method height assignment", for a MSG/VIS08 case (a) and a MSG/IR108 case (b), as explained in the text. The "weighted location" used for the calculation of the AMV displacement between the initial image and the later image is shown as a red cross in the images in the first row

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2.6. "CCC (Cross Correlation Contribution)" height assignment (Cloudy cases with Microphysics correction)

"CCC method" height assignment offers a direct correspondence between the pressure levels defined for HRW cloudy AMVs and Trajectories, and those given to the cloud tops by NWC/GEO-CTTH product, so avoiding any possible incongruence between both products. It also defines a clear correspondence between the elements considered for the AMV pressure calculations and the real features observed in the satellite images.

Taking this into account, several studies have suggested that AMVs are better related to a pressure level different than the cloud top: *Lean & al., 2014* [5], *Hernández-Carrascal & Bormann, 2014* [6], *Salonen & Bormann, 2014* [7].

An empirical relationship has been found in HRW product between the "difference between the AMV pressure calculated with CCC method and the radiosonde wind best fit pressure level" on one side, and the cloud depth represented by the "AMV Liquid/Ice water path" values on the other side. So, a correction of the AMV pressure can be defined with these parameters.

For this procedure, the output of the NWC/GEO-CMIC Cloud microphysics product is used, which provides the "Cloud phase, CPhij" for each cloud pixel, the "Liquid water path, LWPij" for each liquid cloud pixel and the "Ice water path, IWPij" for each ice cloud pixel.

The "AMV cloud phase" is defined in a similar way to the one used for the "AMV cloud type" in the previous chapter, as the phase with the highest sum of "partial contributions to the correlation". It has four possible values: Liquid phase, Ice phase, Mixed phase, Undefined phase.

The "AMV liquid water path (LWP_{CCC})" is then calculated for "Liquid phase AMVs", and the "AMV ice water path (IWP_{CCC})" is calculated for "Ice phase AMVs", considering similar formulae to the ones used in the previous chapter for the "AMV pressure":

$$LWP_{CCC} = \Sigma(CCij \cdot LWPij) / \Sigma CCij.$$

$$IWP_{CCC} = \Sigma(CCij \cdot IWPij) / \Sigma CCij.$$

The empirical relationship between the "difference between the AMV pressure calculated with CCC method and the radiosonde wind best fit pressure level" on one side, and the "AMV Ice/Liquid water path" on the other side, has been tuned in HRW v2018 product for MSG and Himawari-8/9 satellites in the regions used for the validation in **Chapter 3.1**, considering for the tuning a different period than the one used for the validation. For GOES-R, due to the similarities of its ABI imager with the AHI imager included in Himawari-8/9, the same empirical relationship has been used.

For example, for MSG satellite series, it considers 12:00 UTC Cloudy AMVs calculated with MSG2 satellite images between July 2010 and June 2011 in the European and Mediterranean region. Defining separate procedures for Ice and Liquid Cloud Visible AMVs, for Ice and Liquid Cloud Infrared AMVs and for Ice and Liquid Cloud Water vapour AMVs, **Figure 8** is obtained.

The empirical relationship is used to define a "Microphysics correction of the AMV pressure" (for MSG satellite series shown in **Table 2**). Equivalent procedures are defined for Himawari-8/9 and GOES-R satellite series; for more information on them, the "Algorithm Theoretical Basis Document for the Wind product processor of the NWC/GEO" [13] is to be checked.

In this "Microphysics correction", a "double linear/constant regression" works better than a simple linear regression in all possible cases. The correction locates in general the AMVs in a level nearer to the ground, with the main exception of AMVs with small "Ice/Liquid water path" values.

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A control is later defined through the Orographic flag to avoid that AMVs could be located at a level below the ground after the correction. Verifying the AMV statistics for the validation periods defined in **Chapter 3.1**, the "Microphysics correction" causes in general a reduction in all validation parameters, which is largest for the "Normalized bias (NBIAS)".

"CCC method with Microphysics correction" height assignment is implemented as default option for MSG, Himawari-8/9 and GOES-R satellites series. It cannot be used with GOES-N because no NWC/GEO-CMIC product is available for this satellite series. Considering this, it is necessary to run all NWC/GEO-Cloud products (CMA, CT, CTTH, CMIC) before HRW product, so that all this process can be activated. If CMIC product output is not available but the other ones are, HRW product runs "CCC method without Microphysics correction" height assignment.

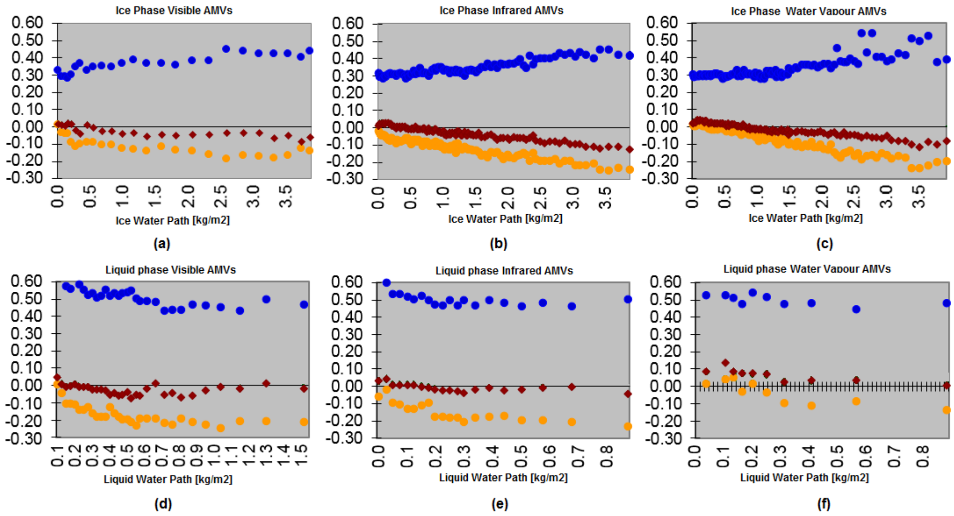

Figure 8: Graphs relating for MSG satellite series the "Difference between the AMV pressure calculated with CCC method and the AMV best fit pressure (in 10^3 hPa)" in red, the NBIAS in yellow and the NRMSVD in blue (both adimensional), with the "AMV Ice/Liquid Water Path (in kg/m²)", for Ice Visible AMVs (a), Ice Infrared AMVs (b), Ice Water vapour AMVs (c), Liquid Visible AMVs (d), Liquid Infrared AMVs (e) and Liquid Water vapour AMVs (f). 12:00 UTC Cloudy AMVs for MSG2 satellite for July 2010-June 2011 in the European and Mediterranean region are used for the tuning

Table 2: Correction for the "AMV pressure" (in hPa), based on the "AMV Ice water path (IWPccc)" or ""AMV Liquid water path (LWPccc)"" values (in kg/m²), for MSG satellite series

Correction for the "AMV pressure" (in hPa) for MSG satellite series, based on the "AMV Ice Water Path (IWPccc)" or "AMV Liquid Water Path (LWPccc)"	
VISIBLE ICE PHASE CLOUDY AMVS Corr.[hPa] = 51 without IWPccc Corr.[hPa] = -14 + 48·IWPccc[kg/m²] if IWPccc < 1.3542 kg/m2 Corr.[hPa] = 51 if IWPccc ≥ 1.3542 kg/m²	VISIBLE LIQUID PHASE CLOUDY AMVS Corr.[hPa] = 16 without LWPccc Corr.[hPa] = -42 + 226·LWPccc[kg/m²] if LWPccc < 0.3540 kg/m2 Corr.[hPa] = 38 if LWPccc ≥ 0.3540 kg/m²
INFRARED ICE PHASE CLOUDY AMVS Corr.[hPa] = 10 without IWPccc Corr.[hPa] = -16 + 37·IWPccc[kg/m²] if IWPccc < 3.3514 kg/m2 Corr.[hPa] = 108 if IWPccc ≥ 3.3514 kg/m²	INFRARED LIQUID PHASE CLOUDY AMVS Corr.[hPa] = 9 without LWPccc Corr.[hPa] = -36 + 251·LWPcccc[kg/m²] if LWPccc < 0.2271 kg/m2 Corr.[hPa] = 21 if LWPccc ≥ 0.2271 kg/m²
WATER VAPOUR ICE PHASE CLOUDY AMVS Corr.[hPa] = -7 without IWPccc Corr.[hPa] = -29 + 34·IWPccc[kg/m²] if IWPccc < 3.3824 kg/m2 Corr.[hPa] = 86 if IWPccc ≥ 3.3824 kg/m²	WATER VAPOUR LIQUID PHASE CLOUDY AMVS Corr.[hPa] = -56 without LWPccc Corr.[hPa] = -109 + 202·LWPccc[kg/m²] if LWPccc < 0.5149 kg/m2 Corr.[hPa] = -5 if LWPccc ≥ 0.5149 kg/m²

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An example of AMVs for MSG is shown in **Figure 9**, considering the different options for the CCC method height assignment ("CCC method with/without microphysics correction", using the low/high "CCC method calculation threshold") and the AMV phase ("ice cloud AMV", "liquid cloud AMV", "mixed/undefined cloud AMV", "clear air AMV").

Another example of AMVs is also shown in **Figure 10**, considering the "AMV pressure correction" defined by "CCC method with microphysics correction", for the AMVs in which this height assignment method was used.

