VERIFICATION OF SCATTEROMETER WINDS

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Abstract

Since several centres produce scatterometer wind products, user guidance would be useful to direct users to the most appropriate product for their application. Moreover, for further product development advanced analysis tools are needed to determine product characteristics and improvement. Since not all scatterometer data sets have the same Quality Control (QC) and coverage, sampling may play a distinct role in product assessment. Another complication in product comparison is in its smoothness. Smooth products will verify well against NWP model fields, but relatively poor against in situ measurements. Here, we elaborate two tools for product comparison. The first is dual product collocation with a representative set of reference data; in the current case from a buoy network. The second tool exists in spectral analysis of the spatial structures in the scatterometer products. Our analyses show that ASCAT scatterometer winds reveal detailed spatial wind characteristics and show a unprecedented verification with buoy data. Moreover, the KNMI SeaWinds product at 25-km sampling shows better verification against buoys than the NOAA SeaWinds product over a common data set of points. While the KNMI SeaWinds QC, when applied to the NOAA SeaWinds product, shows a clear improved buoy verification, NOAA SeaWinds QC has a smaller effect on the buoy verification of the KNMI SeaWinds product. Buoy verification and spectral analysis as presented in this paper are indispensible tools in the further development of the KNMI scatterometer products.

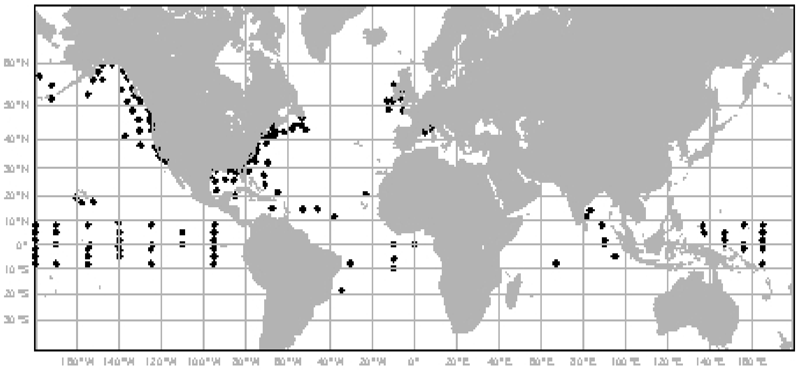

Figure 1: **Global distribution of buoy data used in this study.**

1. INTRODUCTION

The EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF) has over the years specialized in scatterometer data processing. A generic and portable scatterometer wind data processing package has been developed in the EUMETSAT Numerical Weather Prediction (NWP) SAF, which forms the basis of the ASCAT Wind Data Processor (AWDP) and the SeaWinds Data Processor (SDP), both available from KNMI. 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). After more than 10 years of successful operation, the SeaWinds data flow halted on 2009 due to excessive wearing of the rotary joint of the radar beam which got finally stuck. Currently, SDP is used as the starting point to build an OceanSat-II scatterometer Wind Data Processor (OWDP). NRT SeaWinds products were also made available by the US National Oceanographic and Atmospheric Administration (NOAA; manati.orbit.nesdis.noaa.gov/doc/oppt.html). Portabella and Stoffelen (2001, 2002ab) verified that the Physical Oceanography Distribution And Archive Centre (PO.DAAC) SeaWinds products at JPL and the NRT SeaWinds product at NOAA exhibit very similar product characteristics and found some basic differences in the JPL and KNMI QC. Moreover, wind inversion and ambiguity removal follow somewhat different procedures at KNMI than at JPL (Stoffelen and Portabella, 2006; Portabella and Stoffelen, 2004; Stiles, 1999; Vogelzang et al., 2009). In addition to differences between production centres, one centre often produces multiple products from one satellite instrument, appealing to the needs in different application areas.

Scatterometer winds are used in meteorological nowcasting (NWC), NWP and marine applications. In NWC the focus is on timeliness and spatial detail; extreme and dynamical events get most attention, where some (white) noise may be acceptable. On the other hand, for the objective use in NWP, strict QC should be provided with the product, which often proves essential for achieving beneficial impact. NWP analyses focus on the 100-km scales and wind retrieval precision and accuracy are generally required above spatial detail. In forcing the ocean, scales of tens of kilometres are relevant, so here spatial detail is important. So, different application areas require different product characteristics and these product characteristics should be well documented in a standard fashion. This is being further elaborated within the International Ocean Vector Winds Science Team (IOVWST).

