
Homogenization of scatterometer wind retrievals

Bentamy Abderrahim ^{1,*}, Grodsky Semyon A. ², Elyouncha Anis ³, Chapron Bertrand ¹,
Desbiolles Fabien ^{1,4}

¹ Laboratoire d'Océanographie Spatiale; Institut Français pour la Recherche et l'Exploitation de la Mer; Plouzané France

² Department of Atmospheric and Oceanic Science; University of Maryland; College Park MD USA

³ Department of Communication, Information, Systems & Sensors; Royal Military Academy; Brussels Belgium

⁴ Laboratoire d'Océanographie Physique (LPO); Université de Bretagne Ouest (UBO); Brest France

* Corresponding author : Abderrahim Bentamy, email address : Abderrahim.Bentamy@ifremer.fr

Abstract :

Surface winds (10 m equivalent neutral wind velocity) from scatterometer missions since 1992 to present require homogenization to meet the requirements for oceanic and atmospheric climate data records. Sources of differences between winds retrieved from different scatterometer measurements mainly arise from calibration/validation procedures used for each scatterometer and differences in measurement physics. In this study, we focus on the calibration/validation component of the European Remote Sensing Satellite (ERS)-1 and ERS-2 wind speed biases. ERS-1 and ERS-2 data, named as WNF products, are from the Institut Français de Recherche pour l'Exploitation de la MER (IFREMER). In addition to WNF data, the newly calibrated ERS-2 products provided by the European Space Agency (ESA), indicated as ASP2.0 products, are also used. Our approach utilizes collocated satellite-buoy data. Expected values of the normalized radar cross section (NRCS) are calculated from buoy winds for each antenna beam using the Cmod5.n geophysical model function. The comparisons between expected and measured NRCS examine differences along with variables such as backscatter coefficient and incidence angle ranges. The difference between the expected and measured NRCS is then used to set up empirical models aiming at the correction for biases in ERS-1 and ERS-2 WNF NRCS calibrations. Finally, ERS-1 and ERS-2 wind retrievals are reprocessed using the corrected NRCS and Cmod5.n. These earlier corrected ERS-1/2 winds are analysed along with later scatterometer data (QuikSCAT and ASCAT-A) for their deviations from *in situ* buoy winds during 1992–2011 period. The scatterometer data homogeneity is also investigated at global scales based on the use of collocated scatterometer retrievals and atmospheric re-analyses winds derived from ERA Interim and CFSR models.

Keywords : scatterometer, surface wind, homogenization

1 **1. Introduction**

2 Surface wind vectors are vital for operational and scientific issues. For instance, they
3 are routinely used as primary forcing function component for ocean circulation and wave
4 models at global and/or local scales. They are considered as the most important variable for
5 investigating storm surges and wave forecasts at various space and time scales. They have
6 great impact on coastal upwelling, primary productivity, cross shelf transport, deep water
7 formation, ice transport and variability. They are essential for reliable estimation of
8 momentum (wind stress vector), heat fluxes (latent and sensible), and gas fluxes (e.g. CO₂ and
9 H₂O). Long term change in global winds is an important forcing and indicator of the climate
10 change (e.g. Bourassa *et al*, 2010). .

11 One of the main sources of surface wind speed and direction over the global ocean are
12 scatterometers on board polar satellites. Since the launch of the European Remote Sensing
13 Satellite (ERS-1) in August 1991, a total of 10 independent scatterometer missions have been
14 operational. The European Space Agency (ESA) operated two scatterometers onboard the
15 European Remote Sensing Satellites ERS-1 (1991 – 1996) and ERS-2 (1995 – 2011). Three
16 scatterometers have been operated by the National Aeronautic Space Administration (NASA):
17 NASA scatterometer (NSCAT, 1996 – 1997) onboard the Japanese Advanced Earth Observing
18 Satellite (ADEOS-1), SeaWinds onboard QuikSCAT satellite (1999 - 2009), and SeaWinds
19 onboard (ADEOS-2/Midori) (2002 – 2003). The latest scatterometers are the Advanced
20 SCATterometer ASCAT-A (2006 – present) and ASCAT-B (2013 – present) onboard METOP
21 satellites, Ocean SCATterometer (OSCAT) onboard OCEANSAT2 satellite (2009 – present),
22 and HY-2A scatterometer (2011 – present). ASCAT-A/B, OSCAT, and HY-2A, and RapidScat
23 are operated by European Meteorological Satellite organization (EUMETSAT), Indian Space
24 Research Organization (ISRO), the Chinese National Space Center (CAS),and by NASA,
25 respectively. Thanks to the overlapping periods between missions, scatterometer winds are
26 continuously available over global ocean and span more than two decades (1992 – present).
27 The quality of each scatterometer retrievals have been investigated by a number of authors
28 (e.g. Quilfen, 1995; Graber et al 1996; Freilich and Dunbar, 1999, Bentamy *et al*, 2002;
29 Ebuchi *et al*, 2002; Bentamy et al, 2008; Verspeek *et al*, 2010; Sudha and Rao, 2013). They
30 found that remotely sensed winds are comparable to in situ measurements (mainly from
31 moored buoys). Furthermore, scatterometer products relied on each mission have been
32 successfully used for numerous purposes such as ocean model forcing experiments (e.g.
33 Grima *et al*, 1999; Ayina *et al*, 2006), extreme event studies (e.g. Le Marchal *et al*, 2000;

