TOWARDS THE ASSIMILATION OF QUIKSCAT WINDS

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ABSTRACT

At the fourth winds workshop a paper was presented on the importance of ERS scatterometer observations for the forecasting of tropical cyclones with the ECMWF model. Recently, SeaWinds scatterometer measurements from QuikScat have become. SeaWinds on QuikSCAT provides great coverage over the oceans. However, rain contamination, wind direction noise characteristics, and wind direction ambiguity patterns need further study. We describe our work on QuikScat product validation and inversion of the backscatter data to winds. A new procedure to quality control (QC) SeaWinds scatterometer observations, in particular to screen out rain-contaminated points, and a new procedure to assimilate QuikScat observations are presented. Our QC method is based on a methodology that was used to screen anomalous ERS and NSCAT backscatter triplets or quadruplets respectively. The methodology checks whether the consistency of the backscatter measurements at a particular Wind Vector Cell (WVC) is compatible with the consistency as predicted by the Geophysical Model Function (GMF). Rain contaminated points are screened out effectively thus opening the way to effective wind information assimilation. The ERS scatterometer data assimilation procedure is generalised to deal with ambiguous solution sets with more than two solutions of varying probability and quality. ERS provides two ambiguities with about the same quality and probability. Extension of the assimilation procedure is essential to deal with the average 80% probability of the first rank SeaWinds solution and the occurrence of high-probability third and fourth rank solutions.

1. Introduction

ERS scatterometer winds have proven to be very useful for the forecasting of dynamic weather (Isaksen and Stoffelen, 2000; Atlas and Hoffman, 2000). Increased coverage, such as from tandem ERS-1 and ERS-2 measurements, clearly improve the situation (e.g., Stoffelen and Beukering, 1998; Le Meur et al, 1997). Improved coverage from the Ku-band scatterometers NSCAT and SeaWinds have thus great potential. Preliminary attempts to assimilate SeaWinds data have been carried out with mixed success, and improved data characterisation is needed.

The SeaWinds on QuikSCAT mission from NASA is a “quick recovery” mission to fill the gap created by the loss of data from the NASA Scatterometer (NSCAT) after the ADEOS-1 satellite lost power in June 1997. QuikSCAT was launched from Vandenberg Air Force Base (USA) in June 19, 1999. A similar version of the SeaWinds instrument will fly on the Japanese ADEOS-II satellite currently scheduled for launch in late 2001.

The SeaWinds instrument is an active microwave radar designed to measure the electromagnetic backscatter from the wind roughened ocean surface. The instrument is a conically scanning pencil-beam scatterometer, which in comparison with the NSCAT fan-beam scatterometer has the following advantages: higher signal-to-noise ratio, smaller in size, and superior coverage. On the other hand, QuikSCAT has an antenna geometry that is dependent on node number or cross-track location, due to its circular scans on the ocean. The skill of the wind retrieval algorithm depends very much on the number of measurements and their polarization (horizontal HH or vertical VV) and azimuth diversity, where "azimuth diversity" is defined as the spread of the azimuth looks among the measurements in the WVC. The nadir region has fore and aft looks of both beams (HH and VV) nearly 180º apart. At the edges of the swath the outer VV beam fore and aft looks are nearly in the same direction and no inner HH beam information is available. In both areas, the skill of the wind retrieval algorithm is decreased with respect to the rest of the swath (called the sweet zone) where there are four measurements (fore-HH, fore-VV, aft-HH and aft-VV) with enough azimuth diversity.

