ON HIGH-RESOLUTION SCATTEROMETER WINDS NEAR THE COAST

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ABSTRACT

The Advanced SCATterometer (ASCAT) operational processing uses spatial filtering with a Hamming window to avoid noise due to aliasing. The spatial extent of the Hamming windows prevents processing near the coast line. However, sea surface winds near the coast are very important, given that activities related to shipping and transport, off-shore resource exploitation, wind parks and tourism are most intense near the coast. Furthermore, coastal winds are also important for monitoring ecological and erosion processes. To provide ASCAT winds closer to the coast, three different products have been generated with spatial filtering over a circular box, and subjected to validation both in coastal and open ocean areas. The product made with a backscatter averaging cut-off radius R_{max} = 15 km closely resembles the operational ASCAT 12.5-km product. However, the smaller spatial averaging extent of the box compared to the Hamming window, not only allows retrieving winds closer to the coast, but also captures smaller ocean wind variability and it is consequently providing greater consistency of the ASCAT backscatter triplet with the wind Geophysical Model Function (GMF), as observed by a reduced elimination of points by the Quality Control (QC). Due to the low noise observed in this product, we anticipate that in cases with high wind gradients, such as near tropical cyclones, even higher resolution winds than the ones presented here may be worthwhile retrieving.

1. INTRODUCTION

Scatterometer winds are used in meteorological nowcasting (NWC), Numerical Weather Prediction (NWP) and marine applications. In NWC the focus is on timeliness, spatial detail and consistency; where extreme and dynamical events get most attention, and some (white) noise may be acceptable. In NWP, the focus is on timeliness, coverage and consistency with the model dynamics. In forcing the ocean, scales of tens of kilometres are relevant, so here spatial detail is most relevant.

Sea surface winds near the coast are very important, given that activities related to shipping and transport, off-shore resource exploitation, wind parks and tourism are most intense near the coast. Furthermore, coastal winds are also important for monitoring ecological and erosion processes. As an example of this interest, the National Oceanographic and Atmospheric Administration (NOAA) requested the production of coastal winds from ASCAT, in order to better anticipate how the Deepwater Horizon oil spill in the Gulf of Mexico drifted towards the coast, in their attempt to combat immense ecological losses.

KNMI has over the years specialized in scatterometer wind data processing. A generic and portable processing package has been developed in the framework of the EUMETSAT Numerical Weather Prediction (NWP) SAF, which forms the basis of the ASCAT Wind Data Processor (AWDP) and the SeaWinds Data Processor (SDP), openly available to users. AWDP and SDP are (were) used for the near real-time (NRT) operational wind production from the ERS-2, ASCAT and SeaWinds scatterometers at KNMI (www.knmi.nl/scatterometer), in the framework of the EUMETSAT Ocean and Sea Ice Satellite Application

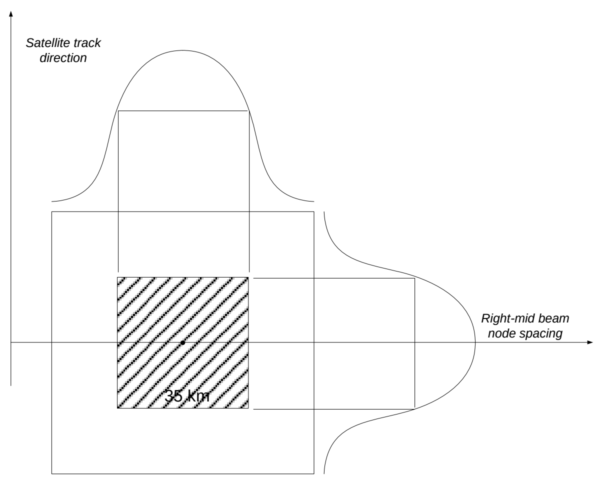

Figure 1. Ground geometry of the spatial smoothing for σ0 values corresponding to the right mid beam for a given WVC (node) N, for the 12.5 km ASCAT level 1 product.

Facility (OSI SAF). Currently, SDP is furthermore being used as the starting point to build an OceanSat-II scatterometer Wind Data Processor (OWDP).

The OSI SAF delivers operational Level 2 wind products in NRT, 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 (σ_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 known as a Hamming window and shown in Figure 1. This function has been selected to allow re-sampling of the averaged backscatter values to any spatial grid without introducing spatial aliasing effects. See the ASCAT product guide [1] for more information on the Level 1 product characteristics.

