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TECHNICAL NOTE[1]

Using QuikSCAT Wind Vectors in Data Assimilation Systems

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Abstract

High quality wind vector fields (swaths) retrieved from QuikSCAT measurements have already found many applications in different fields of meteorology, climatology, and other environmental sciences. To generate these fields, the current retrieval procedure successfully integrates or fuses the first guess wind fields and satellite data. As a result, the QuikSCAT wind field is a blend of satellite information and information from the FG. For most QuikSCAT wind applications, the percentage of independent satellite information, α, (or the ratio of satellite to first guess information) in the wind field is not an essential parameter and does not significantly affect the applicability of the data. In data assimilation applications, where the FG wind fields are one of the constituents of the data assimilation system, the amount of independent satellite information in the data may be at least as important as the error statistics (bias and RMSE) and should be taken into account. The parameter α may help to control a double count of the first guess in the data assimilation system and strongly influence the impact of satellite data on numerical weather prediction models. For different parts of the wind field this parameter will be different. Areas with lower values of this parameter should be assimilated with lower weights (higher errors).

In this study we empirically examine QuikSCAT wind vectors from this point of view. It is shown that amount of independent satellite information is lower in areas where scatterometer has lower accuracy, such as areas where the wind direction is orthogonal to one of the radar look directions, wind speeds are higher, and edges of the swath or nadir are close. It is also shown that these areas fall mainly in the part of the data where the ambiguity removal procedure selects one of the higher (not the first) ambiguities. This fact suggests a simple procedure for data assimilation applications: use the ambiguity removal procedure as a flag, assimilating only the part of the nudged solution where the first ambiguity is selected or assimilate this part of data with higher weight (lower errors).

List of Acronyms

ARP – ambiguity removal procedure
DAS – data assimilation system
FG – first guess
GDAS – NCEP global data assimilation system
ML – maximum likelihood
ML1, … ML4 – first to fourth maximum likelihood solutions or ambiguities
N – nudged solution
NWP – numerical weather prediction
RMSE – root mean square error
VRMSE – vector RMSE
WV – wind vector
WVC – wind vector cell

1. Current QuikSCAT wind vector product

Current retrieval procedure [1] is depicted in Fig. 1. It consists of two major steps; (1) numerical inversion of the QuikSCAT empirical forward model based on the maximum likelihood (ML) principle, this inversion produces from one to four wind vector (WV) solutions or ambiguities; and (2) an ambiguity removal procedure (ARP), which uses NCEP's global model first guess (FG) wind field to select from four algorithm solutions one selected or so-called nudged solution, the ARP also uses a median filter [2] which is not shown in Fig.1. The nudged wind field is smooth and has good statistical properties (bias and RMSE) when compared to the FG or analysis WV field. This field is a very good product for many applications (e.g., for marine meteorologists).

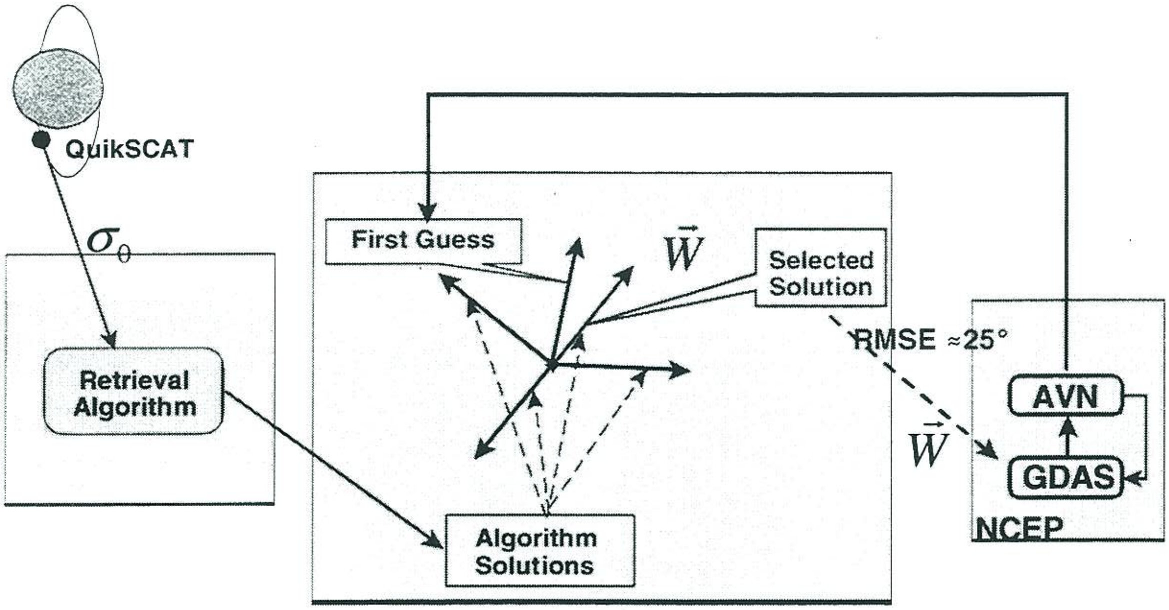

Fig. 1. Current QuikSCAT wind vectors retrieval procedure. RMSE ≈ 25° shown in the figure corresponds to an average RMS error for wind direction of nudged WVs.