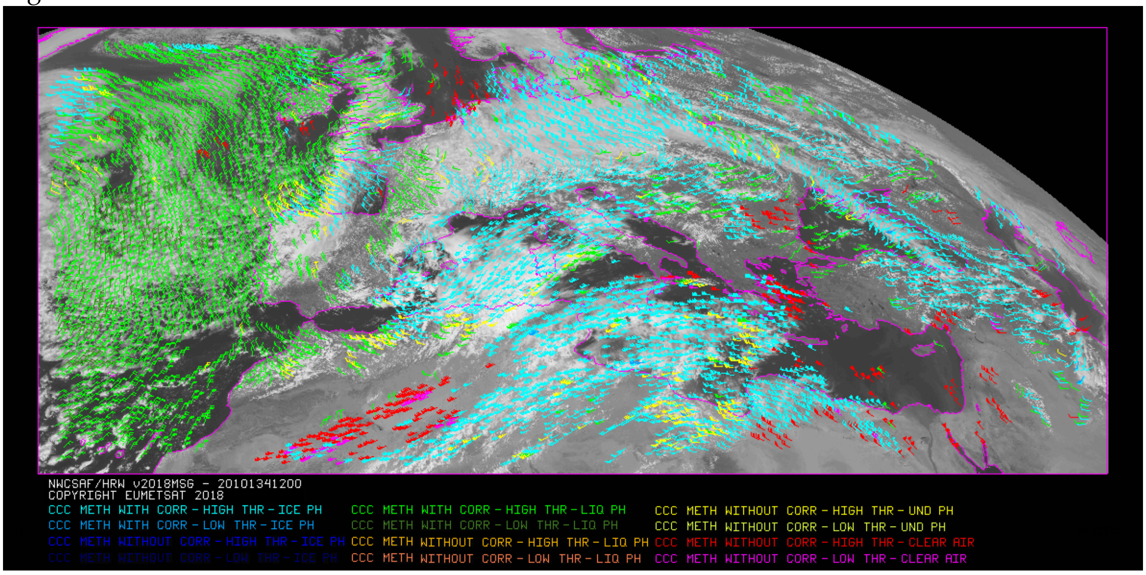

Figure 9: AMV height assignment ("CCC method with or without microphysics correction", using the high or low "CCC method calculation threshold"), and AMV phase ("ice cloud AMV", "liquid cloud AMV", "mixed/undefined cloud AMV", "clear air AMV"), in a NWC/GEO-HRW example for the European and Mediterranean region, with the default conditions for MSG satellites (14 May 2010, 12:00 UTC, MSG2 satellite)

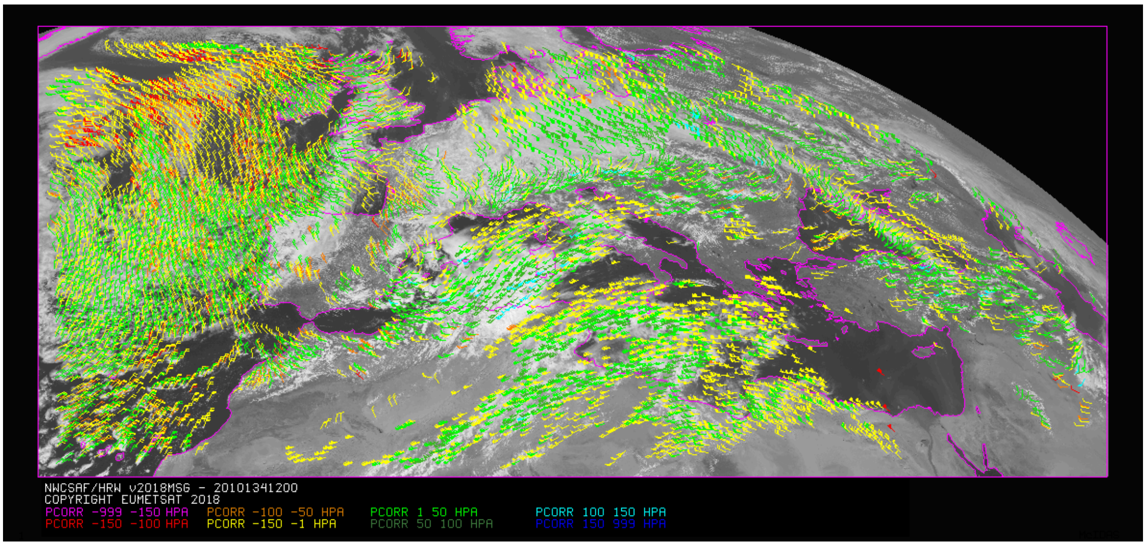

Figure 10: AMV pressure correction (for the cases in which "CCC method with microphysics correction" height assignment has been used), in a NWC/GEO-HRW example for the European and Mediterranean region, with the default conditions for MSG satellites (14 May 2010, 12:00 UTC, MSG2 satellite)

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2.7. "CCC (Cross Correlation Contribution)" height assignment (Clear air cases)

An adaptation of "CCC method" is implemented in HRW product for use with water vapour clear air AMVs because no pressure values can exist in NWC/GEO-CTTH output for clear air pixels.

A "Water vapour clear air AMV" is defined as a "Water vapour AMV" for which the sum of partial contributions to the correlation is larger for the group of clear air pixels than for the group of cloudy pixels, considering all pixels inside the tracking centre for which the partial contribution to the correlation is positive.

The "AMV cloud type" and the "AMV temperature" are calculated in a way similar to the one described in **Chapter 2.5** for the "Water vapour cloudy AMVs", although now the Brightness temperature for each pixel (BTij) from the corresponding satellite image is used instead of the NWC/GEO-CTTH Cloud Top Temperature for the processing. An "AMV temperature error (ΔT_{CCC})" is calculated considering a formula similar to the one used for the "AMV pressure error":

$$\Delta T_{CCC} = (\Sigma(CCij\ BTij^2)/\Sigma CCij - T_{CCC}^2)^{1/2}.$$

Three different temperature values are then defined by the following formulae: $T_{CCC} + \Delta T_{CCC}$, T_{CCC}, $T_{CCC} - \Delta T_{CCC}$. For each one of these values a temperature to pressure conversion is done through interpolation inside the nearest NWP temperature forecast profile, providing three pressure values: P_{CCC} (related to T_{CCC}), P_{CCCMAX} (related to $T_{CCC} + \Delta T_{CCC}$), and P_{CCCMIN} (related to $T_{CCC} - \Delta T_{CCC}$). P_{CCC} is then defined as the "AMV pressure" for the "clear air AMVs". The "AMV pressure error" for the "clear air AMVs" is defined as: $\Delta P_{CCC} = |P_{CCCMAX} - P_{CCCMIN}|/2$.

2.8.Wind calculation

In HRW v2018 product, a parallax correction of the latitude and longitude values of the tracer and tracking centre is implemented in the default configuration. This parallax correction corrects the horizontal deviation in their apparent positions due to their height over the Earth surface.

This parallax correction takes into account the "AMV height (H_{CCC})" calculated with CCC method for Cloudy AMVs, or the geopotential for the "AMV pressure" defined by the NWP geopotential field in all other cases. The general effect of this parallax correction is a very slight reduction in the AMV and Trajectory speeds, more significant when at higher levels of the atmosphere or nearer to the edge of the Earth disk.

Once the latitude and longitude are definitively defined for a tracer in the initial image (considering the "weighted location" inside the tracer defined by "CCC method" in the default configuration), and for its up to three tracking centres in the later image (considering the non-integer displacement of the tracer inside the "tracking area" with the "subpixel tracking" in the default configuration), the wind components related to that displacement are calculated.

The calculation of the wind components considers the displacement along the corresponding "great circle" with the "haversine formula". The haversine formula calculates the "wind speed" and the "bearing angle" of the great circle between the tracer location and the tracking centre location, using as input the corresponding longitude and latitude values, and the time difference between the scanning time of the pixel defining the tracer location in the initial image and the tracking centre location in the later image. The west-to-east and south-to-north wind components in m/s, are then calculated with these wind speed and bearing angle values.

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2.9.Quality Control

The "Quality Indicator method", developed by *Holmlund, 1998* [8] and implemented (although with variations) by all operational AMV algorithm described in [21], is used in HRW product for the Quality control. This method assigns quantitative quality flags to all AMVs and Trajectories, ranging from 0% to 100%: "Quality Indices (QI)".

It is based on normalized functions, related to the expected change of the AMVs considering "temporal vector consistency" (comparison to a "previous AMV" in the previous image at the same location and level), "spatial vector consistency" (comparison to a "neighbour AMV" in the current image at the same location and level), and "vector consistency relative to a background" (NWP wind forecast at the same location and level). For the two scale procedure, an additional "interscale spatial consistency" is computed for detailed AMVs derived from a basic scale tracer (comparing to the corresponding "Basic scale AMV").

The different "Individual Quality Indices" are given by the following formulae, in which SPD is the average wind speed for the evaluated AMV and the reference wind, and DIF is the absolute change in the module of the vector difference:

$QF = 1 - [\tanh[DIF/(\max(0.4SPD, 0.01))+1]]^2$ (in the "forecast vector consistency" test)

$QI_i = 1 - [\tanh[DIF/(\max(0.2SPD, 0.01))+1]]^3$ (in the other consistency tests).

The procedure is repeated for up to three "neighbour AMVs" in the spatial consistency, and up to three "previous AMVs" in the temporal consistency. The contribution from each one of these reference AMVs to the value of the spatial or temporal consistency depends on a "distance factor" to the evaluated AMV. The distance factor is given by the following formulae, in which SPD/DIR/LAT are the speed/direction/latitude of the evaluated AMV, LATDIF/LONDIF are the latitude/longitude difference with respect to the reference AMV, and ER is the Earth radius in kilometres:

$alpha = 200 + 3.5\ SPD$

$gamma = ER \cdot (LATDIF^2 + LONDIF^2)^{1/2} \cdot \cos(270 - DIR - \mathrm{atan}(\cos(LAT)+LATDIF/LONDIF))$

$delta = ER \cdot (LATDIF^2 + LONDIF^2)^{1/2} \cdot \sin(270 - DIR - \mathrm{atan}(\cos(LAT)+LATDIF/LONDIF))$

$factor = (gamma/alpha)^2 + (delta/alpha)^2$

Only reference AMVs with a distance factor smaller than 1, a pressure difference smaller than 25 hPa and a latitude and longitude difference smaller than 1.35° are considered valid here. The three reference AMVs with the smallest distance factor are considered for the Quality control.

