

## **Ocean and Sea Ice SAF**

**Technical Note**

**SAF/OSI/CDOP/KNMI/TEC/RP/176**

# **ASCAT coastal winds validation report**

**Product OSI-104**

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**KNMI**

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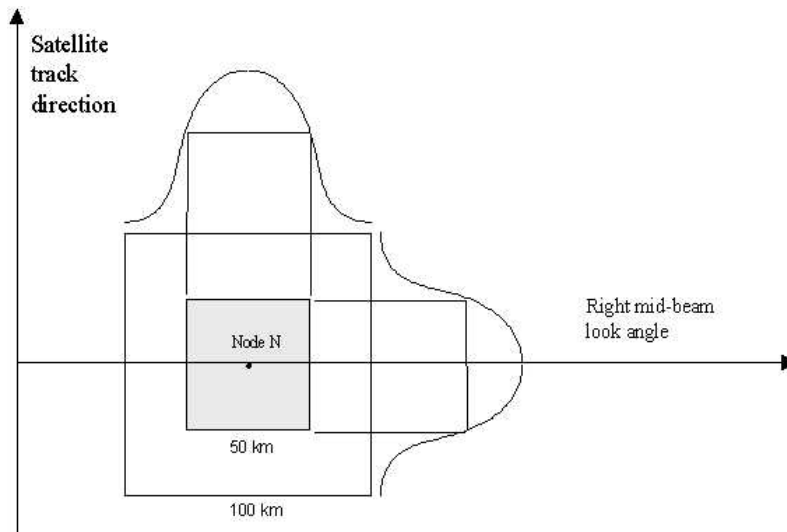
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# 1 Introduction

The Ocean and Sea Ice Satellite Application Facility (OSI SAF) delivers operational level 2 wind products in near-real time, based on the ASCAT level 1 products with 25-km and 12.5-km Wind Vector Cell (WVC) spacing from EUMETSAT. In these products, WVCs closer than ~70 km (25-km products) or ~35 km (12.5-km products) from the coast are flagged because of land contamination. This is due to the fact that - in the case of the 12.5-km product - backscatter measurements ( $\sigma_0$ ) of up to 35 km away from each WVC centre are used in the spatial averaging. The cosine weighting function used for the averaging is shown in Figure 1. Note however that this figure is valid for the 25-km product, for the 12.5-km product the indicated dimensions need to be divided by two. See the ASCAT product guide [1] for more information on the level 1 product characteristics.



**Figure 1: Ground geometry of the spatial smoothing for  $\sigma_0$  values corresponding to the right mid beam for a given WVC (node) N, for the 25-km ASCAT level 1 product (Figure 4 of [1]).**

Apart from the 25-km and 12.5-km level 1 products, also a full resolution (FR) ASCAT level 1 product is available. This product contains the individual radar backscatter values, 256 values along each antenna beam, localised on the surface of the Earth. In the FR product the data are organised along the six antenna beams rather than per WVC in the swath. The sampling of individual backscatter values along-beam is of approximately 2 km for mid beams and 3 km for fore and aft beams. The FR backscatter values represent footprints of approximately  $10 \times 20$  km of various shapes and orientations [1].

In the ASCAT coastal AWDP prototype report [2], it was shown that by properly box-averaging the FR measurements it is possible to derive winds as close to 20-25 km from the coast in the 25-km product. The 12.5-km product was not considered in this report but it can be expected that in this case winds as close as ~15 km from the coast can be computed.

The proximity to the coast will depend on the box size where a smaller box size (backscatter averaging area) may provide winds nearer to the coast and perhaps also some more wind detail. On the other hand, a smaller box size will result in higher noise. Three different cut-off radii for the backscatter averaging area are considered in this report and the resulting winds are compared. We assess the quality of the 12.5-km ASCAT coastal products by comparing the coastal winds to in situ data from moored buoys in coastal regions. Since these may be considered as local winds, they contain all wind scales and provide excellent verification of the detail and noise in scatterometer WVC-mean winds. The product characteristics in non-coastal regions (more than 50 km off the coast) are also compared to those of the operational 12.5-km product. In particular, we verify the spectral characteristics of the diverse wind products. Based on the results, the best setting of the cut-off radius is chosen and this setting will be used in the ASCAT coastal product to be provided to the users.

The results presented in this report are encouraging and warrant the release of the 12.5 km coastal product.