However, from informational point of view, the nudged WV field obtained after the application of the ARP based on using the FG field is a combination of information from two different sources (1) the satellite information about the WV field from QuikSCAT, which is stored in the maximum likelihood solutions, and (2) the information about the same WV field, which was produced by the data assimilation system and atmospheric numerical forecast model and stored in the FG WV field. The ARP actually performs a smooth fusion or integration of these two types of information: the satellite derived information and the FG information.

The contribution of satellite information in the nudged solution varies from area to area; some parts of the WV field may contain very little independent satellite information. To illustrate such a possibility and to show that regular statistics cannot serve as reliable indicators of the situation in these cases, we consider here an extreme case when there is no satellite information about wind direction in the maximum likelihood solutions, which are employed by the ARP to select the nudged solution using the FG WV field.

Let us assume that, for each QuikSCAT WV cell, we have on average N ambiguities ($1 \leq N \leq 4$), and that we have one ambiguity vector per angle equal to $\beta = 360°/N$ degrees. Let us also assume that all satellite derived wind directions for all these ambiguities are changed to random numbers (no satellite information about wind direction!) uniformly distributed in the interval $[0, \beta]$. In this case, the probability distribution function, $P(x) = 1./\beta$, and, after the application of the ARP, the $RMSE_N$ (zero skill or zero satellite information RMSE in the case of N ambiguities) of nudged solution directions vs. the FG WV directions (these directions we also consider as uniformly distributed random numbers) can be calculated as

$$RMSE_N = \sqrt{\int_0^\beta \int_0^\beta (x_1 - x_2)^2 \cdot P(x_1, x_2) \cdot dx_1 \cdot dx_2} = \frac{\beta}{\sqrt{6}} = \frac{360°}{\sqrt{6} \cdot N} \tag{1}$$

Table 1. *Zero skill RMSE for different number of ambiguities N > 1*

N	2	3	4	6
$RMSE_N$	73°	49°	37°	25°

Table 1 summarizes the particular values of $RMSE_N$ for different number of ambiguities, N. These values correspond approximately to zero retrieval skill indicators. For example, if, in the case of four ambiguities (N=4), comparison of the nudged solution WV field area with the analysis gives $RMSE \geq RMSE_N = 37°$, then it indicates that, in this area, the nudged WV field is dominated by the FG and contains very little independent information derived from the QuikSCAT sensor. Table 1 also shows that, in a hypothetical case where the retrieval algorithm produced six ambiguities, the ARP could produce the nudged field with an acceptable *RMSE* about 25°; however, this field would contain no independent satellite information about the wind direction. The entire information about the wind direction would be from the FG field in this case.

Taking into account the above considerations, it make sense to introduce a complimentary characteristic for the QuikSCAT nudged solution – an amount (percentage) of independent satellite information, α, which estimates the contribution of the QuikSCAT information to the nudged WV solution. This parameter will vary spatially; it will be different for different locations, and, from the information theory point of view, the best way to calculate parameter α is to use a Bayesian approach [3]; however, here we introduce a very simplified linear approximation for parameter α,

$$\alpha = (1 - \frac{RMSE}{RMSE_N}) \cdot 100\% \tag{2}$$

2. Using the nudged solution in data assimilation systems

When the QuikSACT nudged WV field is assimilated into a data assimilation system (DAS), the fact that this field contains (100 - α)% of FG information becomes essential because, in the DAS, the QuikSCAT field is mixed with the FG WV field *again*. This is why, for data assimilation applications, the retrievals should be used with caution because, in many cases and in many areas where α is small, assimilating this product may lead to a double count of the FG in the DAS.

The above considerations show that, for data assimilation applications, parameter α may be as important as the error statistics (bias, RMSE, etc.). Data with small α should be suppressed in the DAS or completely excluded from the data stream because (1) they carry very little independent satellite information different from the FG information, and their assimilation is equivalent to assimilating the FG second time, and (2) in variational DAS these data, while introducing a very little new information, increase the dimension of optimization space and reduce the accuracy of assimilating other important data.

In this study, we empirically examine the informational content of QuikSCAT WV fields, and the value of α for these fields using collocations of QuikSCAT WV fields with WV fields from the NCEP global analysis (GDAS) and from NCEP global atmospheric model (AVN) FG (6 hour forecast). Our goal is to identify areas in the nudged QuikSCAT WV field with lower content of independent satellite information. Empirical verification and validation of QuikSCAT WV fields faces significant problems when we try to validate not single vectors, but patterns. For validation of single WVs buoy winds serve as a satisfactory ground truth (of course, buoy data are not a perfect source of ground truth even in this case; they are sparse, not uniformly distributed, etc.); however, for validation patterns (i.e., circulations and fronts) continuous and dense WV fields are required which are not available from ground based observation systems. This is why in this study and elsewhere the analysis and FG WV fields are used as "ground truth". For most of WVs considered in this study, the actual ground truth is unknown. Creation of QuikSCAT and buoy collocations is under way; however, the amount of collected data is still to small to be included in this study.