The weighted sum of these "consistency tests" provides two overall values: the "Quality Index with forecast" and the "Quality index without forecast". The weight of these consistency tests in the overall Quality Indices are: 3 for the temporal and spatial vector consistency tests, and 1 or 0 for the forecast vector consistency test. The value 1 provides the "Quality index with forecast" and the value 0 provides the "Quality index without forecast".

The calculations are equivalent to those used in the EUMETSAT AMV operational algorithm (for which however the weight of the spatial and temporal vector consistency test is 2).

Two corrections are nevertheless applied in the "overall Quality Indices" before using them:

- One correction reduces the "Quality Indices" of AMVs with a speed lower than 2.5 m/s, multiplying them with the linear factor SPD/SPEED_THR (where SPD = speed of the evaluated AMV, SPEED_THR = 2.5 m/s).

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- The other correction has the name of "Image correlation test" and affects visible and infrared AMVs with a pressure higher than 500 hPa. It is a factor defined by the following formula, in which CORR(IR,WV) is the correlation of IR108/WV62 images for MSG satellites, the correlation of IR107/WV65 for GOES-N satellites, or the correlation of IR112/WV62 images for Himawari-8/9 of GOES-R satellites, at the location of the AMV tracking centre:

$$1 - (\tanh((\max(0, \mathrm{CORR(IR,WV)})/0.2)))^{200}$$

The overall "Quality Index with forecast" or "Quality Index without forecast" are used for the filtering of the AMV and Trajectory data, before writing them in the output files. The first one is used as default option. The "Quality Index threshold" for the acceptance of an AMV or Trajectory as valid has a default value of 70%, and a minimum value of 1%. An example of valid AMVs is shown in **Figure 11**, considering this "Quality Index with forecast".

Some additional considerations on the "Quality Control", specific for HRW product, are:

- All calculated AMVs are considered valid for the "spatial vector consistency".
- It is frequent that a quality consistency test cannot be calculated, for example when no reference AMV was found for the comparison. The overall "Quality indices" will thus only include the available quality tests.
- For the temporal consistency of successive AMVs related to the same Trajectory, some limits are defined for the consistency in the speed difference (10 m/s), direction difference (20°) and pressure difference (50 hPa), with the previous AMV in the same Trajectory.
- Each one of the up to three AMVs calculated for each tracer has its own "Quality Indices", but only one of them is selected for the HRW outputs. The selected AMV is the one which is the best for the most of following criteria: interscale spatial quality test, temporal quality test, spatial quality test, forecast quality test and correlation (this one with a triple contribution). If this is not definitive, the AMV with the best forecast quality test prevails. If this is also not definitive, the AMV with the best correlation prevails.

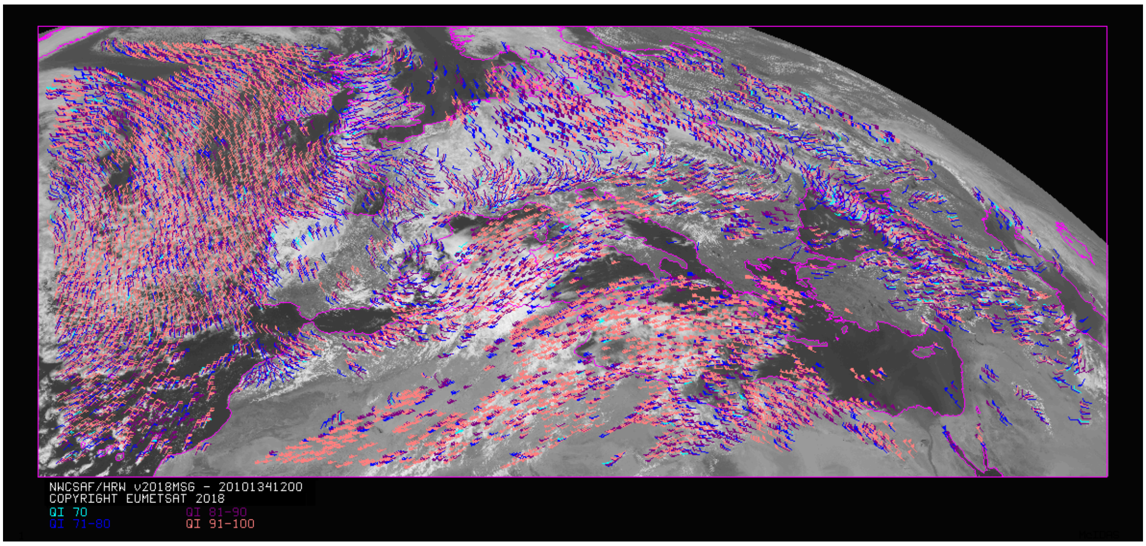

Figure 11: "Quality index with forecast" values, for the NWC/GEO-HRW example for the European and Mediterranean region, with the default conditions for MSG satellites (14 May 2010, 12:00 UTC, MSG2 satellite). Only values for "Quality index without forecast ≥ 70%" are present, because of the use of this threshold for the AMV filtering

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2.9.1. "Common Quality Index without forecast"

Through the experience in the "International Winds Workshops", it was clear that the configuration of the "Quality Indices" is very different for different AMV algorithms, and so a common homogeneous use for AMVs calculated by different AMV producers was not possible.

Because of this, a self-contained Fortran module defined by EUMETSAT and NOAA/NESDIS and calculating a "Common Quality Index without forecast", was distributed by the "International Winds Working Group" in May 2017, so that it would be included as such without modifications by all AMV algorithms. The experience of use of this "Common Quality Index without forecast" in the "2018 AMV Intercomparison Study" [23] showed some skill in filtering collocated AMVs from different AMV algorithms, improving their statistical agreement.

This "Common Quality Index without forecast" module has been implemented in HRW v2018 product, and the parameter is provided as an additional third "Quality Index" for AMVs and Trajectories. Differences of this "Common Quality Index without forecast" with respect to the previous ones are:

- It is only calculated for AMVs and Trajectories with at least two "Trajectory sectors".
- For the spatial consistency, only the closest "neighbour AMV" is considered. For the temporal consistency only the "previous AMV" related to the same Trajectory is considered.
- Four different tests are applied: direction, speed and vector difference tests for the temporal consistency, and vector difference for the spatial consistency (with a double contribution). Formulae for the calculation of these "quality consistency tests" are also slightly different.
- It is not used for the filtering of AMVs and Trajectories by HRW product, so all values between 1% and 100% are possible in the AMV and Trajectory outputs. In the cases for which it could not be calculated, an "unprocessed value" is defined.

An example of valid AMVs is shown in **Figure 12**, considering this "Common Quality Index without forecast".

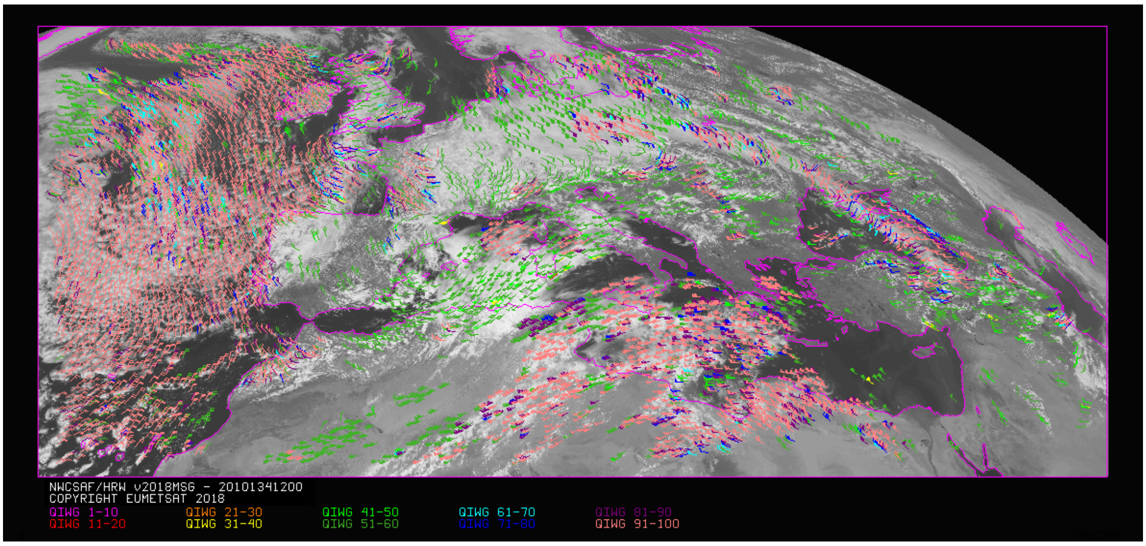

Figure 12: "Common Quality index without forecast" values, for the NWC/GEO-HRW example for the European and Mediterranean region, with the default conditions for MSG satellites (14 May 2010, 12:00 UTC, MSG2 satellite). The differences with **Figure 11**, and the fact that not all AMVs have a valid value for the "Common Quality index without forecast" are to be noticed.

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2.10. Orographic flag

In the default configuration of HRW product, an "Orographic flag" based on new development is calculated for each AMV and Trajectory. The Orographic flag incorporates topographic information, which in combination with NWP data, detects and rejects those AMVs and Trajectories affected by land influence. The reasons for this land influence may be:

- AMVs associated to land features incorrectly detected as cloud tracers.
- Tracers blocked or whose flow is affected by mountain ranges.
- Tracers associated to lee wave clouds with atmospheric stability near mountain ranges.

These tracers present displacements which do not correspond with the general atmospheric flow. Because of this, the corresponding AMVs and Trajectories are not considered as valid.

