STATUS ON THE USE OF SCATTEROMETER DATA AT METEO-FRANCE

Christophe Payan

Centre National de Recherches Météorologiques, CNRM-GAME
CNRS and Météo-France, 42 avenue Coriolis, Toulouse, France

Abstract

Sea surface wind is provided by scatterometer data through a heuristic relation, called Geophysical Model Function (GMF).
Since 2004, data from the scatterometer Seawinds aboard the satellite QuikSCAT have been assimilated in Arpège, the global operational model of Météo-France. Part of these data is rejected by the quality control, mainly because of the contamination by rain or by lack of diversity in direction of the most likely wind solutions. Within the frame of a case study, the track of the 2006 tropical cyclone Gordon by the global model Arpège, an alternative quality control based on the principle of the distance to the cone, is compared to the operational practice.
Furthermore, the launch in 2006 of MetOp-A with the scatterometer ASCAT aboard gave the opportunity to introduce in our operational system another instrument of the same kind named AMI aboard ERS-2. These instruments work in the C-band which is insensitive to rain. Data from ERS-2 are locally inverted using the GMF CMOD5.4, which is a variation of CMOD5 tuned by ECMWF and which allows to absorb a known residual bias of –0.5 $m.s^{-1}$. By contrast, ASCAT wind data used in Arpège come from KNMI. The impact of these new ASCAT data in our assimilation system is slightly positive.

1. INTRODUCTION

An active scatterometer instrument aboard polar-platforms measures the backscattered component of an incident wave from different angles for a same point.
Over the water surface, the combination of these backscattered signals can be linked with the local wind, through a heuristic relation, called Geophysical Model Function (GMF). In practice, the determination of the local wind is deduced from a quadratic cost function, which minimizes the distance between the sample of backscatter signals for a same location point and the GMF. In fact, depending on the type of GMF, several minima can be exhibited, which correspond to different wind solutions, in particular, different in direction. In that case the residual of the minimization, called distance to the cone, can be used as a likelihood that the associated wind solution is the true solution. The smaller this residual, the more likely the wind solution will be. In a larger sense, for a location point, a high residual from the minimization (meaning that the measured backscatter signals are far away from the GMF), means that the wind solutions are not representative of the true wind. Such a concept can be used, for example, to detect instrument anomalies (Isaksen and Janssen, 2003).
Since 2004, data from the scatterometer Seawinds aboard the satellite QuikSCAT (launched in 1999) have been assimilated in Arpège, the global operational model of Météo-France. The limitations of this instrument (contamination by rain, lack of diversity in the angles of view in the nadir swath, and some others limitations) imply a need for a quality control, which gives a rate of rejection of around 70% (figure 1) before these data can be used in our assimilation system. However, the lack of data in rain-contaminated areas together with other points which were pointed out in an internal report (Joly *et al*, 2006) could explain the bad performances of Arpège in the analysis of the dying out of tropical cyclone Gordon, which happened in 2006 over the North-Atlantic basin.
After a description of the current QuikSCAT processing, an alternative quality control, principally based on the “distance to the cone” concept (Portabella and Stoffelen, 2000), is tested. This alternative quality control tries to increase the number of assimilated data, without their quality being degraded. The first objective is to study its impact in the global performances of Arpège, then to look at the impact of the

changes on the track of the tropical cyclone Gordon. Opportunely, the impact is also evaluated for the tropical cyclone Helene, which occurred at the same time and in the same basin.
Furthermore, the launch of the Eumetsat polar satellite MetOp-A during the Autumn 2006 with the scatterometer ASCAT aboard, gave the opportunity to introduce in Arpège, data from AMI aboard ERS-2 (launched in 1995 and operated by ESA) which is another instrument of the same kind. For this last instrument, the inversion from the backscatter signals to the surface wind is homemade, first using GMF CMOD5, which produces a known bias of –0.5 $m.s^{-1}$ against the model background. The impact of the last version of GMF, CMOD5.4, tuned by Abdalla and Hersbach (2007) to absorb this residual bias, is presented here. For ASCAT data, the inversion is operated by KNMI, which is in charge of the calibration/validation in the frame of a Satellite Application Facility (SAF) for Eumetsat and which produces also a quality flag. Statistics and impact on the forecast skill are described in a last part.