## 1.1 References

- [1] EUMETSAT  
*ASCAT products guide*  
 EUM.OPS-EPS.MAN.04.0028, 2004, available on <http://www.eumetsat.int/>.
- [2] Portabella, M., A. Verhoef, and A. Stoffelen  
*ASCAT coastal AWDP prototype*  
 NWP SAF Visiting Scientist Report, NWPSAF-KN-VS-007, 2008
- [3] OSI SAF  
*ASCAT Wind Product User Manual*  
 SAF/OSI/CDOP/KNMI/TEC/MA/126, available on <http://www.osi-saf.org/>.
- [4] Bidlot J., D. Holmes, P. Wittmann, R. Lalbeharry, and H. Chen  
*Intercomparison of the performance of operational ocean wave forecasting systems with buoy data*  
 Wea. Forecasting, vol. 17, 287-310, 2002
- [5] Liu, W.T., K.B. Katsaros, and J.A. Businger  
*Bulk parameterization of air-sea exchanges of heat and water vapor including the molecular constraints in the interface*  
 J. Atmos. Sci., vol. 36, 1979.
- [6] Portabella, M. and A. Stoffelen,  
*Scatterometer backscatter uncertainty due to wind variability*  
 IEEE Transactions on Geoscience and Remote Sensing, 44, 11, 3356-3362, 2006.
- [7] Vogelzang, J., A. Stoffelen, and A. Verhoef  
*On the Quality of High-Resolution Scatterometer Winds*  
 To be submitted to J. Geophys. Res.
- [8] Nastrom, G.D., K.S. Gage, and W.H. Jasperson  
*Kinetic Energy Spectrum of Large and Mesoscale Processes*  
 Nature, vol. 310, 36-38, 1984.
- [9] OSI SAF  
*Ocean and Sea Ice SAF Product Requirement Document*  
 SAF/OSI/CDOP/M-F/MGT/PL/001

## 1.2 Abbreviations and acronyms

ASCAT	Advanced SCATterometer
ECMWF	European Centre for Medium-Range Weather Forecasts
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FR	Full Resolution
GTS	Global Telecommunication System
KNMI	Royal Netherlands Meteorological Institute
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
OSI	Ocean and Sea Ice
QC	Quality Control
SAF	Satellite Application Facility
WVC	Wind Vector Cell

### **1.3 Acknowledgement**

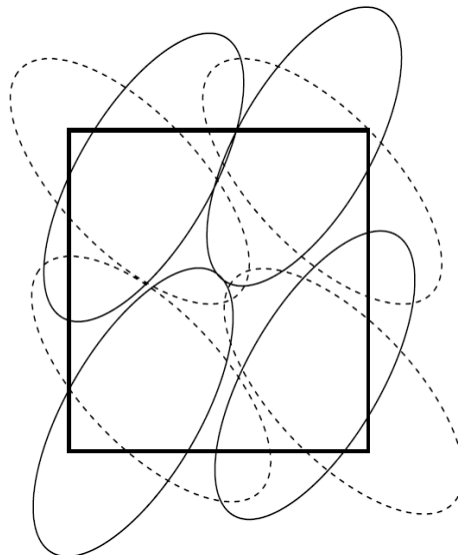
We are grateful to Jean Bidlot of ECMWF for helping us with the buoy data retrieval and quality control. EUMETSAT kindly provided/provides the ASCAT full resolution data from the Data Centre archive and in near-real time. Jur Vogelzang of KNMI provided the wind spectra plots.

## 2 Expectations

It would be of interest to investigate the characteristics of spatial sampling on the backscatter fields for different spatial filter functions and for realistic variable wind fields, but this has not been done for ASCAT. In this report, the coastal product wind retrieval performance is tested, which implies some indirect testing of the backscatter and Kp data as indicated below. This is, improved (degraded) backscatter and Kp inputs will have beneficial (detrimental) effects on the wind retrieval performance.

In the level 1b products, a Hamming window is applied in order to minimise noise (prevent aliasing), as illustrated in Figure 1. One would expect that box averaging, i.e., averaging only over the grey area in Figure 1, would result in more small scale details, but possibly at the expense of some noise (aliasing). However, one should realise that  $\sigma_0$  in the grey box is not sampled by a point response function, but oversampled with a field of view (FOV) of approximately 10 km (along fan beam) by 25 km (across fan beam). So, with all FOVs centred in a WVC, the integrated FOV (IFOV) for that WVC and beam will be a function extending up to 25 km outside the WVC in the direction across the fan beam, see **Error! Reference source not found.** for illustration. This  $\sigma_0$  extent outside the WVC acts to suppress sampling noise or aliasing, since neighbouring WVCs have much overlapping IFOVs for each beam and sample in part the same ocean spatial wind pattern. The spectral shape of the spatial backscatter distribution would flatten at the high-wavelength end when aliasing noise is present. On the other hand, in case of excessive filtering the natural spectral slope of this distribution would be truncated. Later on, wind spectra will be evaluated.

Moreover, since ASCAT has the three fan beams pointing in directions differing by 45 degrees in azimuth, the “egg” shape of the IFOV will extend in different directions as well. Hence, the three beams in any WVC do not sense exactly the same area, resulting in so-called geophysical noise [6]. Since the three beams do not sense the same area, the three backscatter values do not agree with one unique wind, but rather with slightly different area-mean winds, as sampled by the IFOV. This causes some noise in the wind inversion. Geophysical noise is generally well described by the expected wind variability on the ocean surface, the sensitivity of the geophysical model function, and the difference in IFOV of the different beams in a WVC [6]. Since the ocean wind variability is larger in a 50-km IFOV than in a 25-km IFOV, a box-averaged product may potentially experience lower geophysical noise than the Hamming-window product. Geophysical noise has been shown to be statistically significant for winds below 5 m/s but may be expected to generate some spurious noise near large wind gradients as well (fronts, lows), where the wind retrieval Quality Control (QC) is known to be active. QC statistics are thus evaluated for the coastal product.



