MESOSCALE WINDS OVER THE OCEAN

J. Vogelzang, A. Stoffelen, M. Portabella, A. Verhoef, and J. Verspeek

KNMI, Wilhelminalaan 10, 3732 GK, De Bilt, The Netherlands

Abstract

With the succesfull launch of MetOp-A carrying the Advanced Scatterometer (ASCAT) in October 2006, wind scatterometry entered its operational stage. Development of scatterometer processing software and products in Europe is organised through the EUMETSAT Satellite Application Facilities for Numerical Weather Prediction (NWP SAF) and for Ocean and Sea Ice (OSI SAF). Product developments in the NWP SAF are focussed on using the data for Numerical Weather Prediction and short-range weather forecasting. The former is well suited by the SeaWinds products as currently produced at the Royal Netherlands Meteorological Institute (KNMI) at 100-km resolution in preparation of the operational ASCAT production suite. For short-range forecasting or in semi-enclosed sea areas such as the Mediteranean, however, higher resolution is desirable, and therefore demonstration products at 25-km resolution are available from SeaWinds, ASCAT, and the scatterometer on board the Earth Remote Sensing satellite (ERS2). All products are currently provided in the BUFR format to facilitate the development of user interfaces. In the 2DVAR ambiguity removal method KNMI attempts to improve the spatial filtering properties of the wind retrieval by using prior information on the expected meteorological balance, e.g., favouring rotational structures in high-latitude regions. Moreover, solutions in all wind directions, weighted by their inherent probability, can be retained in the processing, the so-called Multiple Solution Scheme (MSS). The 2DVAR method has the advanced filtering properties needed for maintaining small-scale meteorological information in SeaWinds, while reducing noise. This is shown by comparing the autocorrelation of the scatterometer wind fields with that of model by the European Centre for Medium Range Weather Forecasting (ECMWF). It is shown that SeaWinds scatterometer wind fields at high resolution contain noise, but that this noise is effectively removed in the MSS. From an ASCAT example it is also shown that there is still room for improvement in the error model underlying the 2DVAR method. These findings will be helpful in the development of a 12.5-km ASCAT scatterometer wind product in the coastal zone.

1. INTRODUCTION

The all-weather capability of a scatterometer provides unique wind field products of the most intense and often cloud-covered wind phenomena, such as tropical cyclones (for example, see figures 2-4 in Verhoef et al., 2007). As such, it has been demonstrated that scatterometer winds are useful in the prediction of tropical cyclones, e.g., Isaksen and Stoffelen (2000), and extra-tropical cyclones (Stoffelen and Beukering, 1997). At the moment the Advanced Scatterometer (ASCAT) on MetOp-A and the National Aeronautics and Space administration (NASA) SeaWinds scatterometer on QuikScat provide a global near-real time data stream, while the European Space Agengy (ESA) Earth Remote Snsing satellite (ERS2) scatterometer provides regional data over the North Atlantic. With the succesful operation of ASCAT the continuity of scatterometer data is provided to the operational meteorological community for another period of 15 years.

EUMETSAT set up the Satellite Application Facilities (SAF) providing software and data products and services. The Royal Netherlands Meteorological Institute (KNMI) is involved in the scatterometer activities of the following SAFs in preparation for ASCAT (see also www.knmi.nl/scatterometer):

- Numerical Weather Prediction SAF for scatterometer software products;
- Ocean and Sea Ice SAF for scatterometer wind products and Scatterometer Ocean Stress (SOS) products.

This paper will concentrate on the improvements made to scatterometer wind processing within the NWP SAF. The current status of the scatterometer wind services at KNMI is described by Verhoef et al. (2007), while the ocean stress product is presented by Portabella et al. (2007).

