Ocean and Sea Ice SAF

Technical Note
SAF/OSI/CDOP2/KNMI/TEC/RP/221

Reprocessed SeaWinds L2 winds validation report

25 and 50 km wind products (OSI-151)
DOI: 10.15770/EUM_SAF_OSI_0002, 10.15770/EUM_SAF_OSI_0003

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Version 1.4

February 2016

DOCUMENTATION CHANGE RECORD

Issue / Revision	Date	Change	Description
Version 1.0	Nov 2014		Draft version
Version 1.1	Nov 2014	Minor	Version for DRR
Version 1.2	Jan 2015	Minor	Changes according to RIDs on DRR
Version 1.3	Mar 2015	Minor	Updated results after new reprocessing
Version 1.4	Feb 2016	Minor	Some updates connected with release in EDC

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Reference: SAF/OSI/CDOP2/KNMI/TEC/RP/221

Contents

1 Introduction

The EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF) produces a range of air-sea interface products, namely: wind, sea ice characteristics, Sea Surface Temperatures (SST) and radiative fluxes, Surface Solar Irradiance (SSI) and Downward Long wave Irradiance (DLI). The Product Requirements Document [1] provides an overview of the committed products and their characteristics in the current OSI SAF project phase, the Service Specification Document [2] provides specifications and detailed information on the services committed towards the users by the OSI SAF in a given stage of the project.

This report contains validation information about the QuikSCAT/SeaWinds wind Climate Data Record (CDR), produced in the OSI SAF. The complete SeaWinds level 2a data record, spanning the period of 19 July 1999 to 22 November 2009 was obtained from the Physical Oceanography Distributed Active Archive Center (PO.DAAC) at the NASA Jet Propulsion Laboratory (http://podaac.jpl.nasa.gov/). The data have been processed using the SeaWinds Data Processor (SDP) software version 2.2, as available in the Numerical Weather Prediction (NWP) SAF [4]. More information about the processing and the products can be obtained from the Product User Manual [3].

The quality and stability of the SeaWinds wind CDR has been assessed by looking both at backscatter and wind data. Section 2 describes the checks on the backscatter stability over time. Section 3 assesses the Quality Control applied in the products. In section 4, the winds are compared with NWP model data and with wind data from in situ buoys. Section 5 describes triple collocation experiments to assess the quality of winds from scatterometer, NWP model and buoys separately. Section 6 summarises the main conclusions.

Acknowledgement

The NASA/JPL PO.DAAC kindly provided the QuikSCAT level 2a data which have been used as input for the CDR generation. We are grateful to Jean Bidlot of ECMWF for helping us with the buoy data retrieval and quality control.

2 Backscatter data stability

A very important task when creating climate data records is to check the stability over time of the used instruments. For scatterometer data this can be done indirectly by looking at the retrieved winds, but it can also be done directly by looking at the radar backscatter (σ^0) on selected locations of the Earth which are known to have stable geophysical properties. Kumar et al. [5] have looked at SeaWinds backscatter responses over deserts, rain forests and snow covered areas. They found that particularly the snow covered areas show a very stable backscatter with very small standard deviations over time (they studied the 2005-2006 period) and little azimuthal variations. We have looked into the backscatter data over the entire period from 1999 to 2009 in a snow covered area also used in [5]: a 2° × 2° box centred at 77 S, 126 E (Antarctica). We consider the Antarctica region to be more stable in time than the Greenland region used in [5]. Long and Drinkwater describe Antarctic backscatter conditions and their anisotropy in [6]. In Greenland melting events occur regularly during the summer which will definitely influence the radiometric properties of the snow cover.

In order to monitor the instrument, we have taken the backscatter data on 25 km Wind Vector Cell (WVC) level for the 15th day of each month. HH-polarized and VV-polarized and fore and aft beam data have been considered separately. The data for each day, i.e., all backscatter data acquisitions located within the selected box, have been averaged. In this way, we average out diurnal variations and variations due to different flight directions in multiple orbits over one day. Still we can very well establish the backscatter variations over longer time scales.

Figure 1 shows the backscatter variations over time in the Antarctica area. We see σ^0 values that are very constant over time with only small seasonal variability. There appears to be some anisotropy, we observe a difference of approximately 0.2 to 0.3 dB between fore and aft beams of the same polarisation in line with [6]. Apart from this, we see some seasonal variation in the backscatter signals, but only small long term trends, of approximately 0.1 to 0.2 dB over 10 years at maximum. The largest long term variation occurs in the HH aft beam in the period 1999 to 2002. Since the HH fore beam does not show this trend, we attribute it rather to geophysical changes than to instrument drift.

A rule of thumb is that a change of 0.1 dB in backscatter corresponds to a change of 0.1 m/s in wind speed. Hence we conclude that wind speed trends due to instrument drift are very likely to be smaller than 0.1 m/s over the decade of 1999 to 2009.

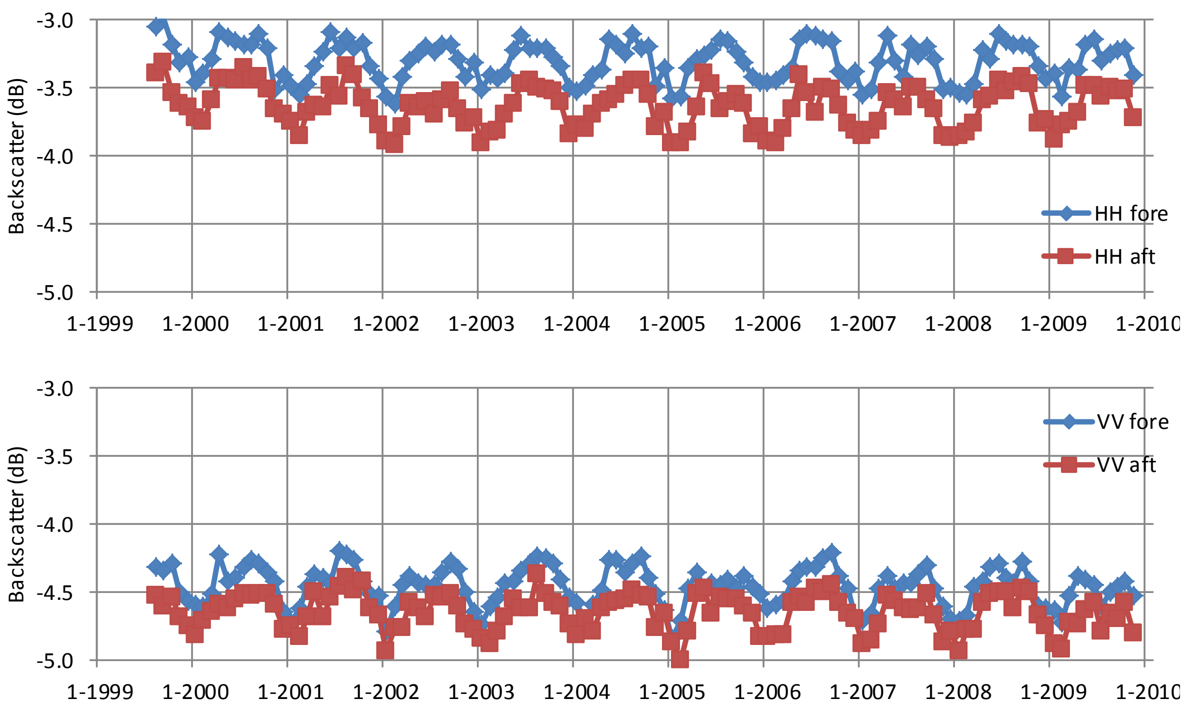

Figure 1: Temporal variation of SeaWinds for HH-polarized σ^0 (top) and VV-polarized σ^0 (bottom) over Antarctica (77 S, 126 E).

3 Quality Control characteristics

A good assessment of the information content of scatterometer winds is particularly important in order to use them in weather and climate analysis. Besides retrieval problems in cases of a confused sea state, a particularly acute problem of Ku-band scatterometry is the sensitivity to rain. Elimination of poor quality data is therefore very important for the successful use of the wind data. As part of the SeaWinds data record validation, we have investigated the geographical distribution of the rejection fraction of WVCs. We have done this for the year 2000 and for the year 2008. In this way we can see if the rejection rates have logical patterns which can be associated with rainy or dry areas and if there are any changes over time which can be attributed to instrument drifts.

