NWC SAF/HIGH RESOLUTION WINDS AMV SOFTWARE EVOLUTION BETWEEN 2012 AND 2014

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Abstract

The “High Resolution Winds AMV software (HRW)”, developed inside the “Satellite Application Facility on support to Nowcasting and very short range forecasting (NWC SAF)” stand alone software package, provides a detailed calculation of Atmospheric Motion Vectors locally and in real time by its users, considering up to seven MSG/SEVIRI channels.

A new version of HRW software has been made available in August 2013. with some new elements: the calculation of trajectories through the continuous tracking of the same tracer, the update of the Quality control process, and the optimization of the algorithm for the default calculation without wind guess in the definition of the tracking area, among other ones. The validation shows additional improvements respect to previous versions, including the increase in the amount of available AMVs with a reduction in their NRMSVD values, and the usability of all AMVs with a QI ≥ 1%.

HRW v2013 has also been validated by external studies (like the NWP SAF AMV monitoring by the MetOffice, and the Second AMV intercomparison study by CIMSS/University of Wisconsin), comparing very positively against other AMV algorithms. The MetOffice has also started to assimilate operationally HRW AMVs in its NWP mesoscale model around the British Isles with a positive impact in the forecast.

A new version (HRW v2015) is now being prepared, including the adaptation of HRW algorithm to GOES-N satellite series, and the inclusion of microphysics information coming from NWCSAF/Cloud products in the AMV height assignment. A relationship has been found between the AMV liquid or ice water path, and the pressure difference between the AMV level and the radio sounding best fit level. A correction of the AMV level based on this relationship increases the amount of AMVs while reduces the NRMSVD and the NBIAS (especially in the infrared and water vapour channels). Nevertheless, a refining of the correction method for the different satellite channels or the different cloud types might be needed to be more effective.

Because of its characteristics and its ease to be obtained and run locally, NWC SAF/High Resolution Winds software has been proposed as option for “Stand alone AMV calculation software”, available to all AMV researchers and users. The good validation results for NWC SAF/HRW software by the external studies should solve any doubts about the usefulness of this AMV algorithm.

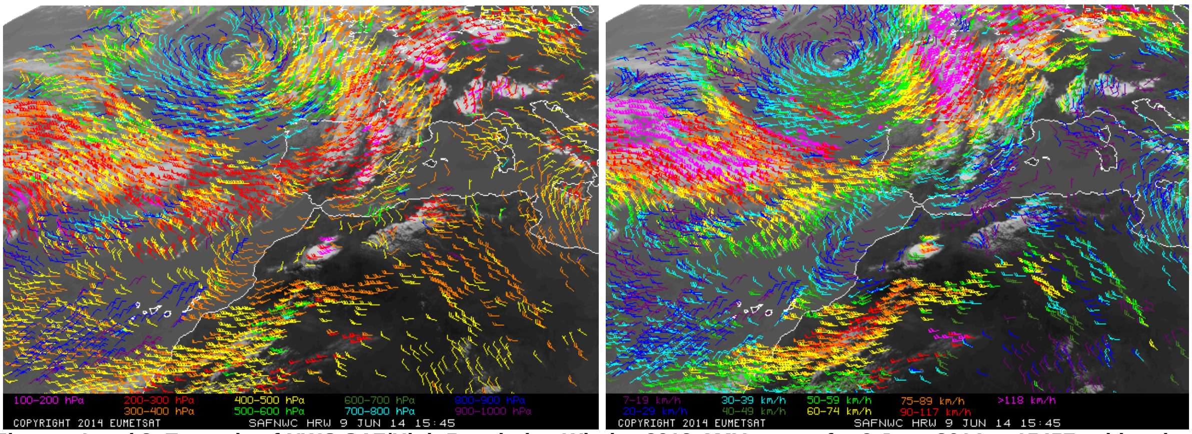
NWC SAF/HIGH RESOLUTION WINDS SOFTWARE VERSION v2013

The “High Resolution Winds (HRW)” is the Atmospheric Motion Vectors (AMV) calculation software included inside the “Satellite Application Facility on support to Nowcasting and Very short range forecasting (NWC SAF)” Software package for MSG satellites (SAFNWC/MSG).
It provides high density sets of AMVs for near real time applications from seven SEVIRI channels (cloudy AMVs from HRVIS, VIS06, VIS08, IR108, IR120, WV062 and WV073 channels; clear air AMVs from WV062 and WV073 channels).