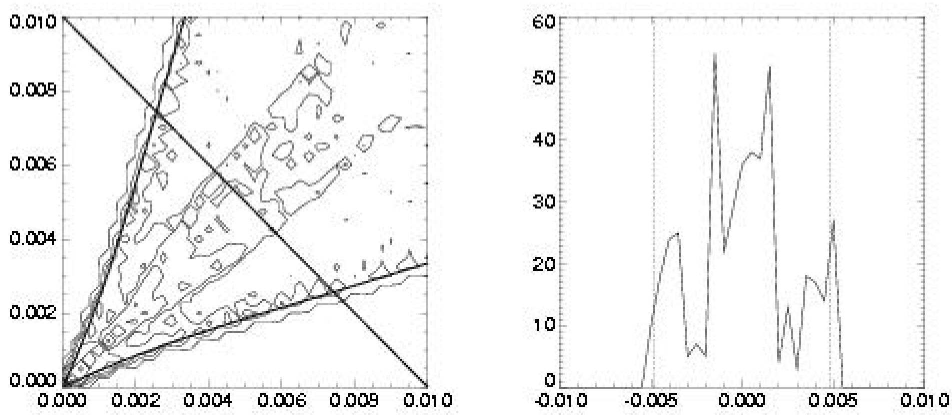

Figure 1. Left: Density-contoured scatter plot of backscatter values for the outer beam for simulated SeaWinds data at WVC 50 with nominally 142 degrees separation between fore and aft look. The scatter plot is build up from Lissajous-type curves that follow an inner revolution and an outer revolution as wind direction changes. The boundary of the outer revolution is shown by the thick lines from the origin outward produced using the NSCAT-2 GMF. Right: Number density along the cross-diagonal thick line of the left plot. The boundaries of the outer and inner Lissajous revolutions are now clearly discernible (Voorrips, 1999). Cross sections of this type are being used to validate aspects of the GMF definition.

The inversion software based on the ERS scatterometer processing (Stoffelen, 1998) modified by Julia Figa (2000) for NSCAT has been adapted for QuikSCAT. In was verified to closely mimic JPL's inversion (Portabella and Stoffelen, 2000). SeaWinds simulations confirm a higher standard deviation of speeds and directions in the outer and nadir parts compared to the sweet zone of the swath. No significant bias is seen in any part of the swath.