Inspection of Figure 2 reveals that the main areas with high rain rejection rates can be associated with east-west oriented bands in the tropics, most notably in the western Pacific. These are regions known to have strong convection and rain, The gulf stream region east of North America is also clearly visible. The bands with high rejection rates near the edges of the Arctic and Antarctic sea ice shelves can be associated with the freezing seasons. When the ice edge rapidly moves due to freezing, there may be areas already covered with sea ice which are not yet assigned as ice by the Bayesian ice screening. These WVCs are still rejected by the Quality Control but they are assigned as 'rain' rather than 'ice'. It is also clear that the patterns in 2000 and 2008 only differ marginally.

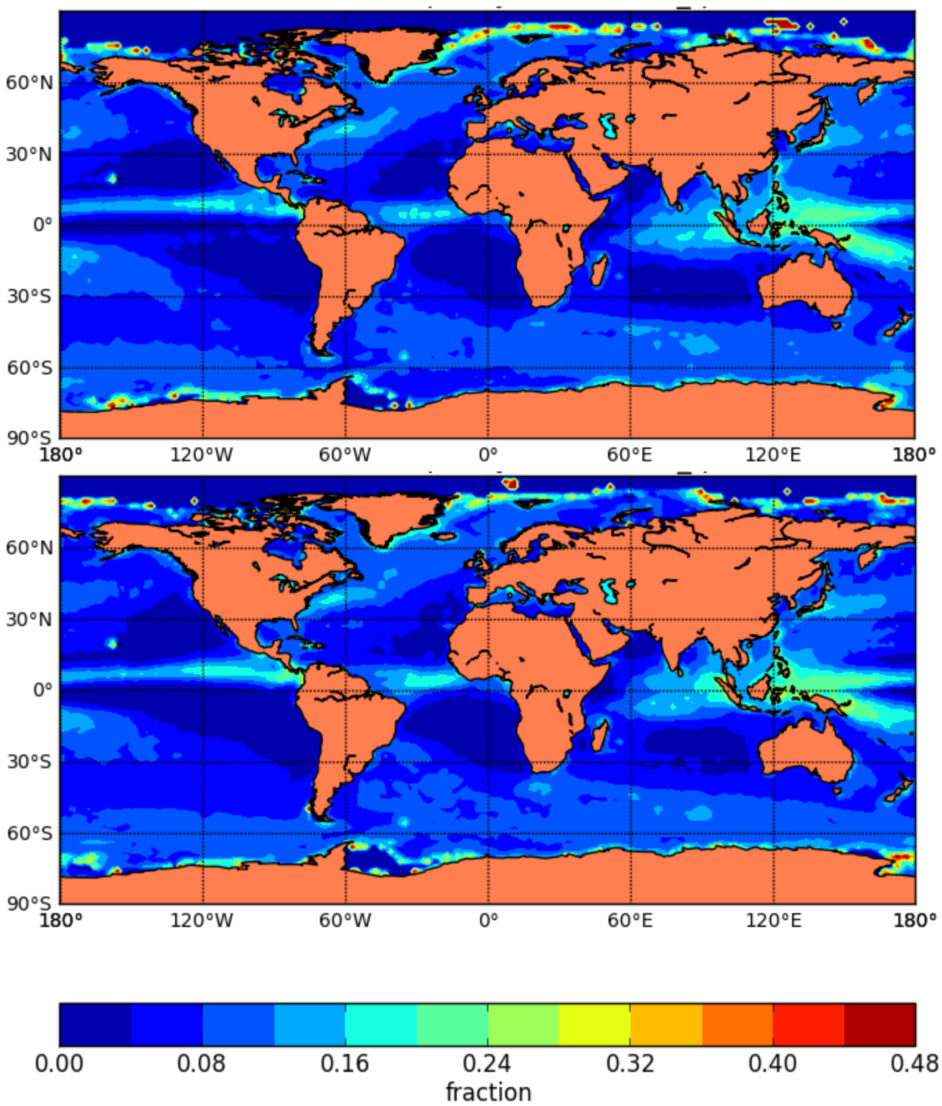

Figure 2: Number of WVCs with KNMI Quality Control (including rain) flag set as a fraction of WVCs where land flag and ice flag are not set. Results are for the entire year 2000 (top) and for the entire year 2008 (bottom).

4 Comparison of winds with NWP model and buoys

4.1 NWP model wind comparisons

The SeaWinds scatterometer winds have been collocated with ECMWF re-analysis (ERA) Interim wind data [7]. Equivalent neutral (U10N) winds have been computed from the real ERA-Interim forecast 10m winds, sea surface temperature, air temperature, Charnock parameter and specific humidity, using a stand-alone implementation of the ECMWF model surface layer physics [8]. The model wind data have been quadratically interpolated with respect to time and linearly interpolated with respect to location and put into the level 2 information part of each WVC. These model winds have been used both to initialise the Ambiguity Removal step in the wind processing and to monitor the scatterometer winds.

Figure 3 shows the monthly averages of wind speed bias and standard deviations of the zonal and meridional wind vector components over the entire period of the reprocessed data set. The wind speed bias is constant within 0.2 m/s over time; there seems to be a jump of +0.1 m/s in February-March 2000 and after that a gradual decrease of the bias towards 2009. The stepwise increase may be connected with the start of data assimilation of SeaWinds data in ERA-Interim on 24 February

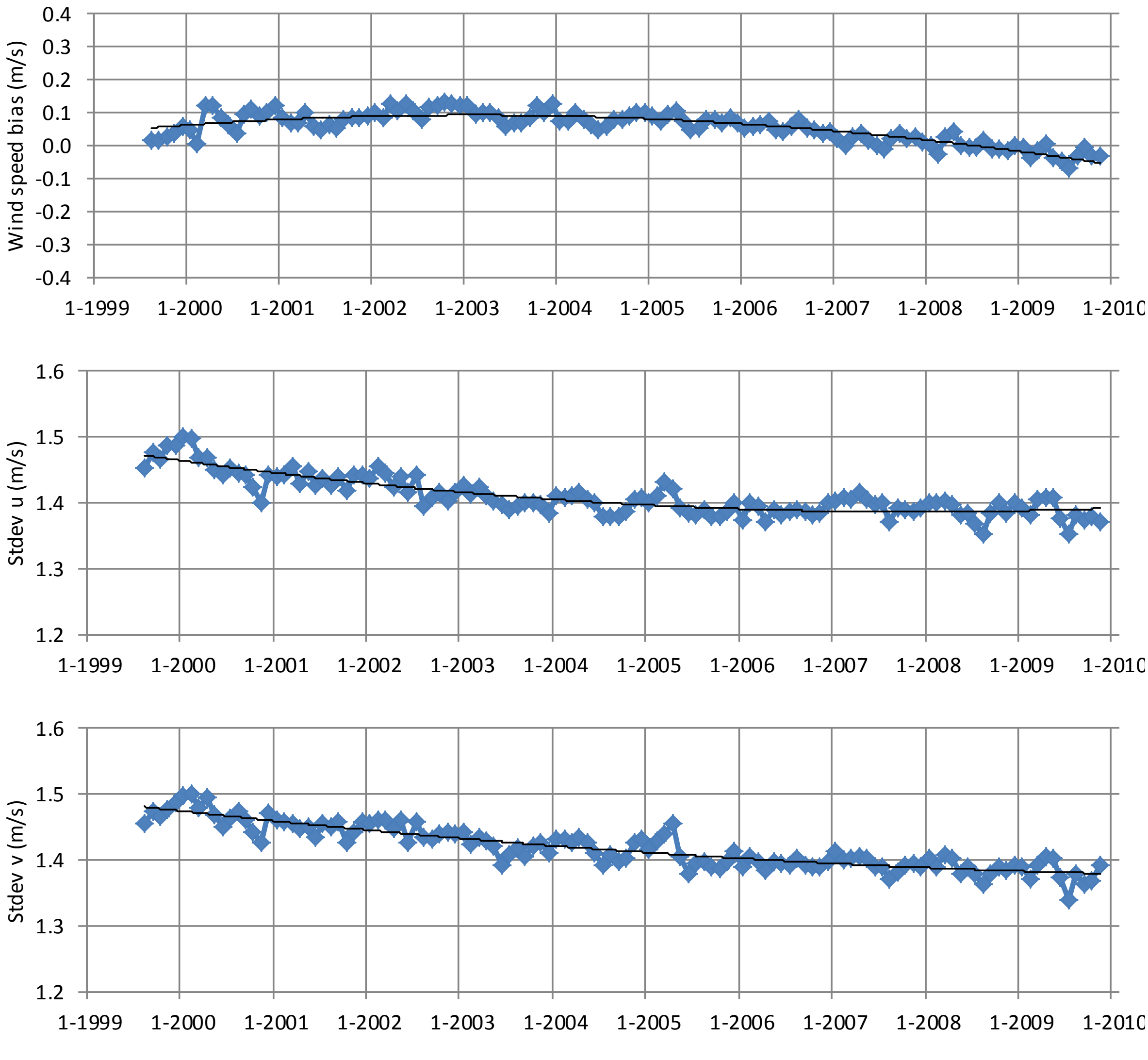

Figure 3: Wind speed bias (top), standard deviation of zonal wind component (middle) and standard deviation of meridional wind component (bottom) of 25 km SeaWinds winds versus ECMWF ERA-Interim model wind forecasts. The plotted values are monthly averages.