2. CURRENT QUIKSCAT DATA PROCESSING

The assimilation of winds from the Seawinds scatterometer, aboard the QuikSCAT satellite, in the common model code IFS/Arpège, was initially undertaken by ECMWF, with an initial contribution by Leidner, completed by Hersbach and Isaksen (ECMWF, 2007). This development, after some minor adjustments due to the French framework, was activated in Arpège in 2004.
This scatterometer consists of two rotating beams operating at Ku-band frequency with incidence angles with respect to the normal of the ocean surface of 46° and 54°. Each beam provides a fore and an aft measurement. They cover a swath width of 1800 km, but only the inner 1400 km is illuminated by both beams. The product has a 25 km resolution, defining 76 across nodes (Jet Propulsion Laboratory, 2001).
In fact, contiguous backscatter measurements are grouped into 50 km boxes (from four 25 km nodes), giving 38 wind-cells at a 50 km resolution. A 50 km resolution allows to reduce the noise, to improve the inversion, the quality control, to reduce the wind direction ambiguity and is more representative of the scales resolved by the increments in 4D-Var (Stoffelen *et al*, 2001).
The Ku-band is a band sensitive to rain, and this needs a particular quality control (QC). The operational rain QC uses a combination of information about the content in rain during the trajectory of the signal, information being furnished with the backscatter signals from NESDIS for each 25 km sub-cells. If one 25 km sub-cell is considered contaminated by rain, the associated backscatter measurements are not used by the GMF QSCAT-1. In the end, if less than three 25 km sub-cells (at least 2 sub-cells rejected by the quality check) are available for the inversion at 50 km, the inverted wind solutions are not assimilated. Up to 4 ambiguous wind solutions per 50 km cell can be retrieved by QSCAT-1. Nevertheless, in the nadir part of the swath, the lack of azimuth diversity between the two inner and the two outer measurements leads to shallow maxima for the Maximum of Likelihood Estimator (MLE) and leads to wind solutions which are pointing in a similar direction. To control this, the 2 wind solutions, chosen a-priori for the assimilation with the two MLE smallest residual must be different by 135° in direction. Additional controls are made, as on far swaths rejection (nodes 1-4 and 35-38, where only measurements from the outer beam are available), datum rejection if the number of ambiguities is less than two or if the model sea-surface temperature is under a threshold (sea-ice contamination). After these numerous checks, if the datum is selected for assimilation, the chosen wind solution is the one closest to the current background, this operation is called de-aliasing. Therefore, one single wind solution by location point is effectively assimilated. To be noticed, there is no geographical thinning (for removing correlation and representativeness errors) but the weight of these data in the assimilation cost function is reduced by a factor four, which correspond to an effective assimilation at a 100 km resolution. More information about the QuikSCAT processing and related references can be found in the IFS documentation (ECMWF, 2007).
The coverage map in figure 1, issued from the operational monitoring, gives a good view of the current scatterometer data selection for an assimilation window of 6 hours before their assimilation. QuikSCAT swaths are easily recognizable by the gaps in the nadir, after the QC operated in the so-called screening step, gaps due to the lack of diversity in direction of the retrieved wind solutions.

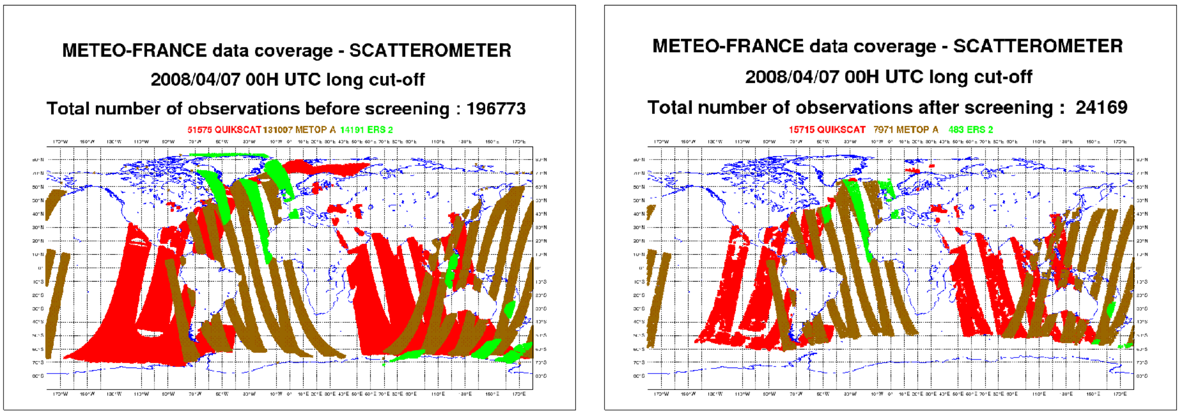

***Figure 1*: Scatterometer data coverage in a 6h assimilation window. On the right, data available before the quality control (screening step). On the left, data selected for the 4D-Var assimilation. QuikSCAT swaths (in red) are marked by gaps in the nadir, due essentially to a lack in direction diversity of the inverted wind solutions. The rejection rate is around 70%. Ascat data (in brown) are marked by a swath twice as large, due to the use of two systems of antennas. ERS-2 data coverage (in green) is only local and is limited to the North-Atlantic and around Australia.**

3. AN ALTERNATIVE QUALITY CONTROL FOR QUIKSCAT DATA

As mentioned in the introduction, the rate of rejection of QuikSCAT data was pointed out as a weakness in our assimilation system, and in particular for tracking tropical cyclones like Gordon which occurred in the North-Atlantic Basin in 2006.