3. Data sample description.

The data sample collected for this study covers two periods of time: from 3/10/2001 to 3/14/2001 and from 4/01/2001 to 4/06/2001. The data include collocations of QuikSCAT WV fields, including the nudged solution and all ambiguities, with analysis and FG WV fields. Several filters have been applied to the data; only data where:

1. All four σ_0 measurements are available (sweet spot)
2. Wind Speed W > 3 m/s
3. Rain Probability < 0.1
4. Number of ambiguities (ML solutions) > 1

where selected. Originally, the data set contained more then 3 millions collocations.

After applying these filters, the total amount of matchups for calculating statistics was about 1,200,000. Table 2 shows some characteristics of the data sample. The second column shows the zero skill RMSE determined by eq. (1). The last four columns show the percentage of cases when the ARP selects *i*-th (*i*=1 to 4) ambiguity. It is important to point out that the current ARP selects the first ambiguity or satellite solution (i.e., agrees with the retrieval algorithm) in 81% of cases!

Table 2. *Some characteristics of the data sample used in this study*

Initial Sample Size	Missed Data	Filtered Out Data	Final Sample Size	$RMSE_N$	Ambiguity selected for nudged solution (% of cases)			
					ML1	ML2	ML3	ML4
3,077,784	1,489,974 (48%)	412,679 (14%)	1,175,131 (38%)	52°	81%	15%	3%	1%

Table 3 shows some wind speed and direction statistics (biases and RMSEs) for the nudged solution (index *N*) and for the first ambiguity (index *ML*).

Table 3. *Some wind speed and direction statistics for the selected sample.*

	Bias	RMSE	VRMSE	α
W_N	-0.5 m/s	1.6 m/s	2.7 m/s	----
θ_N	2°	18°	----	65%
W_{ML}	-0.5 m/s	1.7 m/s	7.9 m/s	----
θ_{ML}	2°	59°	----	100%

The VRMSE presented in the fourth column of the table 3 is the vector RMSE, which integrates the wind speed and wind direction errors into one parameter and can be defined as,

$$VRMSE = \sqrt{\frac{\sum_{i=1}^{n} \left|\vec{W}_1 - \vec{W}_2\right|^2}{n}} \qquad (3)$$

where the absolute value of the difference between two vectors W_1 and W_2 is defined in a standard way,

$$\left|\vec{W}_1 - \vec{W}_2\right| = \sqrt{W_1^2 + W_2^2 - 2 \cdot W_1 \cdot W_2 \cdot \cos(\vec{W}_1 \wedge \vec{W}_2)}$$

The informational content of the nudged WV field is presented by parameter α in the last column of the table. It shows that, on average, about 35% of the information in this field is derived from the FG, not from the QuikSCAT.

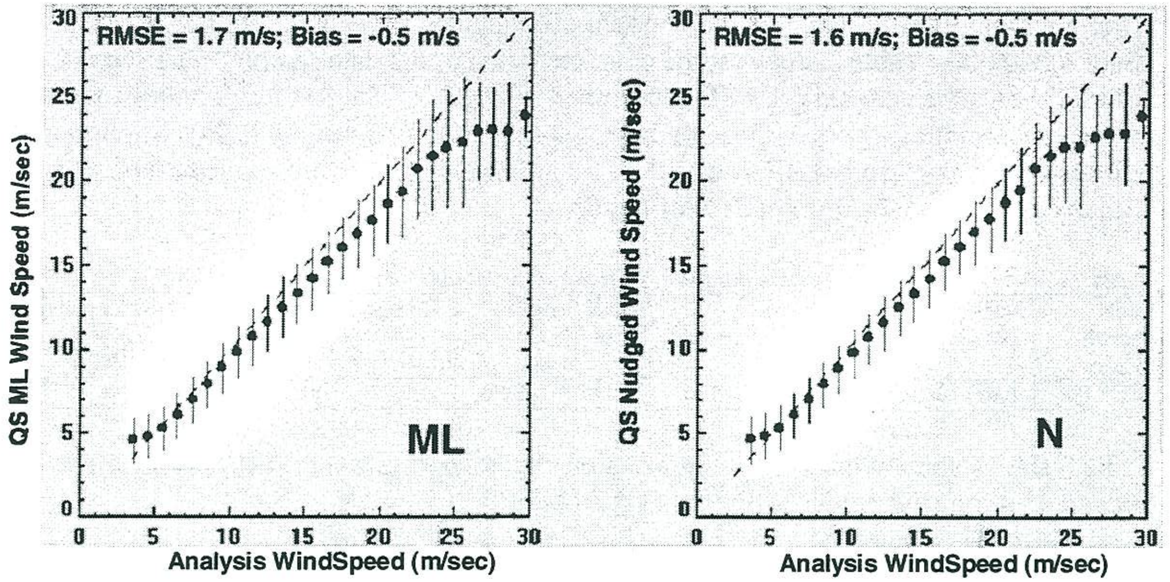

Fig. 2 Satellite solution (ML) – left panel and nudged solution (N) – right panel for wind speed vs. NCEP analysis wind speed.