2. BUOY COMPARISON

Figure 1 shows the buoy data used in this paper, which has been kindly provided by the European Centre for Medium-Range Weather Forecasts, ECMWF. These 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. 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**	
σ_u	σ_v	σ_u	σ_v	σ_u	σ_v	σ_u	σ_v
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. As was shown earlier (*Vogelzang et al*., 2009), KNMI's wind product from SeaWinds data contains less noise than NOAA's, resulting in a better comparison with buoy data.

SeaWinds 25-km product	# wind vectors	speed bias	stdev *u*	stdev *v*
NOAA product, including **outer swath**	3845	0.25	2.54	2.51
NOAA product, no outer swath data	3276	0.20	2.47	2.18
KNMI, no outer swath data	3061	-0.48	1.79	1.88
NOAA product, collocated KNMI	2954	0.15	2.19	1.99
KNMI, collocated with NOAA product	2954	-0.49	1.76	1.83

Table 2: **Statistics of the difference between collocated buoy and scatterometer winds before and after dual collocation. The KNMI SeaWinds 25-km product verifies well with buoys.**

It is of interest to further characterize the differences between the KNMI and NOAA SeaWinds 25-km products, i.e., is the different verification due to inversion, QC, or ambiguity removal? We can use the buoy collocations to investigate this further, by collocating the collocated data sets, i.e., by dual collocation. The top three data rows of Table 2 show collocation statistics for the operational SeaWinds products, but separated for the outer swath region (200 km on each side), that contains winds in the NOAA product, but not in the KNMI product. It is clear that the outer swath partially contributes to increasing the SD of the differences with the buoys. However, the RMS verification of the KNMI product remains much smaller without outer swath region. It is also clear from Table 2 that the KNMI wind speeds are biased low with respect to the buoys, whereas NOAA is biased high. Further wind calibration appears necessary. The two lowest rows of Table 2 represent statistics for the KNMI and NOAA products after dual collocation, i.e., with identical data sampling over the buoys. The KNMI QC further rejects 322 WVCs in the NOAA product with considerable improvement in the NOAA buoy verification. On the other hand, the NOAA QC rejects just an additional 107 WVCs in the KNMI product with only limited improvement in the KNMI buoy verification. The KNMI QC thus appears an useful addition to the NOAA QC, but less so the other way around.

SeaWinds 25-km product	# wind vectors	speed bias	stdev *u*	stdev *v*
New NOAA, including **outer swath**	4023	0.09	2.54	2.33
New NOAA, no outer swath data	3342	0.10	2.57	2.24
KNMI*, including **outer swath** data	3756	-0.49	1.84	1.95
KNMI*, no outer swath data	3033	-0.46	1.85	1.93
KNMI, collocated with KNMI*	2926	-0.48	1.78	1.88
KNMI*, collocated with KNMI	2926	-0.48	1.78	1.87

Table 3: **Same as Table 2, but products based on new NOAA processing, indicated by KNMI*. KNMI* produces good quality outer swath winds.**

NOAA released an experimental product to the operational wind community that, among others, facilitates processing of outer swath data by providing a quadruplet of backscatter data. Table 3 is similar to Table 2, but for NOAA and KNMI products with these additional outer swath data. It is clear that the new NOAA products keeps more WVCs (see table 2), but at the expense of larger RMS differences with the buoys, while the speed bias is somewhat reduced. The new KNMI product (KNMI*) produces outer swath data at very similar quality to the other WVCs. Due to the new NOAA data, KNMI had to adapt the QC procedure which resulted in a slightly poorer verification with buoys. The two bottom rows in table 3, which are the dual collocated data, show that the wind retrieval and ambiguity removal quality has not changed over the common WVCs and that the slight product degradation is entirely due to the new KNMI QC.