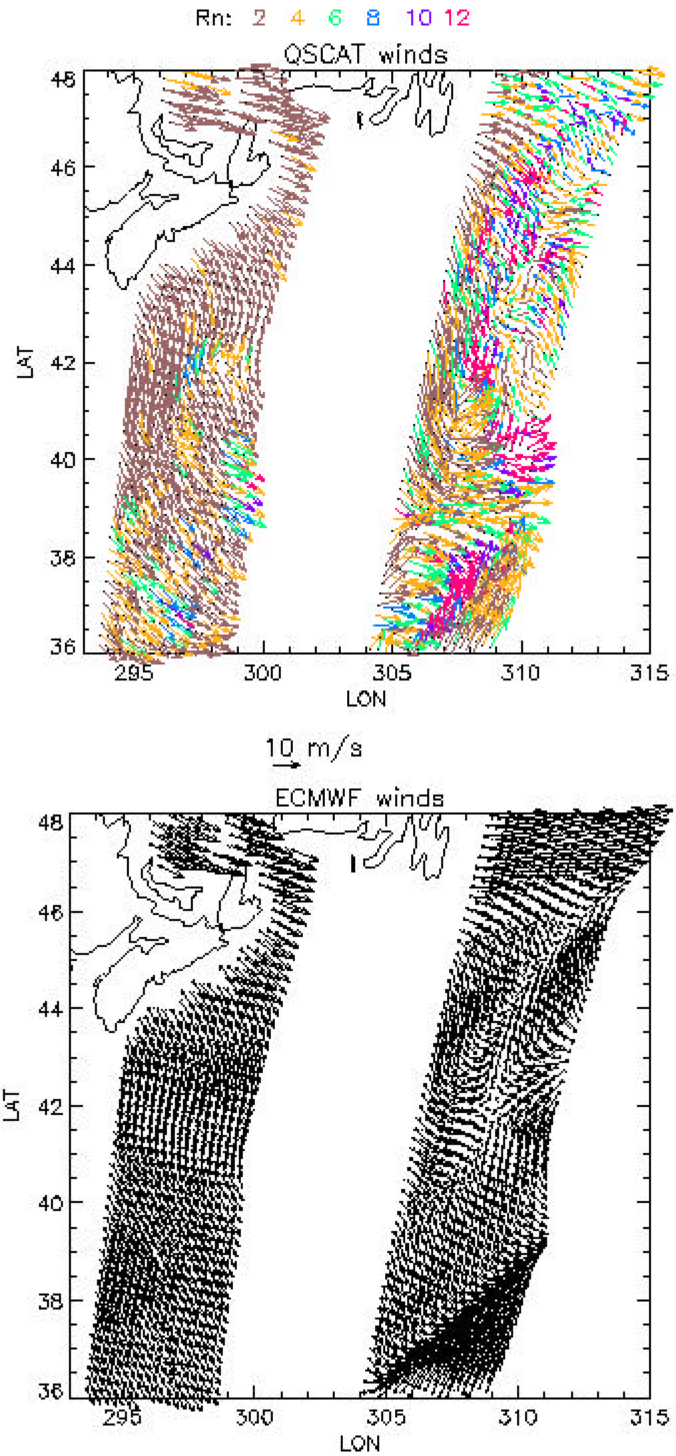

Figure 2. a) Top panel: QuikScat winds in the Atlantic in the development zone of the devastating storms that hit Western Europe during Christmas 1999. Date and time of observation are December 24 22 GMT. The inversion residual is normalised as a function of speed and WVC, such that a number Rn results with an expectation value of one. Rn values for good quality winds between 2 and 4 are thus unlikely, and winds at values above 4 are verified to be generally of bad quality (Portabella and Stoffelen, 2000). The colour code for the Rn values is shown above the plot. Anomalous winds have generally Rn > 4. For Rn < 4 large areas remain that depict relevant and important mesoscale features of the wind field.b) Bottom panel: As for top panel, but ECMWF winds. Dynamical features particularly appearing in the right SeaWinds swath are not well represented in the ECMWF first guess, for example the through orientation and position, and the low at 308E and 41N.

2. Quality control and rain elimination

In contrast with C-band scatterometers such as on ERS and ASCAT, Ku-band scatterometers are sensitive to rain and procedures need to be developed to screen out rain-contaminated measurements.
A quality control procedure is being developed for SeaWinds based on the QC methodology for the ERS scatterometer (Stoffelen and Anderson, 1997; Stoffelen, 1998). In addition to a screening similar to ERS, the procedure acts to remove rain contaminated points (Figa and Stoffelen, 2000). The methodology checks whether the consistency of the backscatter measurements at a particular Wind Vector Cell (WVC) is compatible with the consistency as predicted by the Geophysical Model Function (GMF). A measure of this consistency is provided by the inversion residual. A limitation of this approach is obviously that anomalous geophysical conditions that are still compatible with the GMF are not screened out, such as a few rain points that appear as 15 m/s winds. Such points should ideally be rejected by the QC procedures of NWP data assimilation systems

Alternatively, one could- use the backscatter polarisation ratio, but this has the same limitation and is more restricted (Wentz, 1999); or use the SeaWinds passive noise measurement to detect rain, though this has low accuracy (of 13 K) and a relatively large footprint (> 75 km; Jones, 1999) Particularly in those parts of the SeaWinds swath where azimuth view diversity or polarisation coverage is lacking, notably around nadir and in the far swath, the wind vector may be underdetermined and QC by a consistency check, such as in the above-described methodology, impossible. The part of the swath where this occurs is limited fortunately. SeaWinds on ADEOS may profit from AMSR for rain screening, when all parts of the swath may be controlled.

3. Observation smoothing

SeaWinds data are nominally provided with a sampling of 25 km, whereas most NWP models use scatterometer data at a 100-km density. To reduce wind retrieval noise it is better to average backscatter measurements, ?^{0}, to lower resolution before wind retrieval. For ERS and ASCAT observations the same applies, where it has been shown that averaged winds compare better to the HIRLAM (2000) first guess than thinned data (Stoffelen and Beukering, 1998). A procedure is being tested and incorporated in the inversion module to average backscatter measurements in a resolution cell of varying size.