2000 [7]. This has not been further investigated. The wind vector component standard deviations gradually decrease with time, indicating that scatterometer and model winds are getting closer together. The quality of the ERA-Interim winds gradually improves with time due to the availability of more and more satellite observations which are successfully assimilated into the model. When the model winds improve with time and the scatterometer winds keep the same quality, it can be expected that the standard deviations decrease.

In order to better understand the variations in wind speed bias, we have plotted the monthly averages of the scatterometer and model wind speeds separately in Figure 4. It is clear that the SeaWinds wind speeds are quite constant over time (top plot) with a decrease of only approximately 0.03 m/s in 10 years. This is in line with the results as reported by JPL in their reprocessing [9]. The ERA-Interim model wind speeds increase by approximately 0.07 m/s in the QuikSCAT lifetime (bottom plot in Figure 4). Note that the model winds are collocated winds and hence the plot does not represent all ERA-Interim winds, but only those at the time and location of QuikSCAT overpasses. From Figure 3 (top) and Figure 4 we can conclude that the 0.1 m/s decrease in wind speed bias over the decade of SeaWinds operations is a combination of a small decrease SeaWinds wind speeds and a somewhat larger increase of ERA-Interim wind speeds.

Figure 5 shows the model comparisons for the 50 km SeaWinds wind product. The wind speed bias looks almost the same as the 25 km wind speed bias. The 50 km standard deviations are smaller by approximately 0.1 m/s as compared with the 25 km standard deviations but show the same features and trends. The smaller standard deviations are due to the limited spatial resolution of the ERA-Interim winds. The 25 km wind product resolves small scale features which are to a lesser extent present in the 50 km wind product and absent in the NWP model. Hence it can be expected that the 50 km scatterometer winds closer resemble the model winds and that the standard deviations are smaller.

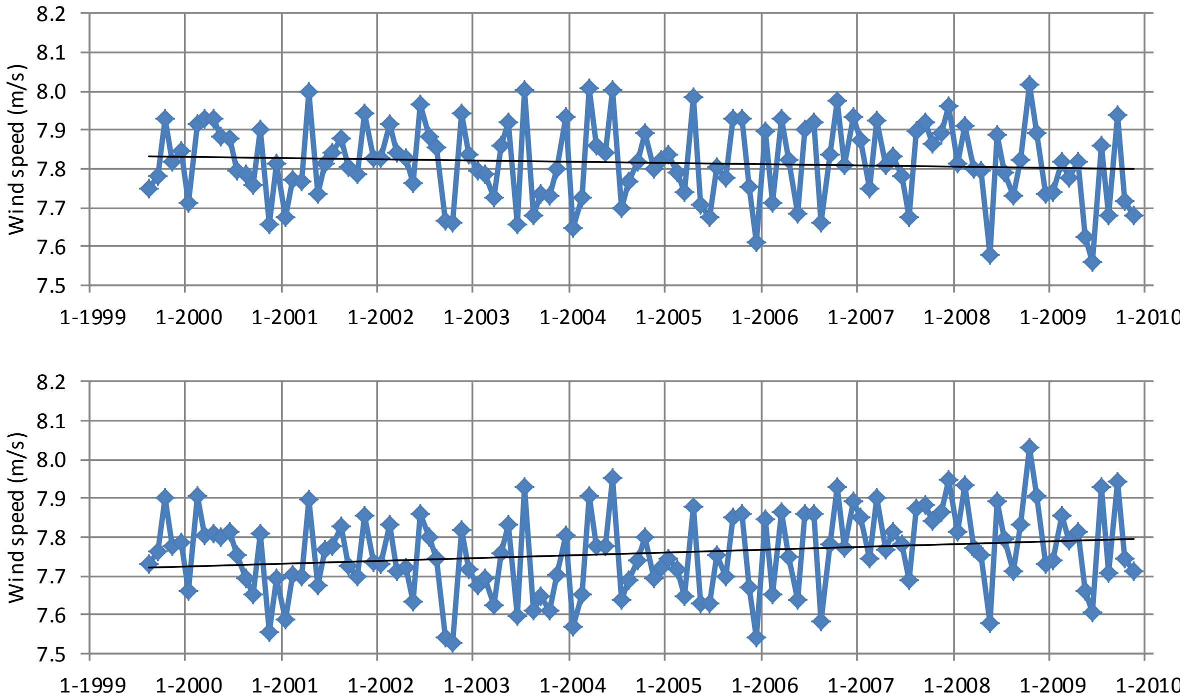

Figure 4: Average SeaWinds wind speed (top) and collocated ERA-Interim wind speed (bottom) of 25 km SeaWinds winds. The plotted values are monthly averages.

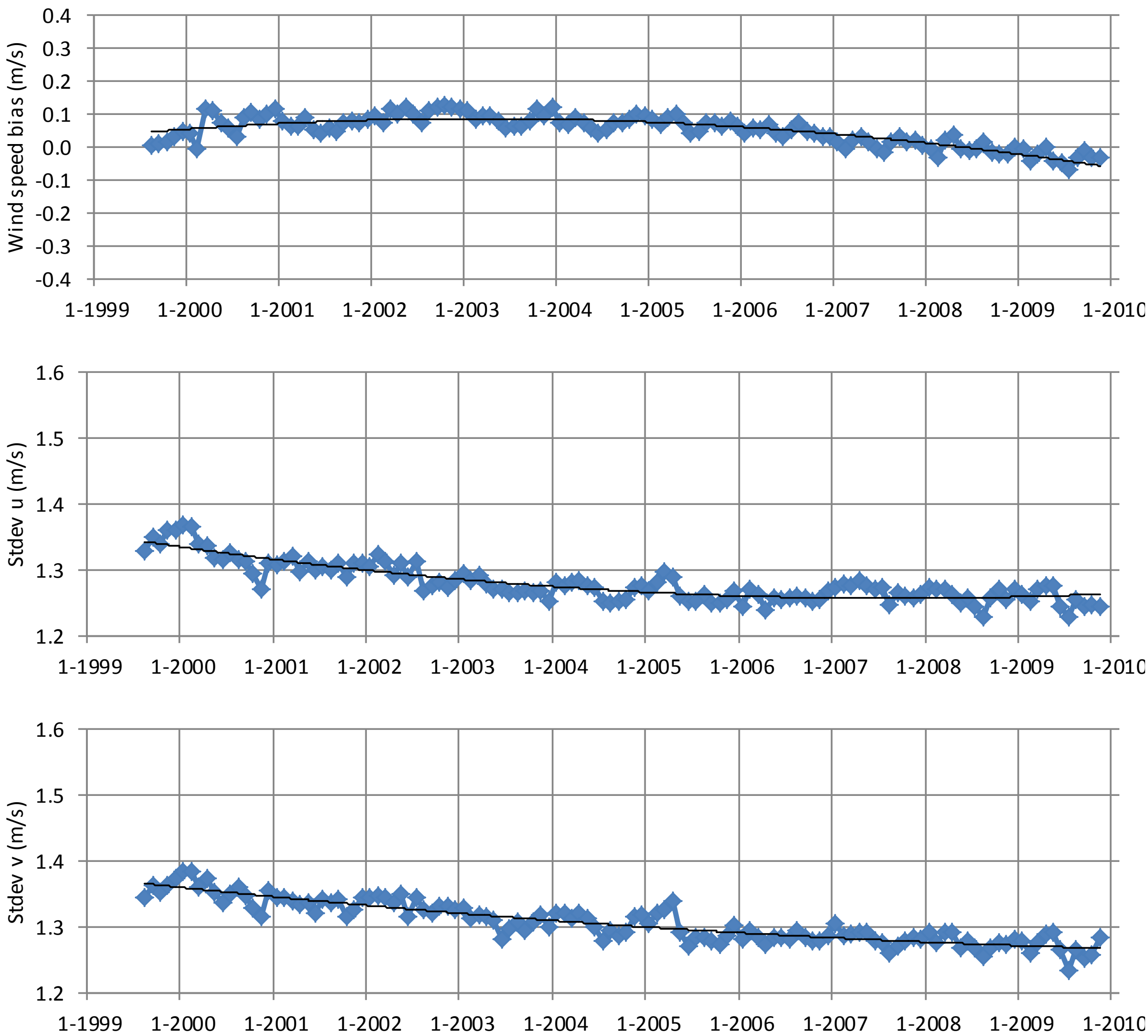

Figure 5: Wind speed bias (top), standard deviation of zonal wind component (middle) and standard deviation of meridional wind component (bottom) of 50 km SeaWinds winds versus ECMWF ERA-Interim model wind forecasts. The plotted values are monthly averages.