The procedure to calculate the "Orographic flag" implies the reading of NWP geopotential data and two topography matrices for the defined satellite and positioning. These matrices define the 3% and 97% centiles of the topography histogram for each pixel, in which data up to 1 degree away are considered. They are called the "Representative Minimum and Maximum height matrices" for each pixel.

These matrices are then converted to "Representative Maximum and Minimum surface pressure matrices" with NWP geopotential data. To do this, the Height matrices are converted to geopotential values, and the geopotentials are then inversely interpolated to NWP pressure to define the "Representative Maximum and Minimum surface pressure" values for each pixel (P_{MIN}, P_{MAX}).

These values represent the highest and lowest representative surface pressure values in locations up to one degree away of each pixel of the image.

After this, the "Orographic flag" is calculated. Possible values are:

- Orog.flag = 0: The "Orographic flag" could not be calculated.
- Orog.flag = 1: $P_{AMV} > P_{MIN}$.
  The AMV was wrongly located below the lowest representative pressure level (mainly due to Microphysics corrections in the "AMV pressure" value).
- Orog.flag = 2: $P_{AMV} > P_{MAX} + (P_{MIN} - P_{MAX})/2$.
  Very important orographic influence in the AMV location.
- Orog.flag = 3: $P_{AMV} > P_{MAX} – 25$ hPa.
  Important orographic influence in the AMV location.
- Orog.flag = 4: Very important orographic influence was found at a previous position of the AMV (for which Orographic flag = 2 or 4).
- Orog.flag = 5: Important orographic influence was found at a previous position of the AMV (for which Orographic flag = 3 or 5)
- Orog.flag = 6: No orographic influence is found in any current or previous position of the AMV.

In the default configuration, all AMVs and Trajectories with any Orographic influence (i.e. with Orographic flag = 1 to 5) are eliminated from the HRW output files.

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2.11. Final Control Check and Output data filtering

After the "Quality control", sometimes an AMV is detected to have a direction or velocity completely different to the ones in its immediate vicinity, without clearly justifying the reason for such changes in direction or velocity. They can be considered as errors. To remove these errors, a function based on new development and called "Final Control Check" is run by HRW product.

This function calculates the velocity and direction histograms for all valid AMVs calculated with the same satellite channel in small areas inside the processing region (square boxes of 5x5 degrees of latitude and longitude). When any of the columns of the velocity or direction histograms has only one element, the AMV is excluded. The procedure considers that the lack in the same area of another AMV with relatively similar velocities or directions is enough to consider that AMV as an error.

Several output data filterings are additionally considered in this step, which depend on the value of several configurable parameters. These configurable parameters are:

- AMV BANDS, which defines the channels for which AMVs and Trajectories are calculated.
- CLEAR AIR AMVS, which defines if "Clear air water vapour AMVs" are calculated. They are included in the default option.
- QI THRESHOLD, which defines the "Quality index threshold" for the AMVs and Trajectories in the output files. As already said, the "Quality index with forecast" or the "Quality index without forecast" can be used for this. The first option is used as default one, with a threshold of 70%.
- MAXIMUM PRESSURE ERROR, which defines the maximum "AMV pressure error" in the output AMVs and Trajectories, with "CCC method" height assignment. Default value: 150 hPa.
- MIN CORRELATION, which defines the minimum correlation in the output AMVs and Trajectories, when "Cross correlation" tracking is used. Default value: 80% (50% for GOES-N).
- FINAL FILTERING, which defines several filterings in the output AMVs and Trajectories, depending on its value, on the "AMV pressure" filtering defined in **Table 3**, on the "AMV cloud type" defined in **Table 1**, and on the "spatial vector consistency" test.

Table 3: AMV filtering related to the "AMV pressure" (in rows) and the satellite channels used for the AMV calculation (in columns). "C" means clear air AMVs removed; "A" means all AMVs removed; "L" means all AMVs removed if so configured (not in the default configuration).

MSG channel		**HR VIS**	**VIS 06**	**VIS 08**	**IR 108**	**IR 120**	**WV 62**		**WV 73**
GOES-N channel		**VIS 07**			**IR 107**		**WV 65**		
Himawari-8/9 or GOES-R channel	**VIS 06**	**VIS 08**			**IR 112**		**WV 62**	**WV 70**	**WV 74**
100-199 hPa			A	A					
200-299 hPa			A	A					
300-399 hPa			A	A					
400-499 hPa							C	C	C
500-599 hPa							A	C	C
600-699 hPa							A	C	C
700-799 hPa							A	A	A
800-899 hPa							A	A	A
900-999 hPa					L	L	A	A	A

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2.12. Autovalidation process of NWC/GEO-HRW product

Considering requests from NWCSAF users, HRW v2018 product offers the option to calculate validation statistics for its AMVs with the algorithm itself (using as reference NWP analysis or forecast components of the wind, interpolated to the AMV final location and level). The validation statistics can be calculated using NWP forecast winds in real time processes, and using NWP forecast or analysis winds in reprocessing tasks. The validation statistics are calculated at the end of the process of each HRW run for each satellite slot.

This process is implemented in the default configuration for validation against NWP forecast winds, with statistics for all layers together and the different satellite channels and AMV types ("basic AMVs" and "detailed AMVs", "cloudy AMVs" and "clear air AMVs") separately. Additional options exist for other separate or joint processing of layers, channels and AMV types.

The parameters calculated in this autovalidation are exactly those defined later in **Chapter 3.1** for the validation of HRW product: Number of collocations (NC), Mean reference wind speed (SPD), Normalized bias (NBIAS), Normalized mean vector difference (NMVD) and Normalized root mean square vector difference (NRMSVD). They are written in the running log of HRW product, and in a specific file defined for that purpose. They can be used by the NWCSAF user as an additional tool for the quality monitoring of the HRW outputs.

The "NWP reference wind" which validates each AMV, the "vector difference with the NWP reference wind", and the "NWP reference wind at the AMV best fit pressure" (all of them defined by their speed and direction, and the last one also by its pressure value), are also calculated and added to the HRW output files by this autovalidation process.

The first one allows NWCSAF users a quick recalculation of the HRW validation parameters for different sampling and filtering options of the data, including for example monthly or yearly totalizations. The second one can be used for example for nowcasting tasks, so that the users are able to detect cases for which the AMV is very different to the NWP forecast wind, and may be aware if a warning is needed in some case due to strong winds unforeseen by the NWP forecast. Finally, the third one can be used for example for verification tasks of the AMV height assignment, to know in which cases there is more or less agreement between the AMV pressure defined for the AMVs and Trajectories, and the one suggested by the NWP model reference.

The calculation of the "NWP reference wind at the AMV best fit pressure" consists of two steps: first, the NWP level with the smallest vector difference between the observation and the NWP wind is found. Then, the minimum is calculated by using a parabolic fit of the vector difference for this NWP level and the two neighbouring levels.

The calculation is based on the procedure defined by *Salonen & al., 2012* [11], and is only defined at some specific circumstances, to avoid broad best fit pressure values which are not very meaningful: the minimum vector difference between the observed and the NWP reference wind at best fit pressure has to be less than 4 m/s, and the vector difference has to be greater than the minimum difference plus 2 m/s outside a band that encompasses the best fit pressure ± 100 hPa. This way, only around a 40%-50% of the AMVs have a defined value for the "NWP reference wind at the best fit pressure".

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2.13. Outputs of NWC-GEO/HRW product

Four different types of outputs are possible for "HRW/High Resolution Winds algorithm", depending on the value of a configuration parameter:

- OUTPUT FORMAT = EUM: one BUFR file corresponding to the "Heritage AMV BUFR sequence" defined by the "International Winds Working Group (IWWG)" more than a decade ago, and which is used by most of AMV operational algorithms, so permitting a common processing for all AMV datasets obtained with this format.
- OUTPUT FORMAT = IWWG: one BUFR file corresponding to the "New 310077 AMV BUFR sequence" defined in 2018 by the "International Winds Working Group (IWWG)", and which is being implemented by most of AMV operational algorithms as a substitute of the previous one, with more information and better identification of all AMV elements. This sequence also permits a common processing for all AMV datasets obtained with this format. This option is to be available since a patch distributed for HRW v2018 product in the Autumn 2019.
- OUTPUT FORMAT = NWC (default option): two different BUFR files for AMVs and Trajectories, related to the ones used in all previous versions of HRW product, so permitting continuity of use throughout the different versions of HRW product.
- OUTPUT FORMAT = NET: one NetCDF file, requested by the NWCSAF users for a common processing of all NWCSAF products.

Considering this, different outputs are obtained for each scale for all these formats ("Basic" and "Detailed" if so configured), for each processing region, for every running slot. If AMVs and Trajectories have been calculated for several channels, they are all included in the same output file.

More details about the contents of HRW product output files can be obtained in the "User Manual for the Wind product processor of the NWC/GEO: Science Part" [12].

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3. Results and Discussion

3.1. Validation of HRW v2018 AMVs

The validation of the default configuration of HRW v2018 AMVs, considering radiosonde winds as reference winds, is shown here for MSG, Himawari-8/9, GOES-N and GOES-R satellite series. The validation statistics defined at the "Third and Fourth International Winds Workshops" [9, 10], and recommended by the Coordination Group for Meteorological Satellites (CGMS) for the international comparison of satellite winds, have been used here:

- NC: Number of collocations between the HRW AMV winds, defined as (Ui,Vi), and the radiosonde reference winds, defined as (Ur,Vr).
- SPD: Mean horizontal speed for the reference radiosonde winds in m/s.
- BIAS: Difference between the mean horizontal wind speed of the reference winds and the collocated HRW AMV winds:

  $$BIAS = (\Sigma((U_i^2 + V_i^2)^{1/2} - (U_r^2 + V_r^2)^{1/2}))/NC$$

  It estimates the systematic error related to the calculation of the AMV wind speed (over- or underestimation of the mean AMV wind speed with respect to the mean reference wind speed).
- MVD: Mean vector difference between the reference winds and the collocated AMV winds:

  $$MVD = (\Sigma VD_i)/NC \qquad \text{where} \qquad VD_i = ((U_i - U_r)^2 + (V_i - V_r)^2)^{1/2}$$

  It estimates the systematic error related to the calculation of the AMV wind vectors.
- RMSVD: Root mean square vector difference:

  $$RMSVD = (MVD^2 + SD^2)^{1/2} \qquad \text{where} \qquad SD = ((\Sigma(VD_i - MVD)^2)/NC)^{1/2}$$

  It estimates the systematic and random error related to the calculation of the wind vectors. It is calculated through the Mean vector difference (MVD), and the Standard deviation (SD) of each vector difference with respect to the mean.