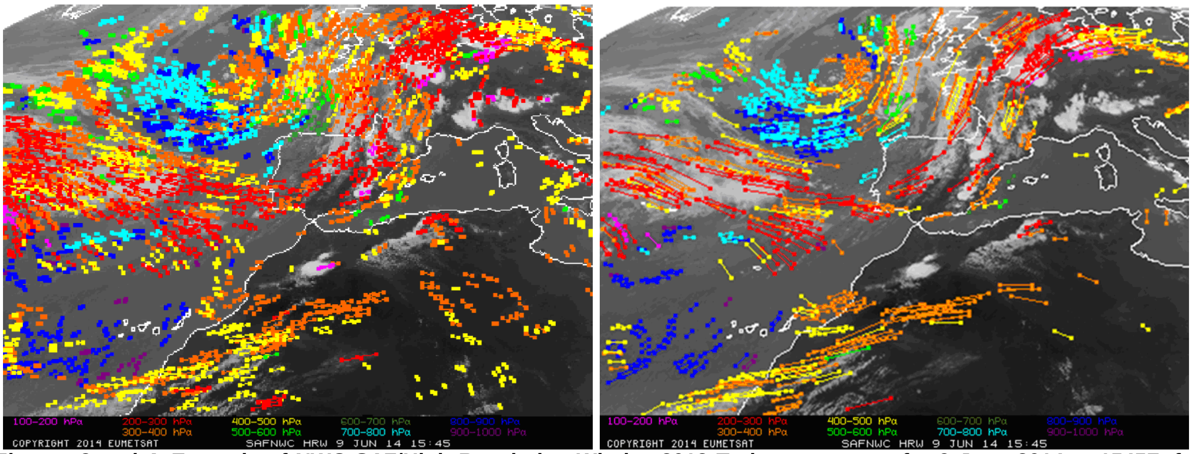
The latest HRW version (v4.0, v2013) was released to users in August 2013, with next main changes:

- The calculation of trajectories through the continuous tracking of the same tracer in consecutive slots (output provided as a different specific Trajectory BUFR file).

- The update of the Quality control process to the current version implemented in the EUMETSAT/MPEF AMV Quality control, including the calculation of the Quality index without use of the forecast contribution.
- The default calculation of AMVs without use of the wind guess in the tracking process, through additional code optimizations, so reducing the dependence of the calculated AMVs from NWP model data.
- The inclusion of the subpixel tracking process in the calculation of AMV speeds and directions.
- The definition of the AMV position inside the tracer as the position of maximum correlation contribution defined by CCC height assignment method.
- The option to provide HRW AMV BUFR output in a format similar to the one for EUMETSAT/MPEF AMVs, easing its use in NWP model assimilation.
- The formal review and recommenting of all HRW code (written in C and Fortran languages), for its clearer understanding by anyone who wants to use and read the code.



Figures 1 and 2: **Example of NWC SAF/High Resolution Winds v2013 AMV output for 9 June 2014 at 1545Z, with colour coding based on the AMV pressure level (left) and the AMV speed (right).**



Figures 3 and 4: **Example of NWC SAF/High Resolution Winds v2013 Trajectory output for 9 June 2014 at 1545Z, for trajectories lasting at least one hour (left) and three hours (right), with colour coding based on the pressure level.**

The comparison of the validation statistics against radio sounding winds for the default configurations of HRW v2012 and v2013 is shown in Figures 5 and 6. The reference validation period of one year between July 2009 and June 2010 in the European and Mediterranean region, considering cross correlation tracking, CCC height assignment and Basic scale AMVs with a tracer size of 24x24 pixels has been considered in these statistics.

It can be seen that there is an important increase in the amount of AMV data (more than 40%, although the amount of HRVIS AMVs reduces because of the much longer time they need when the wind guess is not used in the definition of the tracking area), while at the same time there is a 7% reduction in the mean values of the NMVD and the NRMSVD.

HRW v3.2 AMV Validation (Jul 2009-Jun 2010)	Cloudy HRVIS	Cloudy VIS06	Cloudy VIS08	Cloudy WV062	Cloudy WV073	Cloudy IR108	Cloudy IR120	Clear Air	All AMVs
NC	138633	71213	64022	133011	176648	112833	115171	48178	859709
SPD [m/s]	18.03	11.75	11.71	23.63	21.96	19.68	19.89	16.32	19.08
NBIAS	-0.11	-0.16	-0.16	-0.06	-0.08	-0.11	-0.10	-0.04	-0.09
NMVD	0.32	0.44	0.44	0.29	0.31	0.32	0.32	0.35	0.33
NRMSVD	0.40	0.52	0.52	0.36	0.39	0.41	0.40	0.43	0.41