1 Katsaros *et al*, 2001), and upwelling space and time patterns (Blanke *et al*, 2005; Penven *et al*,
2 2005).

3 The main weakness of using scatterometer data for a long term wind analysis is the lack
4 of consistency between retrievals from different scatterometers. Bentamy *et al* (2012, 2013)
5 have highlighted the differences between surface winds retrieved from ASCAT-A and
6 QuikSCAT, and between ERS-2 and QuikSCAT. Differences in wind retrievals originate from
7 differences in radar physics and procedures used to retrieve near surface winds from measured
8 backscatter coefficients. In the two above papers, a chain of corrections has been applied to
9 individual mission winds to improve the consistency between ERS-2, QuikSCAT, and
10 ASCAT-A. Application of those corrections reduces the global mean of intermission wind
11 difference as well as reduces the magnitude of its geographical patterns.

12 This study considers four scatterometer missions (ERS-1, ERS-2, QuikSCAT, and
13 ASCAT) spanning two decades from 1992 through 2011. Comparisons of each mission winds
14 with collocated in situ winds from ocean buoys reveal stronger deviations for both ERS
15 missions. Calibration of normalized radar backscatter (σ^0 , NRCS) is revisited for ERS-1 and
16 ERS-2 by comparing expected NRCS (calculated from collocated buoy winds using the
17 Cmod5.n Geophysical Model Function, GMF) with measured NRCS. The difference between
18 the expected and measured σ^0 is then used to correct biases in measured NRCS. Finally,
19 ERS-1 and ERS-2 winds are reprocessed using the corrected σ^0 and Cmod5.n. Resulting
20 winds from the four scatterometers are analyzed for their inter mission deviations and
21 consistency with buoy winds during 1992 – 2011

22 **2. Data**

23 **2.1 Scatterometer data**

24 For more than two decades, a sequence of scatterometers onboard polar satellites has
25 been providing unique observations of winds over the global ocean. Continuous surface wind
26 records are available from ten missions spanning late 1991 through present. These missions
27 include C-band (5.3 GHz) scatterometers onboard ERS-1, ERS-2 and METOP-A(ASCAT),
28 and higher frequency Ku-band (13.4 GHz) SeaWinds onboard QuikSCAT (indicated as
29 QSCAT hereafter)

30 Scatterometers are microwave radars that infer near-surface wind velocity from NRCS,
31 (σ^0) measured at a variety of azimuth (χ) and incidence angles (θ). The ocean surface radar
32 backscatter occurs primarily from centimeter-scale capillary/gravity waves (ripples), whose

1 amplitude is in equilibrium with the local near-surface wind. Measurements of NRCS are
2 used to estimate equivalent neutral wind (ENW) speed (W) and direction (φ) at 10m height
3 Equivalent neutral wind is the wind speed that would be associated with the actual wind stress
4 if the atmospheric boundary layer was neutrally stratified. W and φ are related to σ^0 through
5 the Geophysical Model Function (GMF). The latter is a nonlinear function involving θ and χ
6 dependency (e.g. Bentamy et al, 1999; Wentz and Smith, 1999; Hersbach, 2010). Wind
7 retrievals are available at Wind Vector Cell (WVC) along scatterometer swath. Spatial
8 resolution varies between 12.5km² and 50km² for different scatterometer products.

9 In this study we consider the swath data (level 2, L2b) from ERS-1, ERS-2, QSCAT,
10 and ASCAT-A (hereafter ASCAT). Table 1 provides particular characteristics of each
11 scatterometer including its operating period, repeat cycle, radar frequency/wavelength, GMF
12 used for wind retrieval processing, the version of L2b product used in this study, , and
13 WVC spatial resolution. The agencies processing and distributing these data (shown in the
14 last column of Table 1) are Institut Français pour la Recherche et l'Exploitation de la MER
15 (IFREMER), European Space Agency (ESA), NASA Jet Propulsion Laboratory (JPL), and
16 European Meteorological Satellite (EUMETSAT).