KNMI 100-km product	# wind vectors	speed bias	stdev *u*	stdev *v*
no MSS used	3156	-0.21	2.16	2.06
MSS used	3155	-0.25	2.03	2.06
MSS*, no outer swath data	3163	-0.23	2.11	2.07
MSS*, **outer swath** data	3925	-0.25	2.09	2.12
MSS collocated with MSS*	3038	-0.25	2.01	2.04
MSS* collocated with MSS	3038	-0.25	2.04	2.03

Table 4: **Same as Table 2, but products at the 100-km swath grid. MSS is clearly beneficial in the KNMI 100-km product.**

The OSI SAF products at KNMI are based on the so-called Multiple Solution Scheme (MSS). Portabella and Stoffelen (2004) show that this scheme effectively propagates the full wind vector probability density function (PDF), as may be computed from the available backscatter data, to the ambiguity removal step, where a spatially consistent wind pattern is objectively determined from the available PDFs at each WVC. Vogelzang et al. (2009) show that MSS effectively suppresses noise while maintaining important spatial detail. In table 4 MSS is tested for the SeaWinds 100-km product at KNMI and is shown to be also clearly beneficial at this resolution. This is because MSS reduces noisy solutions (sometimes due to rain) in the nadir region of the swath (not shown here). Again, the new NOAA product slightly changes the KNMI QC and deteriorates the MSS* (no outer swath) buoy verification with respect to MSS. KNMI 100-km outer swath winds appear fine and of similar quality to the other WVCs. Also note that averaging the 25-km backscatter data in 100 km WVCs increases the mean backscatter and thus the wind speed bias. Obviously, it also increases the buoy wind difference RMS, since a 100-km WVC is a worse representation of the buoy point measurement than a 25-km WVC.