HRW v4.0 AMV Validation (Jul 2009-Jun 2010)	Cloudy HRVIS	Cloudy VIS06	Cloudy VIS08	Cloudy WV062	Cloudy WV073	Cloudy IR108	Cloudy IR120	Clear Air	All AMVs
NC	47280	100836	91677	189804	262992	251524	252375	43004	1239492
SPD [m/s]	16.14	11.04	11.04	23.51	21.28	19.58	19.74	16.52	19.01
NBIAS	-0.10	-0.18	-0.18	-0.06	-0.08	-0.12	-0.11	-0.00	-0.10
NMVD	0.31	0.42	0.42	0.26	0.28	0.30	0.29	0.33	0.31
NRMSVD	0.38	0.50	0.50	0.32	0.35	0.37	0.36	0.40	0.38

Figures 5 and 6: **Validation statistics against radio sounding winds for NWC SAF/High Resolution Winds v2012 (up) and v2013 (below) Basic scale AMVs in the European and Mediterranean region, for the period July 2009-June 2010, considering all atmospheric layers together (100-1000 hPa). (NC: Number of collocations; SPD: Mean radio sounding wind speed in m/s; NBIAS: Normalized bias; NMVD: Normalized mean vector difference; NRMSVD: Normalized root mean square vector difference).**

The validation of HRW v2013 has also verified:

- The good validation of the Detailed scale AMVs with a tracer size of 12x12 pixels, providing a similar amount of AMVs with even better validation statistics (smaller NMVD and NRMSVD values):

HRW v4.0 AMV Validation (Jul 2009-Jun 2010)	Cloudy HRVIS	Cloudy VIS06	Cloudy VIS08	Cloudy WV062	Cloudy WV073	Cloudy IR108	Cloudy IR120	Clear Air	All AMVs
NC	23453	106066	100123	157088	220841	258347	255583	11623	1133124
SPD [m/s]	15.32	11.22	10.89	24.56	22.72	20.22	20.47	16.89	19.56
NBIAS	-0.09	-0.16	-0.16	-0.05	-0.06	-0.09	-0.08	+0.06	-0.09
NMVD	0.32	0.41	0.42	0.25	0.26	0.28	0.27	0.33	0.29
NRMSVD	0.40	0.49	0.50	0.30	0.32	0.34	0.34	0.41	0.36

Figure 7: **Validation statistics against radio sounding winds for NWC SAF/High Resolution Winds v2013 Detailed scale AMVs in the European and Mediterranean region, for the period July 2009-June 2010, considering all atmospheric layers together (100-1000 hPa).**

- The possibility to use all AMVs with QI ≥ 1%, so doubling the amount of available AMVs while keeping NRMSVD values at 0.50:

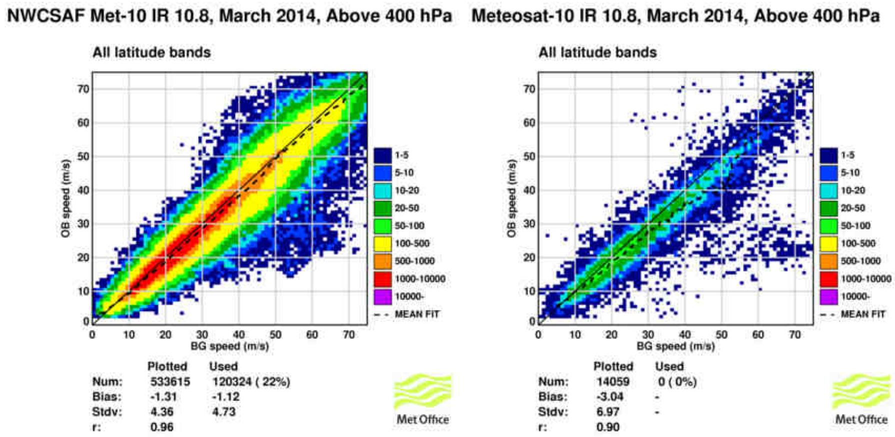
HRW v4.0 AMV Validation (Jul 2009-Jun 2010)	Cloudy HRVIS	Cloudy VIS06	Cloudy VIS08	Cloudy WV062	Cloudy WV073	Cloudy IR108	Cloudy IR120	Clear Air	All AMVs
NC	116737	293256	279776	290907	427707	488159	486724	136309	2519575
SPD [m/s]	14.28	9.76	9.62	21.32	18.86	16.46	16.59	14.72	15.72
NBIAS	-0.18	-0.32	-0.35	-0.09	-0.11	-0.18	-0.17	-0.11	-0.19
NMVD	0.41	0.55	0.56	0.30	0.34	0.38	0.37	0.44	0.41
NRMSVD	0.51	0.66	0.67	0.37	0.42	0.47	0.46	0.55	0.50

Figure 8: **Validation statistics against radio sounding winds for NWC SAF/High Resolution Winds v2013 Basic scale AMVs with QI ≥ 1%, in the European and Mediterranean region, for the period July 2009-June 2010, considering all atmospheric layers together (100-1000 hPa).**