As can be immediately seen from the Table 3, the ARP does not practically affect the wind speed. Wind speed statistics for first ambiguity (ML) are very close to those for nudged solution (N). Fig 2 shows the scatter plots for the first ambiguity (left panel) and the nudged solution (right panel) and demonstrates the same result. On the other hand, for wind direction statistics, the difference between the first ambiguity (satellite solution) and the nudged solution is very significant. The scatter plots presented on Fig. 3 illustrate this situation.

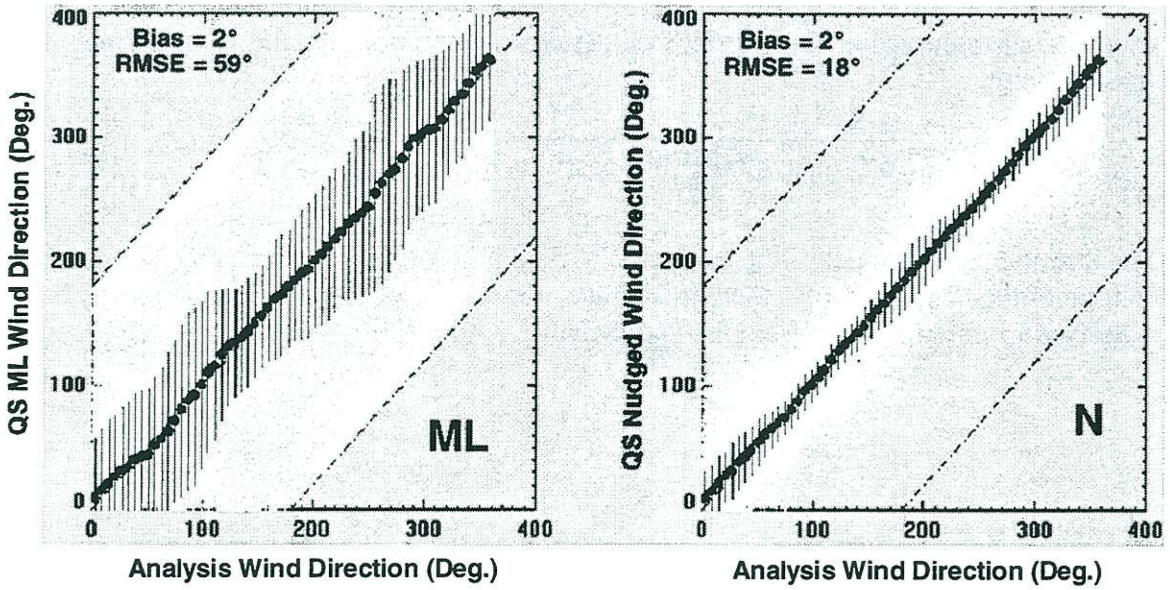

Fig. 3 Satellite solution (ML) – left panel and nudged solution (N) – right panel for wind direction vs. NCEP analysis wind direction.

4. Empirical study of the informational content of the nudged solution

As we mentioned above, for the data sample studied here, on average, two-thirds of the informational content of the nudged WV field constitutes information from QuikSCAT measurements ($\alpha = 65\%$) and one-third – information from the FG WV field. Locally, parameter α may vary significantly from area to area. The purpose of this study is to identify locations and conditions where the FG information dominates the nudged solution and where, correspondingly, the contribution of satellite (QuikSCAT) information is minimal.

It is clear, a priori, that the contribution of satellite information is diminished in the areas where the sensor accuracy and the signal to noise ratio is lower. These areas may be related to situations where the sensor has a lower sensitivity by design, or to situations where the level of noise from the ocean surface or from the atmosphere is significantly higher. In our study we investigated several such situations:

- WV is orthogonal to one of the radar look directions. In this case, the signal shows reduced sensitivity to wind direction.
- WVC is located in nadir area or close to the edge of "sweet spot". Here the sensor is less sensitive to the wind direction signal by design.
- Higher wind speed situations, where the ocean surface noise increases significantly, reducing the signal to noise ratio for both wind speed and wind direction signals; however, it is reasonable to expect a smaller ratio for the wind direction because the signal is weaker than that for the wind speed.

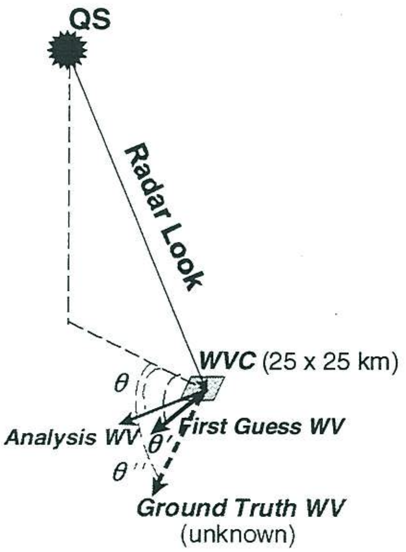

Fig. 4. System of coordinates used in this study. All wind directions are calculated with respect to the horizontal projection of the radar look direction. First guess or analysis wind directions are used as "ground truth", the actual ground truth is unknown.