**Figure 2: Schematic illustration of scatterometer sampling. A target WVC (thick solid line) is sampled from two different perspectives (for simplification), with a beam footprint indicated by solid and dashed lines, respectively. Both sample the WVC wind variability in a different way, leading to spatial representativeness error [6].**

A last aspect of the box-averaging concerns the potential for resolution enhancement in ASCAT wind retrieval. **Error! Reference source not found.** schematically shows crossing FOVs of the fore and aft beam, where the mid beam “eggs” would have yet another orientation (not shown), exactly in between the fore and aft beam orientations. In the wind retrieval, the three IFOVs are combined and a wind is computed. Areas present in only one IFOV of fore, mid or aft, contribute to the geophysical noise as discussed above. The spatial representation of the wind is thus given by that part of the combined IFOVs of fore, mid and aft beam that they have in common. This area is by consequence smaller than any of the IFOVs. Therefore, the wind retrieval process appears to have a potential resolution enhancement capability, but again, at the expense of some noise that may appear in the spectral spatial analysis of the retrieved winds.

In [2] the backscatter noise ( $K_p$ ) is investigated; it is an important property for wind retrieval. In terms of speckle noise,  $K_p$  is inversely proportional to the area sampled. So, a Hamming and box filter with equal IFOV would show equal  $K_p$ . However, as the sample area increases wind variations tend to become larger since larger wind scales have larger amplitude. This is, wind variations may contribute to  $K_p$ . In [6] it is documented that wind variability affects backscatter noise mainly at low winds (< 5 m/s). Increased  $K_p$  would increase the wind retrieval residual (cone distance), which is routinely evaluated in performance analyses and compared for the different scatterometer products.



### 3 Test data

The validations of the coastal product are done using 6 months of ASCAT full resolution data (1 March 2009 to 31 August 2009) which were kindly provided by the EUMETSAT Data Centre. As described in section 3 of [2], two parameters can be set that influence the characteristics of the final wind product:

- (1) The maximum distance  $R_{\max}$  from the 12.5-km WVC centre to search for FR backscatter measurements was set to three different values: 20 km, 15 km and 12.5 km. This yields three data sets which are validated separately. It can be expected that for higher  $R_{\max}$  values there will be less noise in the wind product, but the winds will also contain less small-scale details. The goal is to set  $R_{\max}$  such that we get a product of comparable quality to the operational 12.5-km product in regions far away from the coast.
- (2) For the computation of the land contamination of a FR measurement, a land-sea mask from the ECMWF operational model containing 400 grid points between equator and pole is used, i.e., at about 25-km spacing. A measurement land fraction is calculated using all land-sea mask grid points closer than 20 km from the measurement location. Every grid point found yields a land fraction (between 0 and 1). The land fraction of the measurement is calculated as the average of the grid land fractions, where each grid land fraction has a weight of  $1/r^2$ ,  $r$  being the distance between the FR measurement and the model grid point. The maximum distance was set to 20 km in all cases. Full resolution measurements with a land fraction of more than 0.02 are skipped for the computation of the averaged WVC  $\sigma_0$  value.