4. SeaWinds assimilation

Stoffelen (1998; chapter VI) describes the problem of the assimilation of variables that are related in a non-linear way to the NWP model variables, such as scatterometer backscatter measurements. As a practical solution, he suggests to assimilate retrieved scatterometer winds. This approach is further pursued here for SeaWinds scatterometer observations. Scatterometer winds can be retrieved accurately, since backscatter noise is generally small for all scatterometer systems. Backscatter-only noise results in a wind vector uncertainty of only about 0.5 m/s. However, the interpretation of a radar backscatter measurement, that is more directly related to the anisotropic roughness of the ocean topography, as a wind at 10m height introduces a much larger uncertainty, that can be well modelled as a normal wind component error distribution. Wind vector measurements from a scatterometer have an estimated accuracy of about 2 m/s. The larger uncertainty in the wind domain makes the assimilation of retrieved winds more attractive than the direct assimilation of backscatter measurements. In the direct assimilation of backscatter observations, one transforms the first guess errors and the uncertainty in the Geophysical Model Function (GMF) in a non-linear way to the backscatter space, resulting in a usually skew error distribution in this space. The precise form of the error distribution would depend on wind speed, wind direction, and view configuration. The maximum probability in a skew distribution does generally not overlap with the mean of the distribution, nor has the maximum symmetric properties. The optimal observation cost function is not a priori clear in such a case and requires considerable thought (Stoffelen, 1998). By the assimilation of retrieved winds this problem disappears.

5. Ambiguity removal

NSCAT and SeaWinds use horizontal and vertical polarisation measurements, whereas ERS or ASCAT are solely based on vertical polarisation. This in combination with a varying measurement geometry results in a different wind direction ambiguity structure than for ERS or ASCAT. The near-nadir and far swath areas of SeaWinds are particularly difficult to QC and invert, due to poor sampling in azimuth.