17 Original data listed in Table 1 have been corrected (except ERS-2 ASP2.0, assumed
18 well calibrated) to decrease inter-mission biases. In particular, the original QSCAT winds
19 distributed by NASA/JPL have been corrected for a SST-related bias. This correction depends
20 on wind speed and the sea surface temperature (SST) and accounts for stronger viscous
21 dissipation (especially noticeable at cold SST<5°C) of Bragg waves in Ku-band in
22 comparison with C-band (Bentamy *et al*, 2011; Grodsky *et al*, 2012, Bentamy *et al.*, 2013).
23 This new QSCAT wind is referred to as QSCAT/N. It also employs an enhanced rain filtering
24 based on the regular rain flag along with the multidimensional rain probability, which must be
25 <0.05 for rain free data (Bentamy *et al*, 2011).

26 ASCAT winds have been also modified from their original version distributed by the
27 EUMETSAT. These modified winds are referred to as ASCAT/N. They are corrected for
28 GMF-related bias, which has been parameterized in Bentamy *et al.* (2011) as a function of
29 ASCAT wind speed and direction relative to the mid-beam azimuth.

30 Scatterometers onboard ERS-1 and ERS-2 are identical in design. Both are C-band
31 radars that have three antennae looking 45° forward (fore-beam), perpendicular (mid-beam),
32 and 45° backward (aft-beam) relative to the satellite track and illuminating a 500km wide
33 swath to the right of the satellite track. Fore-beam and aft-beam incidence angles vary from

1 24° (inner swath) to 57° (outer swath), whereas mid-beam incidence angles vary from 18° to
2 46°.

3 ERS-1 and ERS-2 winds are inferred at 50km² spatial resolution using IFREMER
4 version 2 GMF (CMODIFR2 of Bentamy *et al.*, 1999). CMODIFR2 was derived by fitting
5 ERS-1 winds to collocated National Data Buoy Center (NDBC) buoy winds. CMODIFR2 has
6 been applied to ERS-2 without any further adjustments. These ERS-1 and ERS-2 datasets
7 including their corresponding NRCS values are distributed by IFREMER and indicated as
8 WNF products. Land, ice, and rain contaminations are excluded using quality flags included
9 into WNF products.

10 Previous studies have found that ERS-2 WNF wind speed is underestimated versus
11 buoy and QSCAT/N winds (e.g. Bentamy *et al.*, 2002; Bentamy *et al.*, 2013). This ERS-2 wind
12 bias is related to biases in radar calibration and GMF. In fact, the bias versus QSCAT/N is
13 apparently reduced if Cmod5.n GMF is applied instead of CMODIFR2 (Bentamy *et al.*,
14 2013). Recently the Advanced Scatterometer Processing System (ASPS) project run by ESA
15 in collaboration with the Royal Military Academy (RMA) of Belgium has addressed the inter-
16 beam calibration issue by recalibrating ERS-2 σ^0 measurements over quasi-homogeneous
17 tropical rainforests targets. Reprocessed ERS-2 winds (referred to as UWI) are based on
18 Cmod5.n GMF and available globally from June 1997 through January 2001 at nominal
19 50km² and 25km² spatial resolutions (De Chiara *et al.*, 2009; Crapolicchi *et al.*, 2012). Only
20 high resolution data are used in this study. But, the UWI reprocessing are only available
21 from the middle of 1997 only, thus does not overlap with ERS-1.

22 **2.2 Buoy data**

23 The ground truth surface wind speed and direction and accompanying oceanic and
24 atmospheric parameters are obtained from moored buoys. Two buoy networks are used in this
25 study. The first network is maintained by the National Data Buoy Center (NDBC). NDBC
26 buoys are moored off US coasts spanning middle latitude range from 20°N to 65°N. The
27 second network operates in the tropics and includes Tropical Atmosphere Ocean (TAO),
28 Prediction and the Research Moored Array in the Atlantic (PIRATA), and the Research
29 Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA)
30 buoys. TAO, PIRATA, and RAMA are moored in the tropical Pacific, Atlantic, and Indian,
31 respectively and are referred to as tropical buoys (www.pmel.noaa.gov/tao/). To provide
32 compatibility with scatterometer winds, the buoy measurements are transformed into ENW at
33 standard 10m height using the COARE3.0 algorithm of Fairall *et al.* (2003). This algorithm

1 requires the knowledge of sea surface temperature (SST), air temperature (T_a), and relative
2 humidity (Rh) (or related variables). All these parameters are available from the tropical
3 buoys. However, only a few NDBC buoys provide air humidity measurements. Therefore, Rh
4 is set to 80% when it is unavailable.