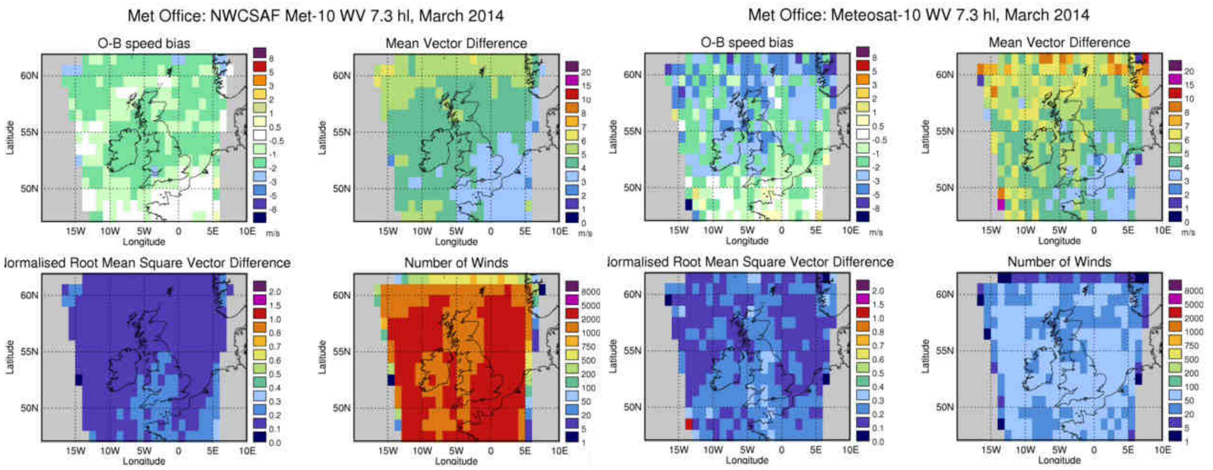
External institutions have also started to validate NWC SAF/High Resolution Winds software. The United Kingdom MetOffice includes since 2013 the HRW AMVs in the AMV Monitoring web pages of the Satellite Application Facility for Numerical Weather Prediction (NWP SAF).

It is a monthly updated verification of the HRW AMVs around the British Isles, in comparison with EUMETSAT/MPEF AMVs. It includes speed scatter plots and the spatial distribution of next validation parameters: number of AMVs, bias, MVD, NRMSVD. It is publicly available at next web links:

- http://nwpsaf.eu/monitoring/amv/14_03/density_ukv.html
- http://nwpsaf.eu/monitoring/amv/14_03/map_ukv.html



Figures 9 and 10: **Example of speed scatter plots verified by the NWP SAF AMV monitoring. IR10.8 high levels NWC SAF/HRW AMVs are compared with the EUMETSAT/MPEF AMVs for the month of March 2014.**



Figures 11 and 12: **Example of the spatial distribution of the number of AMVs, the Bias, the Mean vector difference (MVD) and the Normalized root mean square vector difference (NRMSVD), verified by the NWP SAF AMV monitoring. WV7.3 high levels NWC SAF/HRW AMVs are compared with the EUMETSAT/MPEF AMVs for the month of March 2014.**

The comparison with EUMETSAT/MPEF AMVs shows the very high density of NWC SAF/HRW data (one to two orders of magnitude larger), with similar and often better validation parameters (especially since March 2014, in which HRW v2013.1 was implemented by the MetOffice, modifying the AMV level for high level AMVs, adding a constant value of +40 hPa).

	2013 DEC	2014 JAN	2014 FEB	2014 MAR	2014 APR	2014 MAY
NWCSAF AMV BIAS	-3.38	-2.99	-2.68	-1.31	-1.31	-0.42
EUMETSAT AMV BIAS	-3.93	-3.61	-3.23	-3.04	-2.00	-2.33
NWCSAF AMV STD	5.34	5.39	5.10	4.36	4.37	4.08
EUMETSAT AMV STD	6.86	6.59	6.13	6.97	4.70	4.98
NWCSAF AMV NUM	807017	644560	553310	533615	728237	574661
EUMETSAT AMV NUM	19323	12030	12546	14059	15502	14932

Figure 13: **Validation parameters (Bias and Standard deviation against NWP model background wind, and Number of AMVs) verified by the NWP SAF AMV monitoring, comparing NWC SAF/HRW AMVs with EUMETSAT/MPEF AMVs for the six month period December 2013 to May 2014.**

Considering the Second AMV intercomparison study, in which AMVs produced by seven different institutions have been compared considering the same input datasets and four different experiments:

- BRZ – Brazil Weather Forecast and Climatic Studies Centre
- JMA – Japan Meteorological Agency
- CMA – People's Republic of China Meteorological Administration
- NOA – United States National Oceanic and Atmospheric Administration
- KMA – Republic of Korea Meteorological Administration
- EUM – European Organisation for the Exploitation of Meteorological Satellites
- NWC – Satellite Application Facility on Support to Nowcasting,

the NWC SAF/HRW AMVs provide often the best validation statistics.