In all these cases, the accuracy of QuikSCAT measurements is reduced, and, therefore, the accuracy of retrieved wind vectors (especially wind directions) have to be lower if our retrievals are based on satellite measurements only. The satellite solution (first ambiguity) clearly demonstrates this tendency (see below). However, if we examine the nudged solution in these areas, we usually do not find any decline of accuracy, on the contrary, in some cases, accuracy is higher. If we remember now that, in the case of QuikSCAT, we determine the accuracy by using the FG or analysis WV fields as "ground truth", the explanation of the described phenomenon becomes obvious: in these problematic areas where the accuracy of the satellite measurements and satellite solutions decline, the nudged solution is dominated by the FG, that is, the parameter α drops off significantly. In the data assimilation application, these are the areas where we can expect significant effects related to the double count of the FG. In the sections below these general statements are illustrated by data statistics. In these sections, we use for the wind direction satellite coordinates. All wind directions are calculated with respect to the radar look direction as shown in Fig. 4. To distinguish them from the wind direction in geophysical and meteorological coordinates, we will call them "relative wind directions" This system of coordinates is selected simply because some of the effects mentioned above are easier to observe and identify in this system of coordinates.

4.1 WVs orthogonal to radar look directions.

Fig. 5 shows wind direction RMSEs for the first ambiguity solution (left panel) and the nudged solution (right panel) as functions of the relative (vs. FG) wind directions. First forward look is shown; however, similar situations take place for the three other looks. As shown in Fig. 5 (left panel), wind direction errors for the first ambiguity solution are significantly higher when the WV is orthogonal to the radar look direction (relative wind direction is about ±90°). Errors for the second ambiguity (not shown) also demonstrate well-pronounced maximums at relative wind directions of about ±90°.

On the other hand, the nudged solution (right panel), which is 96% composed of the first and second ambiguity (see Table 2), demonstrates an opposite trend. In these areas it shows the best accuracy with respect to the FG "ground truth". The only plausible explanation for this effect is to assume that the FG dominates the nudged solution in these areas. Since all ambiguities have poor wind direction accuracies in these areas, the ARP selects, in these cases, one of several available ambiguities, which, more or less randomly, happened to be closest to the FG WV. This is why situations, where higher ranked ambiguities are selected, have significantly higher percent of cases with the relative wind direction close to ±90° (see Section 5).

It is clear that, in these areas, parameter α has lower values; the contribution of the FG information is significantly higher here. In data assimilation applications, these cases should be excluded from the data stream, or weighted with lower weights (subscribed higher errors), despite the fact that, formally speaking, these data have high accuracy if compared with the analysis or the FG.

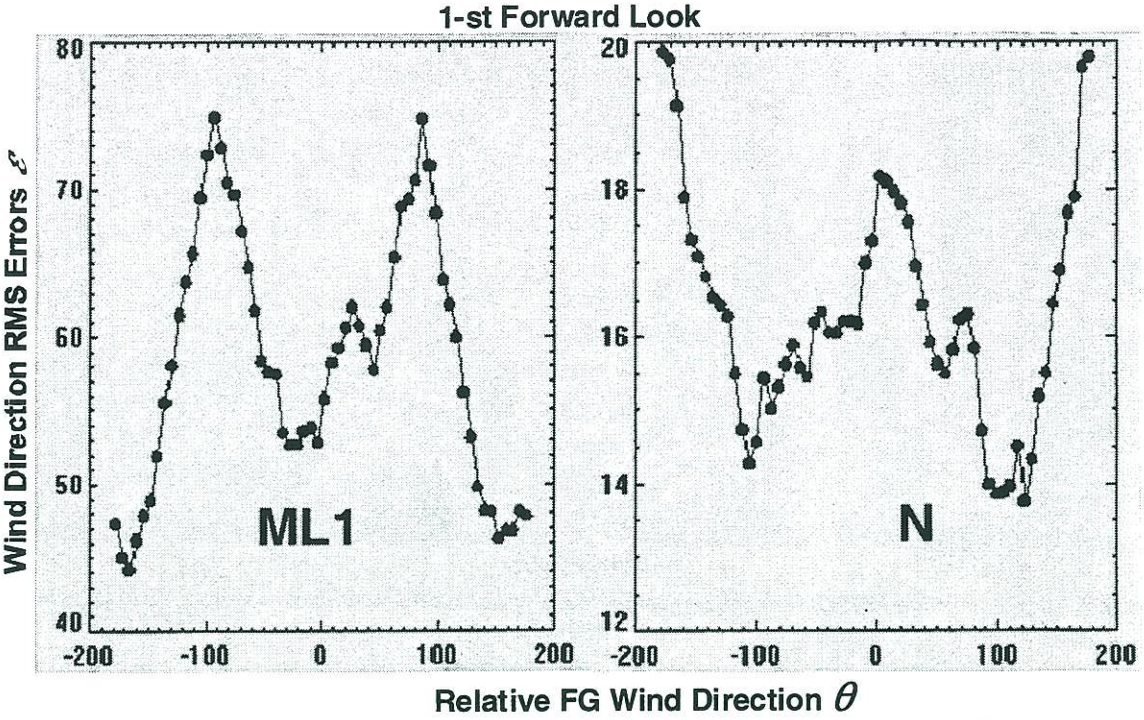

Fig. 5 Wind direction RMSEs (in degrees) as functions of relative FG wind directions. The left panel shows errors for the first ambiguity solution (ML1) and the right one for the nudged (N) solution.