5

6 **2.3 Numerical Weather Prediction (NWP) data**

7 Era-Interim (Simmons *et al.*, 2006) refers to the re-analyses of atmospheric parameters
8 produced by the European Center for Medium Weather Forecasts (ECMWF). It uses 4D-
9 variational analysis on a spectral grid and spans 1989 - present on a fixed 0.75° grid
10 (<http://www.ecmwf.int/en/research/climate-reanalysis/era-interim>). The main parameters used
11 in this study are zonal and meridional wind components at 10m height, specific air humidity,
12 air temperature at 2m, and sea surface temperature available at synoptic times (00h:00,
13 06h:00, 12h:00, 18h:00 UTC).

14 NCEP Climate Forecast System Reanalysis (CFSR) (<http://rda.ucar.edu/pub/cfsr.html>) is
15 developed by the US NOAA NCEP. The data used for this study are from the NOAA's
16 National Operational Model Archive and Distribution System (NOMADS), which is
17 maintained by the NOAA's National Climatic Data Center (NCDC) (Saha *et al.* Co-authors,
18 2010). The coupled model consists of a spectral atmospheric model on T382 grid (38km)
19 with 64 hybrid vertical levels and the GFDL Modular Ocean Model. The atmosphere and
20 ocean models are coupled with no flux adjustment. The NCEP-CFSR uses the Gridpoint
21 Statistical Interpolation (GSI) data assimilation system for the atmosphere. Flow dependence
22 for the background error variances is included as well as first order time interpolation to the
23 observation. Variational quality control of observations (Andersson and Järvinen 1999) is
24 also included. An ocean analysis for SST is also performed using Optimal Interpolation (OI).
25 A full range of observations is used as in the other re-analyses which are quality controlled
26 and bias corrected, including satellite radiances. Observations of ocean temperature and
27 salinity are also used.

28 **2.4 Data collocation**

29 In this study we use satellite-buoy and satellite-satellite collocations to assess the
30 accuracy of wind retrievals and to separate and correct for biases in radar calibration.

31 *2.4.1 Sattelite-buoy.*

1 The accuracy of wind retrievals is evaluated by comparing in-situ buoy measurements
2 with quasi-simultaneous scatterometer data. Here we use satellite-buoy data pairs collocated
3 in space and time. The spatial limit for collocation is set based on the spatial resolution of
4 particular satellite wind product, which is 25km for ERS-2 UWI, ASCAT, and QuikSCAT and
5 increases to 50km for ERS-1 and ERS-2 WNF. The temporal criterion is 30 min for all
6 products. Only scatterometer retrievals indicated as selected, quality controlled solutions are
7 used herein. The quality controls applied on remotely sensed data are from flags available
8 with scatterometer L2b products.

9 *2.4.2 Satellite-satellite.*

10 Radar calibration issue for the WNF product is evaluated by collocating ERS-2 WNF
11 and UWI products. The WNF and UWI data are available simultaneously over the same
12 scatterometer swath, but at different spatial resolution of 50km×50km and 25km×25km,
13 respectively. The difference in spatial resolutions leads to a difference in the incidence angle
14 range for WVCs between the two products. To achieve the consistency in geometry of
15 observations, only WNF and UWI WVCs differing by less than 1° in the incidence angle and
16 separated by less than 50km are selected. The collocated UWI data are then spatially
17 interpolated on corresponding WNF WVCs. Collocated ERS-2 WNF and ERS-2 UWI data
18 have much larger records (in comparison with satellite-buoy collocations). They are available
19 over the global ocean because these collocations were produced from the same original
20 scatterometer measurements. To reduce enormous number of these collocated observations,
21 only their subset spanning January - March 2000 is further considered.

22 *24.2 Satellite-model*

23 ERA Interim and CFSR are available four times a day (00h:00; 06h:00; 12h:00; 18h:00
24 UTC) on their corresponding regular grids. Atmospheric re-analyses winds are interpolated in
25 space and time over scatterometer swaths using a bilinear method.