At the moment two scatterometer data processors are available: the SeaWinds Data Processor (SDP) and the ASCAT Wind Data Processor (AWDP). SDP is operational (current version 1.5) while AWDP cab be obtained under beta license. AWDP is expected to become operational early 2008. The software, consisting of source code, installation scripts and user manuals, can be requested at the NWPSAF site www.metoffice.gov.uk/research/interproj/nwpsaf/scatterometer/index.html. AWDP is also capable of processing ERS data. SDP and AWDP share many routines, especially for inversion, ambiguity removal, and BUFR file handling.

2. SCATTEROMETER PROCESSING

Figure 1 shows an overview of the scatterometer wind processing packages. The radar cross section of the ocean surface (σ_0) as a function of the wind vector and the observation geometry is predicted by an empirical Geophysical Model Function (GMF).

Processing starts with reading all input, notably the measured values of the radar cross section of the ocean surface, σ_0, into the software. The second step is the inversion, which is performed in σ_0-space. The inversion procedure finds those points on the GMF that are closest to the measured σ_0 values. The corresponding wind vectors are the so-called ambiguous solutions. In general the inversion procedure yields more than one solution. The standard procedure is to select the points on the GMF with minimum distance to the observation. The number of solutions depends on the observation geometry: typically two for ERS and ASCAT, and up to four for SeaWinds. The distance between each solution and the observation can be interpreted as a measure of the probability of that solution being the correct one (Portabella and Stoffelen, 2001; Portabella, 2002). For SeaWinds in the nadir swath region there are multiple points on the GMF (wind solutions) that have similar distances to the observation. The Multiple Solution Scheme (MSS) offers the possibility to retain up to 144 solutions with their probability. In this way also solutions with a somewhat lower probability are retained and the ambiguity removal method has more choice for finding the best solution (Portabella, 2002).

During quality control the distance between each solution and the observation is normalised to a probability. Observations that lie too far from the GMF are rejected as they are most probably contaminated by rain, land, or sea ice.

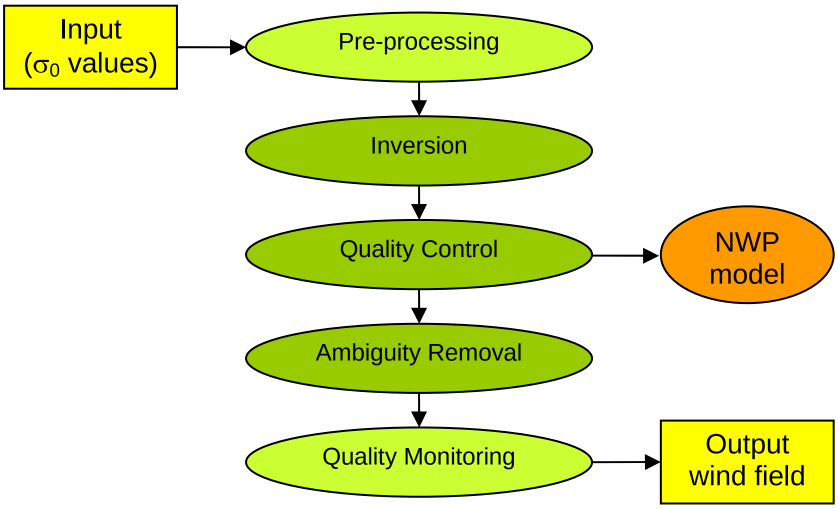

Figure 1: **Schematic view of KNMI scatterometer wind processing software**

For Numerical Weather Prediction the results can now be fed into the NWP model. The assimilation step in the model is supposed to select the scatterometer wind solution that fits best with other observations, taking the error structures and probabilities of the solution and the other observations into account properly. For stand alone applications the optimal solution must be selected by some kind of Ambiguity Removal (AR) method. A simple AR method is the so-called First Rank method, selecting the solution with the highest probability (the one closest to the measured σ_0 values). When a model prediction (background) is available, one may also select the solution closest to the model (closest-to-background).