Here, AMVs are compared to the nearest radiosonde wind with a maximum distance of 150 km and a maximum pressure difference of 25 hPa. Due to the variable magnitude the parameters can have in different samples, SPD parameter is used for normalization. This way, the following relative parameters based on the previous ones are used in the validation; these parameters are independent of the magnitude of the winds and can more easily be compared in different samples of data:

- NBIAS = BIAS / SPD (Nomalized bias).
- NMVD = MVD / SPD (Normalized mean vector difference).
- NRMSVD = RMSVD / SPD (Normalized root mean square difference).

The validation of HRW v2018 AMVs for the different satellite series is shown considering all AMVs together and three separate layers (high: 100-400 hPa; medium: 400-700 hPa; low: 700-1000 hPa) in **Tables 4 to 7** in the following pages. When the tables are compared:

- Considering the density of AMV data for the different satellites, equivalent amounts of MSG, Himawari-8/9, GOES-R AMVs are obtained for regions of similar size. The smaller amount of GOES-N AMVs is explained by the smaller number of satellite channels used in its processing.
- Considering the distribution of AMVs in the different layers, the proportion of AMVs for the High/Medium/Low layer for the different satellites series is:
  - For MSG: 52%/25%/23% (for validated AMVs) and 45%/23%/32% (for calculated AMVs).

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    - For GOES-N: 86%/7%/7% (for validated AMVs) and 69%/12%/19% (for calculated AMVs).
    - For Himawari: 82%/14%/4% (for validated AMVs) and 78%/14%/8% (for calculated AMVs).
    - For GOES-R: 86%/12%/2% (for validated AMVs) and 82%/11%/7% (for calculated AMVs).
- Here, the higher density of tracers related to low and very low clouds has a good impact in the distribution of AMVs in the different layers for MSG satellite series. This contributes to a better characterization of the wind in the different atmospheric levels.

  Considering Himawari-8/9 and GOES AMVs, the higher concentration of AMVs in the High layer is basically caused by the regions used for the validation (with large high altitude and desert areas, and so less frequent low clouds). Considering for example AMVs calculated in the Himawari-8 Full Disk for IR112 channel, the distribution of AMVs for the High/Medium/Low layer is 52%/15%/33%, more in consonance with the result for MSG satellite series.
- Considering the different layers, the validation parameters are progressively higher for the High layer, Medium layer and Low layer. This is a general result of all AMV calculation algorithms.
- Considering the different satellite channels, MVD and NRMSVD parameters seem very different considering all layers together, with changes up to a 50% between the best case and the worst case for each satellite series. This is mostly caused by the different proportion of AMVs in the different layers for each channel. Inside each one of the layers, the differences are much smaller.
- Comparing with the equivalent statistics for MSG AMVs, the validation statistics for Himawari-8/9 AMVs show better NMVD and NRMSVD values (up to a 10% smaller), due to its larger proportion of High layer AMVs. NBIAS parameter shows similar values but with an opposite sign. Considering each layer, validation parameters are similar in the High layer, while the NMVD and NRMSVD are up to a 15% worse for the Medium and Low layer for Himawari.
- Comparing with the equivalent statistics for MSG AMVs, the validation statistics for GOES-N AMVs have differences up to a 15%, in many cases for the better.
- Comparing with the equivalent statistics for Himawari-8/9 AMVs, the validation statistics for GOES-R AMVs are equivalent for the High Layer, and around a 15% better for the Medium and Low layer. Comparing with GOES-N AMVs, the validation statistics for GOES-R are similar (with differences generally smaller than a 10%), but with at least five times more AMVs.
- Considering the "Product Requirement Table" defined by EUMETSAT for the operational use of HRW product, the "Optimal accuracy" is reached in the High layer, and the "Target accuracy" is reached in the Medium and Low layer for the four satellite series. EUMETSAT declared HRW product operational more than ten years ago, and with these validation results it can be considered this way for the four satellite series.

With all this, the main circumstance to be taken into account when using HRW product is the variability with the time of the amount and density of AMVs and Trajectories. This is related to the presence of cloudy areas or cloudless areas with humidity patterns in the processing region.

Considering the Trajectories, the limitation is also related to the persistence in time of the tracers defining the Trajectories: after one hour only about 30% to 50% of the tracers persist; after three hours only about 5% to 15% of the tracers persist. The persistence is different considering different meteorological situations, in which the temporal change of the atmospheric structures can be quicker or slower. So, the density of Trajectories can be very different in different parts of an image.

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3.1.1. Validation for MSG satellite series

The validation of HRW v2018 AMVs for MSG satellite series in **Table 4,** is based on AMVs calculated during the yearly period July 2009–June 2010 at 12:00 UTC, with MSG2 satellite images, in the region covering Europe and the Mediterranean Sea shown in **Figure 13**.

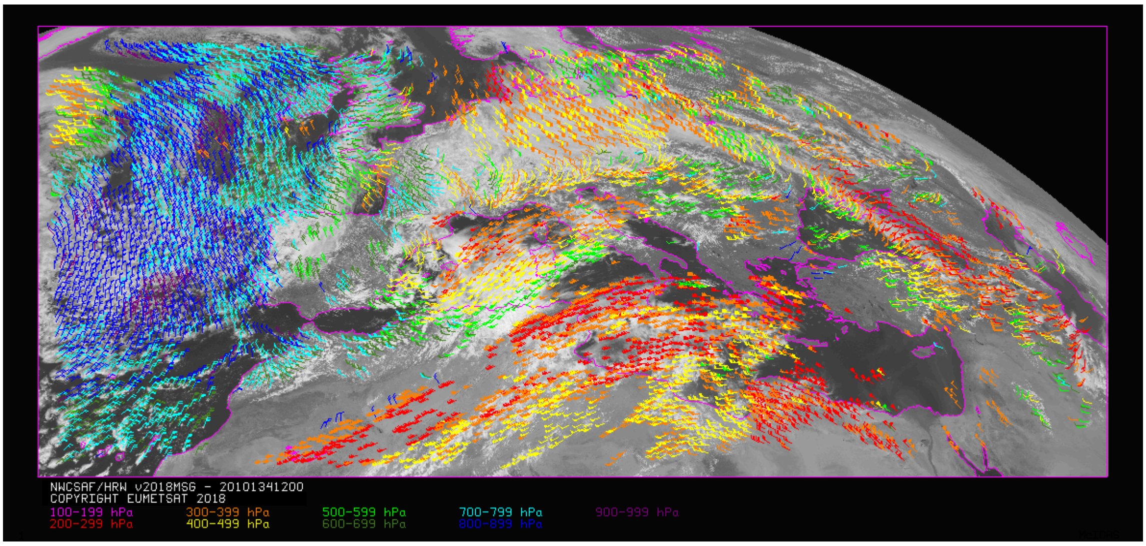

Figure 13: NWC/GEO-HRW v2018 AMV output example in the European and Mediterranean region considering the default conditions for processing (14 May 2010 12:00 UTC, MSG-2 satellite). Colour coding based on the AMV pressure

Table 4: Validation for NWC/GEO-HRW v2018 AMVs against radiosonde winds, considering all AMVs together and three separate layers: high: 100-400 hPa; medium: 400-700 hPa; low: 700-1000 hPa. (Jul 2009-Jun 2010, 12:00 UTC, MSG2 satellite, European and Mediterranean region).

NWC/GEO-HRWv2018 MSG-2, Jul '09 – Jun '10		Cloudy HRVIS	Cloudy VIS06	Cloudy VIS08	Cloudy IR 108	Cloudy IR 120	Cloudy WV62	Cloudy WV73	Clear Air	All AMVs
NC		67288	98861	90082	226314	228664	139042	227273	20383	1097907
SPD [m/s]		12.87	10.28	10.25	17.50	17.72	22.78	20.14	17.42	17.23
NBIAS	All	-0.03	-0.13	-0.13	-0.08	-0.07	-0.02	-0.05	+0.01	-0.07
NMVD	Layers	0.35	0.41	0.42	0.30	0.30	0.26	0.29	0.30	0.32
NRMSVD		0.42	0.49	0.49	0.37	0.37	0.32	0.36	0.37	0.39
NC		15919			119091	124905	128731	157689	20383	566718
SPD [m/s]		21.13			21.85	21.81	23.23	22.63	17.42	22.19
NBIAS	High	-0.03			-0.07	-0.06	-0.03	-0.06	+0.01	-0.05
NMVD	Layer	0.25			0.26	0.26	0.26	0.26	0.30	0.26
NRMSVD		0.30			0.32	0.32	0.32	0.32	0.37	0.32
NC		15447	31346	29700	65544	64179	10311	60432		276959
SPD [m/s]		12.88	11.72	11.49	14.29	14.44	17.13	14.95		13.91
NBIAS	Medium	-0.05	-0.15	-0.16	-0.09	-0.08	+0.04	-0.02		-0.08
NMVD	Layer	0.35	0.38	0.38	0.35	0.35	0.36	0.37		0.36
NRMSVD		0.42	0.45	0.46	0.43	0.43	0.44	0.46		0.44
NC		35922	67515	60382	41679	39580		9152		254230
SPD [m/s]		9.21	9.61	9.63	10.11	10.14		11.51		9.79
NBIAS	Low	-0.02	-0.11	-0.11	-0.11	-0.10		-0.02		-0.09
NMVD	Layer	0.45	0.43	0.44	0.40	0.40		0.41		0.42
NRMSVD		0.53	0.51	0.51	0.48	0.47		0.48		0.50

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3.1.2. Validation for Himawari-8/9 satellite series

The validation of HRW v2018 product for Himawari-8/9 satellite series in **Table 5,** is based on AMVs calculated during the half-yearly period March–August 2018 at 00:00 UTC, with Himawari-8 satellite images, in the region covering China, Korea and Japan shown in **Figure 14**.