26 **3. Validation method**

27 **3.1 Buoy comparison results**

28
29 Comparisons are performed for all valid collocated data available during the periods
30 March 1992 – June 1996 for ERS-1 WNF, March 1996 – January 2001 for ERS-2 WNF, April
31 1997 – January 2001 for ERS-2 UWI, July 1999 – November 2009 for QSCAT, and April
32 2007 – March 2011 for ASCAT. Statistical parameters of scatterometer and buoy winds are
33 summarized in Tables 2 and 3 (see Bentamy et al, 2011 for parameter’s description). To avoid

1 an impact of outliers a robust regression method of Street *et al.* (1988), which iteratively
2 assigns weights to data, is applied. Outliers are filtered by excluding data with the assigned
3 weight <0.05 . The regression symmetrical coefficient (b_s) in Tables 2, 3 is produced by linear
4 regression of satellite and buoy winds, $w_{sat} = b_s * w_{buoy} + a_s$, which accounts for errors in
5 both, buoy and satellite data Two types of correlation coefficients are included. Scalar
6 correlation (ρ) for wind speed is the conventional Pearson's correlation coefficient. Wind
7 direction correlation is evaluated as a vector correlation (Crosby *et al.*, 1993). It provides a
8 scalar measure of consistency between two vector fields and varies between -2 and +2.

9 The agreement between buoy and scatterometer wind speeds is excellent. The wind
10 speed correlation coefficients of all scatterometer products are higher than 0.87. The
11 associated b_s values are close to unity. The RMS differences (estimated from Bias and STD
12 values) $<1.60\text{m/s}$ are lower than scatterometer accuracy specifications. The wind speed RMS
13 at Tropical buoys is slightly weaker than that at NDBC. This is mainly related to difference in
14 wind speed distributions over NDBC and Tropical network regions (e.g. Bentamy *et al.*,
15 2008). One should notice that ERS-2 UWI and ASCAT have similar statistics. They rely on
16 the use of same C-band geophysical model GMF to retrieve surface winds from the two
17 scatterometers. Cmod5.n was developed on the basis of ERS-2 scatterometer backscatter
18 coefficient measurements (Hersbach *et al.*, 2007). Quite similar results are found for wind
19 direction comparisons. Indeed, for ERS-1 WNF, ERS-2 WNF, QSCAT, and ASCAT the
20 correlation coefficients characterizing NDBC and Tropical comparisons are higher than 1.20
21 and 1.60, respectively. The lowest wind direction correlations are found for ERS-2 UWI.
22 Furthermore, except for ERS-2 UWI, STD values are lower than 20° .

23 **3.2 Reprocessing of ERS-1 and ERS-2 WNF wind retrievals**

24

25 Both ERS-1 WNF and especially ERS-2 WNF winds tend to be underestimated in
26 comparison with buoy winds (Tables 1, 2). This is associated with the calibration of ERS-1
27 and ERS-2 radars and GMF issues (e.g. Bentamy *et al.*, 2013, see also references therein).
28 Indeed, the reprocessing of ERS-2 wind retrievals based on the use of Cmod5.n GMF has
29 improved correspondence with buoy data (Bentamy *et al.*, 2013). Therefore, we achieve better
30 consistency between ERS-1 and ERS-2 winds as a result of their reprocessing with Cmod5.n
31 GMF.

32 Prior to applying Cmod5.n for the wind reprocessing we compare measured (σ_m^0) and

1 expected (σ_e^0) backscatter coefficients to estimate radar calibration issues that may be still
 2 present in the WNF products. The expected σ_e^0 is calculated from Cmod5.n forced by
 3 collocated buoy wind velocity. The measured backscatter coefficient is evaluated from
 4 scatterometer data following the Bentamy *et al.* (2008) approach. The azimuth dependence of
 5 σ^0 is represented by truncated Fourier series:

$$6 \quad \sigma^0 = A_0 + A_1 \cos \chi + A_2 \cos 2\chi \quad (1)$$

7 χ is the wind direction relative to antenna azimuth .

8 The coefficient A_0 in (1), referred to as the power coefficient, mainly carries the
 9 information on wind speed. The harmonic coefficient A_1 describes the upwind and downwind
 10 asymmetry. The coefficient A_2 describes the difference in backscatter coefficient extrema. A_0 ,
 11 A_1 , and A_2 are functions of wind speed, incidence angle, and polarization. According to the
 12 study objective dealing with wind speed consistency, we next focus on A_0 , which is calculated
 13 as:

$$14 \quad A_0 = (\sigma_u^0 + \sigma_d^0 + 2\sigma_c^0)/4 \quad (2)$$

15 where σ_u^0 , σ_d^0 , σ_c^0 are the upwind ($\chi = 0^\circ$), downwind ($\chi = 180^\circ$), and crosswind ($\chi =$
 16 90° or 270°) values of the backscatter coefficient. Using buoy wind direction, we selected
 17 only those data that correspond within $\pm 10^\circ$ either to up-, down-, or cross-wind direction.
 18 The selected data are binned 1m/s in buoy wind speed and 0.2° in incidence angle (θ), from
 19 which measured A_0 is calculated based on (2). Only bins for which data count exceeds 10 are
 20 retained for investigations. The calculations are performed for A_0 derived from ERS-1 WNF,
 21 ERS-2 WNF, and ERS-2 UWI backscatter measurements, σ_m^0 .