Gordon, from 11 to 25 September, is described in the best track report by Blake (2006), from the National Hurricane Centre of Miami, Regional Specialized Meteorological Centre for the Tropical Cyclones for the Atlantic. From the 16th onwards, Gordon is progressively lost by the Arpège assimilation, and completely disappears in the last assimilation of the 19th (no more closed surface isobar), whereas it crosses the Azores Islands towards Western Europe.

We propose here to test the modifications in the QuikSCAT processing in order to improve the number of available data, especially near the rain systems.

Portabella and Stoffelen (2001) have defined a quality indicator called the normalized residual (Rn) as

$$Rn = MLE / < MLE >$$

where MLE is the Maximum Likelihood Estimator of a particular wind solution, and $< MLE >$ is the expected MLE for a particular cell and for the wind solution in terms of speed. $< MLE >$ is computed from real data, then filtered with an iterative process to remove data too far away from the GMF. For a "rainy" cell, Rn is expected to be high, whereas for a "windy" cell, Rn should be of the order of 1. This approach, which is purely self-consistent, does not need any other external information and allows to deal with unexpected geophysical phenomena other than rain. The authors showed a good correlation of Rn with the ECMWF background and with rain information from collocated SSM/I data. From this study, a threshold function dependent on the wind speed and on the cell number was defined and which fixes a level of rejection. In practice, if one 25 km sub-cell is rain-contaminated, the 50 km wind is not assimilated (whereas one missing 25km sub-cell is allowed in the operational QC).

This quality control is implemented in the IFS/Arpège code, but is only used as a diagnostic. Hersbach *et al* (2003) have shown that for a tropical cyclone, many more potentially high quality data are retained in the vicinity of the system with this alternative quality check.

Another mean to increase the number of active data is to ignore the two most likely but to choose the most likely and opposite in direction, following the practice of the ECMWF, and this without any significant deterioration of the quality in the nadir part of the swath (Hersbach *et al*, 2003). This automatically allows to reduce the rejection rate due to the lack in direction diversity.

To test this alternative quality control, an updated version of the operational model Arpège (valid from September 2007 until February 2008) is used, in its stretched version T358C2.4 (between T149 (133 km Gaussian grid) over the South-Western Pacific and T859 over Western Europe (23 km Gaussian grid)), 46 levels on the vertical and with a 4DVar assimilation at T149 (133 km Gaussian grid), 6 hours window. The choice of an updated version is for practical reasons, and it gives the opportunity to look if this updated version, with its many changes, too long for being listed here, could improve the track of

Gordon. Reference and experiment are running from September 14 till October 4, one week before the complete loss of Gordon by the assimilation.

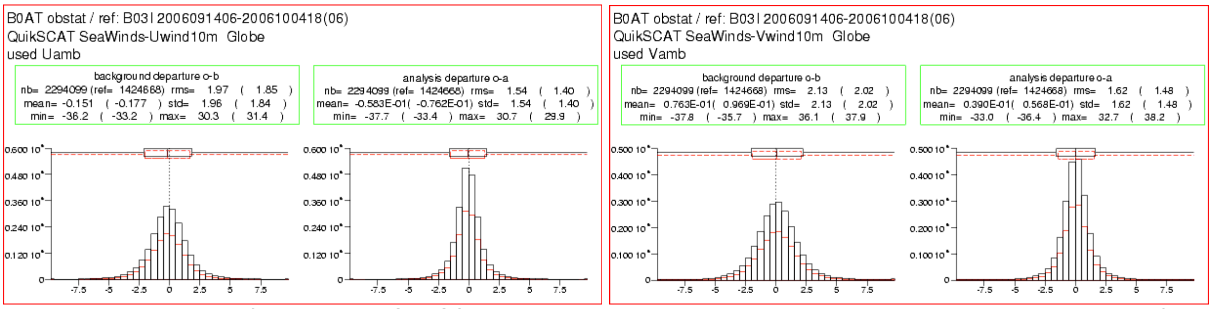

***Figure 2*: Histograms of assimilated QuikSCAT data departures wrt the model Background and the Analysis, for U component on the left, V component on the right (in m.s^{-1}). The experiment with the new quality control has more active data in the assimilation (in black), wrt the reference with the operational use (in red), statistic values indicated in parentheses for this latter.**

The impact of the new control in terms of model fit to QuikSCAT data is shown in figure 2. The number of active data is improved by more than 61%. The bias is also slightly improved whereas the rms for each component against the model background is slightly increased (rms wind difference vector of 2.9 m.s^{-1} against 2.7 m.s^{-1} with the operational QC).