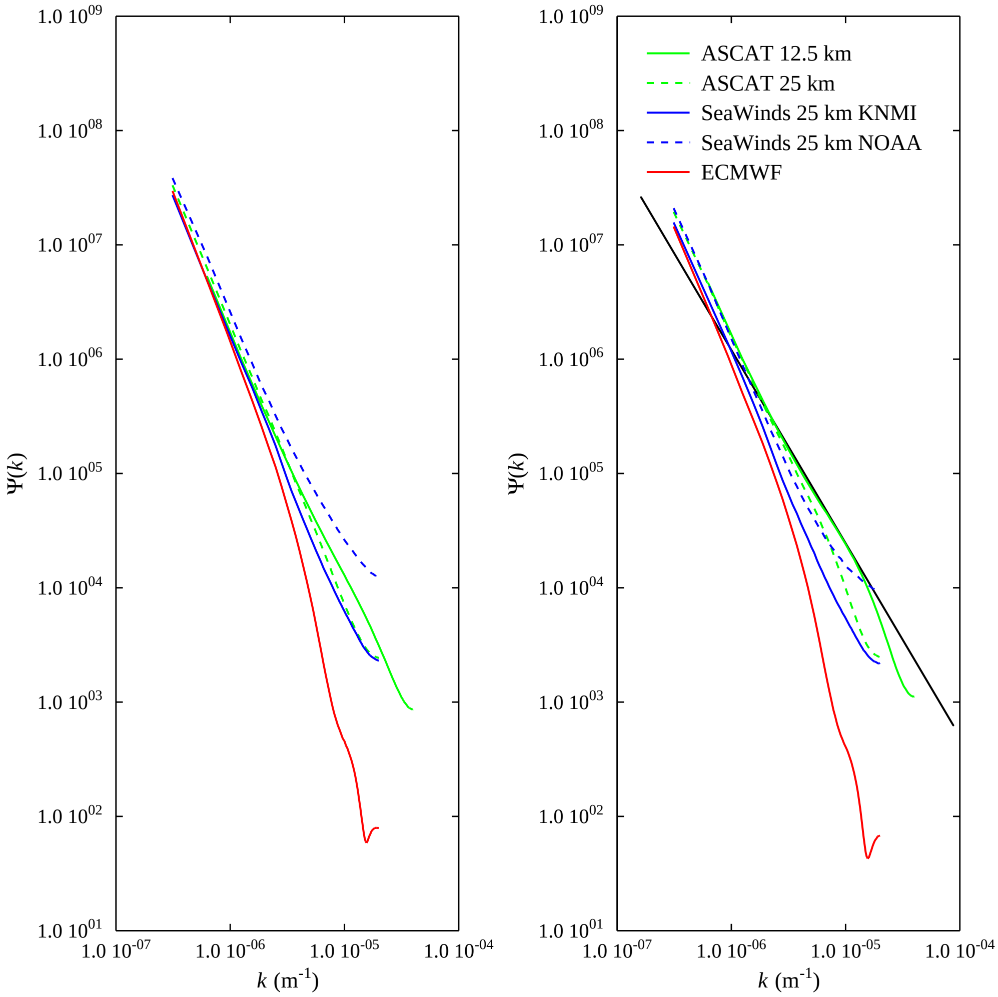

Figure 2: **Spectra for the wind components *u* (left) and *v* (right) for ASCAT (green curves), SeaWinds (blue curves) and the ECMWF model (red curves). The black solid line in the right panel shows a *k^-5/3 spectrum.***

3. WIND SPECTRA

Aircraft measurements and buoy measurements have been used to construct atmospheric wind spectra (e.g., Nastrom and Gage, 1985; Wikle et al., 1999). A general finding is that tropospheric wind spectra exhibit a dependency on the wave number, k, of $k^{-5/3}$ for $k > 2.10^{-5}$ radians/m corresponding to wavelengths smaller than 300 km. The $k^{-5/3}$ regime corresponds to 3D turbulence. The aspect ratio of 3D turbulence in the atmosphere is however very large with horizontal scales about hundred times larger than vertical scales. Spectra are usually plotted on a log-log scale where the logarithm of spectral density in m^3s^{-2} is given as a function of wave number. Nastrom and Gage (1985) analysed a large data set of aircraft wind measurements over the globe and found that the logarithm of the wind variance spectral density varies by 0.4, i.e., just less than half an order of magnitude, from one case to the next. Moreover, the zonal and meridional wind show very similar behaviour, as may be expected for 3D turbulence. The $k^{-5/3}$ law is shown in the right panel of Figure 2 by the solid black line.

Figure 2 shows the spectra of the zonal (u ; left hand panel) and meridional (v ; right hand panel) wind components for the wind products in table 1 (green curves for ASCAT, blue curves for SeaWinds), together with the ECMWF model wind spectra (red curves). The spectra were obtained using samples of 128 consecutive wind vectors. Isolated missing values were linearly interpolated. Though the sample length is typically 3200 km (1600 km for ASCAT 12.5 km winds), there are still variations in the wind at scales larger than the sample length. These were removed by high pass filtering each sample with the first difference method before the FFT operation and correcting the resulting spectrum with the first difference transfer function (*Percival and Walden,* 1992). The spectra are normalized such that its integral over all positive values of the spatial frequency k equals the total variance.

Figure 2 shows that the ASCAT 12.5 km product (solid green curves) contains more small scale information than the 25 km product (dashed green curves). This is easily understood when viewing the scatterometer winds as a spatial average: the smaller the averaging area, the more variability in the wind.

Figure 2 also shows that the spectra of NOAA's SeaWinds wind product tend to become horizontal at high spatial frequencies (small scales), in particular for the meridional wind component v. This is another indication of the noise in the NOAA product that is filtered out in the KNMI product. The ASCAT spectra show no sign of such a noise floor. The ASCAT 25-km product contains slightly more signal at small scale than KNMI's SeaWinds 25-km product, but more notably for the meridional wind component v. Note the rapid cut-off at small scales in the ECMWF model winds (red curves). Such reduced small-scale variability arguably improves medium-range weather prediction.

In terms of spectral slope at high wave numbers in the 3D turbulence regime, we note that the slopes of ECMWF, KNMI 25-km SeaWinds, 25-km ASCAT and 12.5-km ASCAT decrease as -4.0, -2.1, -2.0, and -1.9 respectively. Note that from these products the ASCAT-12.5-km product contains most small-scale wind variance, while, as seen from Table 1, it provides at the same time the best buoy verification. This suggests that the additional small-scale variance in the 12.5-km ASCAT spectra actually verifies with the local buoy data. The NOAA SeaWinds product contains yet more small-scale variance than the ASCAT 12.5-km product, but its spectral variance does not follow a linear spectrum close to 3D turbulence, nor does it verify well with the local buoy winds. This is, the abundant small-scale variance in the NOAA SeaWinds product appears as noise.

4. YET HIGHER ASCAT RESOLUTION

Given the excellent ASCAT results in the previous section, the question emerges whether further enhanced resolution products would be useful. Given the excellent quality of the ASCAT 12.5-km product, one would expect increased resolution to be quite useful in cases with large wind gradients, such as in extreme weather.