4.2 Buoy wind comparisons

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 [10]. 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 Liu, Katsaros and Businger (LKB) model ([10], [11]) in order to enable a good comparison with the 10-m scatterometer winds.

A scatterometer wind and a buoy wind measurement are considered to be collocated if the distance between the 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. Note that the collection of available buoy data changes over time: buoys are removed, temporarily or permanently, whereas on the other hand new buoys are deployed on new locations. In order to rule out variations in representativeness, we have taken a sub-set of the available buoys, containing only buoys that have produced wind data in all years between 1999-2009. The approximately 100 used buoys are listed in Appendix A and a map of the buoy locations can also be found there.

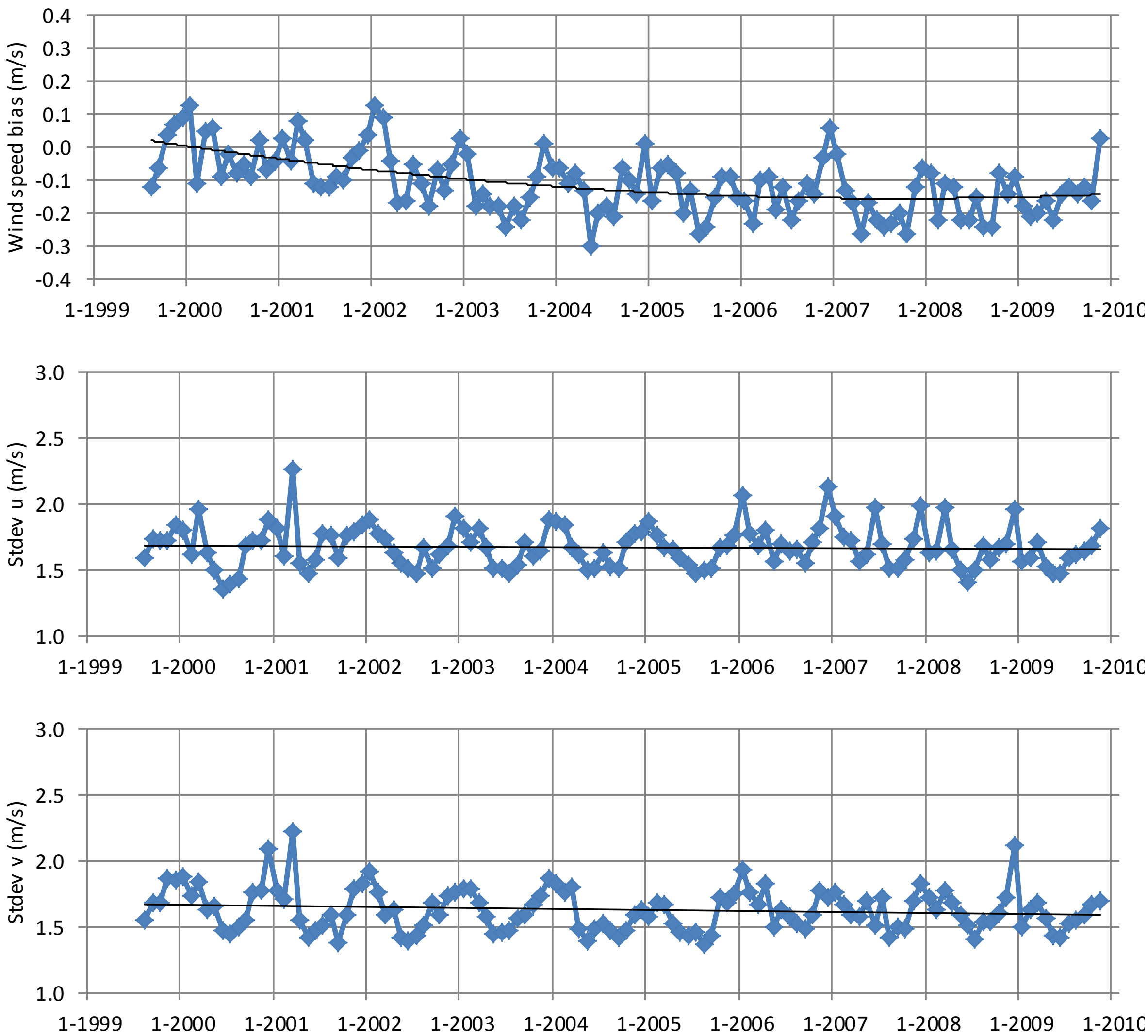

Figure 6: Wind speed bias (top), standard deviation of zonal wind component (middle) and standard deviation of meridional wind component (bottom) of 25 km SeaWinds winds versus buoy winds. The plotted values are monthly averages.

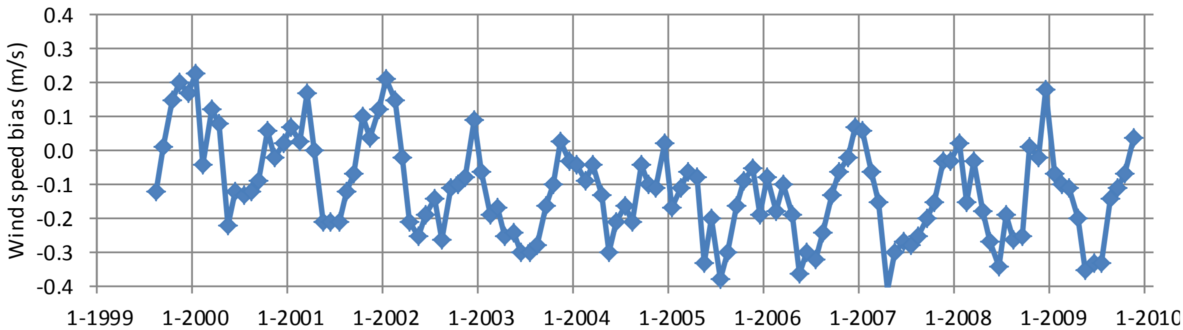

Figure 7: Wind speed bias of 25 km SeaWinds winds versus extratropical buoy winds. Only buoys with latitudes above 25° N are shown. The plotted values are monthly averages.

Figure 6 shows the wind statistics of SeaWinds 25 km winds versus buoy winds. A clear yearly oscillation is visible for the wind speed bias and wind component standard deviations. Seasonal weather variations cause differences in the distribution of wind speeds. These differences cause variations in the spatial representativeness errors associated with the scatterometer wind validation and thereby variations in the difference statistics.

The seasonal oscillations are significantly less prominent in the comparisons with model wind data in the previous section. On the other hand, the oscillations appear stronger when we look at the wind speed bias for only the extratropical buoys in the northern hemisphere, i.e., when we rule out the tropical buoys from the top plot in Figure 6. This is shown in Figure 7. When we consider the wind speed biases for the tropical buoys only (not shown), we see only a very weak yearly oscillation. So the oscillations are indeed connected with seasonal variations in specific regions.

It is clear from the top plot in Figure 6 that the wind speed bias of scatterometer winds versus buoy winds also gradually decreases over the QuikSCAT era, just as the wind speed bias versus ERA-Interim winds does (Figure 3). The decrease of the wind speed bias against buoys (approximately 0.15 m/s) is somewhat larger than the decrease of the wind speed bias against model winds (approximately 0.10 m/s).

The wind component standard deviations in Figure 6 are quite constant over time, indicating that the wind quality of both observing systems does not change much.