In spite of this light degradation of the model fit to the observations, in terms of forecast skill, the impact of the new QC is neutral or positive on every model parameter (geopotential, temperature, wind and humidity). The largest positive impact is a gain in rms reaching 2 gpm in geopotential at 200 hPa at +72h forecast over Europe, 1 gpm over the Northern Hemisphere, with radiosondes as a control (figure 3). This positive impact is probably due to the gain in information given by the increase in active data.

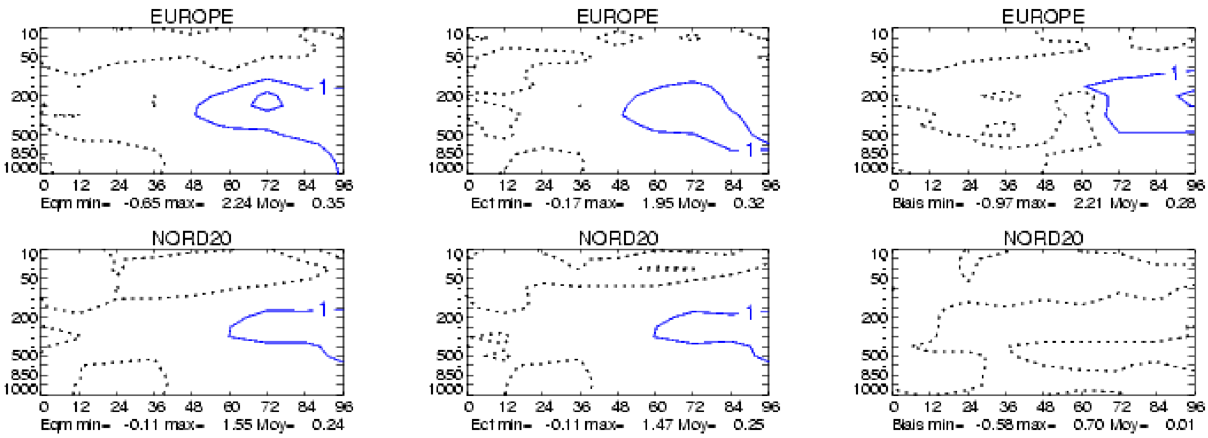

***Figure 3*: From left to right, root mean square, standard deviation and bias departures on the geopotential forecasts between the experiment with the new QuikSCAT QC and the operational check, with radiosondes as a control, on different areas (Europe on top, North20 on bottom), from 15 September to 8 October 2006 (20 cases). Solid line indicates a positive impact with the new QuikSCAT QC, dot-dashed line a negative impact and dotted line a neutral impact. One isoline every 1 gpm.**

By contrast, there is no significant impact about the track of the tropical cyclone Gordon. The sequence of the Mean Sea Level Pressure analysis was studied over the North Atlantic ocean during September, using the ECMWF model and the NHC best track as controls. Visually, there are no significant differences in the large-scale patterns. The new QC allows to use more QuikSCAT data near the vicinity of Gordon. Figure 4 (right) shows the analysis of 20 September at 6 hours, when Gordon crosses the Azores Islands, with a minimum pressure of 980 hPa and 70 knots of wind, according to the NHC. The track of Gordon is completely lost by the operational model as well as with the new QC, whereas it is still well defined by the ECMWF analysis, even if the minimum pressure is slightly shifted with respect to the NHC best track. The minimum pressure north-north eastward the Azores is linked with a secondary front in a large-scale pattern, marked here by the large trough. ECMWF will analyse this secondary minimum during the following analysis (at 12UTC) getting a shape in better agreement with the new QC.