4.2 WV close to nadir or edges of "sweet spot".

Fig. 6 shows wind direction RMSEs for the first ambiguity solution (left panel) and the nudged solution (right panel) as functions of the across the swath cell number. The fist ambiguity shows a significant increase of errors in the nadir area and in the areas close to the edge of the "sweet spot". For the nudged solution (right panel), a very different situation can be observed; the accuracy varies insignificantly across the swath. The amplitude of these variations does not exceed of about ±2° around an average value.

The situation here is similar to the previous case: the nudged solution, when compared to the FG, demonstrates a very good accuracy in the areas where satellite solution (first ambiguity) demonstrates poor accuracy because of the well understood sensor problems. This effect also can be explained assuming that the FG dominates the nudged solution in these areas. Since all ambiguities have poor wind direction accuracies in these areas, the ARP selects, in these cases, one of several available ambiguities, which, more or less randomly, happened to be closest to the FG WV. As we will show in Section 5, situations, where higher ambiguities are selected, have a significantly higher percent of cases, which belong to nadir and close to the edges areas.

The parameter α has lower values in these areas; the contribution of the FG information is significantly higher here. These cases should be treated specially in data assimilation applications.

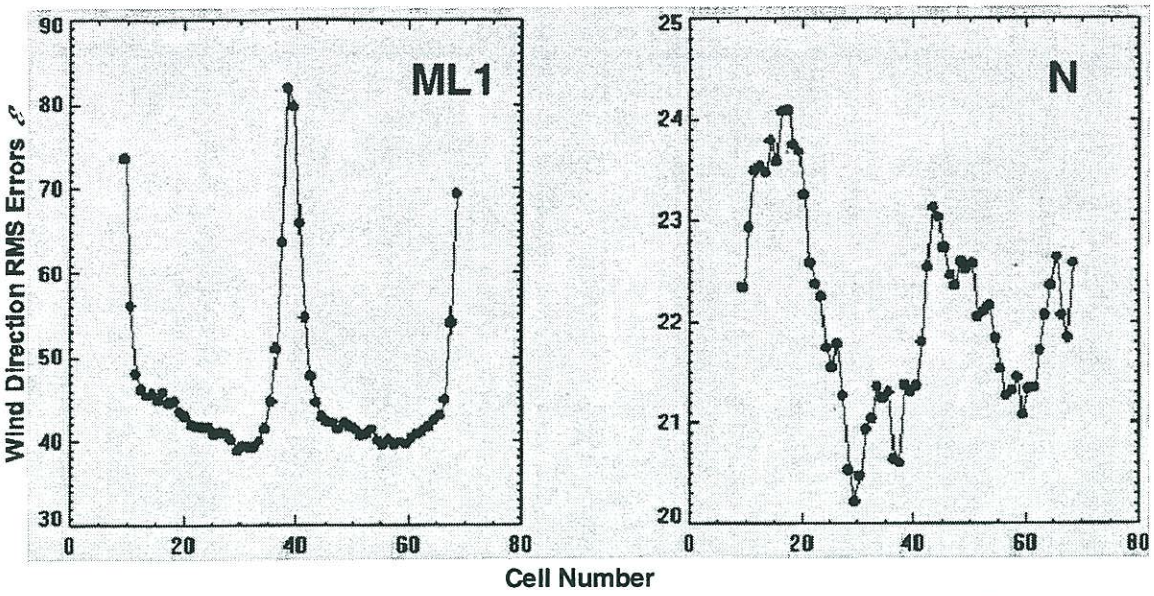

Fig. 6 Wind direction RMSEs (in degrees) as functions of across the swath cell number. The left panel shows errors for the first ambiguity solution (ML1) and the right one for the nudged (N) solution.

4.3 WVs associated with higher wind speed situations.

Fig. 7 shows wind direction RMSEs for the first ambiguity solution (left panel) and the nudged solution (right panel) as functions of the wind speed. As Fig. 7 shows, wind direction errors for the satellite (first ambiguity) solution (left panel) are significantly higher when wind speeds are low or high. In both cases the decreasing of the signal to noise ratio causes this effect. At low wind speeds, the signal to noise ratio declines because of decreasing the signal level. The situation is different at high wind speeds, the reason for dropping the signal to noise ratio in this case is the change in the surface physics (white capping, wave breaking, foam, bulbs), which causes the increase of the noise level.