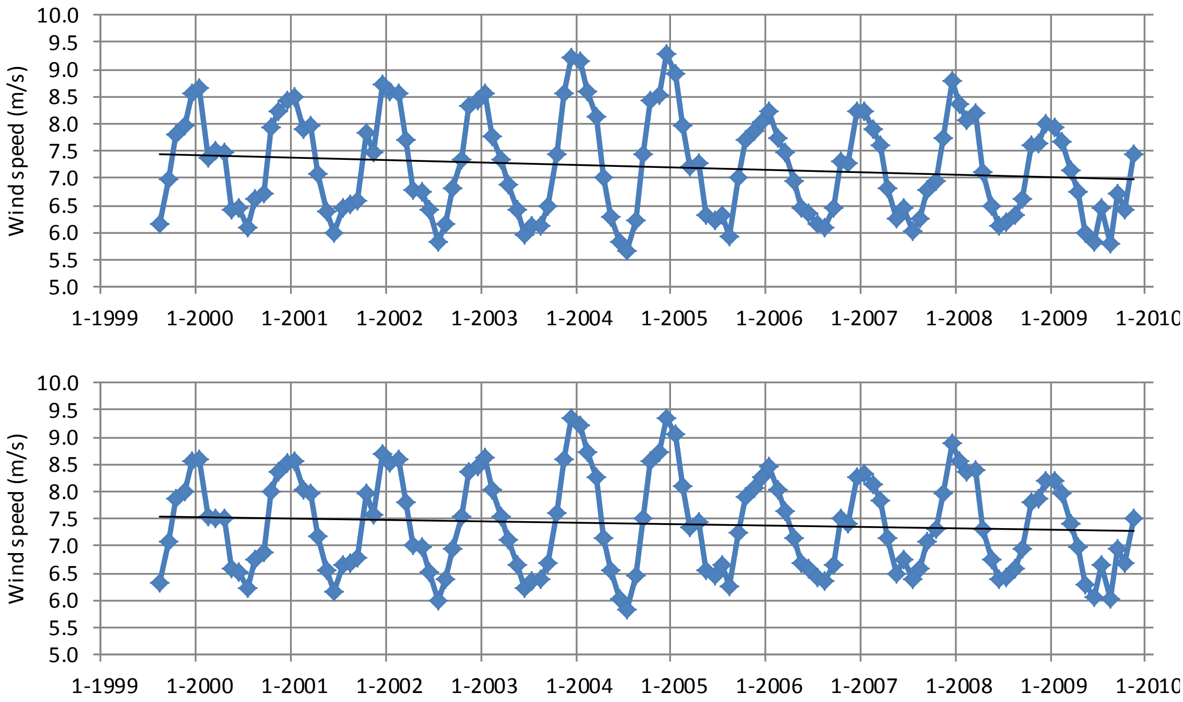

Figure 8: Average SeaWinds wind speed (top) and collocated buoy wind speed (bottom) of 25 km SeaWinds winds. The plotted values are monthly averages.

Analogous to Figure 4, we have plotted the monthly averages of the scatterometer and buoy wind speeds separately, see Figure 8. From these plots it is clear that wind speeds decrease in both observing systems: by approximately 0.5 m/s for SeaWinds and by approximately 0.3 m/s for the buoys. Inspection of the collocation results for tropical and extratropical buoys reveals that the wind speeds (from buoys and scatterometer) are quite constant on the locations of the extratropical buoys and that the wind speed decrease shown in Figure 8 can be completely attributed to a decrease in wind speeds in the tropics. The decrease of the wind speeds in the tropics is supported by Figure 9 where the average wind speeds for the collocations of SeaWinds winds, buoy winds and NWP winds in the tropics are shown. The scatterometer and buoy winds decrease by approximately 0.4 m/s over the 10 years period. The decrease in the tropical ERA-Interim winds appears to be slightly less: approximately 0.2 m/s over 10 years. Note that the results in Figure 9 are based on a limited set of data: only those locations and times where SeaWinds and buoy winds were available, approximately 500 acquisitions per month. In 2004, the number of available buoy wind measurements was even lower, approximately 100 per month. This explains the deviation of the curves in Figure 9 for 2004. It would be interesting to investigate this phenomenon in more detail, e.g. by looking at the SeaWinds and ERA-Interim tropical winds only, but this has not been done in the scope of this report.

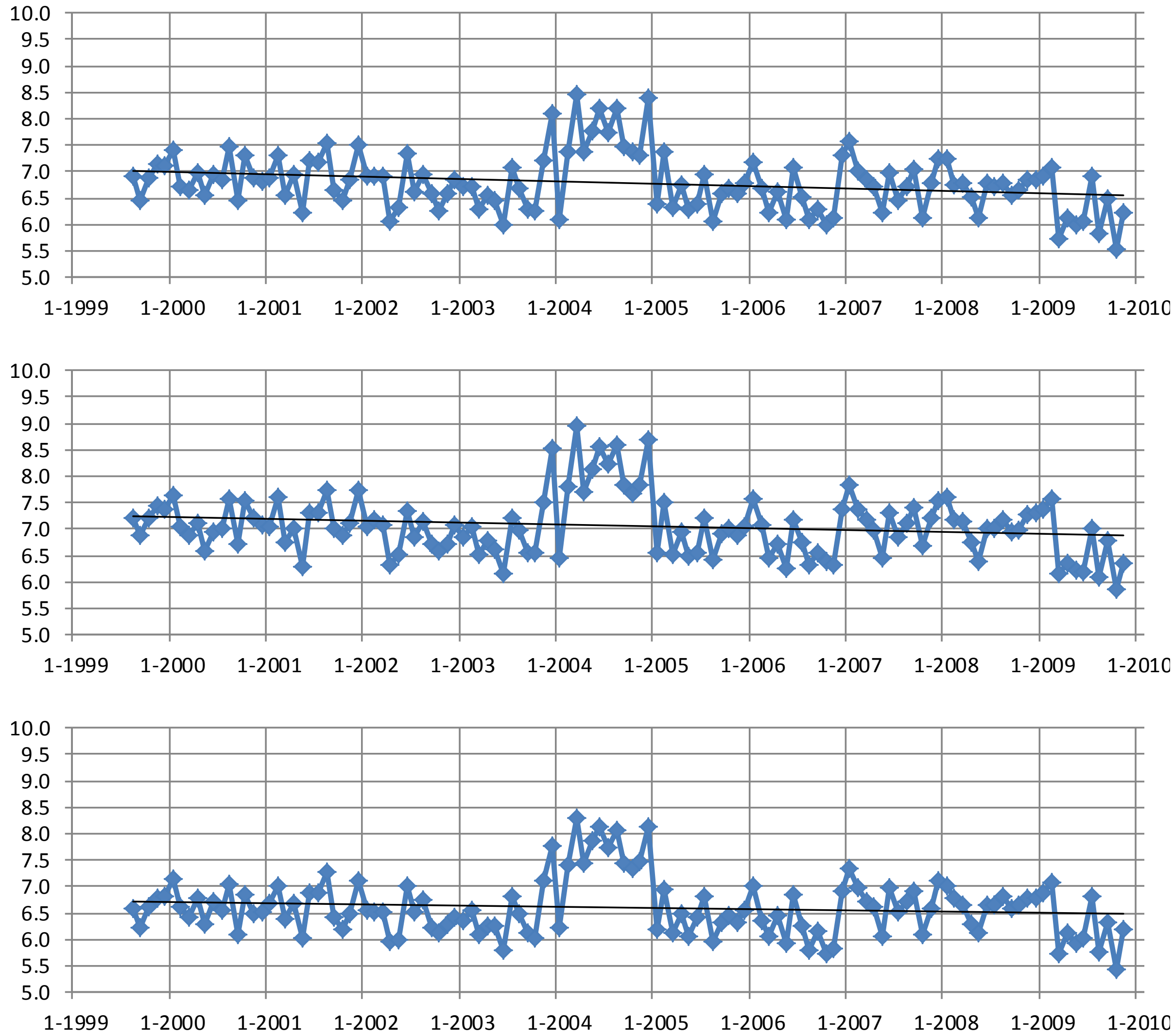

Figure 9: Average collocated SeaWinds wind speed (top), buoy wind speed (middle) and ERA-Interim wind speed (bottom) for tropical buoys. Only buoys with latitudes below 25°N are shown. The plotted values are monthly averages.