The key might be the extensive but exigent search of tracers by HRW algorithm, which under similar conditions to other centres provides a smaller amount of AMVs but with very good statistics, and which under their operational configuration, provides a much larger amount of AMVs while keeping good statistics.

Site	Number	P Bias	P Rms	Spd Bias	Spd Rms	Dir Bias	Vec Rms
BRZ	153	0.63	19.77	0.55	5.61	-3.07	10.05
JMA	154	-3.00	21.50	-2.26	7.64	8.89	9.60
CMA	237	-1.11	18.58	-1.30	6.40	5.28	7.74
NOA	131	0.35	22.75	1.48	5.79	9.01	7.70
KMA	326	-0.63	21.91	-0.73	4.72	2.68	6.38
EUM	307	0.22	22.87	-0.61	4.73	1.99	6.07
NWC (Prescribed conf. EUM Clouds)	73	-0.76	17.53	-0.60	3.48	-3.74	4.67
NWC (Operational conf. EUM Clouds)	2375	-1.06	22.79	-0.39	3.90	0.46	5.12
NWC (Operational conf. NWC Clouds)	2797	-0.65	21.64	-1.23	4.49	-1.55	5.67

Site	Number	Vec Diff.	Vec Rms
BRZ	1590	8.01	9.43
JMA	3514	4.91	5.88
CMA	4743	6.38	7.02
NOA	2274	5.90	6.83
KMA	4574	5.16	6.52
EUM	6583	3.91	4.84
NWC (Prescribed conf. EUM Clouds)	1419	3.05	3.40
NWC (Operational conf. EUM Clouds)	53010	3.23	3.65
NWC (Operational conf. NWC Clouds)	52464	3.77	4.04

***Figures 14 and 15:* Validation of the different AMV algorithms in the AMV intercomparison study against radio sounding winds (left) and NWP wind forecast (right) for 17 Sep 2012 1215Z, considering a prescribed configuration and the best available height assignment method for each centre.**

The United Kingdom MetOffice has also started to include the NWC SAF/HRW AMVs in its operational NWP data assimilation in the UKV region (around the British Isles, with a resolution of 1.5 km). Since January 2014 100-400 hPa HRW AMVs are assimilated; since a very new future 400-900 hPa HRW AMVs over sea are also confirmed to be assimilated. The forecast impact of both types of AMVs together is shown in next tables, being positive for most variables and especially significant for the surface visibility.

Parameter	Control Data	Test Data	Test - Control
0Z 6Z 12Z 18Z	Mean ETS	Mean ETS	Wted ETS Diff
Surface Visibility	0.029	0.043	0.277
6 hr Precip Accum	0.246	0.248	0.021
Total Cloud Amount	0.173	0.174	0.010
Cloud Based Height (3/8 Cover)	0.166	0.168	0.020

Parameter	Control Data	Test Data	Test - Control
0Z 6Z 12Z 18Z	Mean Skill	Mean Skill	Wted Skill Diff
Surface Temp	0.617	0.617	-0.008
Surface Wind	0.560	0.560	0.004

```
Total Weighted Score (%)
Control Case   = 32.441
Test Case      = 32.765
Test - Control =  0.323 (1.00 % change)
```

***Figure 16:* Forecast impact of the assimilation of the NWC SAF/HRW AMVs in the UKV region, considering the meteorological variables used in the MetOffice NWP Forecast verification index, for the period 28 Sep to 28 Oct 2013.**

EVOLUTION OF NWC SAF/HIGH RESOLUTION WINDS

Next version of High Resolution Winds (v2015) in expected to have next improvements:

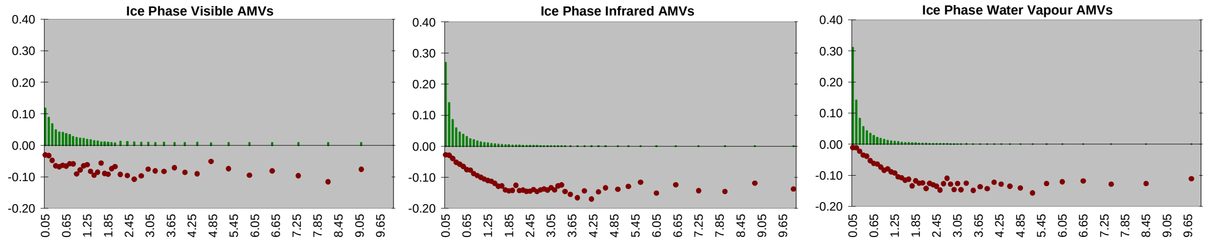
- The adaptation of HRW algorithm to GOES-N satellite series, extracting AMVs from 0.6 μm High resolution visible channel, 10.7 μm infrared channel and 6.5 μm water vapour channel. This will be an initial step for the later adaptation of HRW algorithm to other geostationary satellites in later HRW versions.
- The inclusion of Cloud microphysics information from NWC SAF/Cloud products in the AMV height assignment, considering next parameters: cloud phase, effective radius, cloud optical thickness and/or cloud liquid/ice water path.

Considering the Cloud microphysics provided by NWC SAF/Cloud products, an option is studied to modify CCC height assignment method through next procedure:

- First, the AMV Cloud phase is calculated as the cloud phase of the pixels with largest correlation contribution.
- For AMVs with larger ice phase contribution (and so defined as "ice phase AMVs"), the pixel value of the "ice water path" is calculated with the formula proposed by Heymsfield et al. 2003: $IWP_{ij} = (\tau_{ij} / 0.065)^{1.190}$,
- For AMVs with larger liquid phase contribution (and so defined "liquid phase AMVs"), the pixel value of the "liquid water path" is calculated with the formula proposed by Stephens et al. 1978: $LWP_{ij} = (2 * \tau_{ij} * reff_{ij} * \rho_w)/3$,

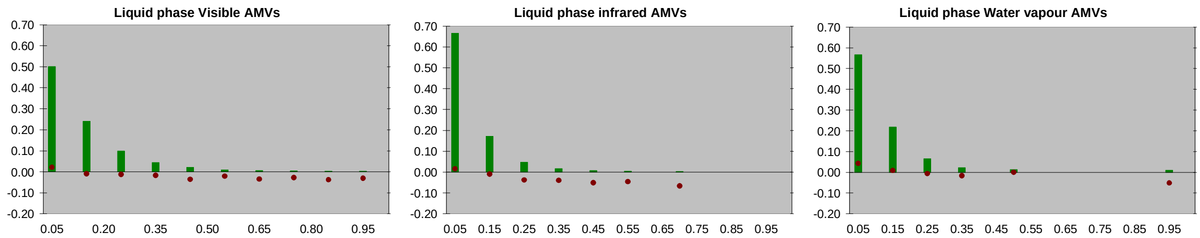
being on one side ρ_w the water density, and on other side τ_{ij} the optical thickness and $reff_{ij}$ the effective radius for each pixel, as provided by NWC SAF/Cloud products.
The "AMV liquid/ice water path" is then calculated as the correlation contribution weighted sum of pixel values, considering only the pixels over the correlation threshold (similarly to other parameters calculated by CCC method like the "AMV pressure").

Next figures display for the "Ice phase AMVs" the relationship between the Pressure difference with the radio sounding best fit level and the "AMV ice water path" (IWP_{AMV}).
The radio sounding best fit level is always lower than the AMV level (because of the negative values of the pressure difference). There is also a linear increase of the Pressure difference with the best fit level for larger IWP_{AMV} values up to a maximum IWP_{AMV} value, over which the Pressure difference becomes constant. This relationship is very clear for the infrared and water vapour channels, in which the fitting correlation reaches a value of 98%. The relationship is instead less defined for the visible channels.



***Figures 17, 18 and 19*: Relationship for the "Ice phase AMVs" calculated in visible (left), infrared (centre) and water vapour channels (right), between the Pressure difference with the radio sounding best fit (in red, in 10^5 Pa) and the "AMV ice water path", in the European and Mediterranean region for the year July 2009-June 2010, considering all atmospheric layers together (100-1000 hPa). Negative pressure difference values mean that the best fit level is lower than the AMV level. Green bars show the percentage of AMV data with each "AMV ice water path value".**

Next figures display for the "Liquid phase AMVs" the relationship between the Pressure difference with the radio sounding best fit level and the "AMV liquid water path" (LWP_{AMV}). The radio sounding best fit level is generally lower than the AMV level (except when the LWP_{AMV} is near zero). There is also a linear increase of the Pressure difference with the best fit level with larger LWP_{AMV} values (although the fitting correlation can be only around 79% in some of these cases).