The nudged solution (right panel) shows no significant increase in errors at high wind speeds. In these areas it shows the best accuracy with respect to the FG "ground truth". This effect also can be explained assuming that the FG dominates the nudged solution in these areas. Since all ambiguities have poor wind direction accuracies in these areas, the ARP selects in these cases one of several available ambiguities, which, more or less randomly, happened to be closest to the FG WV. For events when the ARP selects higher ambiguities, a significantly higher percent of cases belongs to higher wind speeds (see Section 5).

In these areas parameter α has lower values, the contribution of the FG information is significantly higher here. In data assimilation applications, these cases should be excluded from the data stream, or weighted with lower weight (subscribed higher errors), despite the fact that, formally speaking, these data have high accuracy if compared with the analysis or the FG.

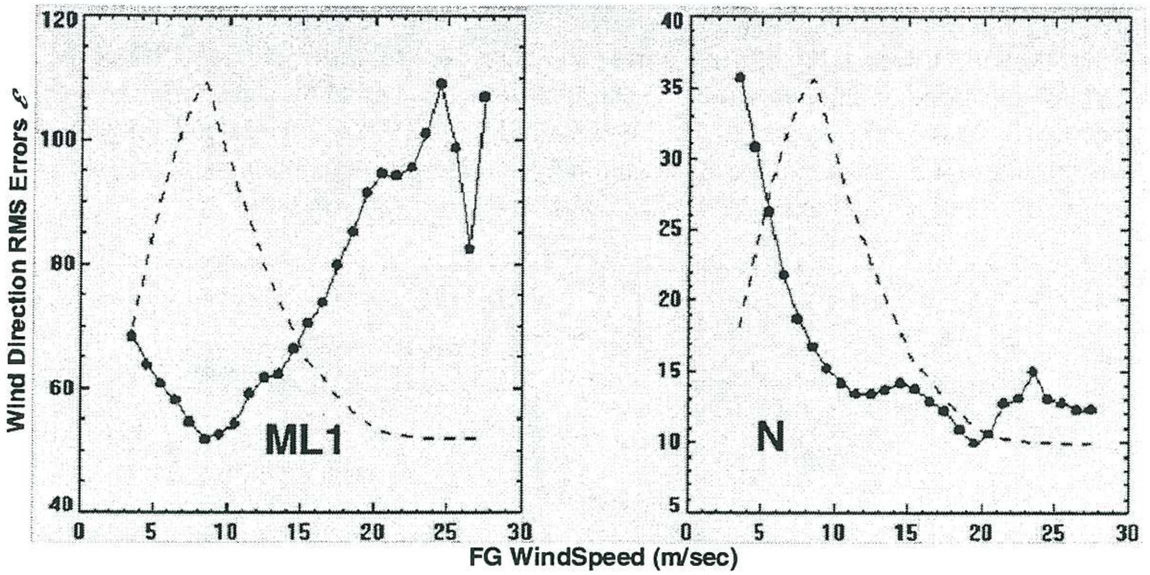

Fig. 7 Wind direction RMSEs (in degrees) as functions of wind speed (FG wind speed). The left panel shows errors for the first ambiguity solution (ML1) and the right one for the nudged (N) solution.

5. Using existing APR as a flag

As was shown in Section 3, 81% of the cases presented in the selected data sample, correspond to the situation where the ARP, based on the use of the FG WV field, supports the satellite solution that is the first ambiguity is selected. This result suggests that we can use the ARP as a flag; this means that we use data only if the ARP selects the first ambiguity (i.e., we always use the satellite solution, but only where it is supported by the ARP). In this case we loose 19% of data; however, retrieved WVs demonstrate very good statistical characteristics shown in the table 4.

Table 4.

	N(81%) =ML1(81%)	N(19%)	ML1(19%)
Bias	1°	2°	1°
RMSE	18°	25°	132°
VRMSE	3.1 m/s	3.8 m/s	17.5 m/s
α	67%	47%	100%

In the second column, table 4 shows statistics for those 81% of the nudged solution where it consists of the first ambiguity (first ambiguity is selected by the ARP). At the same time, these are statistics for the 81% of the satellite solution, which is included in the nudged solution. The percent of independent satellite information ($\alpha = 67\%$) for this part of the data is slightly higher than average (see Table 3). The third and fourth columns of the table show statistics for the residual 19% of the data. For the nudged solution (the third column) this residual part is composed of second, third and fourth ambiguities. The fourth column shows statistics for the residual 19% of the first ambiguity. Comparison of these last two columns shows that both the RMSE and the parameter α should be taken into account when the data are used in a DAS. In the third column for the nudged solution, the RMSE is satisfactory; however, the percentage of independent satellite information is significantly below the average value. On the other hand, the first ambiguity solution demonstrates an unacceptably high RMSE here. Taking into account the significantly lower value of the parameter α here, we recommend these 19% of the data to be excluded or flagged when the satellite data are used in data assimilation applications. In this section we further investigated these 19% of the nudged solution to show that there is a very significant overlap between the problematic areas discussed in the previous sections and these 19% of the data in the nudged solution.