Figure 10 shows the buoy comparisons for the 50 km SeaWinds products. The results very much resemble the 25 km statistics (Figure 6). The 50 km standard deviations are slightly (on average 0.02 m/s) higher than the 25 km standard deviations. The buoy winds are point measurements whereas the scatterometer winds are spatial averages over approximately the size of a WVC. Since the 25 km products resolve smaller scale features than the 50 km products, it can be expected that the 25 km winds better resemble the buoy winds, resulting in lower standard deviations.

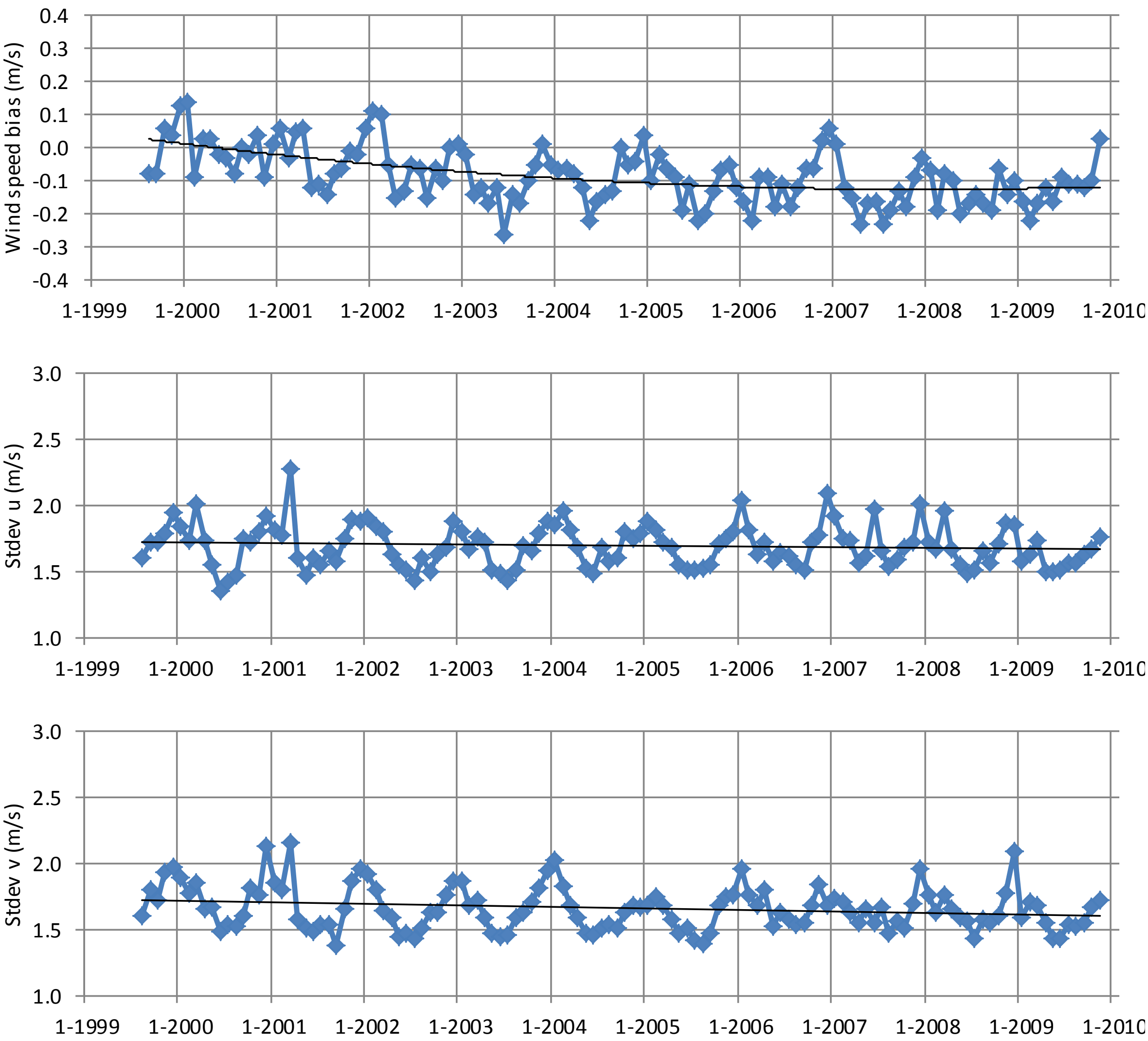

Figure 10: Wind speed bias (top), standard deviation of zonal wind component (middle) and standard deviation of meridional wind component (bottom) of 50 km SeaWinds winds versus buoy winds. The plotted values are monthly averages.

5 Triple collocation results

A triple collocation study was performed to assess the errors of the SeaWinds, ECMWF and buoy winds independently. The triple collocation method was introduced by Stoffelen [12]. Given a set of triplets of collocated measurements and assuming linear calibration, it is possible to simultaneously calculate the errors in the measurements and the relative calibration coefficients. The triple collocation method can give the measurement errors from the coarse resolution NWP model perspective or from the intermediate resolution scatterometer perspective, but not from the fine resolution buoy perspective without further assumptions on the local buoy measurement error. A wind signal present in buoy measurements but not in scatterometer measurements is therefore contained in the buoy error. This matter is extensively introduced by Vogelzang et al. [13].

Collocated data sets of SeaWinds 25 km and 50 km, ECMWF and buoy winds spanning the whole period of 10 years were used in the triple collocation. Table 1 lists the error variances of the buoy, SeaWinds and ECMWF winds from the intermediate resolution scatterometer perspective. When we compare the 50 km product with the 25 km product, we see an increase of the buoy wind error standard deviations and a decrease of the ECMWF wind standard deviations. This is due to the coarser resolution of the 50 km product, which contains less small scale information and in this respect resembles better the ECMWF winds and resembles worse the buoy winds. The errors of the 25 km SeaWinds winds are larger than those of the 50 km winds. This is most probably due to the larger noise in the 25 km wind retrievals. The buoy errors for the 25 km product are comparable to the errors reported in Table 5 of [13] (‘SeaWinds-KNMI’ entry), whereas the ECMWF errors are smaller by approximately 0.1 m/s in [13]. This may be due to the lower resolution of the ERA-Interim winds used in this reprocessing. In [13], data from the operational ECMWF model were used. On the other hand, the 25 km scatterometer winds show larger error values (by approximately 0.1 m/s) in [13]. This may be due in part to the improvements in wind retrieval and quality control implemented in the latest version of SDP. The scatterometer winds are of good quality: at 50 km scale the error in the wind components is less than 0.5 m/s; at 25 km scale it is less than 0.7 m/s.

	Scatterometer		Buoys		ECMWF	
	ε_u (m/s)	ε_v (m/s)	ε_u (m/s)	ε_v (m/s)	ε_u (m/s)	ε_v (m/s)
25 km SeaWinds	0.64	0.54	1.39	1.41	1.28	1.35
50 km SeaWinds	0.46	0.40	1.50	1.49	1.20	1.28

Table 1: Error standard deviations in *u* and *v* wind components from triple collocation of SeaWinds 25 km and 50 km wind products with buoy and ECMWF forecast winds, seen from the scatterometer perspective. The results were obtained for the period of July 1999 to November 2009.

The wind retrieval skill of rotating pencil beam scatterometers like SeaWinds depends on the position in the swath. This is due to the varying number of backscatter measurements and changing beam azimuth angles with the sub-satellite cross track location [14]. Especially in the nadir and outer parts of the swath, the beam azimuth diversity is small and wind retrieval is more challenging. In those areas the SeaWinds wind field output is less determined by the local WVC solution pattern, but more by the spatial consistency with neighbour WVCs through the spatial filtering of MSS solutions in 2DVAR, thus locally compromising spatial resolution. In Figure 11 we detail the triple collocation results for the 50 km wind product (bottom line in Table 1) as a function of WVC number. For the 25 km wind product we obtained similar results which are not shown here.

The scatterometer winds (green curves) have higher error standard deviations in the middle and at the edges of the swath, notably for the zonal (*u*) wind component, as expected. If any difference, one expects that the buoy (ECMWF) winds have larger (smaller) error standard deviations in the nadir and outer swath parts, but this is not so clear. The buoy winds (blue curves) do have similar variations in errors as the scatterometer winds, i.e., larger buoy errors on swath locations with larger scatterometer errors. Contrary to this, the NWP winds (red curves) have smaller errors on locations with larger scatterometer errors. The anticipated effects are more obvious when we look at the zonal (*u*) wind components (closed dots) than in the meridional (*v*) components (open dots). Indeed, the effective resolution of the SeaWinds wind products is coarser in swath regions with smaller wind retrieval skill, i.e., in the nadir and far outer swath. In such cases, we obtain broader minima in the inversion residual and this gives the 2DVAR Ambiguity Removal step more freedom to adjust the wind directions following its spatial filter functions, which are rather coarse in effective resolution [15]. A coarser scatterometer wind resolution will reduce the errors in the NWP wind field (also coarse resolution) and increase the errors in the buoy winds (finer resolution containing small scale information not seen by the scatterometer).