It is well known that such simple methods have serious drawbacks. Therefore KNMI developed a two-dimensional variational AR method called 2DVAR (Vogelzang, 2007). Assuming the error statistics of solutions and background known, 2DVAR calculates an analysis using standard methods (Daley, 1991) and selects the solution closest to the analysis. Processing ends with quality monitoring and output of the results in BUFR format.

Recently, important improvements were made to the processing chain. The inversion procedure has been improved at low wind speeds by removing an attractor at the minimum wind speed of the GMF lookup table (0.2 m/s). The 2DVAR procedure has been revised thoroughly. It now satisfies the single observation test, a case with a single observation and Gaussian error statistics that can be solved analytically. Detailed information on 2DVAR is given by Vogelzang (2007). Note that 2DVAR can be considered as a simple data assimilation system and thus is able to give important information on how to assimilate scatterometer observations in NWP models.

3. QUALITY OF SCATTEROMETER WIND FIELDS

The quality of a scatterometer wind field can be studied in three ways:

1. Comparison with independent measurements from ships and buoys.
2. Statistical analysis.
3. Case studies.

In the remainder of this paper we will concentrate on statistical analysis, augmented with a few examples.

Figure 2 shows the spectrum of the zonal wind component *u* as a function of spatial frequency *k* for scatterometer measurements by SeaWinds at 25 km resolution using MSS (blue curve) and the corresponding ECMWF background (green curve). The spectrum was obtained by Fourier transformation of the autocorrelation function as described by Vogelzang (2006). All SeaWinds data from December 2004 were used.

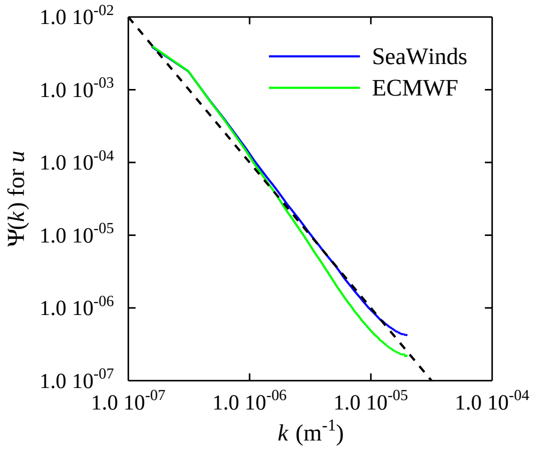

Figure 2: **Spectrum for the zonal wind component *u* obtained from SeaWinds measurements (blue) and ECMWF model calculations (green) versus the spatial frequency *k*. The dashed curve is for a k^{-2} spectrum.**

At low spatial frequencies of the order of 10^{-7} m^{-1} (spatial scale ≈ 10000 km) the spectra are indistinguishable. At higher frequencies the observed spectrum lies above the calculated one. The difference is 25% at $k = 10^{-6}$ (spatial scale 1000 km) and a factor of 2 at $k = 10^{-5}$ (spatial scale 100 km). For the wind energy this means that the scatterometer signal contains four times as much signal as the ECMWF model field. The scatterometer spectrum falls off like k^{-2} (indicated by the dashed curve in figure 2) while the model spectrum shows steeper decay. It is possible to estimate the noise level from the spectrum, since white noise has a constant spectrum. When noise is present one expects the spectrum to flatten at high frequencies. Indeed figure 2 shows some flattening, but this is not caused by noise since the ECMWF model contains no spatial noise in the wind vectors. The flattening of the curves in figure 2 is caused by numerical effects in the FFT operation involved: the autocorrelation does not go to zero fast enough.