Apart from the 25-km and 12.5-km Level 1 products, also a full resolution (FR) ASCAT Level 1 product is available via the EUMETSAT Data Centre. This product contains geolocated individual radar backscatter values, 256 values along each antenna beam. In the FR product the data are organized along the six antenna beams rather than per WVC in the swath. The sampling within the ASCAT swath of individual backscatter values along-beam is of approximately 2 km for mid beams and 3 km for side beams. The FR backscatter values represent footprints of approximately 10 × 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. In this report, we assess the quality of the 12.5-km ASCAT coastal product 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-averaged 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 compare the spectral characteristics of the diverse wind products.

2. EXPECTATIONS

Figure 5 shows the buoy data used in this paper, which has been kindly provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). The open ocean buoys are mainly in the Tropics and near the coast of Europe and North America. Table 1 shows the buoy comparison of several operational scatterometer wind products: the ASCAT products on 12.5 km and 25 km grid size, the SeaWinds product on a 25 km grid, all as processed by the OSI SAF (labelled "KNMI"), and the SeaWinds 25 km product disseminated by NOAA (manati.orbit.nesdis.noaa.gov/doc/oppt.html). Table 1 is based on collocated data from October 2008 with all buoys that are not blacklisted by ECMWF. Collocations are registered when their time difference is 30 minutes at most and the spatial distance less than the scatterometer grid size divided by the square root of two, where only the closest Wind Vector Cell (WVC) to the buoy is considered.

ASCAT 12.5 km		ASCAT 25 km		SeaWinds 25km KNMI		SeaWinds 25km NOAA	
SD_u ms^{-1}	SD_v ms^{-1}	SD_u ms^{-1}	SD_v ms^{-1}	SD_u ms^{-1}	SD_v ms^{-1}	SD_u ms^{-1}	SD_v ms^{-1}
1.67	1.65	1.70	1.64	1.76	1.83	2.19	1.99

Table 1: Standard deviation of the difference between collocated buoy and scatterometer winds for October 2008. The ASCAT 12.5-km product shows the best verification against buoys of all available scatterometer products.

Table 1 shows that the ASCAT 12.5 km product compares most favourably to the buoys. This is because the scatterometer gives the average wind over an area, while the buoy measures at a single point. The buoy winds therefore contain more variance than the scatterometer winds, resulting in a representation error that decreases with decreasing scatterometer footprint, hence is minimal for the 12.5-km product in this set of products. Note also that the ASCAT results compare better with buoys than those of SeaWinds. This is due to ASCAT's more favourable measurement geometry and instrumental noise. KNMI's wind product from SeaWinds data contains less noise than NOAA's, resulting in a better comparison with buoy data [7].

Table 1 also suggests low noise in the 12.5-km product. One would expect that box averaging, i.e., averaging only over the grey area in Figure 1, would result in more small scale details, i.e., improved buoy verification, but on the other hand possibly at the expense of some noise (aliasing), leading to poorer buoy verification. However, one should realize that σ^0 in the grey box is not sampled by a point response function, but rather is oversampled with a field of view (FOV) of approximately 10 km (along fan beam) by 25 km (across fan beam). So, with all FOVs centered 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 Figure 2 for illustration. This σ^0 extent outside the WVC acts to suppress sampling noise or aliasing, since neighboring WVCs have much overlapping IFOVs for each beam and sample in part the same ocean spatial wind pattern.

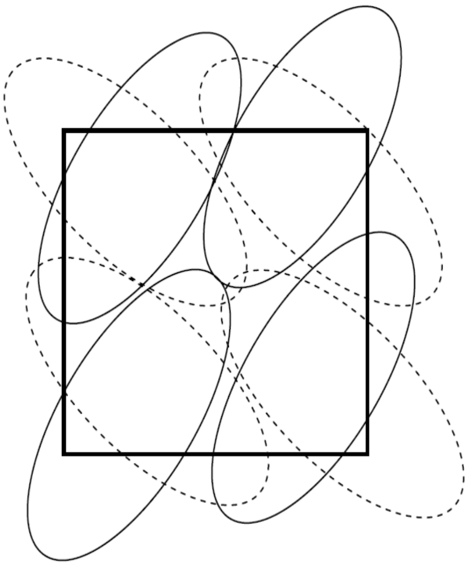

Figure 2. Schematic illustration of scatterometer sampling. A target WVC (thick solid line) is sampled from two different perspectives (for simplification), with a beam footprint indicated by solid and dashed lines, respectively. Both sample the WVC wind variability in a different way, leading to spatial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

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 σ^0s 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 AWDP QC is known to be active.