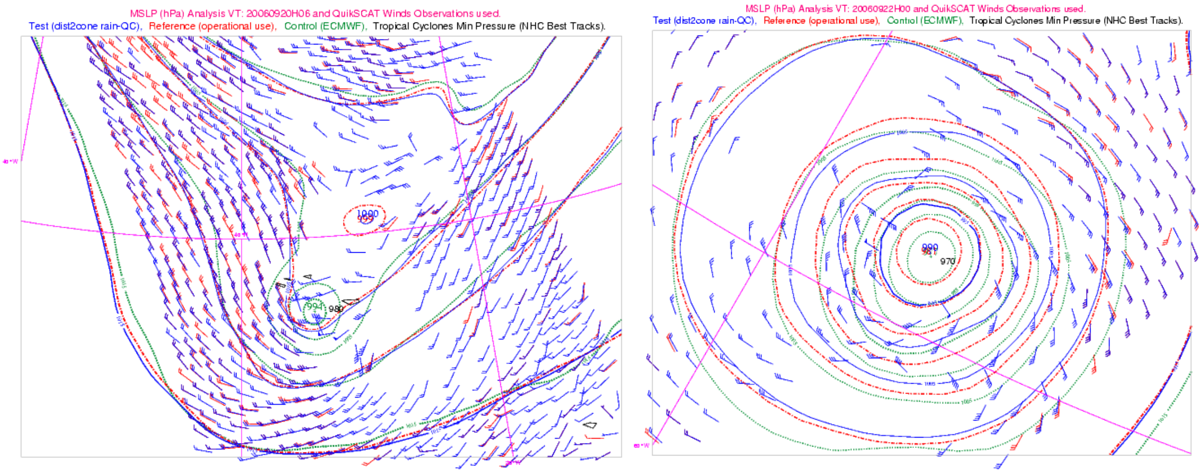

***Figure 4*: different MSLP analysis (one isobar every 5 hPa) and QuikSCAT data used for these analysis (meteorological barbs). The new QuikSCAT QC is in solid line (blue), the reference (QuikSCAT operational use)is in dot-dashed line (red), the control (ECMWF analysis) is in dotted line (green).**
On the right, analysis for the 20 September 2006, 06 UTC, with the minimum pressure (here 980hPa, in black), from the NHC best track, positioned at the centre of Gordon when it crosses the Azores Islands. On the left, analysis for the 22 September 2006, 00 UTC, centred on the tropical cyclone Helene, with the capture of the first close isobar (at 1010 hPa). This close isobar is very similar for models (excepted a light southward extension for ECMWF (until 50 km)) The minimum pressure analyzed by ECMWF (977 hPa) is very close to the NHC analysis (970 hPa in black).

In fact, this study gave us the opportunity to look at the impact of the tropical cyclone Helene which occurred during the same period and in the same area. Helene (from 14 to 28 September) follows a similar parabolic trajectory in the middle of the North Atlantic ocean as Gordon. The peak of intensity occurs on the 18th with a minimal pressure of 955 hPa and 105 knots winds, exactly like Gordon (Brown, 2006). But Helen is a wider cyclone, and is better tracked by Arpege. Visually, assimilated QuikSCAT data are more numerous with the new QC near the cyclone, without any significant differences in the position of the system and well positioned by the analysis. The main difference is in the minimum pressure in the core of the cyclone. With the new QC, the sea pressure is at best equal and up to 9 hPa higher than with the operational use, while the minimum pressures from the models are always higher than the NHC analysis, which is a common trend for global models.
Figure 4 (left) shows the analysis on the 22^{d} at 00 UTC, when the maximal difference occurs. Pressure field with the new QC is more compact but limited in the deepening (990 hPa instead of 981 hPa with the operational use). Although the number of active QuikSCAT data is clearly larger in the vicinity of Helene (in fact, there is no data with the operational QC), the maximum wind is limited at less than 47 knots (instead of 75 knots estimated by the NHC). As a matter of fact, it is quite difficult to draw any conclusion about the quality of the data in this present case. According to the NHC report (Brown, 2006), a buoy reports 47 knots 24 hours later, then 44 knots 2 hours later, while Helene gets closer to it, and so in good agreement with QuikSCAT winds reported here. And there is no other conventional data available for 3 days prior the 22^{d} and the following day. On the other hand, several authors report that the retrieved wind speed in higher wind speed regime are not properly represented in the QSCAT-1 GMF (Fernandez *et al*, 2006) and are consistently underestimated (Von Ahn *et al*, 2006). According to Donely et al (1999), speeds are valid only up to 25 m.s^{-1} (nearly 50 knots), whereas until 80 knots can be retrieved by JPL 25 km product, near the tropical cyclones (Hersbach, 2003 and Brown, 2006). Moreover, the bias correction in the 50 km inversion processing decreases the speed when the wind becomes stronger (up to –7 m.s^{-1} for an inverted speed of 35 m.s^{-1}), whereas the speed bias is globally slightly positive against the model background.
More investigations are necessary, in particular in the distribution and in the strength of QuikSCAT data in the surroundings of Gordon and Helene, on the impact of the bias correction for high speed and in terms of impact in the trajectory and intensity forecasts.