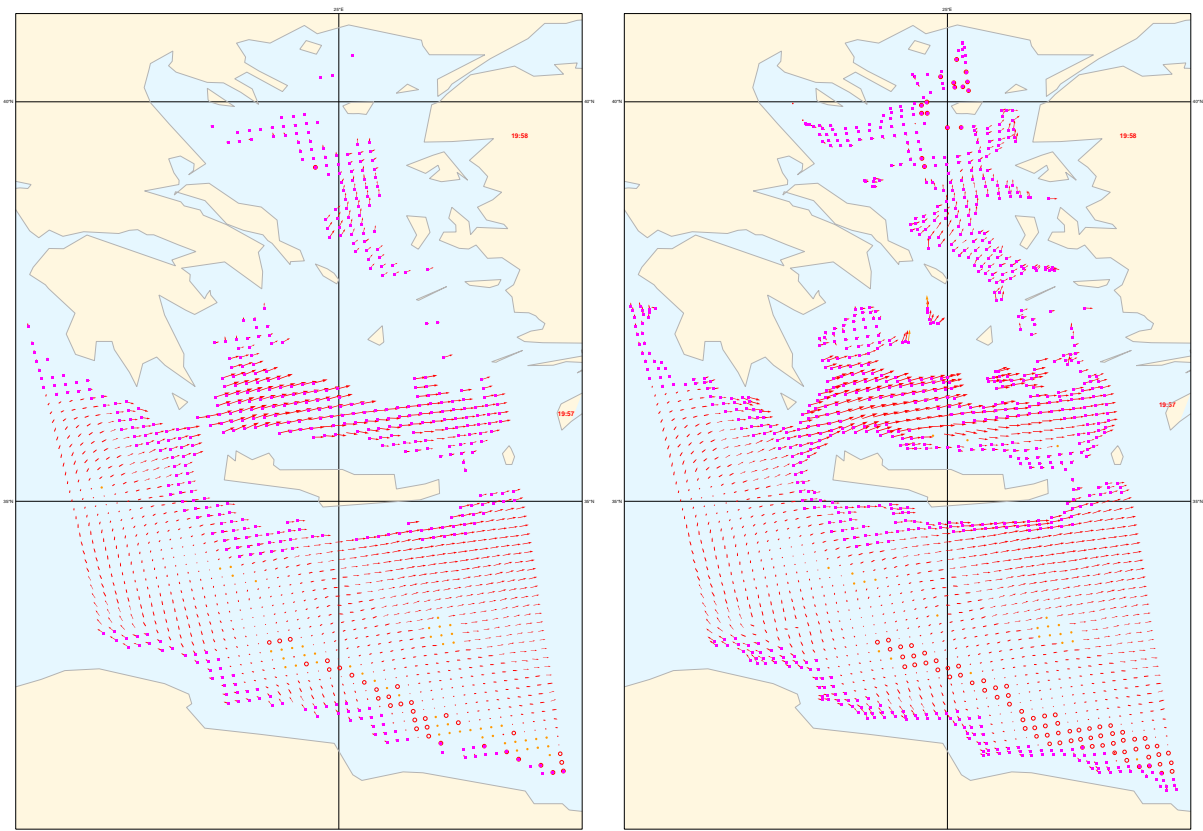
Using the three settings of  $R_{\max}$ , the 6 months of ASCAT data have been reprocessed. The level 1b part of the 12.5-km OSI SAF operational wind data was used together with the full resolution data. After the replacement of the level 1 backscatter data by the averaged  $\sigma_0$  values, the rest of the wind processing was done in the same way as for the operational products [3] and the level 2 wind part of the OSI SAF wind products was overwritten by the coastal winds.

The ASCAT Wind Data Processor (AWDP) version 1.1 was used for the processing, but the code was changed as needed to produce the three different data sets. The algorithm to average the full resolution backscatter data is the same as described in [2].

## 4 Comparison with operational data

Figure 3 is an example to show the difference between the operational 12.5-km ASCAT product and the coastal product. It is clear that the coastal product is capable to compute winds closer to the coast which yields many more wind vectors, especially in the areas between the isles in this part of the Mediterranean.

Note that the three coastal product data sets used in this report have been constructed using a land-sea mask containing 400 grid points between equator and pole. After the reprocessing was finished, ECMWF implemented a land-sea mask containing 640 grid points between equator and pole, i.e. with a spacing of approximately 15.6 km as compared to 25 km. This mask will be used in the near-real time production of the ASCAT coastal product and yields winds even closer to the coast than in Figure 3.



**Figure 3: Example of operational 12.5-km ASCAT product (left) and corresponding coastal product with  $R_{\max} = 15$  km (right) in the eastern part of the Mediterranean at 2 March 2009 19:57 UTC. The purple squares correspond to WVCs where the land flag is set, but where reliable winds can still be computed.**

Figure 4 shows two-dimensional histograms of the coastal product with  $R_{\max} = 15$  km compared with the operational 12.5-km data. It is clear from the plots that this coastal product very much resembles the operational product, there is no wind speed bias and the wind component standard deviations (bottom plots) are quite small, 0.39 m/s for the  $u$  component and 0.53 m/s for the  $v$  component. Most of the deviations appear to be connected with differences in ambiguity selection resulting in winds  $180^\circ$  apart, mostly at the lower wind speeds (see  $u.v$  plots). The corresponding results for the coastal products with  $R_{\max} = 12.5$  km and  $R_{\max} = 20$  km are not shown here, but they very much resemble those in Figure 4. The product with  $R_{\max} = 15$  km yields the lowest wind component standard deviations but the differences between the three coastal products are small, less than 0.05 m/s.