In fact, the autocorrelation will never go to zero because the trade winds are correlated over large time spans. Vogelzang (2006) has shown that a better noise estimate can be obtained directly from the autocorrelation. A white noise component adds variance but is not correlated and will therefore cause a delta function peak in the autocorrelation at zero distance. As a result, the autocorrelation shows a discontinuity at short distance. This is illustrated in figure 3 which shows the autocorrelation in the zonal wind component *u* calculated from all SeaWinds data from December 2004 processed at 25 km resolution with and without MSS (green and red curves, respectively) and the corresponding NCEP background (blue curves). The autocorrelation equals 1 at zero distance by definition. The left hand panel of figure 3 shows that the autocorrelation in *u* goes through zero at a distance of about 2000 km and is negative up to 3200 km. It will oscillate for larger distances (no results shown)

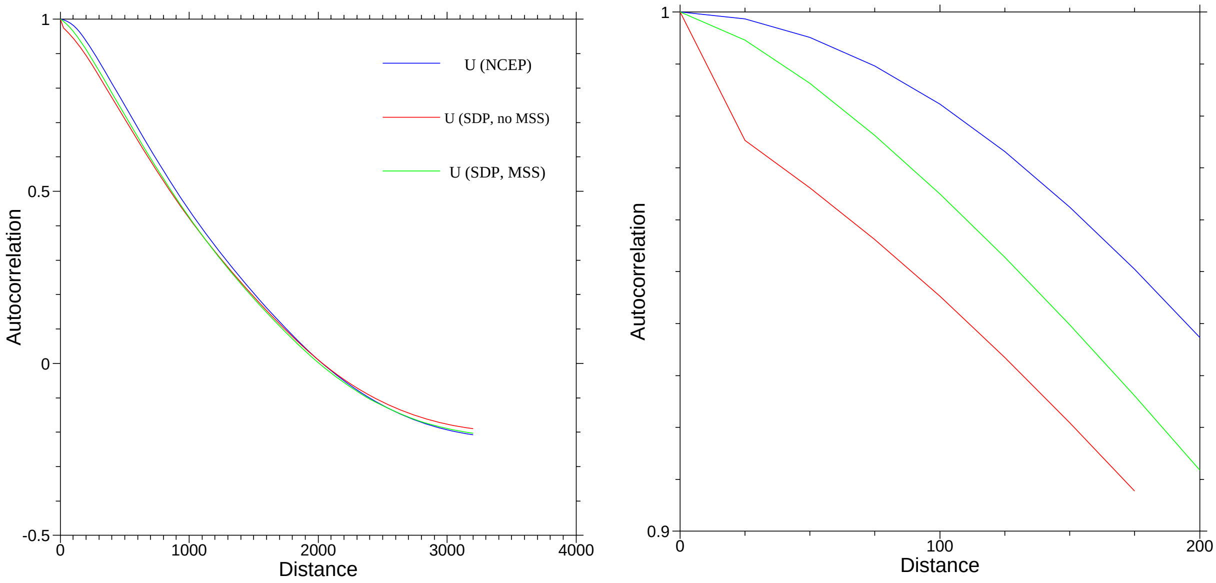

Figure 3: **Autocorrelation as a function of distance for the zonal wind component u obtained from SeaWinds processed without and with MSS (red and green curves, respectively) and the corresponsing NCEP background (blue curves). The left hand panel shows the full autocorrelation, the right hand panel an enlargement at short distances.**

The right hand panel in figure 3 shows an enlargement at small distances. The autocorrelation of the scatterometer wind component u calculated without MSS (red curve) shows a clear discontinuity that is absent when applying MSS (green curve). Also the NCEP model yields an autocorrelation that goes to 1 continuously as the distance approaches zero.