A last aspect of the box-averaging concerns the potential for resolution enhancement in ASCAT wind retrieval. Figure 2 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.

3. COASTAL PRODUCT

The validations of the coastal product are done using 6 months of ASCAT FR 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 σ_0 value.

Using the three settings of R_{max}, the 6 months of ASCAT data have been reprocessed. The 12.5-km OSI SAF operational wind data were reprocessed together with the FR data. After the replacement of the Level 1 backscatter data by the averaged σ_0 values, the rest of the wind processing was done in the same way as for the operational products [3].

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. It is planned to use the new mask in the near-real time production of the ASCAT coastal product and obtain winds even closer to the coast than in Figure 3.

4. COMPARISON WITH OPERATIONAL DATA

Figure 3 shows an example of the difference between the operational 12.5-km ASCAT product and the coastal product. It is clear that the coastal product is capable to

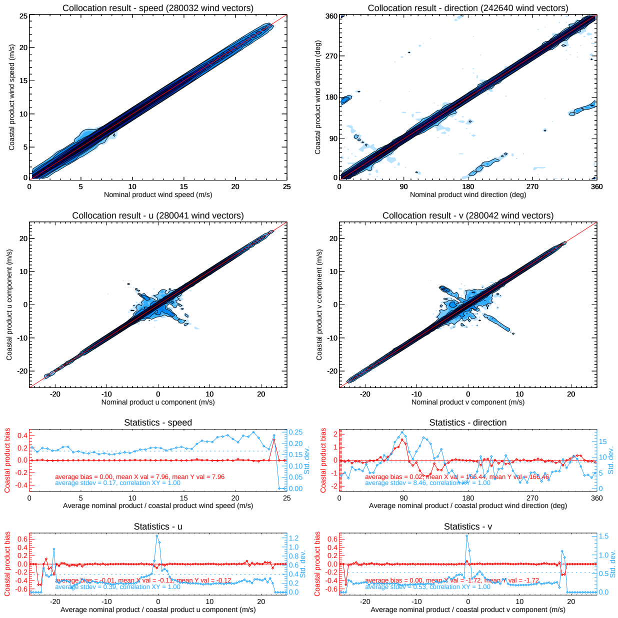

Figure 4. Two-dimensional histograms of wind speed, direction, u and v components of coastal product with Rmax = 15 km from 1 March 2009 4:57 to 8:20 UTC (top). The biases (red) and standard deviations (blue) as a function of the average buoy and scatterometer results are shown at the bottom