22 For each wind speed and incidence angle the expected backscatter coefficients (σ_e^0),
 23 calculated from Cmod5.n forced by collocated buoy winds, are used to estimate the expected
 24 A_0 based on (2). The best correspondence between expected and measured A_0 is found for
 25 ERS-2 UWI (Figures 1 g, 1h, 1i) that reflects better post flight backscatter calibration in the
 26 UWI product. Mean differences (resp. STD) between expected and measured power
 27 coefficients A_0 for ERS-2 UWI are -0.36dB (resp. 1.08dB), -0.60dB (1.54dB), and -0.57dB
 28 (1.10dB) for fore-, mid-, and aft-beam, respectively. The three associated correlation
 29 coefficients exceed 0.98. The discrepancy between expected and measured power coefficients
 30 is stronger for ERS-1 WNF and ERS-2 WNF than that for ERS-2 UWI. It is more noticeable
 31 for low A_0 corresponding to low winds. But, even for buoy winds $>3\text{m/s}$, the mean difference

1 and STD reach -1dB and 2dB for ERS-1 WNF and ERS-2 WNF, respectively. Correlation
2 between expected and measured power coefficients remain relatively high (~0.95) for the two
3 WNF products, but it is lower than that for the UWI.

4 Figure 1 illustrates a persistent overestimation of measured A_0 in comparison with
5 expected values, which is indicative of a low bias in ERS wind retrievals and suggests the
6 need for correction of the WNF backscatter coefficients to reduce the bias in the scatterometer
7 winds.

8 NRCS correction for ERS-1 WNF and ERS-2 WNF is based on a linear regression
9 analysis of expected (σ_e^0) and measured (σ_m^0) NRCS using a linear regression analysis.
10 Various regression analyses would be used to determine the linear relationship between
11 measured and predicted σ^0 (e.g. Bentamy *et al*, 2011). However, one should notice that both
12 σ_m^0 and σ_e^0 have their own uncertainties, neither measured nor expected σ^0 can be selected as
13 a reference ('ground truth') for the analysis (e.g. Bentamy *et al*, 2011). Indeed, both sources
14 have errors related to buoy wind and scatterometer backscatter coefficient measurements.
15 Additional errors are related to the procedure of estimation of σ_e^0 and to the spatial and
16 temporal separations between buoy and scatterometer data. In this study, the symmetrical
17 regression analysis, also called the reduction of major axis is used (e.g. Trauth, 2007;
18 Bentamy *et al*, 2011). It aims to minimize the distances separating regression fit and both,
19 σ_m^0 and σ_e^0 . Outliers, detected through the application of robust regression algorithm (Street
20 *et al*, 1988), are excluded.

21 The regression is performed for each incidence angle bin because Figure 1 clearly
22 indicates that NRCS correction should depend on θ . Such kind of analysis requires a large
23 sampling length of collocated buoy and scatterometer data. All available and valid NDBC and
24 tropical (TAO and PIRATA) hourly data are used together and collocated with ERS-1 and
25 with ERS-2 measurements based on space and time criteria described above. The resulting
26 sampling lengths of ERS-1/buoy and ERS-2/buoy collocations are 17156 and 23405,
27 respectively. These collocated data are split into two subsamples, which are randomly
28 selected. The first subsample (67% of collocated data) is used to determine the regression
29 slope and intercept coefficients, whilst the second subsample is utilized for the validation.

30 of the corrected σ^0 . Figure 2 shows examples of the validation results. It indicates the
31 mean differences between predicted σ_e^0 and measured σ_m^0 as a function of incidence angles.
32 Results related to ERS-1 and ERS-2 are shown in Figure 2a and Figure 2b, respectively.