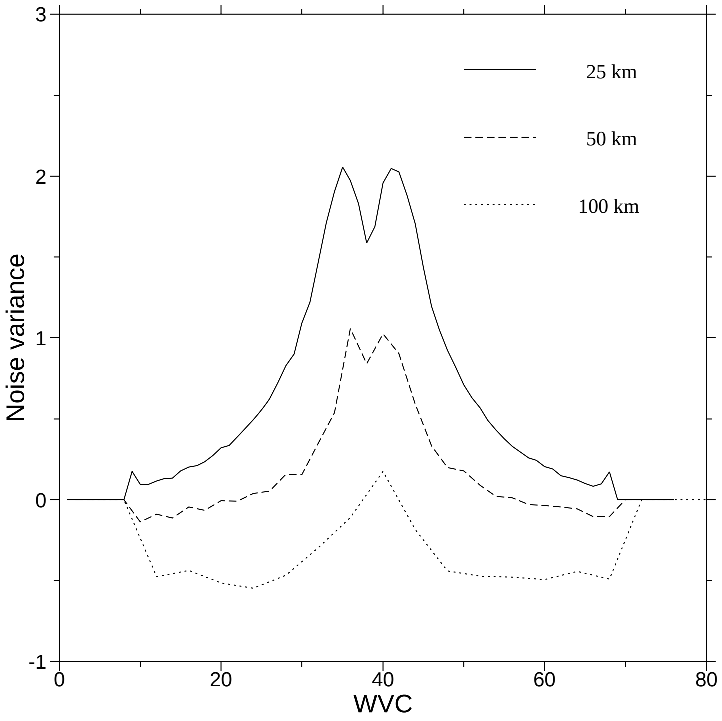

Figure 4: **Noise variance in the SeaWinds wind field as a function of wind vector cell (WVC) number at a resolution of 25 km (solid curve), 50 km (dashed curve), and 100 km (dotted curve).**

The size of the discontinuity can be estimated by extrapolating the autocorrelation to zero. The distance between the extrapolated autocorrelation at zero distance and 1 is a direct measure for the variance in the noise contribution (Vogelzang, 2006). Simple quadratic extrapolation proved to be adequate. Figure 4 shows the noise variance in the SeaWinds scatterometer winds of December 2004 processed without MSS at a resolution of 25 km (solid curve), 50 km (dashed curve), and 100 km (dotted curve). As the resolution increases the noise is averaged out. Also the extrapolation distance increases leading to larger extrapolation errors that may cause negative - and therefore unphysical – variances. Figure 4 shows that the noise variance in SeaWinds wind fields at 25 km resolution may be up to 2 m^2/s^2 in the nadir part of the swath, wind vector cells (WVC) 31–46, where the observation geometry is unfavourable. Note that the outer swath, WVC 1-10 and 67-76, is not processed.

4. SOME CASES

Figures 3 and 4 suggest that MSS may be effective for removing noise in high resolution SeaWinds wind fields. This is corroborated by figure 5 which shows hurricane Dean observed on August 16, 2007, and processed with and without MSS at 25 km resolution. The purple arrows indicate observations rejected by the 2DVAR quality control. This happens when the observation part of the cost function exceeds a value of 12.

The left hand panel of figure 5 shows the result without MSS. Indeed the wind field is rather noisy. The right hand panel, obtained with MSS, yields a much smoother wind field. Note that there are almost no reliable wind measurements in centre of the hurricane, due to the heavy rains associated with such systems. SeaWinds operates at K_u-band and is more sensitive to rain than ERS or ASCAT that operate at C-band (see also Verhoef et al., 2007).