4. AMI (ERS-2) AND ASCAT (METOP-A) DATA ASSIMILATION (INSTRUMENTS IN C-BAND)

The AMI scatterometer on-board the European Remote sensing Satellite ERS-2 (launched in 1995), and the ASCAT instrument on-board MetOp-A (launched in 2006) operate in the C-band, which is insensitive to rain. A set of 3 antennas pointing 45° forward, sideways and 45° backward with respect to the flight direction, provide 50 km diameter foot prints every 25km (data are over-sampled). For ERS-2, the swath width is 500 km, defining 19 nodes, on the right-hand side from the flight direction. For Metop-A, a double set of antennas allows two 550 km-wide swaths, on both sides of the satellite track, with a 700 km gap, defining at last 42 nodes (figure 1). Since 2003 (failure of an onboard tape), the coverage of ERS-2 has been only local and function of ground segments location and currently limited to around North America, Australia and Western Europe (figure 5).

The CMOD5 GMF performed by Hersbach *et al* (2007) was first used to retrieve wind solutions from ERS-2 backscatter signals (two solutions, opposite in direction). The quality control is similar to the one operated for the QuikSCAT Data, and is well described in the IFS documentation (ECMWF, 2007). The thinning procedure leads to select at best one observation out of 16, for an effective assimilation at 100 km resolution, instead of the initial 25 km grid. On average, 900 data are assimilated per day. The de-aliasing between the two likely solutions is made during the assimilation as it is the case for the QuikSCAT data. ERS-2 data were introduced in the operational assimilation in September 2007. But at the same time, Abdalla and Hersbach (2007) proposed a new tuning of the GMF, called CMOD5.4, which allows to absorb a known residual bias in speed of around -0.5 $m.s^{-1}$, by applying:

$$CMOD5.4(u_{10}, c') = CMOD5\left(u_{10} - 0.45 m.s^{-1}, c\right)$$

where u_{10} is the wind speed at 10 meters retrieved by the GMF, c' the new tuning, c the old tuning (in fact a set of 28 coefficients). The impact of this new CMOD5.4 can be seen from the experiment which was carried out in June 2007 (from 31 May to 1 July 2007 exactly) against a reference with CMOD5 (Fig.5).

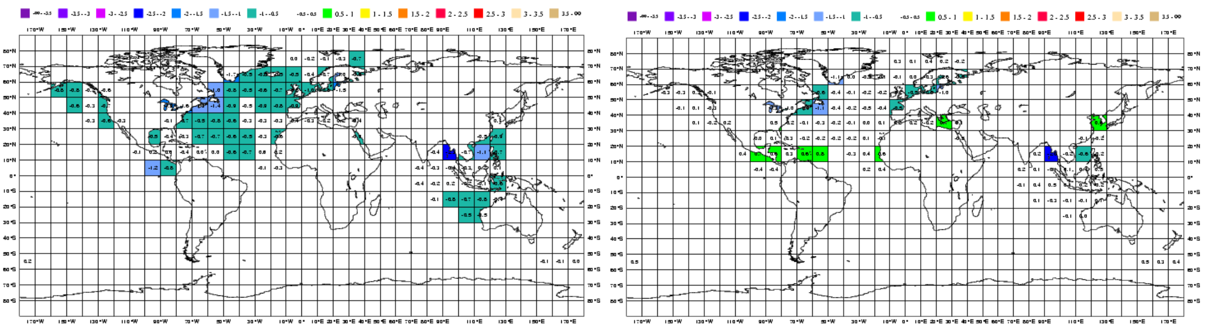

Figure 5**: ERS2 speed bias (assimilated observations - background) in June 2007. On the left, winds retrieved with CMOD5 give an averaged bias of –0.5 $m.s^{-1}$. On the right, with CMOD5.4, the bias is reduced to –0.1 $m.s^{-1}$. Mean by 10°x10° boxes.**

By contrast, ASCAT wind data introduced in Arpège come from KNMI, in the frame of an Eumetsat SAF. Backscatter signals are calibrated in function of the tuning of the instrument (bias correction in the measurement space), then, the CMOD5.5 GMF is used to retrieve wind data. CMOD5.5 is a variation of CMOD5, which allows also to absorb the -0.5 $m.s^{-1}$ bias but with a constant correction. Besides the checks already described with ERS-2 data, the quality flags produced by the KNMI are also used, following the recommendations of the ASCAT Wind Product User Manual (KNMI, 2008). If one of the following flags is set, such as, monitoring flag (failure in different controls), KNMI QC flag (poor quality of the backscatter information) and variational QC flag (spatial inconsistency), then, the observation is rejected. Furthermore, data are also rejected if the land fraction is not null. The thinning is operated at a 100 km resolution (for ERS-2 data), giving around 30 000 data effectively assimilated per day.