1 Dashed and Full and lines illustrate the results of (σ_e^0 minus measured σ_m^0) and of (σ_e^0
2 minus corrected σ_m^0), respectively. Measured σ_m^0 tend to be overestimated with respect to the
3 expected backscatter coefficients, σ_e^0 , (Figure 2) Not surprisingly, the results are in agreement
4 with the power coefficient A_0 in Figure 1. The difference, $\sigma_e^0 - \sigma_m^0$, is reduced for the
5 corrected measured backscatter coefficients calculated from the application of the
6 symmetrical regression results. The correction reduces the mean difference $\sigma_e^0 - \sigma_m^0$ by about
7 30%. The lowest mean and standard deviation (not shown) are found for inner swath locations
8 (low incidence angles). For instance, the associated RMS difference related to ERS-1 mid-
9 beam vary between 1 and 1.5dB for $\theta < 25^\circ$, while RMS values reach 1.90dB for $\theta > 40^\circ$.

10 To further assess the quality of the correction procedure reliability, corrected ERS-2
11 WNF σ^0 are compared to ERS-2 UWI over global ocean. Indeed, the latter exhibit the best
12 comparison results versus predicated backscatter coefficient (Figure 1 g), h), and i)). The
13 comparison is performed based on the use of collocated ERS-2 WNF and UWI (section 2.4).
14 Figure 3 shows mean differences between ERS-2 UWI and ERS-2 WNF backscatter
15 coefficients as a function of incidence angles. The statistics are estimated from remotely
16 sensed data collected from January through March 2000. Dashed and full lines illustrate the
17 result associated with uncorrected and corrected ERS-2 WNF σ^0 , while the colors aim to
18 distinguish the results associated with each beam like in buoy comparisons (Figure 2) the
19 uncorrected ERS-2 WNF σ^0 tend to be overestimated versus ERS-2 UWI. On average, biases
20 related to the uncorrected σ^0 differences fall within -0.20dB and -0.10 dB range and are
21 reduced as a result of the correction. Indeed the biases are lower than 0.07dB.

22
23 Based on the method and the related results described in (Bentamy et al, 2013), ERS-1
24 and ERS-2 scatterometer wind speeds are reprocessed using the corrected backscatter
25 coefficients and Cmod5.n GMF. As for ASCAT and QSCAT, these newly reprocessed ERS-1
26 and ERS-2 retrievals are referred as ERS-1/N and ERS-2/N. The gross statistics of deviations
27 from buoy data for these new retrievals are listed in brackets in Table 2 and Table 3. Because
28 neither of buoys locates in cold SST $< 5^\circ\text{C}$, the results for QSCAT/N are very close to those for
29 QSCAT and therefore not shown. Although, the statistics obtained for ASCAT L2b and
30 ASCAT/N are slightly different, the results are statically comparable. Indeed, the main impact
31 of ASCAT bias correction relies on high wind conditions (wind speed exceeding 18 m/s). The
32 latter are undersampled in buoy and ASCAT collocated data set. The main changes are found

1 for the reprocessed ERS winds in comparison with WNF winds. Indeed, the reprocessed ERS-
2 1 and ERS-2 winds show significant reduction in the time mean as well as in RMS wind
3 speed differences. The new bias values are quite small, and the associated RMS differences
4 are even lower than for ERS-2 UWI, QSCAT, and ASCAT.

5 The results in Tables 2 and 3 reflect statistics averaged over the period of operation of
6 each satellite. It is important to ensure that validation results are not time dependent. This
7 could be determined by examining differences, in terms of bias and STD, between buoy and
8 scatterometer data as a function of time. The results are illustrated in Figure 4 and 5 for
9 NDBC and Tropical buoy comparisons, respectively. For each month of comparison periods,
10 difference between available collocated buoy and scatterometer wind speeds are
11 arithmetically averaged and the associated STD are calculated. Full lines indicate time series
12 of monthly mean differences, while dashed lines indicate $\text{bias} \pm \text{STD}$. Along the duration of
13 each scatterometer period, the related monthly biases are quite close to the total bias (Tables 2
14 and 3). No significant time changes are depicted. Based on mean differences and the
15 associated STD, results shown in Figures 4 and 5 state that no systematic biases are found.
16 Changes of a few tenths of m/s are mainly due to changes in sampling lengths of collocated
17 data and/or to wind seasonal variability. For instance there is a factor of 3 between the number
18 of collocated NDBC and ERS-1 and NDBC and QSCAT. The change in sampling lengths
19 arises from changes between scatterometer sampling schemes and especially on changes in
20 the number of buoys available for the collocation. For instance, the numbers of Tropical buoy
21 available for ERS-1, ERS-2, QSCAT, and ASCAT collocations are on average about of 19, 24,
22 32, and 28, respectively. As expected the inter-annual wind distributions may also have
23 significant impact on buoy and scatterometer comparisons. For instance, the percentage of
24 low winds (lower than 3m/s) reported from NDBC buoys reaches a maximum of 37% in
25 August 1992, whereas it is only about 20% during summer months (June-July-August). Low
26 winds that are not adequately detected by ERS 1/2 lead to a negative bias between NDBC and
27 ERS-1 wind speeds. Monthly difference time series calculated from NDBC and scatterometer
28 winds (Figure 4) indicate different trends for ERS-1 and ERS-2 biases. The latter tends to be
29 negative. Such changes between ERS-1 and ERS-2 bias trends, is mainly relied on changes in
30 low wind speed distribution derived from NDBC buoy measurements. Indeed, the sampling
31 lengths of NDBC low wind speeds ($<4\text{m/s}$), reported from collocated buoy and scatterometer
32 data, are of 1175 and 1935 for ERS-1 and ERS-2 periods, respectively. We may notice that
33 during overlapping periods of any pair of scatterometers, their associated biases are very