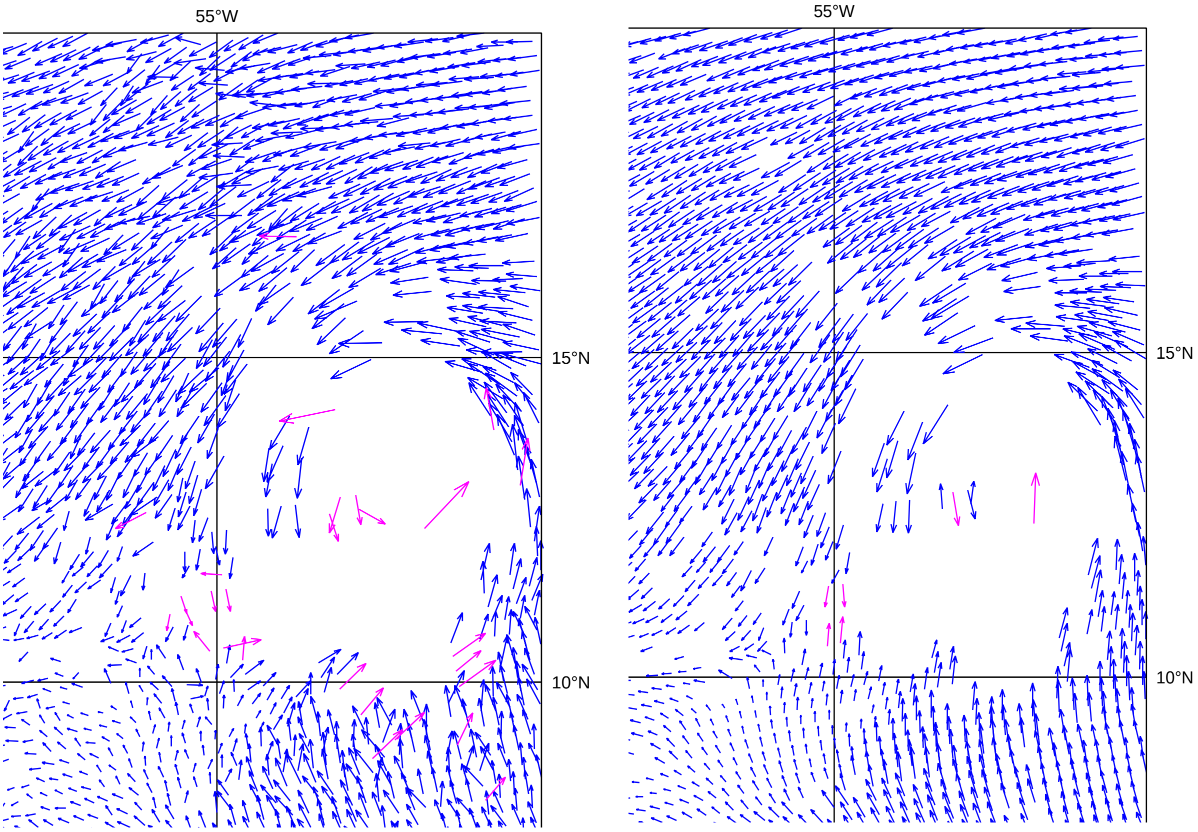

Figure 5: **Hurricane Dean observed with SeaWinds at 25 km resolution on August 16 2007. The left hand panel shows the result obtained without MSS, the right hand panel with MSS. Purple arrows indicate solutions rejected by the 2DVAR quality control.**

Figure 6 shows an interesting case recorded by ASCAT east of India on August 29, 2007. The result obtained with standard processing (upper left) clearly shows a cyclone rotating clockwise (the region is in the tropics on the southern hemisphere). The cyclone is absent in the ECMWF background (upper right). Note that the wind directly north and northeast of the centre of the cyclone obviously has the wrong direction: part of the wind field there is oriented counterclockwise. This indicates a problem with ambiguity removal. Application of the MSS offers no satisfactory solution (lower left): the resulting wind field does show a cyclone but it is located at the wrong position. With MSS the 2DVAR ambiguity removal has the possibility of choosing a solution with smaller probability, but here it leads to too much influence of the background.

At this moment 2DVAR assumes Gaussian background error statistics with a correlation length R_b of 600 km in the tropics and 300 km in the extratropics as standard settings. The difference in correlation length reflects the difference in wind field structure for the area's. The tropics are characterized by large scale wind structures while the extratropics show frequent smaller size cyclones. If in this example, which is located in the tropics, the background error correlation length is reduced from its standard value of 600 km to 300 km the problems with ambiguity removal are resolved, as shown in the lower right panel of figure 6.