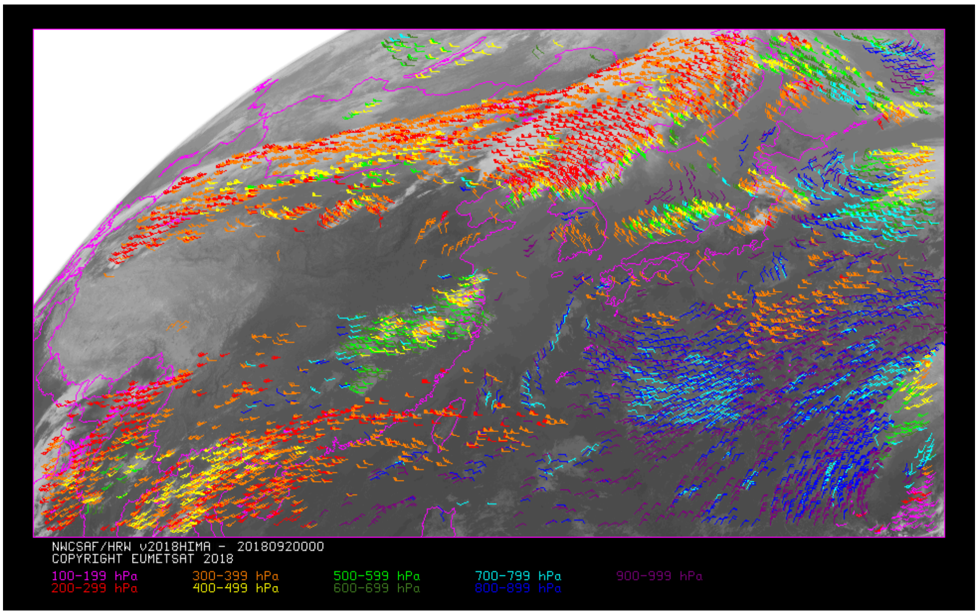

Figure 14: NWC/GEO-HRW v2018 AMV output example in the China/Korea/Japan region considering the default conditions for processing (2 April 2018 00:00 UTC, Himawari-8 satellite). Colour coding based on the AMV pressure

Table 5: Validation for NWC/GEO-HRW v2018 AMVs against radiosonde winds, considering all AMVs together and three separate layers: high: 100-400 hPa; medium: 400-700 hPa; low: 700-1000 hPa. (Mar 2018 – Aug 2018, 00:00 UTC, Himawari-8 satellite, China/Korea/Japan region).

NWC/GEO-HRW v2018 Himawari-8, Mar-Aug 2018		**Cloudy VIS06**	**Cloudy VIS08**	**Cloudy IR 112**	**Cloudy WV62**	**Cloudy WV70**	**Cloudy WV74**	**Clear Air**	**All AMVs**
NC		36841	71618	287147	189457	246356	280899	85148	1197466
SPD [m/s]		21.70	19.95	19.58	23.60	22.58	21.94	19.32	21.46
NBIAS	All	+0.00	-0.00	+0.04	+0.06	+0.06	+0.04	+0.06	+0.05
NMVD	Layers	0.24	0.26	0.27	0.26	0.27	0.26	0.30	0.28
NRMSVD		0.29	0.31	0.35	0.32	0.33	0.33	0.38	0.35
NC		26769	48276	196718	183124	214714	229291	85148	984040
SPD [m/s]		25.83	24.52	22.61	23.73	23.44	23.31	19.32	23.06
NBIAS	High	-0.01	-0.01	+0.04	+0.06	+0.05	+0.03	+0.06	+0.04
NMVD	Layer	0.22	0.23	0.25	0.26	0.26	0.25	0.30	0.25
NRMSVD		0.26	0.27	0.31	0.31	0.31	0.30	0.38	0.31
NC		4200	9507	65466	6333	31642	51608		168756
SPD [m/s]		14.67	14.18	14.68	20.08	16.72	15.85		15.60
NBIAS	Medium	+0.10	+0.09	+0.05	+0.17	+0.21	+0.11		+0.11
NMVD	Layer	0.32	0.33	0.35	0.36	0.43	0.38		0.37
NRMSVD		0.40	0.42	0.49	0.47	0.54	0.50		0.50
NC		5872	13835	24963					44670
SPD [m/s]		7.90	7.97	8.53					8.27
NBIAS	Low	-0.03	+0.03	-0.01					+0.00
NMVD	Layer	0.44	0.47	0.43					0.45
NRMSVD		0.54	0.58	0.53					0.55

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3.1.3. Validation for GOES-N satellite series

The validation of HRW v2018 product for GOES-N satellite series in **Table 6,** is based on AMVs calculated during the yearly period July 2010–June 2011 at 05:45/11:45/17:45/23:45 UTC with GOES-13 satellite images, in the Continental United States shown in **Figure 15**.

These times have to be used because no images exist exactly at the main synoptic hours. Validation four times a day is also considered, to reduce the issue of the small number of validated visible AMVs (dawn or dusk conditions occurs at the main synoptic hours, 00:00 and 12:00 UTC, with the largest number of radiosonde observations).

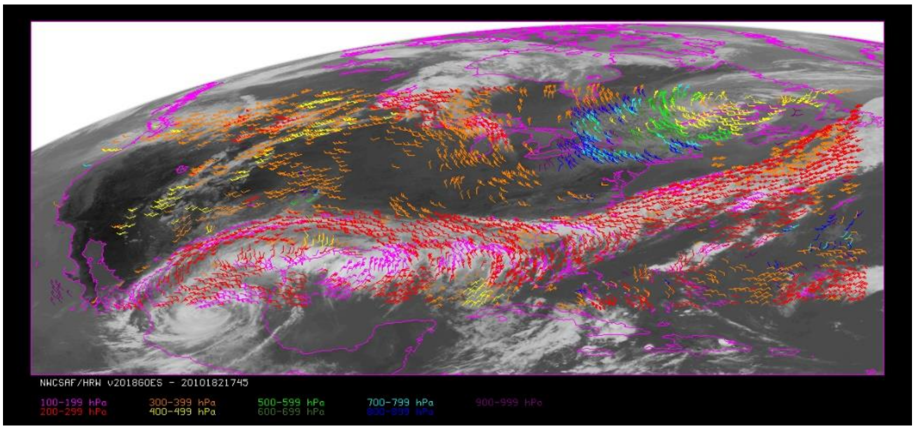

Figure 15: NWC/GEO-HRW v2018 AMV output example in the Continental United States region considering the default conditions for processing (1 July 2010 17:45 UTC, GOES-13 satellite). Colour coding based on the AMV pressure

Table 6: Validation for NWC/GEO-HRW v2018 AMVs against radiosonde winds, considering all AMVs together and three separate layers: high: 100-400 hPa; medium: 400-700 hPa; low: 700-1000 hPa. (Jul 2010 – Jun 2011, 05:45/11:45/17:45/23:45 UTC, GOES-13 satellite, Continental United States).

NWC/GEO-HRW v2018 GOES-13, Jul 2010 – Jun 2011		**Cloudy VIS07**	**Cloudy IR 107**	**Cloudy WV65**	**Clear Air**	**All AMVs**
NC		9282	287572	247350	64486	608690
SPD [m/s]		21.33	21.82	25.22	14.64	22.43
NBIAS	All	-0.01	-0.08	-0.04	+0.04	-0.05
NMVD	Layers	0.24	0.29	0.26	0.37	0.28
NRMSVD		0.31	0.37	0.33	0.49	0.36
NC		6828	215848	235439	64486	522601
SPD [m/s]		25.28	24.74	25.44	14.64	23.82
NBIAS	High	-0.01	-0.09	-0.04	+0.04	-0.05
NMVD	Layer	0.23	0.28	0.26	0.37	0.28
NRMSVD		0.28	0.35	0.33	0.49	0.35
NC		243	33933	11911		46087
SPD [m/s]		18.29	17.04	20.84		18.03
NBIAS	Medium	-0.11	-0.05	+0.00		-0.03
NMVD	Layer	0.34	0.35	0.29		0.33
NRMSVD		0.45	0.43	0.37		0.41
NC		2211	37791			40002
SPD [m/s]		9.46	9.44			9.44
NBIAS	Low	-0.02	-0.09			-0.09
NMVD	Layer	0.35	0.40			0.39
NRMSVD		0.43	0.49			0.49

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3.1.4. Validation for GOES-R satellites

The preliminary validation of HRW v2018 product for GOES-R satellite series in **Table 7** is based on AMVs calculated during the half-yearly period March–August 2018 at 00:00 and 12:00 UTC, with GOES-16 satellite images, in a region covering the Continental United States, such as shown in **Figure 16**. This validation considers GOES-R mode 3 scanning, with full disk images separated every 15 minutes, which was operational before April 2019.

A significant validation period was not ready for the preparation of this paper with GOES-R mode 6 scanning, with full disk images separated every 10 minutes, operational since April 2019. However, due to the similarities found between Himawari-8 (with images every 10 minutes) and GOES-16 (with images every 15 minutes), and the similarities between both imagers (AHI and ABI), the impact of the change in the GOES-R scanning mode is assumed to be not significant.