During level 1 ASCAT processing the individual radar measurements are gridded to average cross sections that can be handled by AWDP. In order to minimise noise (prevent aliasing), a Hamming window is applied as indicated in figure 5. Note that figure 5 pertains to a grid size of 25 km; for a grid size of 12.5 km all sizes have to be divided by 2. The result of this procedure is that the effective resolution decreases: the ASCAT 25-km products are based on weighted radar cross section averages over an area of 100 km by 100 km with a spatial resolution of 50 km. Small-scale features are smoothed by the filter.

One would expect that box averaging, i.e., averaging only over the grey area in figure 5.4, would result in more small scale details, but possibly at the expense of some noise (aliasing). However, one should realise that σ^0 is the grey box is not sampled by a point response function, but multiple times with a field of view of approximately 3 (along fan beam) by 25 km (across fan beam). So, when all FOVs are centred in a WVC, the integrated FOV (IFOV) for that WVC will be a function extending up to 25 km outside the WVC in the direction across the fan beam. This σ^0 extent outside the WVC acts to suppress sampling noise or aliasing, since neighbouring WVCs have much overlapping IFOVs for each beam.

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 (Portabella and Stoffelen, 2006). 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 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 (Portabella and Stoffelen, 2006). Moreover, geophysical noise is only substantial below 5 m/s and not expected to generate much spurious noise in the retrieved winds.

Therefore, one may expect reasonable enhanced resolution capability for ASCAT. To test this, EUMETSAT has processed the ASCAT data from the period December 17, 2008 to January 11, 2009 using box averaging rather than a Hamming window.

The spectra in figure 4, based on all data from this period, confirm that the box averaging indeed leaves more small scale details in the retrieved wind fields, without any sign of increased instrumental noise. Moreover, the box-averaged spectrum at small scales (of the order of 100 km) falls off with an exponent near -5/3, the value predicted from Kolmogorov’s turbulence theory and found from other measurements (e.g., *Wikle et al.*, 1999). The Hamming-averaged spectra fall off steeper with an exponent of about -2, a value found in earlier studies, e.g., *Freilich and Chelton*, 1986.

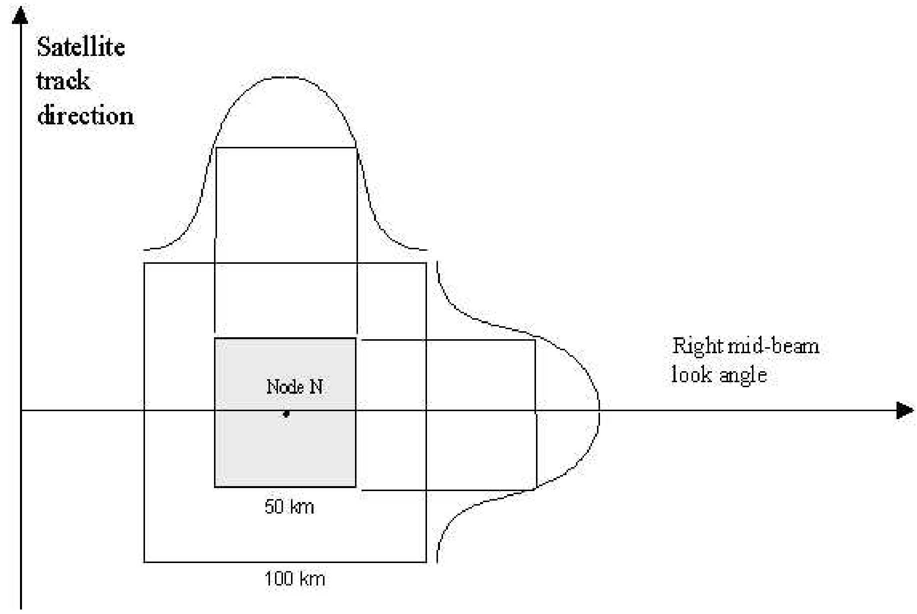

Figure 3 **Illustration of the Level 1 processing at each Node N for the 25-km ASCAT product (courtesy EUMETSAT).**