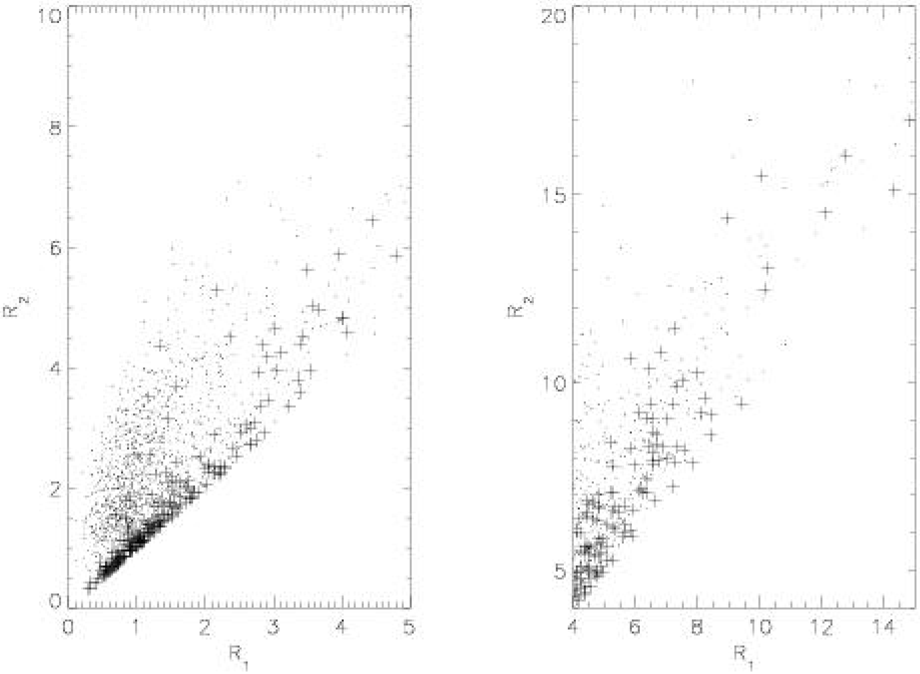

Figure 3. Scatter plot of first rank normalised inversion residual R_1 against second rank solution residual R_2 only for cases with two solutions. Dots indicate pairs where the first rank is the one closest to the NWP wind velocity; plusses are pairs where the second rank is selected. The left panel highlights the lower range residuals of 1,500 pairs, whereas the right panel only shows higher range pairs of a total of 15,000 pairs. For Rn values smaller than three the first rank is almost always selected, unless $R_1 \approx R_2$. For higher Rn either rank may be selected, indicating less predictive value in Rn. Note however that many of these are screened by our QC. As such, SeaWinds ranking information in Rn appears to be an excellent predictor.

The ERS scatterometer cost function may be generalised to be able to cope with all scatterometer data. All scatterometer data can be characterised by multiple wind vector ambiguities that each have different probability and accuracy. A procedure is being developed that estimates this probability and accuracy and as such provides the input for a general scatterometer cost function. The working of the cost function for ambiguity removal is being tested and documented (Voorrips, Stoffelen, and Portabella, 2000).

Generally data assimilation systems constrain to a background or first guess field and to observations (e.g., Courtier, 1998 and 1999). The observation term consists of a contribution from each observation and is related to the probability of a meteorological state, given the measurements. For scatterometer data we may write

$$p(\mathbf{s}^{0} \mid \mathbf{v}) = \sum_{i=1}^{M} p_i^p \, p_i(Rn_i) N(\mathbf{v}_i, \mathbf{e}_i) \qquad (1)$$

where p_i^p is the prior probability of a solution i, $i \in [1, M]$, i.e., without knowledge of Rn. It is solely dependent on the wind direction sector that a solution represents and only relevant in case of more than two solutions ($M > 2$). $p_i(Rn_i)$ is the probability of a solution based on the normalised residual of the solution i. It is assumed to be independent of p_i^p. $N(\mathrm{v}_i, \varepsilon_i)$ is a normal distribution with maximum at the wind solution v_i and error width ε_i. For ERS scatterometer data (Stoffelen, 1998) the values $M = 2$, $p_i^p = 0.5$, $p_i(Rn_i) = 1$, and $\varepsilon_i = 1.5$ m/s are used. For NSCAT or SeaWinds, the prior probability p_i^p just depends on the azimuths of the solutions (Figa and Stoffelen, 2000). Since the wind error in the sweet zone is mainly dependent on the geophysical interpretation and less on the retrieval process, ε_i does not vary much from one solution to the next, As such, the main modelling effort is in $p_i(Rn_i)$. Figures 4 and 5 illustrate this. Figure 5 shows that *Rn* can very well be interpreted as a probability, thus facilitating the implementation of equation 1.