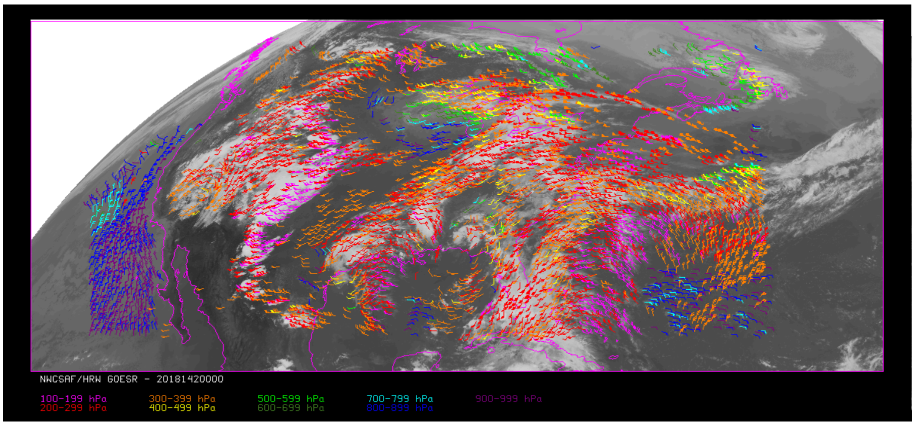

Figure 16: NWC/GEO-HRW v2018 AMV output example in the Continental United States region considering the default conditions for processing (22 May 2018 00:00 UTC, GOES-16 satellite, mode 3 scanning). Colour coding based on the AMV pressure

Table 7: Validation for NWC/GEO-HRW v2018 AMVs AMVs against radiosonde winds, considering all AMVs together and three separate layers: high: 100-400 hPa; medium: 400-700 hPa; low: 700-1000 hPa (Mar 2018–Aug 2018, 00/12:00 UTC, GOES-16 satellite, Continental United States).

NWC/GEO-HRW v2018 GOES-16, Mar-Aug 2018		Cloudy VIS06	Cloudy VIS08	Cloudy IR 112	Cloudy WV62	Cloudy WV70	Cloudy WV74	Clear Air	All AMVs
NC		8630	31657	416089	330893	401488	433933	171870	1794560
SPD [m/s]		22.36	20.30	20.07	23.43	22.79	22.38	16.84	21.57
NBIAS	All	+0.01	+0.00	+0.04	+0.05	+0.04	+0.02	+0.06	+0.04
NMVD	Layers	0.23	0.25	0.27	0.26	0.26	0.26	0.32	0.27
NRMSVD		0.28	0.31	0.34	0.32	0.32	0.32	0.41	0.34
NC		6952	23845	300271	316898	353596	367433	171870	1540865
SPD [m/s]		25.06	23.02	22.12	23.60	23.43	23.26	16.84	22.44
NBIAS	High	+0.00	-0.00	+0.04	+0.04	+0.03	+0.02	+0.06	+0.03
NMVD	Layer	0.21	0.23	0.26	0.25	0.25	0.24	0.32	0.26
NRMSVD		0.26	0.28	0.32	0.31	0.31	0.30	0.41	0.32
NC		638	3368	77915	13995	47892	66500		210308
SPD [m/s]		17.33	15.81	16.86	19.59	18.07	17.51		17.51
NBIAS	Medium	+0.09	+0.06	+0.03	+0.15	+0.16	+0.09		+0.09
NMVD	Layer	0.29	0.30	0.31	0.36	0.38	0.35		0.34
NRMSVD		0.38	0.37	0.40	0.45	0.48	0.43		0.43
NC		1040	4444	37903					43387
SPD [m/s]		7.41	9.09	10.46					10.25
NBIAS	Low	+0.17	+0.00	-0.02					-0.02
NMVD	Layer	0.63	0.44	0.38					0.39
NRMSVD		0.76	0.54	0.47					0.48

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3.2. "AMV Intercomparison Studies" with MSG and Himawari-8/9 satellite data

In 2014 and 2018, two "AMV Intercomparison Studies" analyzed the AMV outputs from seven AMV algorithms across the world, considering respectively the same triplets of MSG-2 IR108 full disk images of 17 September 2012, and Himawari-8 IR104 full disk images of 21 July 2016 [21, 22]. All other input needed for the AMV calculation (additional satellite channels, ECMWF NWP grids, and Scene and Cloud products provided respectively by EUMETSAT or NOAA) were also provided so that the AMV extraction process would be exactly equivalent for all AMV producers.

The studies analyzed the AMV algorithms for the following seven producers:

- Brazil Weather Forecast and Climatic Studies Center (CPTEC/INPE).
- European Organization for the Exploitation of Meteorological Satellites (EUMETSAT).
- Japan Meteorological Agency (JMA).
- Korea Meteorological Administration (KMA).
- National Oceanic and Atmospheric Administration (NOAA).
- Satellite Application Facility on support to Nowcasting (NWCSAF, NWC/GEO-HRW).
- China Meteorological Administration (CMA, only in the "2014 Intercomparison" with MSG).

Considering the "2014 AMV Intercomparison Study" with MSG satellite images [22], next conclusions were extracted:

- The tracking step of all AMV algorithms works correctly, with displacement differences which are statistically not significant.
- Significant differences occur in the AMV outputs, when only the MSG-2 IR108 images and NWP model data are used for the height assignment. The differences are related to the way the "AMV temperature" is defined by each algorithm. Considering the AMV validation against radiosonde winds and the NWP background winds, NWC/GEO-HRW product shows the lowest vector RMS of 5-6 m/s.
- Using a prescribed configuration for the AMV extraction, a smaller number of AMVs and fewer differences in the AMV validation occur for the different AMV producers.
- Using the specific height assignment method of each AMV algorithm, the impact is positive for all AMV algorithms except Brazil and Japan. NWC/GEO-HRW product shows again here the lowest vector RMS of 4 m/s.

Considering all this, NWC/GEO-HRW product shows the best results of all AMV algorithms with MSG satellites. Its comparative advantage with respect to other AMV algorithms are so shown: a better density of AMVs with better validation results. And its applicability to operational use is so fully demonstrated.

Other external validation sources like the "NWPSAF AMV Monthly Monitoring" [24], shows a similar positive result comparing NWCSAF with EUMETSAT AMVs in the British Isles area.

The key for this result seems to be the height assignment method (CCC method) used by NWC/GEO-HRW algorithm, and its extensive but exigent procedure for the definition of tracers. This induces a smaller number of AMV but with very good statistics in similar conditions to other AMV algorithms, while in its operational specific conditions the number of AMVs increases significantly with still very good statistics.

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Considering the "2018 AMV Intercomparison Study" with Himawari-8 satellite images [23], the main goal was to verify the advantages of the calculation of AMVs with this new generation of geostationary satellites, with better spatial and temporal resolution and new spectral channels, and to extract conclusions about the best options for the calculation of AMVs considering the options taken by the different centers. Next conclusions were extracted:

- Using a prescribed configuration with the specific height assignment method of each centre, the distribution of "AMV pressures" is very different for all centres (with only EUMETSAT and NWCSAF being similar due to the common use of "CCC method"), while the distribution of other parameters (speed, direction, "Common Quality Index") is similar for all centres.

  Considering the validation of all AMV algorithms against radiosonde winds, JMA algorithm shows the lowest vector RMS of 5 m/s, and NOAA and NWC/GEO-HRW algorithms are tied in second position with a vector RMS of 7 m/s.

  Considering collocated AMVs against NWP analysis winds, differences between centres reduce very much, with only JMA algorithm having better values and Brazil algorithm having worse values than all the rest (which share a vector RMS of 4 m/s). JMA AMVs show additionally to be nearer the AMV best fit pressure; much more than all other datasets.
- Using the specific configuration and the specific height assignment method of each centre, the distribution of "AMV pressures" is again very different for all centres while the distribution of other parameters is still similar. This way, it is seen that the differences in the height assignment process drive the majority of differences observed.

  Considering the validation of all AMV algorithms against radiosonde winds, JMA algorithm shows again the lowest vector RMS of 6 m/s, and NOAA and NWC/GEO-HRW algorithms are tied again in second position with a vector RMS of 7 m/s.

  Considering collocated AMVs against NWP analysis winds, the differences between centres are larger due to the specific configuration used of each centre for the AMV extraction. JMA algorithm shows again the best values, and NOAA and NWC/GEO-HRW algorithms are tied again in second position. Considering the fitting to the AMV best fit pressure, JMA AMVs are again nearer to the AMV best fit pressure; much more than all other datasets.
- A validation was also made, collocating the AMVs from all centres with NASA's CALIPSO satellite, which provides an independent measurement of cloud top heights. The evaluation is qualitative, because CALIPSO is a line-of-site measurement, with few collocations with AMVs (tens of matches only). In this validation, AMVs from all centres are in general located near the cloud base for high level and semitransparent clouds, and near the cloud top for low and medium level clouds. Curiously, the AMV pressures for the different centers in this specific case are similar, in apparent disagreement with the previous results.

Considering all this, JMA AMV algorithm for Himawari-8/9 has the best overall performance considering all validation and checking elements, due to its updated height assignment procedure: "optimal estimation method using observed radiance and NWP vertical profile". This is the most significant result of this study.

Considering NWC/GEO-HRW algorithm, it has the second best results together with NOAA AMV algorithm. With this, its applicability to operational use with Himawari-8/9 satellite series is also fully demonstrated.

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3.3. Real time output of NWC/GEO-HRW product

Real time graphic displays of NWC/GEO-HRW latest version AMVs and Trajectories, generated by the NWC/GEO Reference System with MSG satellite series 24 hours a day, are available at the NWCSAF Help Desk website (http://www.nwcsaf.org). The specific links for HRW outputs are located at:

- http://www.nwcsaf.org/hrw_p (AMVs shown with a colour code based on the AMV pressure).
- http://www.nwcsaf.org/hrw_ws (AMVs shown with a colour code based on the AMV speed).
- http://www.nwcsaf.org/hrw_1h (Trajectories related to tracers existing at least one hour, with a colour code based on the AMV pressure).
- http://www.nwcsaf.org/hrw_3h (Trajectories related to tracers existing at least three hours, with a colour code based on the AMV pressure).