***Figures 20, 21 and 22*: Relationship for the "Liquid phase AMVs" calculated in visible (left), infrared (centre) and water vapour channels (right), between the Pressure difference with the radio sounding best fit (in red, in 10^5 Pa) and the "AMV liquid water path", in the European and Mediterranean region for the year July 2009-June 2010, considering all atmospheric layers together (100-1000 hPa). Negative pressure difference values mean that the best fit level is lower than the AMV level. Green bars show the percentage of AMV data with each "AMV liquid water path value".**

Defining a correction of the AMV height with the calculated IWP_{AMV} and LWP_{AMV} values, and the relationship between the Pressure difference with the radio sounding best fit and these IWP_{AMV} and LWP_{AMV} values, and recalculating the AMV validation statistics after the AMV height correction, next values are obtained:

With microphysics corr. (Jul 2009-Jun 2010)	Cloudy HRVIS	Cloudy VIS06	Cloudy VIS08	Cloudy WV062	Cloudy WV073	Cloudy IR108	Cloudy IR120	Clear Air	All AMVs
NC	46137	102303	92322	225974	308506	296381	300244	43943	1415810
SPD [m/s]	14.78	10.77	10.79	22.55	20.48	18.29	18.48	16.59	18.35
NBIAS	-0.05	-0.16	-0.17	-0.02	-0.06	-0.08	-0.07	-0.00	-0.07
NMVD	0.31	0.42	0.42	0.26	0.28	0.29	0.29	0.32	0.30
NRMSVD	0.38	0.50	0.50	0.32	0.34	0.35	0.35	0.40	0.36

Figure 23: **Validation statistics against radio sounding winds for NWC SAF/High Resolution Winds v2013 Basic scale AMVs in the European and Mediterranean region, for the period July 2009-June 2010, considering all atmospheric layers together (100-1000 hPa), considering the AMV height correction based on Cloud microphysics. (NC: Number of collocations; SPD: Mean radio sounding wind speed in m/s; NBIAS: Normalized bias; NMVD: Normalized mean vector difference; NRMSVD: Normalized root mean square vector difference).**

Comparing with Figure 6, where the same AMV dataset was validated without height correction based on cloud microphysics, the amount of AMVs increases around a 15%, with smaller NBIAS values (especially in the infrared and water vapour channels), and a slight although positive impact in the NRMSVD values. Nevertheless, the correction method can imply a refining for the different satellite channels or the different cloud types to be more effective.

HIGH RESOLUTION WINDS AS “STAND ALONE AMV CALCULATION SOFTWARE”

NWC SAF/High Resolution Winds software was proposed in the 11th International Winds Workshop in 2012 as option for the “Stand alone AMV calculation software”, available to all AMV researchers and users. The good validation results for NWC SAF/HRW software by independent studies (by the MetOffice or the AMV intercomparison study) should solve any doubts about the usefulness of this AMV algorithm.

In case of interest on using NWC SAF software, all National Meteorological Services within EUMETSAT Member or Cooperating States are automatically considered as potential users. Any other organisation may also apply to become user of it.

Up to now, all applicants have become users of NWC SAF software without restrictions: over 100 institutions from all around the world (Europe, Africa, Americas, Asia), including national meteorological services, universities, research institutions, public service providers, public and private companies.

To become a user of NWC SAF software, Pilar Rípodas or Ana Sánchez should be contacted through the email addresses pripodasa@aemet.es or asanchezp@aemet.es.

The software delivery is authorized to the registered users according to their Licence Agreement, to be signed by EUMETSAT (represented by Agencia Estatal de Meteorología) and the applicant user. Once the Licence Agreement is signed, access credentials to the NWC SAF Helpdesk Restricted Area are provided, from which the NWC SAF software can be downloaded, and so installed and run locally at the user premises.

Any more info about the NWC SAF/HRW software can be obtained from the NWC SAF Helpdesk webpage (http://www.nwcsaf.org) or through direct contact with the “High Resolution Winds” developer Javier García-Pereda (jgarciap@aemet.es).

REFERENCES

NWC SAF Helpdesk, with general information on the “Satellite Application Facility on support to Nowcasting and Very short range forecasting”, its software packages and its products: www.nwcsaf.org.