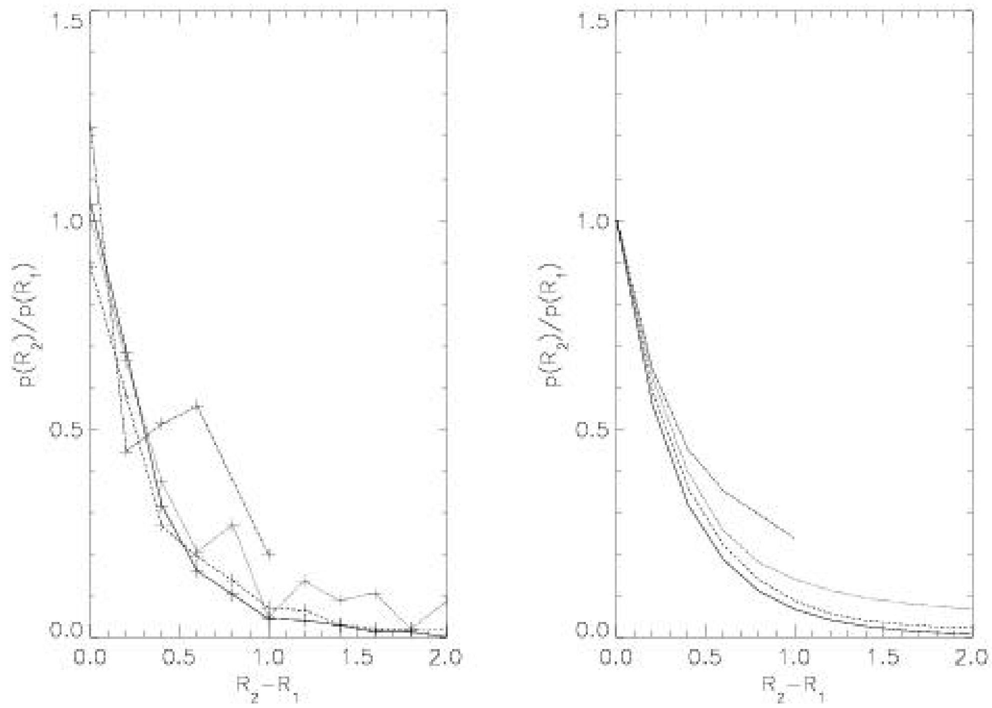

Figure 4. Ratio of the number of realisations of R2 and the number of realisations of R1 as a function of R2 – R1, and for values of R1 = 0.5 (solid), R1 = 1.1 (dashed), R1 = 1.7 (dotted), and R1 = 2.1 (dash-dot). The left plot is based on real data and the right plot is constructed using an exponential relationship p(Rn). The normalised residual can be well explained in terms of a wind solution probability.

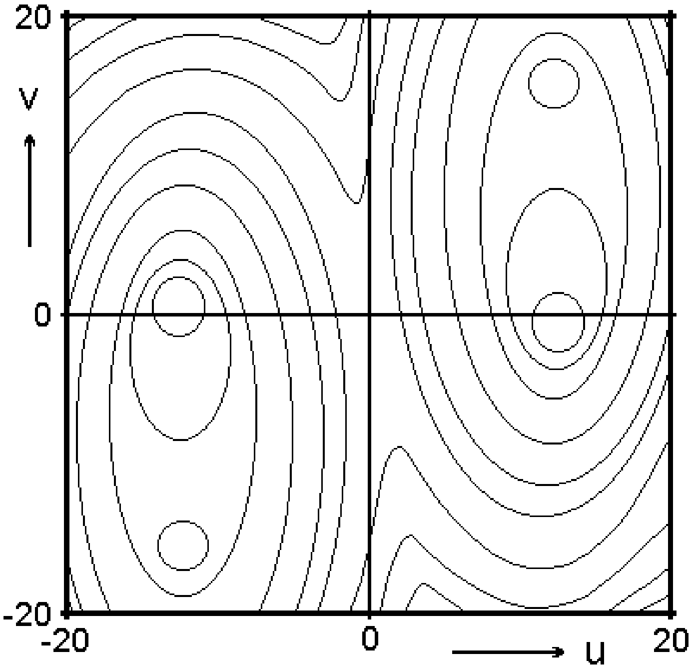

Figure 5. Illustration of wind probability contours as a function of the wind components u and v for a SeaWinds wind vector cell with measurements at four different azimuths including two polarisations. Multiple minima exist, resulting in a slightly more complex variational assimilation.

The generalised methodology may also be applied for those parts of the swath where the wind vector cannot be fully determined, because of limited azimuth or polarisation coverage, and where the ambiguity pattern can be of greater complexity. However, in these parts of the swath the solution minima may be less well defined than in the sweet zone. In that case, the width of the minimum can be decomposed into two independent wind components, e.g., along the wind vector solution and across or any other orthogonal set, that model the possible anisotropy of the retrieval solution minimum width. ε_i is then determined by these widths and the isotropic geophysical interpretation error of about 1.5 m/s in a component. Another limitation is that for some parts of the swath QC may be difficult and assimilation therefore more risky (see section 2 above). AMSR on ADEOS-II is likely to ease this problem.