The impact of these new data in Arpège, as in the same version used for the QuikSCAT study, was evaluated in June 2006, with the addition of ERS-2 winds inverted with CMOD5.4 (instead of CMOD5 in the reference). The quality of active data (figure 6) is superior to other observation systems of same type.

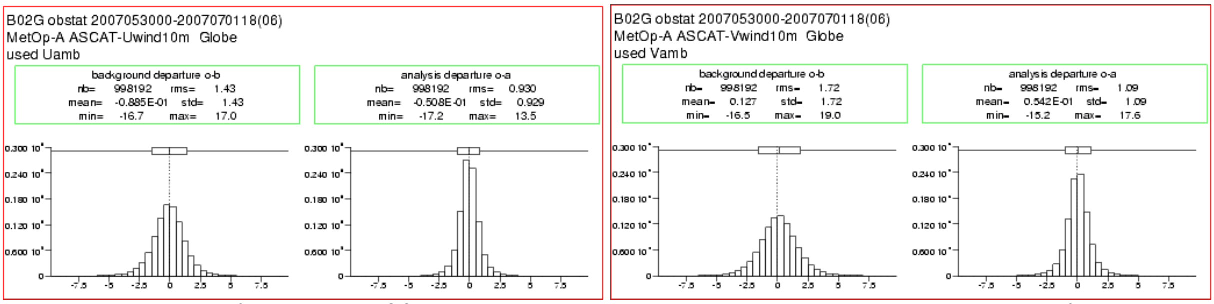

***Figure 6*: Histograms of assimilated ASCAT data departures wrt the model Background and the Analysis, for component U on the left, component V on the right (inm.s^{-1}), in the experiment.**

In terms of forecast error until +96 hours, there is no significant quantitative gain on the classic meteorological fields as winds or geopotential. But the bootstrap test, which measures if scores are statistically significant, shows a positive impact at higher levels (pressure < 300 hPa), in the Northern Hemisphere and in the Tropics, less pronounced in the Southern Hemisphere, with radiosondes as control (figure 7). Unfortunately, during the experiment period, there was no tropical cyclones and the impact on particular mid-latitude systems was not studied.

Paramètre Z ; 32 cas

Domain	NORD20									TROPIQ								
Range	0	12	24	36	48	60	72	84	96	0	12	24	36	48	60	72	84	96
10								-		++		+					--	
30		++	++	++			-			++	++	+	+					--
50		++	++	++							++			++				
70		++	++	++	++						++		+	++				
100	+	++	++	+	++					++		+	+					
150		+								++	++	++	+	+				
200												++						
250												++				-		
300												++						-
400							+											-
500							++				++							
700											+							-
850																		
925																		
1000																		

Domain	SUD20									EUROPE								
Range	0	12	24	36	48	60	72	84	96	0	12	24	36	48	60	72	84	96
10				-					+					--		--	--	--
30					-				+			++	++	++				-
50		++									++	++	++	++				
70		++				++					++	++	++	++				
100						++					++	++	++	++				
150												++						
200											-					+		
250											--							
300																		
400	+																	
500	++												--					
700													--					
850					++						+							
925					++													
1000	+		+		++													

Domain	AMNORD									ASIE								
Range	0	12	24	36	48	60	72	84	96	0	12	24	36	48	60	72	84	96
10													+					
30		++	++		++				++									
50		++	++	++	++				+									
70		+	++	++	++													
100		+		+	++													
150																		
200			-															
250			--	-														+
300																		++
400		--									+					++		+
500		--													+	++	+	++
700							+											
850			++				++											
925		--					++		+			-						
1000	++						+											

***Figure 7*: bootstrap test on the geopotential rms error, forecasts until +96h (32 cases), with radiosondes as control, on different domains. + + (resp - -) means the experiment is better (resp worse) than the reference experiment at 95%, + (resp. -) means the experiment is better (resp. worse) than the reference experiment at 90%. The experiment is with CMOD5.4 for ERS-2 and with the assimilation of ASCAT data. The reference experiment is with CMOD5 for ERS-2 and ASCAT data are not used.**