Though the cyclone was absent in the ECMWF background, it did show up in the prediction after assimilation of the ASCAT data, though at the wrong position (Hersbach, 2007). This example illustrates that adjustment of the error structure parameters may improve assimilation of scatterometer data in NWP models.

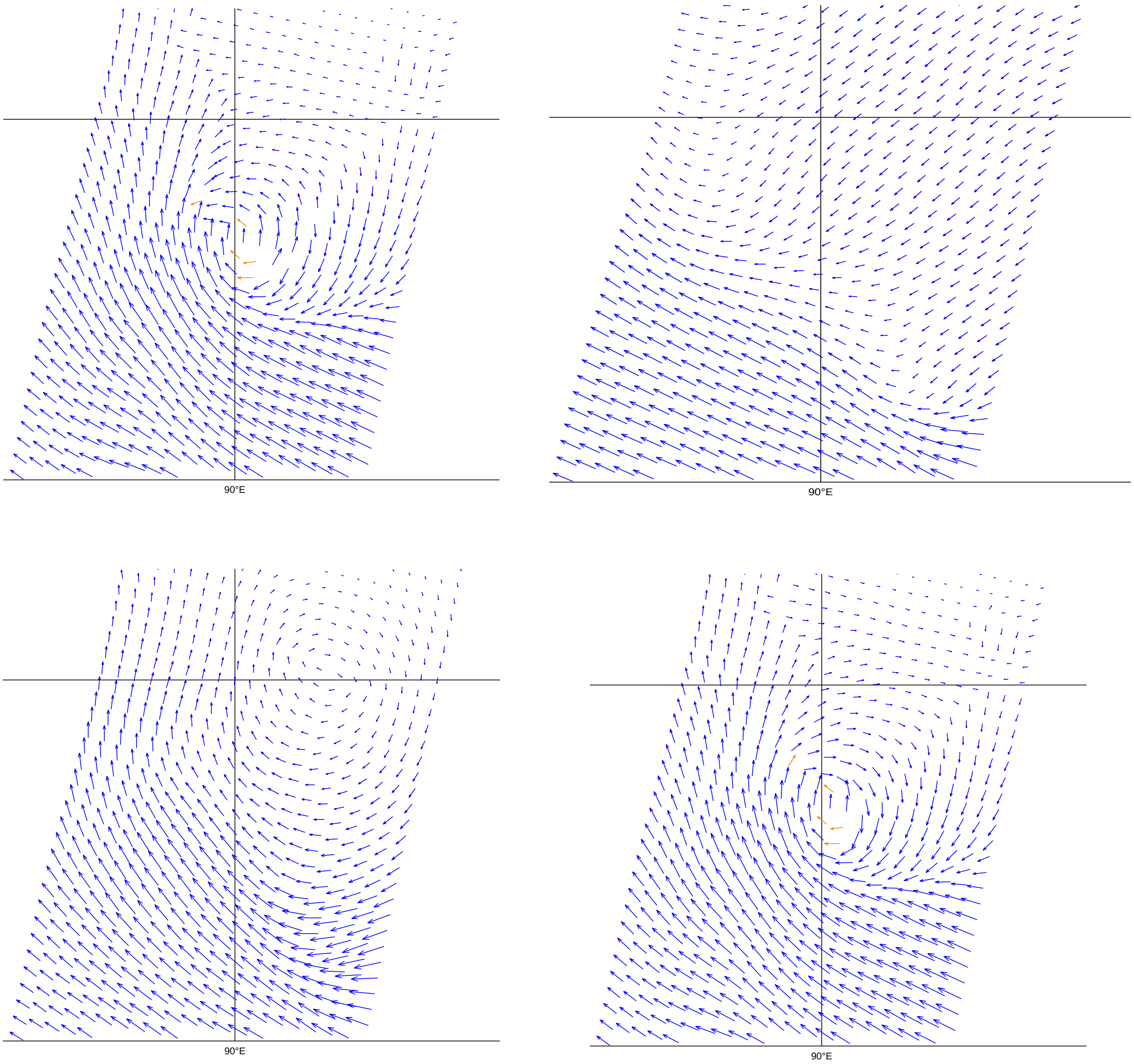

***Figure 6:* Low pressure area east of the coast of India observed by ASCAT on August 31, 2007. Upper left: standard processing with background error correlation length R_b = 600 km; upper right: ECMWF background; lower left: processing with MSS; lower right: processing with reduced background error correlation length R_b = 300 km.**

5. OUTLOOK TO THE FUTURE

In the coming years the various scatterometer processors developed in the NWPSAF project will be further improved. The SeaWinds Data Processor (SDP) will be upgraded early 2008 to version 2.0 featuring processing of the outer swath and improved error modelling in 2DVAR.

The ASCAT Wind Data Processor (AWDP) will become operational early 2008 for a resolution of 25 km. An improved version processing at 12.5 km resolution will be available for beta users late 2008. Further improvement with better coverage of the coastal zone is expected as beta version in 2009.

SDP and ADWP (source code, installation scripts and manuals) can be obtained from the NWPSAF web site at www.metoffice.gov.uk/research/interproj/nwpsaf/scatterometer/index.html.

6. CONCLUSIONS

This paper gives an overview of the status of the SeaWinds Data Processor (SDP) and the ASCAT Wind Data Processor (AWDP) developed within the NWPSAF. Recently important improvements were made in the inversion at low wind speeds and in the 2DVAR ambiguity removal method.