6. Conclusions

Within the EUMETSAT-funded NWP Satellite Application Facility, SAF, a SeaWinds processing package is being developed that checks, spatially averages, and inverts backscatter data. After these steps a 2D-VAR ambiguity routine will be run to investigate the ambiguity removal properties of the cost function and observation operator as proposed here. After these tests, application in 3D- or 4D-Var (e.g., Courtier, 1998 and 1999) data assimilation systems is a straightforward development.
Following our procedure, we expect that carefully screened, smoothed, and assimilated SeaWinds scatterometer data from QuikSCAT and ADEOS-II have great potential in NWP.

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REFERENCES

Atlas, R., and R.N. Hoffman, 2000: The Use of Satellite Surface Wind Data to Improve Weather Analysis and Forecasting? , To appear in *Satellites, Oceanography, and Society*.

Courtier, P., et al, 1998, The ECMWF implementation of three dimensional variational assimilation (3D-Var). Part I: Formulation, *Quart. J. Royal Meteol. Soc.* 124, 1783-1808.

Courtier, P., et al, 4D-Var, ECMWF documents, 1999.

Figa, J., and A. Stoffelen, 2000, "On the Assimilation of Ku-Band Scatterometer Winds for Weather Analysis and Forecasting", IEEE-IGARS special issue on scatterometer applications, accepted.

HIRLAM, 2000:
http://www.knmi.nl/hirlam.

Isaksen, L., and A. Stoffelen, "ERS-Scatterometer Wind Data Impact on ECMWF's Tropical Cyclone Forecasts", IEEE-IGARS special issue on scatterometer applications, accepted.

Jones, Linwood, and David G. Long, 1999, QuikSCAT Radiometric Calibration and Special Brightness Temperature Product, *Proceedings from the QuikSCAT cal/val - early science meeting*, 2-5 November 1999, JPL, Pasadena, California.

KNMI satellite section web site.
http://www.knmi.nl/onderzk/applied/en/sd_index.html

Le Meur, Didier, Lars Isaksen, and Ad Stoffelen, ? Impact of ERS-1/ERS-2 scatterometer tandem on the ECMWF 3D-var assimilation system? , *Proc. Of the third ERS symposium – space at the service of our environment*, Florence, 17-21 March 1997, ESA special report, ESTEC, Noordwijk, the Netherlands, 1997.

Portabella, Marcos, and Ad Stoffelen, EUMETSAT QuikSCAT Fellowship Progress Report, KNMI, de Bilt, the Netherlands, 2000.

Stoffelen, Ad, 1998a, "Scatterometry", PhD thesis, ISBN 90-393-1708-9.
http://pablo.ubu.ruu.nl/~proefsch/01840669/inhoud.htm.

Stoffelen, A. C. M. and D. L. T. Anderson, 1997c, Ambiguity removal and assimilation of scatterometer data, *Q. J. Roy. Meteorol. Soc*., 123, 491-518.

Stoffelen, Ad and Paul van Beukering, "The impact of improved scatterometer winds on HIRLAM analyses and forecasts", BCRS study contract 1.1OP-04, report published by BCRS, Delft, The Netherlands, and HIRLAM technical report #31, published by IMET, Dublin, Ireland, 1997.

Voorrips, Aart, 2000, Preliminary work in the QuikSCAT observation operator definition, KNMI.
(PDF http://www.knmi.nl/onderzk/applied//pdf/QuikSCAT_OO.pdf)
(Postscript http://www.knmi.nl/onderzk/applied/ps/QuikSCAT_OO.ps)

Vries, de, John, and Ad Stoffelen, 2000, 2D variational ambiguity removal, Project report for the BCRS, KNMI, de Bilt, the Netherlands.

Wentz, Frank, Deborah Smith, and Carl Mears, 1999, Rain and the QuikSCAT winds, *Proceedings from the QuikSCAT cal/val - early science meeting*, 2-5 November 1999, JPL, Pasadena, California.