5. CONCLUSIONS

The test of an alternative QC for QuikSCAT data, based on the distance to the cone for rain contamination and the choice of the most likely solution and its opposite in direction, does not allow to really improve the track of tropical cyclone Gordon(2006), but, on the contrary, limits the deepening by the model Arpège of the wider tropical cyclone Helene(2006). The geophysical interpretation of backscatter signals in a chaotic sea-surface state, the limitations of the used GMF QSCAT-1 and/or the high wind speed bias correction are probably the causes of the latter. Unfortunately, the impact on forecasts of these tropical patterns are yet to be evaluated. The use of a modified GMF, like QSCAT1-MOD (Jelenak and Chang, 2008), which better describes higher wind speeds and/or a revision of the bias correction for high speed, or an additional check on the speed, could be studied, with regard to the new NESDIS QuikSCAT stream, announced to be operational for June 2008, which imposes a new tuning of the distance to the cone rain QC (change of the MLE). Nevertheless, the global effect in terms of analysis and forecast scores are positive, with an increase of the analysis precision (many more data and not too degraded in quality) and with a gain (up to 1 gpm) in geopotential forecast error rms over the Northern hemisphere, with radiosondes as a control.
Wind data from ERS-2 were operationally introduced in Arpège in September 2007, and, since February 2008, they have been inverted with CMOD5.4, which allows to remove a bias on speed. In this last

operational change, the high quality wind ASCAT KNMI product was also assimilated. The experiment showed a small but statistically significant impact in terms of forecast.

REFERENCES

Abdalla S. and Hersbach H., 2007. The technical support for global validation of ERS Wind and Wave Products at ECMWF (April 2004 - June 2007). Final report for ESA contract 18212/04/I-LG, ECMWF.

Blake, E. S., 2006. Tropical Cyclone Report Hurricane Gordon (AL072006) 10-20 September 2006. *National Hurricane Centre*.

Brown, D, P, 2006. Tropical Cyclone Report Hurricane Helene (AL082006) 12-24 September 2006. *National Hurricane Centre*.

Donelly, W. J., Carswell, J. R., McIntosh, R. E., Chang, P., Wilkerson, J., Marks, F. and Black, P., G., 1999. Revised ocean backscatter at C and Ku band under high wind conditions. *J. Geophys. Res.*, **104**, C5, 11485-11497.

ECMWF, 2007. IFS Documentation CY31R1. *European Center of Medium Weather Forecast*

Fernandez, D. E., Carswell, J. R., Frasier, S., Chang, P. S., Black, P. G., and Marks, F. D., 2006. Dual-polarized C- and Ku-band ocean backscatter response to hurricane-force winds. *J. Geophys. Res.*, **111**, C08013, doi:10.1029/2005JC003048

Hersbach, H., Isaksen, L, Leidner, S. M. and P. A. E. M. Janssen, 2003. Operational Assimilation of QuikSCAT data at ECMWF. AMS Conference.

Hersbach, H., Stoffelen, A. and De Haan, S., 2007. An improved C-band scatterometer ocean geophysical model function: CMOD5. *J. Geophys. Res.*, **112**, C03006, doi:10.1029/2006JC003743,2007

Isaksen, L. and Janssen, P.A.E.M., 2004. Impact of ERS Scatterometer Winds in ECMWF's Assimilation System. *Q. J. R. Meteorol. Soc.,* **130**, 1793-1814

Jelenak, Z. and Chang P. S, 2008. Changes in NOAA/NESDIS QuikSCAT NRT Processing. Personal communication.

Jet Propulsion Laboratory, 2001. QuikSCAT Science Data Product User's Manual. Version 2.1. *Jet Propulsion Laboratory* D-18503

Joly, A., Bouyssel, F., Bouttier, F., Raynaud, P., Benichou, H., Arbogast, P., Kuscu, E., Payan, C. and Fourrié, N., 2006. Assimilations sequence of ARPEGE, ARPEGE-Tropiques and IFS, when the tropical cyclone « Gordon » is inserted in the western stream, Internal Report (in French)

KNMI, 2008. Ascat Wind Product User Manual. Ocean and Sea Ice SAF, KNMI, Version 1.4

Portabella, M. and Stoffelen, A., 2001. Rain Detection and Quality Control of SeaWinds. *J. Atm. and Oceanic Tech.*, **18**, 1171-1183

Stoffelen, A., De Vries, J. and Voorrips, A., 2001. Towards the Real-time use of QuikSCAT Winds. *BCRS project report*.

Von Ahn, J., Sienkiewicz and Chang, P., 2006. Operational impact of QuikSCAT Winds at the NOAA Ocean Prediction Center. *Weather and Forecasting*, **21**, 4, 523-539