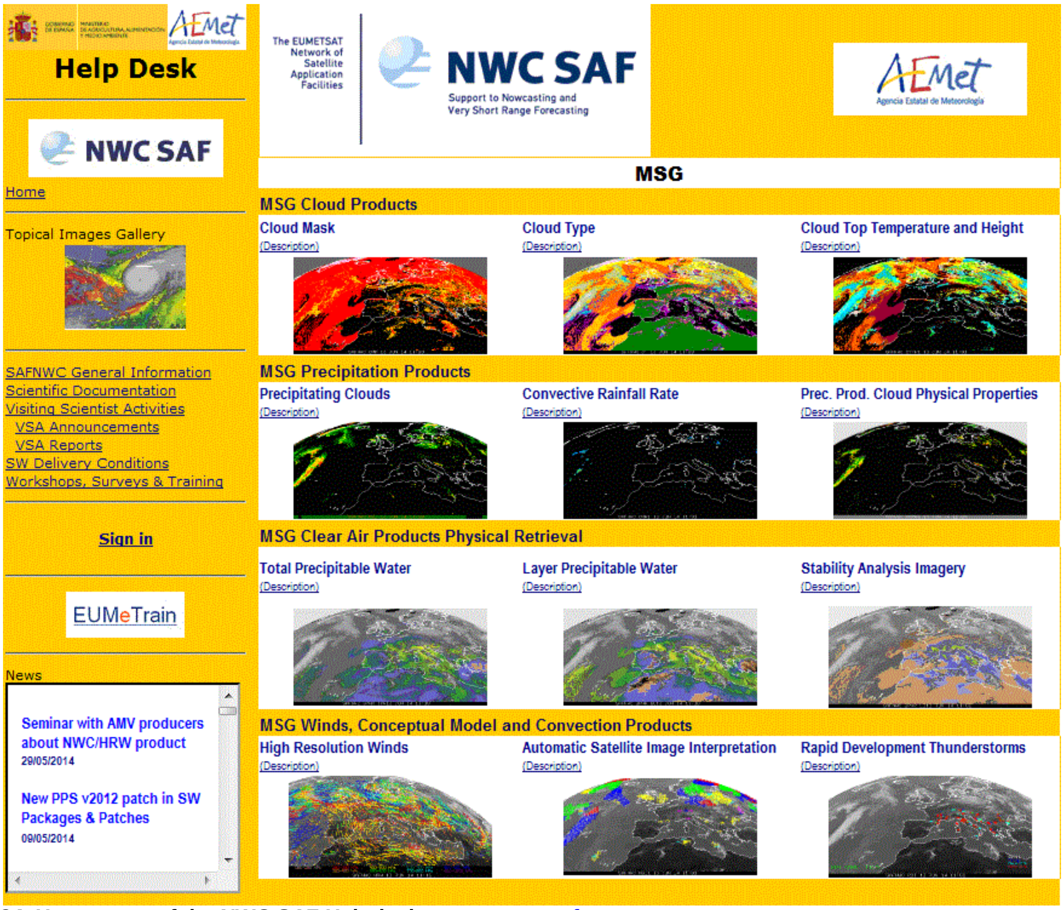


Figure 24: **Home page of the NWC SAF Helpdesk at www.nwcsaf.org**

Official documentation of "NWC SAF/High Resolution Winds (HRW)" software (available at the NWC SAF Helpdesk at http://www.nwcsaf.org/indexScientificDocumentation.html):

1. García-Pereda, J., 2013a: Algorithm Theoretical Basis Document for High Resolution Winds (HRW-PGE09 v4.0). NWC SAF Document SAF/NWC/CDOP2/INM/SCI/ATBD/09.
2. García-Pereda, J., 2013b: Product User Manual for High Resolution Winds (HRW-PGE09 v4.0). NWC SAF Document SAF/NWC/CDOP2/INM/SCI/PUM/09.
3. García-Pereda, J., 2013c: Validation Report for High Resolution Winds (HRW-PGE09 v4.0). NWC SAF Document SAF/NWC/CDOP2/INM/SCI/VR/13.

Other presentations at the International Winds Workshops with relevant information:

4. García-Pereda, J. and R. Borde, 2012: NWC SAF High Resolution Winds (HRW) as Stand alone AMV calculation software. Proceedings, *11th International Winds Workshop, Auckland, New Zealand.*
5. Kelly, G., P. Lean and S. Migliorini, 2014: Operational use of NWC SAF AMV package in the MetOffice mesoscale forecasting system. Proceedings, *12th International Winds Workshop, Copenhagen, Denmark.*
6. Lean, P., S. Migliorini and G. Kelly, 2014: Characterizing AMV height assignment errors in a simulation study. Proceedings, *12th International Winds Workshop, Copenhagen, Denmark.*
7. Santek, D., J. García-Pereda, C. Velden, I. Genkova, S. Wanzong, D. Stettner and M. Mindock, 2014: AMV intercomparison project. Proceedings, *12th International Winds Workshop, Copenhagen, Denmark.*

Scientific papers related to Cloud microphysics parameters:

8. Heymsfield, A.J., S. Matrosov and B. Baum, 2003: Ice water path – Optical depth relationships for cirrus and deep stratiform ice cloud layers. *Journal of Applied Meteorology*, **42**, 1369-1390.
9. Stephens, G. L., 1978: Radiation profiles in extended water clouds: II. Parameterization schemes. *Journal of the Atmospheric Sciences*, **35**, 2123-2132.