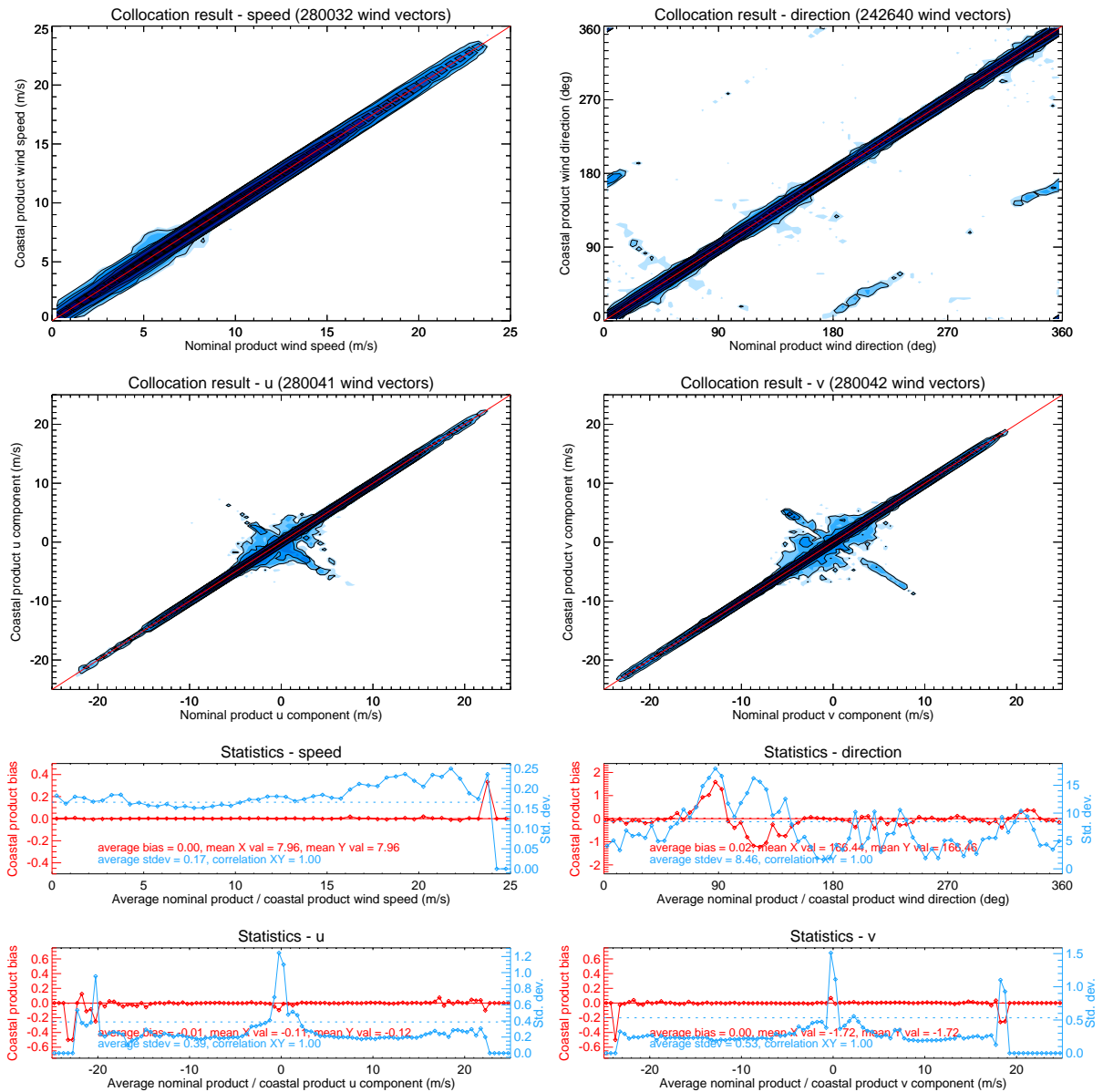


Figure 4: Two-dimensional histograms of wind speed, direction (w.r.t. wind coming from the North),  $u$  and  $v$  components of ASCAT coastal product with  $R_{max} = 15$  km from 1 March 2009 4:57 to 8:20 UTC (top). The biases (red) and standard deviations (blue) as a function of the average buoy and scatterometer results are shown in the bottom.