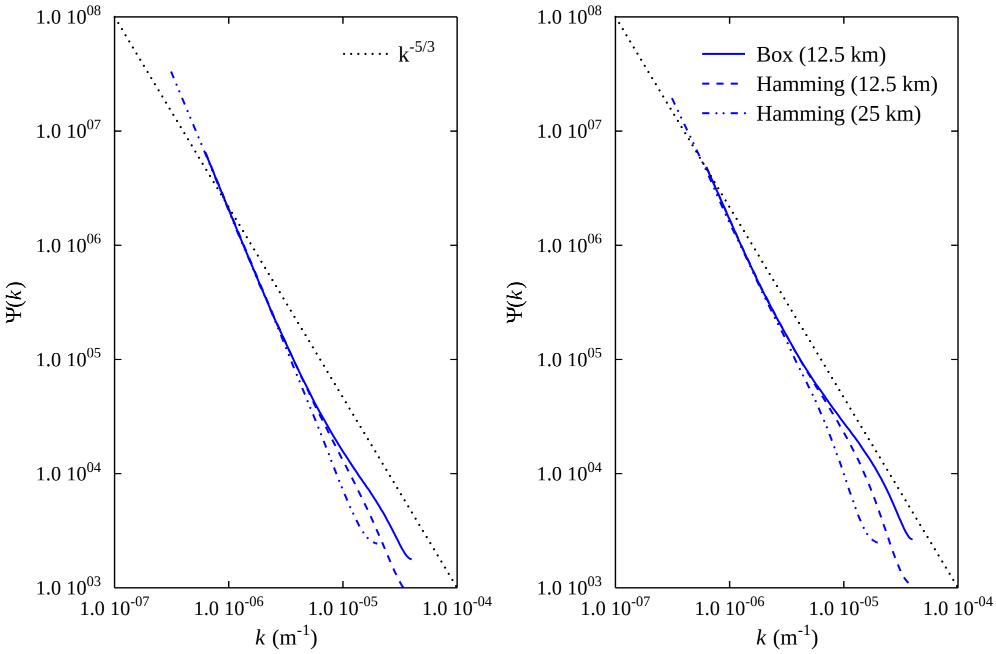

Figure 4: **ASCAT spectra for the meridional wind components *u* (left) and *v* (right) for box averaging in level 1 processing at 12.5 km (solid curves) and for the standard level 1 processing at 12.5 km (dashed curves) and 25 km (dot-dashed curves). The dotted lines show a** *k^-5/3* ***spectrum.***

5. CONCLUSIONS

Since several centres produce scatterometer wind products, user guidance would be useful to direct users to the most appropriate product for their application. Moreover, for further product development, advanced analysis tools are needed to determine product characteristics and improvement. Here, we elaborate two tools for product comparison. The first is dual product collocation with buoy data. The second tool exists in spectral analysis of the spatial structures in the scatterometer products. Dual collocation shows that not all scatterometer data sets have the same Quality Control (QC) and coverage and sampling plays a distinct role in product assessment. Another complication in product comparison is in its smoothness. A combination of spectral content analysis and dual collocation clearly reveals noisy products on the one hand and smooth products on the other. Smooth products verify relatively poor against in situ measurements and show steep spectra. Noisy products also verify relatively poor against in situ measurements but rather show flat spectra.

ASCAT winds are unprecedented in that they provide excellent buoy verification and, at the same time, a spectral slope in line with other (in situ) spectral measurements. Due to the lack of noise in the current ASCAT products resolution enhancement is being tested through box averaging rather than by a Hamming window. Small scales in the 12.5-km product are better preserved with box averaging. A further advantage of the box averaging is that ASCAT winds nearer to the coast may be retrieved. A coastal prototype AWDP is being tested at KNMI.

Operational ASCAT wind products on 25 km and 12.5 km grid size are disseminated and presented on the OSI SAF web site at www.osi-saf.org and www.knmi.nl/scatterometer. The AWDP software can be obtained free of charge from the NWP SAF web site at www.nwpsaf.org. Further improvement of the ASCAT winds can, among others, be expected from the new sea ice model that is currently being implemented. Improved global coverage may be achieved by the OceanSat-II scatterometer, launched in 2009 and we await the first data from this instrument. The Chinese HY-2 scatterometer would be further great complement for many applications

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