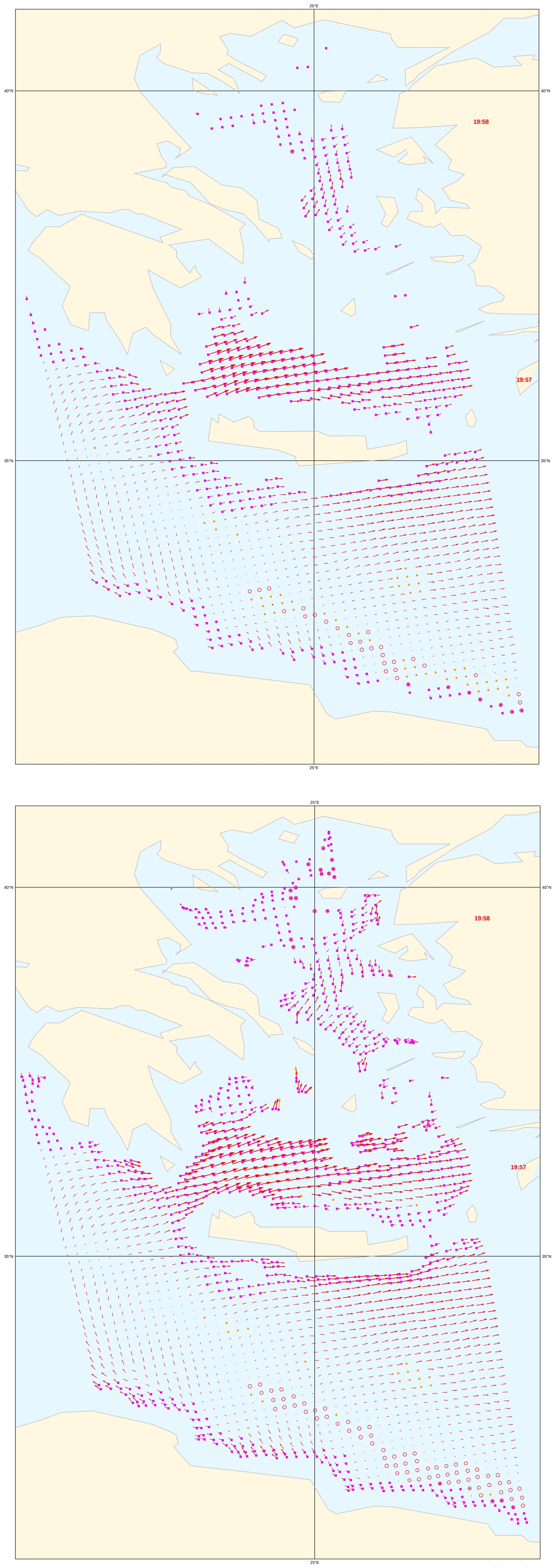

Figure 3. (Right) Example of operational 12.5 km ASCAT product (left) and corresponding coastal product with Rmax = 15 km (right) in the eastern part of the Mediterranean at 2 March 2009 19:57 UTC. The purple squares correspond to WVCs where the land flag is set, but where reliable winds can still be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

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.

Figure 4 shows two-dimensional histograms of the coastal product with Rmax = 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° apart mostly at the lower wind speeds (see u.v plots). The corresponding results for the coastal products with Rmax = 12.5 km and Rmax = 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 are small, less than 0.05 m/s.

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. 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 kilometers from the coast.

(2) A set of approximately 35 moored coastal buoys which are located between approximately 10 and 50 kilometers 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.

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 √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.

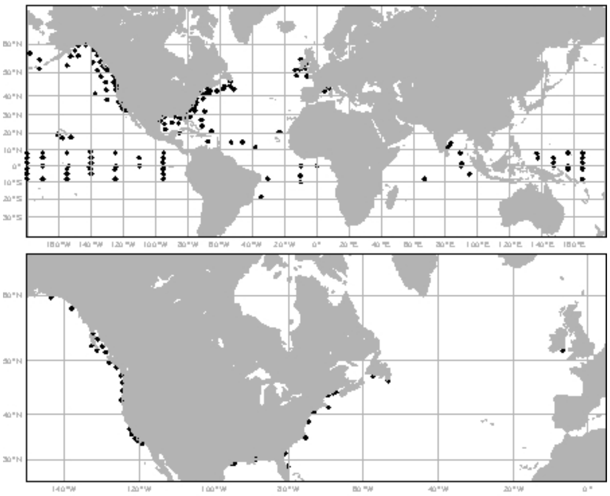

Figure 5. Locations of the non-coastal (top) and coastal (bottom) moored buoys used in the comparisons

	12.5-km product	Wind count	Bias ms^{-1}	SDu ms^{-1}	SDv ms^{-1}
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	12761	-0.28	1.43	1.56
6	R_{max} = 20 km, collocated	12761	-0.28	1.43	1.54
7	R_{max} = 15 km, collocated	12761	-0.29	1.44	1.54
8	R_{max} = 12.5 km, collocated	12761	-0.29	1.45	1.57

Table 2: Buoy collocation results of OSI SAF ASCAT 12.5-km operational and coastal wind products from March to August 2009 in non-coastal areas.

5.1 Results in non-coastal areas

In Table 2 we compare the 12.5-km operational and coastal products with various settings of R_{max} 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.

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 2 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 12.5-km product. 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 3 we compare the 12.5-km operational and coastal products with various settings of R_{max} 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 count	Bias ms^{-1}	SD*u* ms^{-1}	SD*v* ms^{-1}
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	4596	-0.23	1.51	1.57
5	R_{max} = 15 km, collocated	4596	-0.24	1.51	1.57
6	R_{max} = 12.5 km, collocated	4596	-0.25	1.54	1.58

Table 3: Buoy collocation results of OSI SAF ASCAT 12.5-km operational and 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 3) the 12.5-km product 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 2). If the backscatter averaging would take too many land contaminated full resolution σ_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 asses 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 flavors 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 $2 \cdot 10^{-6}$ m^{-1}). The coastal product with R_{max} = 12.5 km yields the highest values at high spatial frequencies indicating the presence of many small scales in the winds. The spectrum of the R_{max} = 15 km product is closest to the one of the operational 12.5-km product, the R_{max} = 20 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.