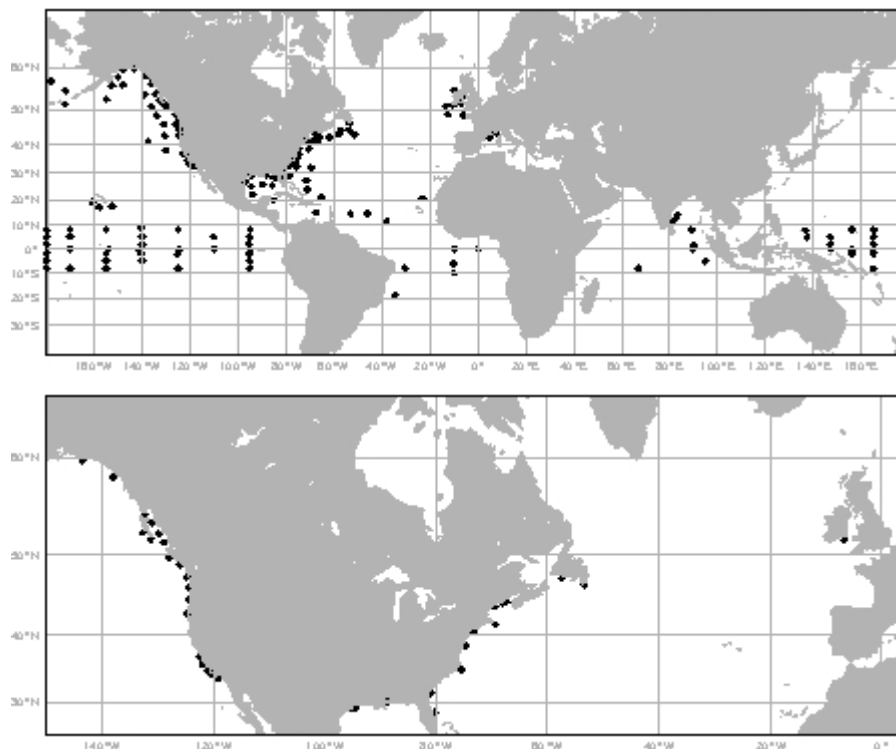
## 5 Buoy validations

In this report, scatterometer wind data are compared with in situ buoy wind measurements. The buoy winds are distributed through the Global Telecommunication System (GTS) and have been retrieved from the ECMWF MARS archive. The buoy data are quality controlled and (if necessary) blacklisted by ECMWF [4]. We used two sets of buoy data:

- (1) A set of approximately 150 moored non-coastal buoys spread over the oceans (most of them in the tropical oceans and near Europe and North America) which are also used in the buoy validations that are routinely performed for the OSI SAF wind products (see the links on <http://www.knmi.nl/scatterometer/osisaf/>). Most of these buoys are located more than 50 kilometres from the coast.
- (2) A set of approximately 35 moored coastal buoys which are located between approximately 10 and 50 kilometres from the coast. We used the web site of the National Data Buoy Centre (<http://www.ndbc.noaa.gov/>) to search for buoys located near the coast. The buoy identifiers of the used buoys are listed in Appendix A.

A buoy cannot be present both in data set (1) and (2). See Figure 5 for the locations of the buoys used in the comparisons. A scatterometer wind and a buoy wind measurement are considered to be collocated if the distance between the Wind Vector Cell (WVC) centre and the buoy location is less than the WVC spacing divided by  $\sqrt{2}$  and if the acquisition time difference is less than 30 minutes.

The buoy winds are measured hourly by averaging the wind speed and direction over 10 minutes. The real winds at a given anemometer height have been converted to 10-m equivalent neutral winds using the LKB model [4,5] in order to enable a good comparison with the 10-m scatterometer winds.



**Figure 5: Locations of the non-coastal (top) and coastal (bottom) moored buoys used in the comparisons.**

## 5.1 Results in non-coastal areas

In Table 1 we compare the 12.5-km operational and coastal products with various settings of  $R_{\max}$  (see section 2) in the regions far away from the coast. The wind speed bias and the standard deviations of the  $u$  and  $v$  wind components are shown in this table.

12.5-km product	# wind vectors	speed bias	stdev $u$	stdev $v$
1 Operational	14513	-0.28	1.46	1.58
2 $R_{\max} = 20$ km	15373	-0.29	1.43	1.56
3 $R_{\max} = 15$ km	15476	-0.29	1.46	1.59
4 $R_{\max} = 12.5$ km	15498	-0.29	1.48	1.61
5 Operational, collocated data set	12761	-0.28	1.43	1.56
6 $R_{\max} = 20$ km, collocated data set	12761	-0.28	1.43	1.54
7 $R_{\max} = 15$ km, collocated data set	12761	-0.29	1.44	1.54
8 $R_{\max} = 12.5$ km, collocated data set	12761	-0.29	1.45	1.57

**Table 1: Buoy collocation results of OSI SAF ASCAT 12.5-km operational and coastal wind products from March to August 2009 in non-coastal areas.**

The entries 1 to 4 of the table show that the coastal products yield more buoy collocations (# wind vectors) than the operational product, and that the number of collocations increases slightly with decreasing  $R_{\max}$ . This increase cannot be connected to the increase of the number of wind vectors in coastal areas so it must be due to a decrease in the number of Quality Controlled wind vectors with the decrease of  $R_{\max}$ . The smaller the area of backscatter averaging, the smaller the wind variability in the WVC area. Large sub-WVC wind variability is known to result in backscatter triplets far away from the Geophysical Model Function [6] with an increased rate of rejection by the Quality Control (QC) step. The wind speed bias and wind component standard deviations of all four products are fairly constant although the component standard deviations slightly increase with decreasing  $R_{\max}$ .

Entries 5 to 8 of Table 1 show the results for the common set of WVCs present in all four products. It appears that all products have comparable quality, but with a small increase of the wind component standard deviations of the product with  $R_{\max} = 12.5$  km. The coastal product with  $R_{\max} = 15$  km shows results slightly better to those of the operational product for the common points and some reduced QC otherwise.

## 5.2 Results in coastal areas

In Table 2 we compare the 12.5-km operational and coastal products with various settings of  $R_{\max}$  (see section 2) in the coastal regions (less than 50 km from the coast). The wind speed bias and the standard deviations of the  $u$  and  $v$  wind components are shown in this table.