3.4. Use of NWC-GEO/HRW product

No specific system is operational in 2019 for the procurement of NWC/GEO product outputs, generated by the NWCSAF Reference System or any other external institution.

As already said, “HRW/High Resolution Winds product” is provided inside “NWC/GEO software package”, which has to be installed and run locally by the NWCSAF users in their own hardware resources, to obtain the corresponding HRW outputs of AMVs and Trajectories.

The right to use, copy or modify NWC/GEO software package is in accordance with the corresponding policy defined by EUMETSAT. In case of interest on using “NWC/GEO software package” and “HRW/High Resolution Winds product”, all National Meteorological Services within EUMETSAT Member and Cooperating States are automatically considered as potential users. All other organizations may also apply to become user of NWCSAF software. This is done contacting through email at safnwchd@aemet.es.

All applicants have become users of NWC/GEO software without restriction up to now, with institutions and researchers from all around the world (Europe, Africa, Americas, Asia,…), and all types of institutions: National Meteorological Services, Universities, Public service providers, Public and private companies.

The access to NWC/GEO software package and documentation is authorized to users through the “Licence Agreement”, to be signed by EUMETSAT (represented by AEMET) and the applicant user. Once the “Licence Agreement” is signed, “Access Credentials” to the NWCSAF Helpdesk (www.nwcsaf.org) restricted area are provided, from which the NWC/GEO software package can be downloaded. All software, libraries and elements needed to run the software are provided this way.

Hardware resources used to run NWC/GEO v2018 software package are small and relatively easy to obtain. The Linux environments defined in **Table 8** have been used for the development and testing. These resources are enough for the operational and near real time generation of the full set of NWC/GEO products with MSG satellites in a continental region (~2 million pixels). The generation of products in a larger area could require additional resources related to memory, disk and/or CPU.

The correct running in other environments cannot be currently guaranteed.

Table 8: Environments used for development/testing of NWC/GEO v2018 software package.

	Environment used for development and testing	Environment used for testing
Operative System	Linux RHEL release 6.4 (Santiago)	Ubuntu 18.04.1 LTS
CPU	4 x Intel® Core™ CPU i5-4590 @ 3.30 Ghz	8 x Intel® Xeon ® CPU E5-2650 v3 @ 2.30 Ghz
Architecture	x86_64	x86_64
Memory	16 GB	16 GB
Disk	500 GB	500 GB
Shells	bash; ksh	sh; ksh
Compilers	GCC compilers 4.4.7 gcc; g++; gfortran	GCC compilers 7.3.0 gcc; g++; gfortran
gzip	gzip 1.3.12	gzip 1.6
make	GNU Make 3.81	GNU Make 4.1

3.5. Installation and running of NWC-GEO/HRW product

For the running of "NWC/GEO" software package and "NWC/GEO-HRW" product, two main steps are identified. The user manually interacts with the NWC/GEO software package during the installation step, and then the HRW product execution step is manually or automatically run (in this case, monitored by a "Task Manager").

The "software installation step" only requires the decompression of a few gzip compressed tar files, and the running of a few installation scripts.

The "software execution step" is the processing of satellite images from a defined satellite in a region defined by the user, with the different executables for the different requested NWC/GEO algorithms (including HRW product executable).

The running of each one of these executables relies on the running of the corresponding command together with three parameters: the required image time, the "region configuration file" (identifying the region inside the satellite disk in which the algorithms are calculated), and the "model configuration file" (identifying the specific configuration of that algorithm for the running).

The running also depends on a "satellite configuration file", which defines the conditions for the satellite used in the processing. All these "configuration files" are ASCII files, in which several parameters are defined and modifications can be easily performed with a text editor.

Considering this, as already said in previous chapters, the default running of HRW product implies the consecutive running of all next products for the same image and region so that the amount and quality of calculated AMVs and Trajectories is optimal: CMA/Cloud Mask, CT/Cloud Type, CTTH/Cloud Top Temperature and Height, CMIC/Cloud Microphysics and finally HRW/High Resolution Winds.

The "HRW model configuration file" includes a total of 61 parameters which can modify the conditions for the extraction of AMVs and Trajectories. In a small description of these parameters:

- There are "Identification parameters" which define the algorithm, the satellite channels used in the AMV and Trajectory calculation, and the time difference between image slots for the tracer definition and tracking.

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- There are "Output parameters" which define the HRW product output format and content.
- There are "Output filtering parameters" which define options for the process (calculation or not of clear air AMVs, Trajectories, and Detailed AMVs and Trajectories), and the different filterings used for the AMV and Trajectories in the output files (based on the Quality Index threshold, AMV pressure error and correlation thresholds, solar and satellite zenith angle thresholds, and the "Orographic flag" and "Final Control check" defined in **Chapters 2.10 and 2.11**).
- There are "Working region description parameters", which define latitude and longitude limits for the calculations.
- There are "Tracer parameters", which define the dimension and distance between tracers, the use or not of a higher density for low tracers, and the gradient threshold and contrast used by "gradient method" in **Chapter 2.2.1** for the tracer search.
- There are "Tracking parameters", which define the different options for the tracking method to be used, the use or not of the "wind guess" for the definition of the "tracking area", the size of this "tracking area", and the use or not of the "Parallax correction" described in **Chapter 2.8** to define the AMV location and wind.
- There are "Validation parameters", which define if Validation statistics are calculated for the AMVs, if the NWP analysis or forecast is used for these statistics, and if the vector difference between the AMV and the NWP wind and the NWP wind at the best fit pressure are calculated.
- There are "NWP parameters", which define the NWP variables and levels needed for the processing, and the way these NWP variables are extracted from the corresponding grids.

3.6. Documentation of NWC-GEO/HRW product

Full details on the installation and running of "NWC/GEO software package" and "HRW/High Resolution Winds algorithm" can be obtained from the official NWC/GEO documentation, available in the NWCSAF Helpdesk (www.nwcsaf.org). The main documents for this are:

- "User Manual for the NWC/GEO: Software Part" [12].
- "User Manual for the Wind product processor of the NWC/GEO: Science Part" [13].
- "Algorithm Theoretical Basis Document for the Wind product processor of the NWC/GEO" [14].
- "Scientific and Validation Report for the Wind product processor of the NWC/GEO" [15].

Additionally, since 2016, a description of all NWC/GEO algorithms, involved interfaces and data types, is provided for the NWCSAF users with the support of "Doxygen tool" in "html format", from comments included within the C and Fortran code of HRW product. This way, all this information can be easily navigated with a web browser.

Through this process, every single step throughout all functions of HRW product has been described with detailed comments, so that any AMV developer can precisely know all the process of HRW product.

For any additional doubt or question on NWCSAF Consortium, and about how to get, install and run "NWC/GEO software package" and "HRW/High Resolution Winds algorithm", as already said the NWCSAF Helpdesk can be contacted through the email address: safnwchd@aemet.es.

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4. Conclusions

Considering the NWCSAF "High Resolution Winds (NWC/GEO-HRW) product" for calculation of AMVs and Trajectories, inside its "NWC/GEO software package" for geostationary satellites:

- It is easy to get, install and use. It is fully portable and independent from external applications.
- The code is fairly easy to read (with functions written in C and Fortran languages, and a code extensively commented to help its understanding), and fully documented.
- There is a fully dedicated Helpdesk where NWCSAF users find support and help on the installation and use of the software.
- It has been adapted to MSG, Himawari-8/9, GOES-N and GOES-R satellite series, so permitting the calculation of AMVs and Trajectories throughout all the planet Earth in all areas which can be observed with geostationary satellites.
- Considering the validation for all satellite series, equivalent validation statistics are obtained for all of them, and so NWC/GEO-HRW product can be used with the same quality throughout all the planet Earth with these satellites.
- In the "2014 and 2018 AMV Intercomparison Studies" [21, 22], NWC/GEO-HRW is one of the two best AMV algorithms for both MSG and Himawari-8/9 satellites, calculating a high number of AMVs with very good validation statistics. Other external validation sources like the "NWPSAF AMV Monthly Monitoring" [24], shows a similar positive result comparing NWCSAF with EUMETSAT AMVs with MSG satellites in the British Isles area.

The "Coordination Group for Meteorological Satellites (CGMS)" has officially also recognized in its "2012 Meeting Report" [25] (p.117):

- "NWCSAF High Resolution Winds" fulfills the requirements to be a portable stand-alone AMV calculation software due to its easy installation and usability.
- It has been successfully adapted by some CGMS members and serves as an important tool for development. It is modular, well documented, and well suited as stand-alone AMV software.
- Although alternatives exist as portable stand-alone AMV calculation software, they are not as advanced in terms of documentation and do not have an existing Helpdesk.

With all this, the NWCSAF "High Resolution Winds (NWC/GEO-HRW) product" becomes a very useful source of AMVs and Trajectories for the weather analysis and forecasting, most especially in the near term nowcasting.

It is useful for the monitoring of the general atmospheric flow, of small scale circulation and wind singularities, of convergence at low levels or divergence at the top of developed systems. It is also useful for the watch and warning of dangerous wind situations. It can also be used in form of objectively derived fields, assimilated in numerical weather prediction (NWP) models together with many other data, or used as an input in analysis and forecast applications.

Registering as NWCSAF user and using "NWC/GEO software package" and "NWC/GEO-HRW High Resolution Winds product" are so suggested. Very especially for those operational meteorologists or researchers without access to AMV products similar to it, and who might benefit from its use. Feedback from all users is also very welcome.

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Author Contributions:

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Conflicts of Interest:

The authors declare no conflicts of interest.

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