7. CONCLUSIONS

The operational ASCAT scatterometer wind products, based on spatially filtered backscatter data using a Hamming window, compare favorably with buoy data, particularly at high sampling (12.5 km). Box-filtered backscatter data provides lower land contamination near the coast and thus reliable winds can be computed in the coastal area, which is of great economic and ecological importance. Three different ASCAT coastal products have been validated following [9]. All three provide wind quality well within the OSI SAF quality specifications (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

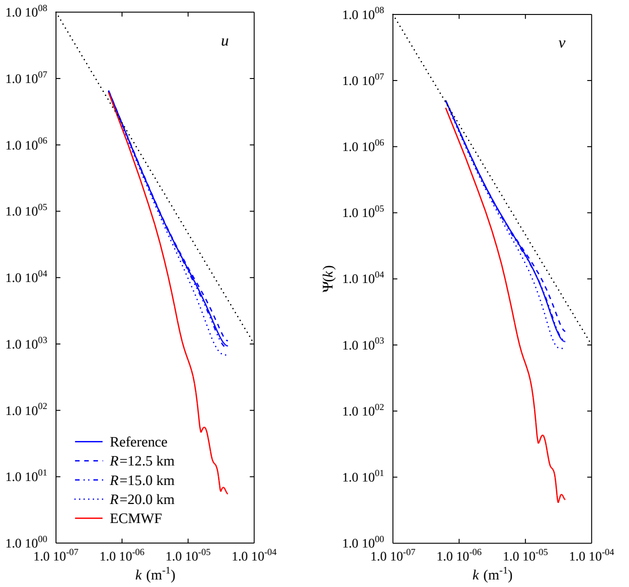

Figure 6: Wind spectra of ASCAT operational and coastal wind products. The results for the u wind components are shown in the left hand side plot and for the v wind component in the right hand side plot. The results are for the operational product ('Reference') and for the coastal products with different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

the wind component spectra. However, the box-averaged 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. An experimental ASCAT coastal product has been put available within the OSI SAF with R_{max} = 15 km (available through scat@knmi.nl).

We note that the required characteristics of the wind products are application dependent. This is, in applications interested in high wind gradients, such as on 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.

7.1 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, centers 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;
- 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 normalization and QC settings.

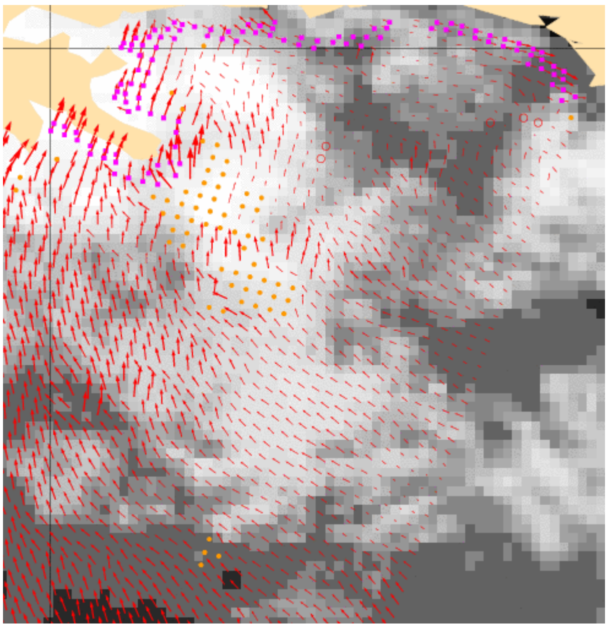

Figure 7: Example of experimental 12.5 km ASCAT coastal product with Rmax = 15 km in the Gulf of Mexico. The purple squares correspond to WVCs where the land flag is set, but where reliable winds can still be computed. The orange dots show rejection by the AWDP QC, due to the oil spill damping of wind-induced sea surface roughness.

As mentioned in the conclusions, experimental higher resolution products, e.g., with Rmax = 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.

Wind conditions in the coastal regions may be very variable. Therefore, we look forward to the global availability of more and more scatterometer wind data streams. Currently, ASCAT on MetOp-A and the scatterometer on the ESA ERS-2 scatterometer provide winds over coastal waters, but this is being complemented by the Indian OceanSat-II scatterometer, launched in 2009, the HY-2A scatterometer, due for launch in 2011 and the MetOp-B ASCAT, planned for 2012, and the Cine-French Ocean satellite ,CFOSAT, rotating fan-beam scatterometer in 2014. These systems may be able to provide winds every 6 hours across the globe [10].

Acknowledgements

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.

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