12.5-km product	# wind vectors	speed bias	stdev $u$	stdev $v$
1 $R_{\max} = 20$ km	4752	-0.23	1.54	1.59
2 $R_{\max} = 15$ km	4768	-0.22	1.54	1.61
3 $R_{\max} = 12.5$ km	4789	-0.23	1.57	1.60
4 $R_{\max} = 20$ km, collocated data set	4596	-0.23	1.51	1.57
5 $R_{\max} = 15$ km, collocated data set	4596	-0.24	1.51	1.57
6 $R_{\max} = 12.5$ km, collocated data set	4596	-0.25	1.54	1.58

**Table 2: Buoy collocation results of OSI SAF ASCAT coastal wind products from March to August 2009 in coastal areas.**

The number of buoy collocations (# wind vectors) slightly increases with decreasing  $R_{\max}$ , like in the non-coastal case (see entries 1 to 3 in the table). This may again be connected to the decrease of wind variability when backscatter averaging is done over a smaller area, but in this case we also observe that we get some more wind data near to the coast with a smaller value of  $R_{\max}$ . This can be understood since it is easier to fit WVCs without land contamination in bays and between isles when the backscatter averaging area is smaller.

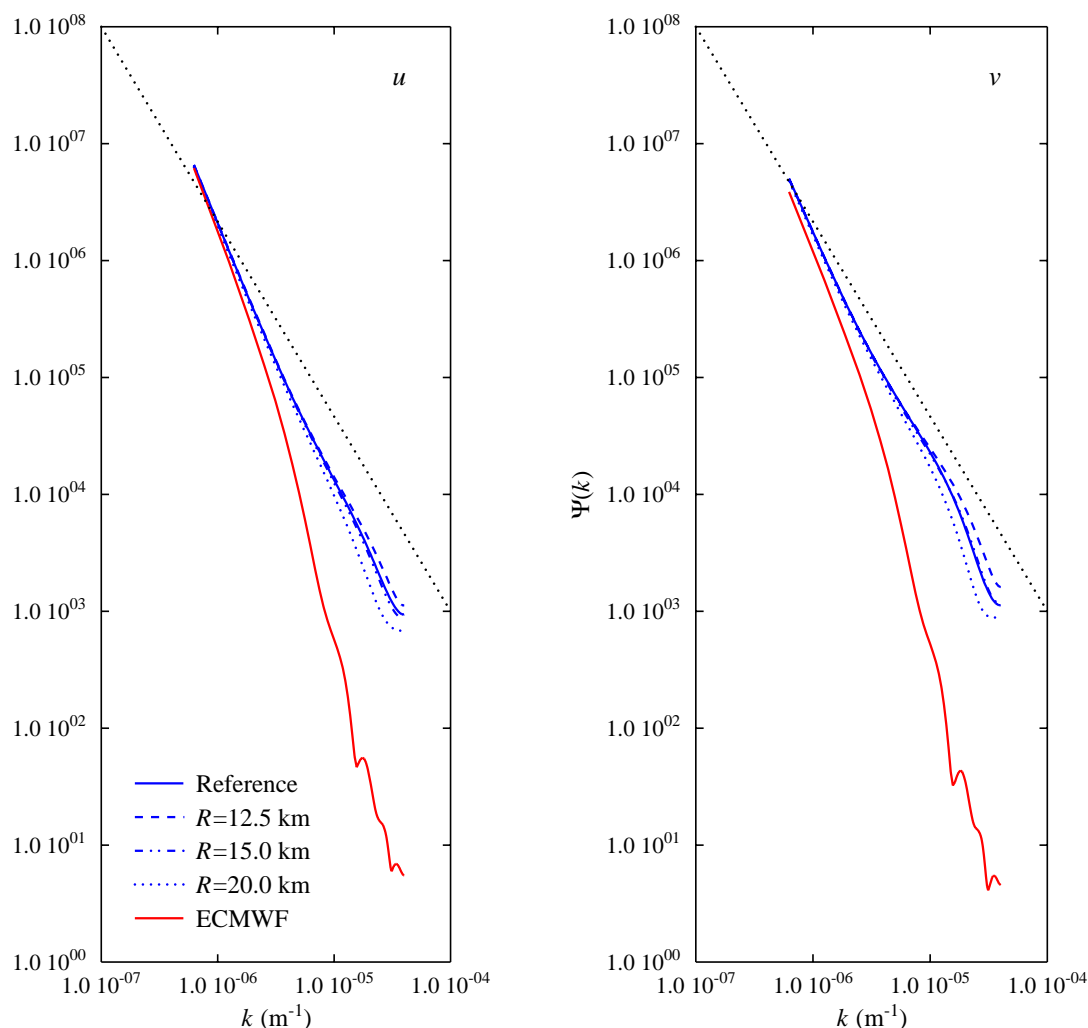
Like in the non-coastal areas, the wind component standard deviations slightly increase with decreasing  $R_{\max}$ . When we consider the common set of WVCs present in all three coastal products (entries 4 to 6 in Table 2), the product with  $R_{\max} = 12.5$  km again appears slightly degraded with respect to the two other products.