It is shown that scatterometer wind fields may reveal details that are not visible in NWP model results. The noise in SeaWinds wind fields at 25 km resolution can be effectively removed with the Multiple Solution Scheme (MSS). Detailed scatterometer wind fields can be used as stand alone information source for nowcasting and oceanographic applications. The assimilation of scatterometer measurements in NWP models can be improved and is subject of ongoing research. In the near future it will be possible to process ASCAT data at 12.5 km resolution and to extend the processing area closer to the coast line.

ACKNOWLEGDEMENT

This work is funded by EUMETSAT in the framework of the NWP SAF.

REFERENCES

Daley, R. (1991) Atmospheric data analysis. Cambridge University Press, Cambridge, UK.

Hersbach, H. (2007) Private communication.

Isaksen, L. and A. Stoffelen (2000) ERS-Scatterometer Wind Data Impact on ECMWF's Tropical Cyclone Forecasts. IEEE-Transactions on Geoscience and Remote Sensing (special issue on Emerging Scatterometer Applications) **38** (4), pp. 1885-1892.

Portabella, M. and A. Stoffelen (2001) Rain detection and quality control of SeaWinds. Journal of Atmospheric and Oceanic Technology **18**, pp 1171-1183.

Portabella, M. (2002) Wind field retrieval from satellite radar systems. Thesis, University of Barcelona, Spain.

Portabella, M., A. Stoffelen, A. Verhoef, J. Verspeek and J. Vogelang (2007) Towards a high-resolution gridded ocean forcing, these proceedings.

Stoffelen, A. and P. van Beukering (1997) 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. Available from KNMI.

Verhoef, A., A. Stoffelen, M. Portabella, J. Verspeek, and J. Vogelzang (2007) EUMETSAF SAF and EARS scatterometer wind services at KNMI, these proceedings.

Vogelzang, J. (2006) On the quality of high resolution wind fields. Technical Report NWPSAF-KN-TR-002, UKMO, UK, www.metoffice.gov.uk/research/interproj/nwpsaf/scatterometer/index.html.

Vogelzang, J. (2007) Two dimensional variational ambiguity removal. Technical Report NWPSAF-KN-TR-004, UKMO, UK, www.metoffice.gov.uk/research/interproj/nwpsaf/scatterometer/index.html.