The mid swath results of the meridional component (*v*) are not fully understood and more research is needed to better understand the triple collocation results here.

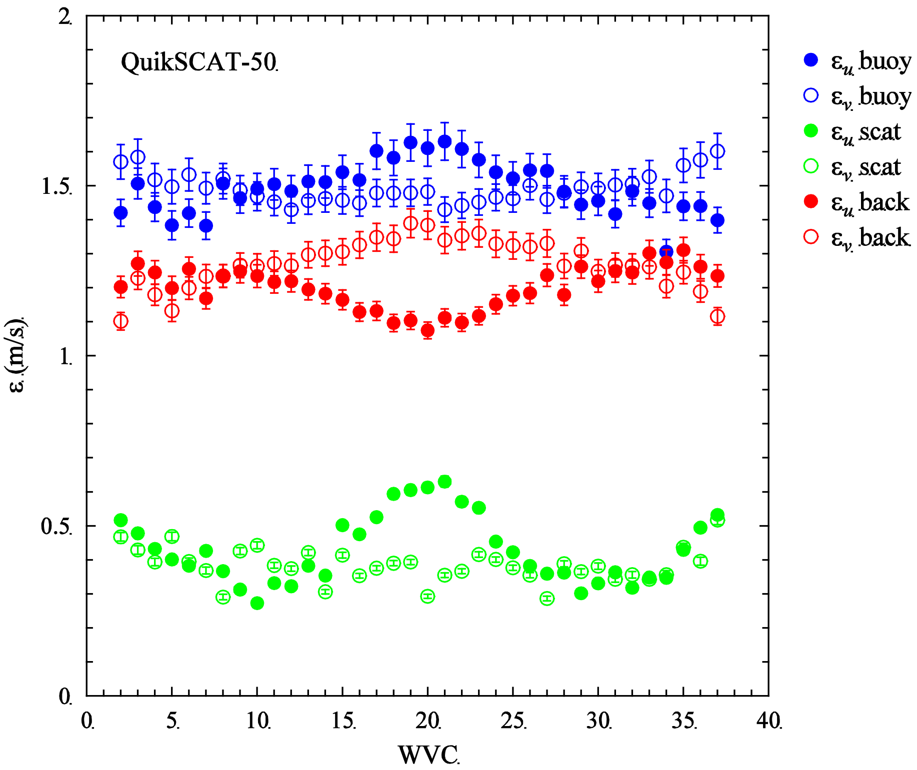

Figure 11: Error standard deviations in *u* and *v* wind components from triple collocation across the swath of SeaWinds 50 km wind products with buoy and ECMWF forecast winds, seen from the scatterometer perspective.

From the triple collocation analysis, we can also determine the calibration of the scatterometer winds. The calibration coefficients *a* and *b* relate the observed scatterometer wind *w* to the 'true' wind *t* according to $t = a \times w + b$. This is done separately for the *u* and *v* wind components. The calibrations have been computed per year to see if there is any trend or glitch visible indicating instrument changes over time, see Figure 12. The calibration coefficients indicate whether the scatterometer and ECMWF winds are underestimated ($a > 1$) or overestimated ($a < 1$). We see values close to 1, the slightly lower values for QuikSCAT can probably be attributed to non-linearity's in the wind retrieval, i.e., a not fully linear relationship between buoy *u* or *v* wind component and corresponding scatterometer wind component. Apart from some yearly variations, a small increasing trend appears to be present in the calibration coefficients of both ECMWF and scatterometer wind components. This indicates that the ECMWF and scatterometer wind speeds gradually decrease when compared with the buoy winds, in line with the results from section 4.

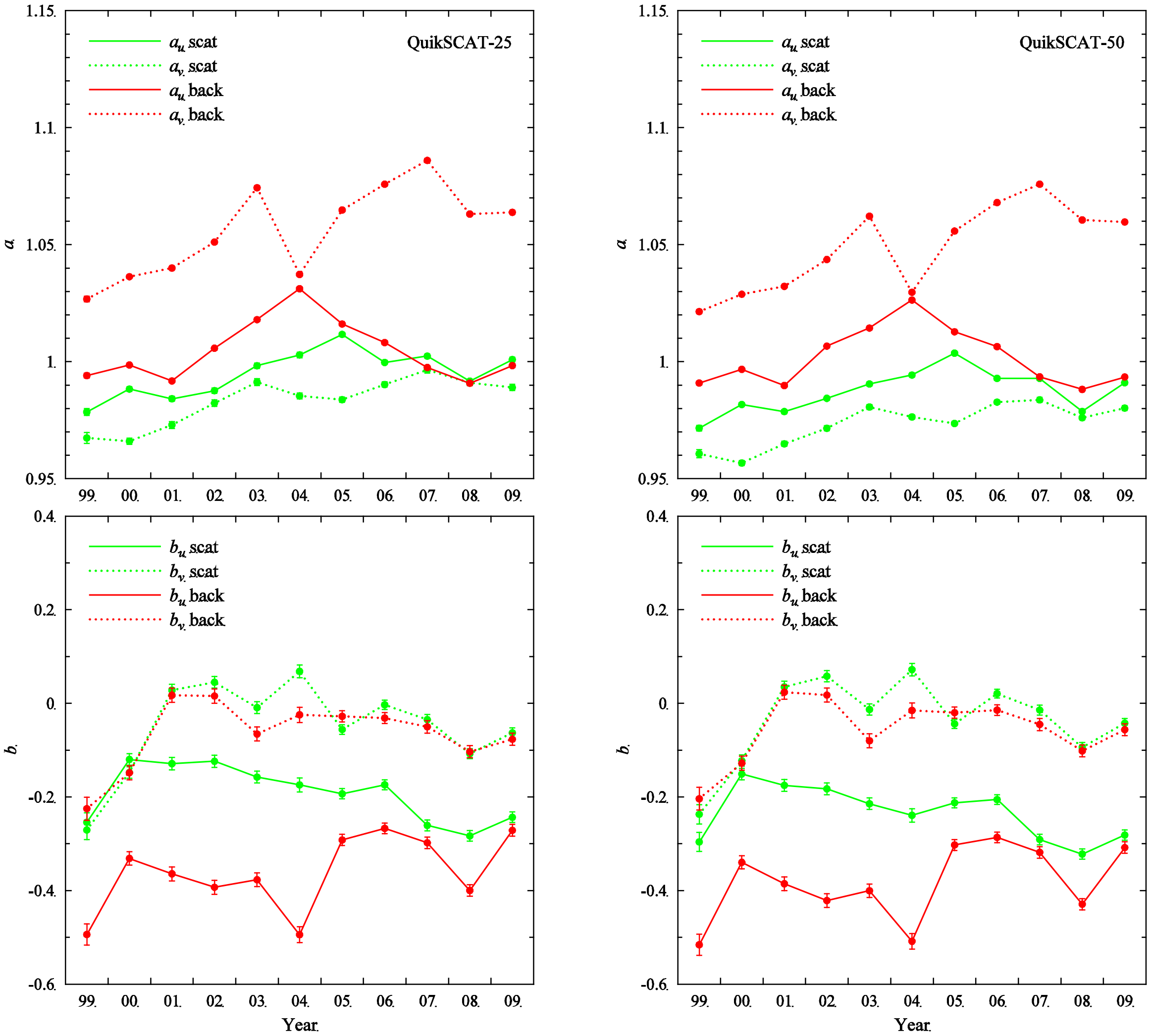

Figure 12: Triple collocation results for the wind component calibration coefficients *a* (top) and *b* (bottom) of the SeaWinds 25 km (left) and 50 km (right) winds and the ECMWF winds relative to the buoy measurements, per year.

6 Conclusions

The quality and stability of the SeaWinds CDR has been assessed by looking both at backscatter and wind data.

The backscatter values appear to be very constant in time over a selected area on Antarctica. For both HH and VV polarized beams, we obtain time series with long term trends of less than 0.1 dB. From these very stable results, we conclude that the observed SeaWinds backscatter drifts appear negligible.