The wind speed bias in the coastal areas is approximately -0.23 m/s as compared to -0.29 m/s in the non-coastal areas (see Table 1). If the backscatter averaging would take too many land contaminated full resolution  $\sigma_0$  values into account, it could be expected that the averaged WVC backscatter is higher since land areas yield higher radar reflectivities. This would result in significantly higher wind speed biases near the coast which is clearly not the case. In this sense the way of backscatter averaging and land screening as described in [2] proves to be adequate.

We note furthermore that wind speed biases are seasonally dependent and that the biases found here over 6 months are within expectation.

## 6 Spectral analysis

Wind component spectra are a means to detect noise and assess the relative amount of small scale information in a wind product [7]. Figure 6 shows the wind spectra of the operational ASCAT product and the three flavours of the coastal product. It appears that all products have comparable spectra with a slope close to the  $k^{-5/3}$  spectrum which is shown as a black dotted line in the plots. According to a host of measurements, among which from aircraft [8], and the 3D turbulence theory of Kolmogorov, the wind spectra follow such spectra for scales smaller than about 500 km (spatial frequency  $2 \cdot 10^{-6} \text{ m}^{-1}$ ). The coastal product with  $R_{\text{max}} = 12.5 \text{ km}$  yields the highest values at high spatial frequencies indicating the presence of many small scales in the winds. The spectrum of the  $R_{\text{max}} = 15 \text{ km}$  product is closest to the one of the operational 12.5-km product, the  $R_{\text{max}} = 20 \text{ km}$  product shows the least small scale information (lowest values in the spectrum tail). None of the spectra shows significant flattening at high spatial frequencies which indicates that there is little white noise in the winds.



**Figure 6: Wind spectra of ASCAT operational and coastal wind products. The results for the  $u$  wind components are shown in the left hand side plot and for the  $v$  wind component in the right hand side plot. The results are for the operational product ('Reference') and for the coastal products with different  $R_{\text{max}}$  settings. The spectra of the ECMWF global model forecasts are also shown. The plots cover the period of 1 to 31 March 2009.**

## 7 Conclusions

Three different ASCAT coastal products, with backscatter averaging cut-off radii  $R_{\max} = 20, 15$  and  $12.5$  km, have been validated. All three provide wind quality well within the OSI SAF product requirements [9] (wind speed bias less than  $0.5$  m/s and wind component RMS better than  $2.0$  m/s), both in non-coastal and coastal regions.

The coastal product made with a backscatter averaging cut-off radius  $R_{\max} = 15$  km most closely resembles the operational  $12.5$ -km product, both with respect to the wind component standard deviations and to the shape of the wind component spectra. The coastal product provides slightly more winds after QC than the operational product, probably due to the smaller spatial averaging extent, therefore smaller ocean wind variability and consequently greater consistency of the backscatter triplet. This setting will be used in the implementation of the ASCAT coastal product in the OSI SAF.

We note that the required characteristics of the wind products are application dependent. This is, in applications interested in high wind gradients, such as near tropical cyclones, even higher resolution products than the ones presented here may be worthwhile, since intense small-scale details may become visible. The limited amount of noise visible in the  $12.5$ -km products is very encouraging in this respect.



## 8 Future work

Although the coastal product following from the current AWDP settings performs very well, some aspects need further elaboration. The first aspect lies in the improved QC for the coastal product. This indicates that in cases with variable winds (fronts, centres of lows, hurricanes), box processing results in more consistent backscatter triplets, i.e., closer to the CMOD5.N GMF in measurement space. Along the same lines, one may expect lower geophysical noise at the relatively more variable spatial backscatter conditions at low winds [6]. The box processing appears also less problematic in the ambiguity removal, thus resulting in spatially more coherent wind patterns. Since the spatial consistency check in 2DVAR is most active in variable wind conditions, this asset of the coastal processing may be another sign of physically more robust processing. However, these aspects need further detailed elaboration in order to increase our understanding of the differences between Hamming and box processing.

Other aspects that need elaboration are:

- More detailed geophysical validation, since coastal winds are more likely influenced by currents, fetch and water depth effects.
- Processing over a full year, we know that there are seasonal bias variations of scatterometer winds with respect to buoys and NWP models and the current work only covers the NH summer period;
- Use of the ASCAT land/sea mask versus higher resolution ECMWF land/sea masks;
- Tuning of AWDP to the coastal processing, i.e., ocean calibration, noise normalisation and computation, and QC settings.

As mentioned in the conclusions, experimental higher resolution products, e.g., with  $R_{\max} = 7.5$  km posted at 6,25 km may be worthwhile in extreme weather conditions with large wind gradients, such as hurricanes or polar lows.

## 9 Appendix A: List of coastal buoys

These are the buoy identifiers of the buoys in coastal areas (approximately 10 to 50 km from the coast) that were used in the validations in section 5. The buoy locations can be looked up on <http://www.ndbc.noaa.gov/>.

41008	44251	46082
41009	44255	46083
41025	46011	46132
42007	46013	46145
42012	46015	46147
42035	46023	46183
42043	46025	46185
44009	46028	46204
44018	46029	46206
44025	46041	46208
44027	46042	62094
44032	46050	
44034	46054	