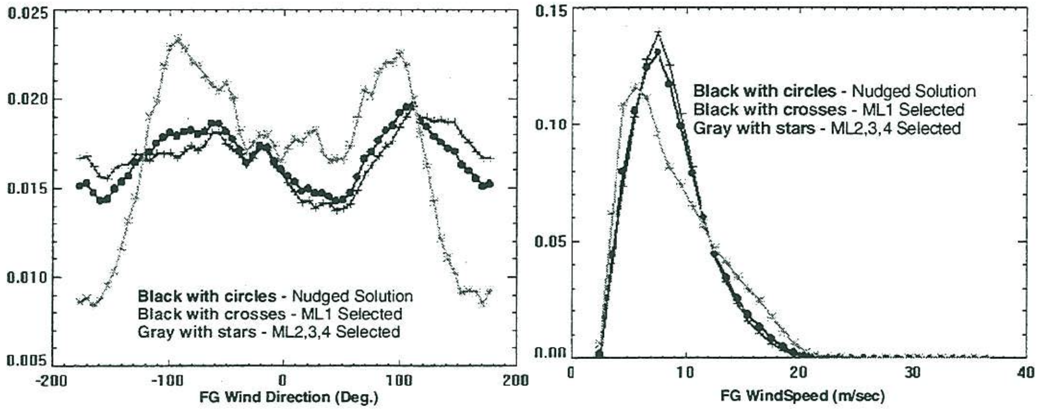

Fig.8 Probability distribution of different wind directions (left panel) and wind speeds (right panel). The black curve with circles shows the distribution for the entire nudged solution, the black curve with crosses - for 81% of the nudged solution where the first ambiguity is selected, and the gray curve with stars – for the residual 19% of the nudged solution.

Fig. 8 clearly demonstrates that the residual 19% of the nudged solution have significantly higher concentration of ±90° wind directions (left panel) and high wind speed events than first 81% of data. Fig. 9 demonstrates a similar tendency with respect

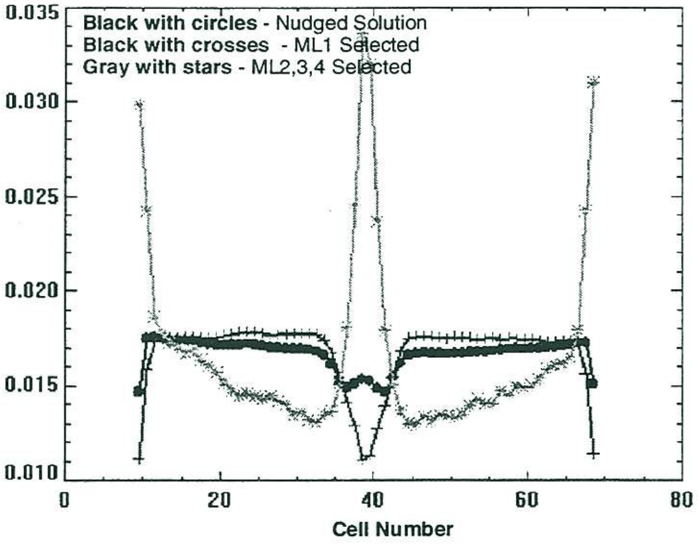

Fig.9 Probability distribution of different across the swath positions. The black curve with circles shows the distribution for the entire nudged solution, the black curve with crosses - for 81% of the nudged solution where the first ambiguity is selected, and the gray curve with stars – for the residual 19% of the nudged solution.

to the nadir and close to the edge of the sweet spot areas. The residual 19% of the nudged solution contain a significantly higher amount of WCs in nadir areas and areas close to the edge of the sweet spot where the sensor retrieval accuracy is lower.

The results presented in this section clearly show that most of problematic data discussed in the previous sections populate the residual 19% of the nudged solution. Here the ARP does not support the satellite solution (first ambiguity) and selects one of higher ambiguities. This part of the data has a lower content of satellite information, and therefore, a higher contribution of FG information, which can lead to a double count of the FG in the DAS.

6. Conclusions

In this study we discussed WV fields retrieved from QuikSCAT measurements from the point of view of data assimilation applications. The current retrieval procedure successfully integrates or fuses the FG and satellite data. The QuikSCAT wind field is a blend of satellite information and information from the FG. This is a very good product for many applications (marine forecasters, climate studies, etc.). However, for data assimilation, the amount of independent satellite information in the data, α, may be at least as important as error statistics (bias and RMSE). Parameter α may strongly influence the impact of satellite data on NWP models. The amount of independent satellite information, α, should be taken into account in the DAS. For different parts of the wind field α will be different. Areas with lower values of α should be assimilated with lower weights (higher errors).

It is shown that values of α are lower in areas where the scatterometer has lower accuracy, such as areas where the wind direction is orthogonal to one of the radar look directions, wind speeds are higher, and edges of the swath or nadir are close. It is also shown that these areas fall mainly in the part of the data where the ARP selects one of the higher (not the first) ambiguities. This fact suggests a simple procedure for data assimilation applications: use the ARP as a flag, assimilating only that part of the nudged solution where the first ambiguity is selected.

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List of Abstracts, Reports, Articles, etc. by members of the Branch. The numbers are referred to as OPC Contribution Numbers from Number 1 to 110 and as OMB Contribution Numbers from Number 111 and greater.

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