The scatterometer wind biases against ERA-Interim and buoy winds show a gradual decrease of 0.10 to 0.15 m/s over 10 years. Inspection of the data in different regions on the Earth reveals that there is a relatively large variability in bias results depending on season and climatological region. Moreover, there appears to be a gradual change in the wind regime in the tropics. Nevertheless, the analysed SeaWinds backscatter and wind changes suggest a drop in instrumental bias of no more than 0.1 dB (equivalent to 0.1 m/s) in ten years. As such, the produced SeaWinds wind data record meets the requirements set by the World Climate Research Programme (WCRP) [16]: accuracy better than 0.5 m/s, stability better than 0.1 m/s per decade. From the figures in section 4, we conclude that the OSI SAF product requirements ([1], better than 2 m/s in wind component standard deviation with a bias of less than 0.5 m/s in wind speed on a monthly basis) are also well met.

The triple collocation results show that the scatterometer winds are of good quality, however some variations as a function of swath position are not yet fully understood and subject to further research.

In the scope of this validation report, no attempt was made to connect the bias and standard deviation changes over time to decadal and inter-annual climate oscillations, such as the Madden–Julian oscillation (MJO), the Pacific Decadal Oscillation (PDO), the El Niño–Southern Oscillation (ENSO), and the North Atlantic Oscillation (NAO). We hope that climate scientists will use the CDR to better understand and explain these phenomena.

7 References

[1] OSI SAF,
Product Requirements Document,
SAF/OSI/CDOP2/M-F/MGT/PL/2-001, 2015

[2] OSI SAF,
Service Specification Document,
SAF/OSI/CDOP2/M-F/MGT/PL/2-003, 2015

[3] OSI SAF,
SeaWinds wind Climate Data Record Product User Manual,
SAF/OSI/CDOP2/KNMI/TEC/MA/220, 2015

[4] Vogelzang, J., A. Verhoef, J. Verspeek, J. de Kloe and A. Stoffelen,
SDP User Manual and Reference Guide
NWPSAF-KN-UD-002, 2014

[5] Kumar, R., S.A. Bhowmick, K. N. Babu, R. Nigam, and A. Sarkar,
Relative Calibration Using Natural Terrestrial Targets: A Preparation Towards Oceansat-2 Scatterometer
IEEE Transactions on Geoscience and Remote Sensing, 49, 6, 2268-2273, 2011,
doi:10.1109/TGRS.2010.2094196

[6] Long, D. and M. Drinkwater,
Azimuth variation in microwave scatterometer and radiometer data over Antarctica
IEEE Transactions on Geoscience and Remote Sensing, 38, 4, 1857-1870, 2000,
doi:10.1109/36.851769

[7] Dee, D. et al.,
The ERA-Interim reanalysis: configuration and performance of the data assimilation system
Quarterly Journal of the Royal Meteorological Society, 137: 553–597, 2011, doi:10.1002/qj.828

[8] Hersbach, H.,
Assimilation of scatterometer data as equivalent-neutral wind
ECMWF Technical Memorandum 629, 2010

[9] Fore, A., B. Stiles, A. Chau, B. Williams, R. Dunbar and E. Rodriguez,
Point-Wise Wind Retrieval and Ambiguity Removal Improvements for the QuikSCAT Climatological Data Set
IEEE Transactions on Geoscience and Remote Sensing, 52, 1, 51-59, 2014,
doi:10.1109/TGRS.2012.2235843

[10] 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

[11] 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

[12] Stoffelen, A.
Toward the true near-surface wind speed: error modeling and calibration using triple collocation
J. Geophys. Res. 103, C4, 7755-7766, 1998, doi:10.1029/97JC03180

[13] Vogelzang, J., A. Stoffelen, A. Verhoef and J. Figa-Saldana
On the quality of high-resolution scatterometer winds
J. Geophys. Res., 116, C10033, 2011, doi:10.1029/2010JC006640

[14] OSI SAF,
Algorithm Theoretical Basis Document for the OSI SAF wind products,
SAF/OSI/CDOP2/KNMI/SCI/MA/197, 2014

[15] Vogelzang, J., A. Stoffelen, A. Verhoef, J. de Vries and H. Bonekamp
Validation of two-dimensional variational ambiguity removal on SeaWinds scatterometer data
J. Atm. Oceanic Technol., 7, 26, 1229-1245, 2009, doi:10.1175/2008JTECHA1232.1

[16] Global Climate Observing System,
Systematic Observation Requirements for Satellite-based Products for Climate Supplemental

details to the satellite-based component of the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC - 2011 Update, December 2011, GCOS Report 154, http://www.wmo.int/pages/prog/gcos/Publications/gcos-154.pdf

8 Abbreviations and acronyms

2DVAR	Two-dimensional Variational Ambiguity Removal
CDR	Climate Data Record
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA	ECMWF re-analysis
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GTS	Global Telecommunication System
HH	Horizontal polarisation of sending and receiving radar antennas
JPL	Jet Propulsion Laboratory
KNMI	Royal Netherlands Meteorological Institute
LKB	Liu, Katsaros and Businger
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
OSI	Ocean and Sea Ice
PO.DAAC	Physical Oceanography Distributed Active Archive Center
QC	Quality Control
QuikSCAT	US Quick Scatterometer mission carrying the SeaWinds scatterometer
SAF	Satellite Application Facility
SDP	SeaWinds Data Processor
u	West-to-east (zonal) wind component
v	South-to-north (meridional) wind component
VV	Vertical polarisation of sending and receiving radar antennas
WCRP	World Climate Research Programme
WVC	Wind Vector Cell

9 Appendix A: List of used buoys

These are the buoy identifiers of the 101 buoys used in the validations and triple collocations in sections 4 and 5. The buoy locations can be looked up on http://www.ndbc.noaa.gov/ and are shown in Figure 13. Only buoys yielding data in each year of the QuikSCAT operations have been used.

13008	41026	44251	51004	51302	52311
15001	42001	44255	51006	51303	52312
15002	42002	46001	51007	51304	52313
32303	42020	46029	51008	51305	52315
32304	42035	46035	51009	51306	52316
32305	42036	46036	51010	51307	52321
32315	42039	46041	51011	51308	61001
32316	42040	46042	51014	51309	62001
32317	43001	46050	51015	51310	62029
32318	43301	46132	51016	51311	62081
32319	44005	46147	51017	52001	64046
32320	44008	46184	51018	52002	
32321	44009	46205	51019	52003	
32322	44011	46206	51020	52004	
32323	44014	46207	51021	52006	
41004	44025	46208	51022	52079	
41009	44140	51001	51023	52309	
41010	44141	51002	51301	52310	

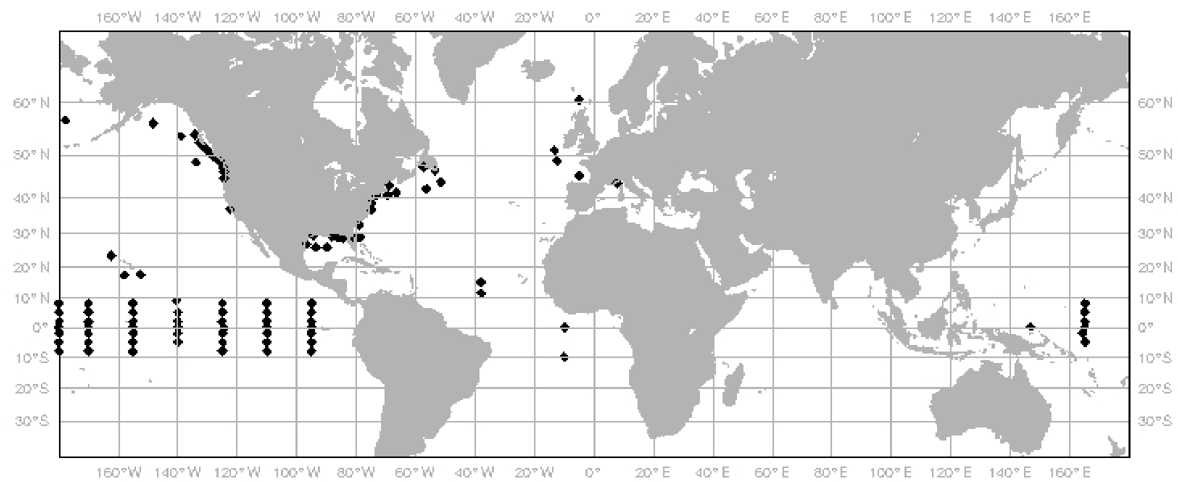

Figure 13: Location of the used buoys.