1 close. However, some discrepancies are depicted. For instance, Figure 4 indicates QSCAT/N
2 and ASCAT/N bias difference during the period April – December 2007 when original
3 ASCAT retrievals are estimated as “real”, not ENW at 10m, winds (Bentamy et al, 2008).
4 Correlation coefficient time series (not shown) vary mostly between 0.88 and 0.97. The
5 highest values are found for QSCAT/N and ASCAT/N whereas the lowest are related to ERS-
6 1 and ERS-2 and especially for summer months. This is clearly due to the sampling issues
7 mentioned above.

8 **4. Global consistency analysis**

9 In the previous section, we established that ERS-1/N, ERS-2/N, QSCAT/N, and
10 ASCAT/N exhibit quite similar statistics with respect to buoy data. Although such
11 comparisons remain the most reliable method to estimate the quality of remotely sensed data,
12 it is spatially limited. This section aims to investigate, based on statistical analysis, the
13 consistency of the four scatterometer wind sources at global as well as at regional and local
14 scales. For such purpose, comparisons are performed versus ERA Interim and CFSR 10m
15 wind speed estimates. This analysis aims first to assess the long term consistency of the
16 remotely sensed data, and secondly to assess the comparisons of scatterometer and NWP
17 (wind speeds at various spatial and temporal scales. CFSR as well as ERA Interim are
18 considered as references. However, they are assumed ensuring long time series consistency of
19 surface winds.

20 The purpose aiming to assess the consistency of long time series of surface wind speed
21 retrievals based on the use of NWP requires ensuring that their long time variations are not
22 scatterometer dependant. Indeed, both numerical models assimilate ERS-1, ERS-2,
23 QuikSCAT and ASCAT observations. To meet this requirement, monthly ERA Interim and
24 CFSR wind speed anomalies are calculated over North, Tropical, and South Atlantic Oceans
25 during the period March 1992 – March 2011 (not shown). The departures from annual mean
26 concurrent with start and/or end periods of a given scatterometer observations would be used
27 as dependency indicators. The analysis of anomaly time series do not lead to any significant
28 change associated with change in scatterometer availability for assimilation processing.
29 Therefore, hereafter, ERA Interim and CFSR wind speeds are assumed time consistent.

30 To reduce the impact of difference in spatial resolutions for NWP and scatterometer
31 winds, both are averaged over $1^{\circ}\times 1^{\circ}$ grid cells over scatterometer swaths. The resulting
32 collocated data are monthly averaged. The monthly averages are arithmetically formed on the
33 $1^{\circ}\times 1^{\circ}$ grid using all available and valid data falling within the grid cell. As expected, the

1 sampling lengths of $1^{\circ}\times 1^{\circ}$ collocated NWP and remotely sensed data rely on scatterometer
2 characteristics. On average, in inter-tropical oceanic basins the monthly number of collocated
3 data at grid of 1° is about 15 for ERS-1 and ERS-2 and of 40 for QSCAT and ASCAT. At high
4 latitudes, this number reaches or exceeds 30 for ERS-1 and ERS-2, and 70 for QSCAT and
5 ASCAT.

6 **4.1 Global spatial distributions**

7 The monthly averages are utilized to estimate annual wind speed means during
8 operating period of each scatterometer. Spatial variability of annual scatterometer wind speeds
9 (first column) are shown in Figures 6 and 7, along with mean (second column) and STD
10 (Third column) differences between NWP and scatterometer data, for CFSR and ERA Interim
11 comparisons, respectively. Spatial statistics associated to ERS-1/N, ERS-2/N, QSCAT/N, and
12 to ASCAT/N are shown in first, second, third, and fourth Figure rows, respectively.

13

14 Some difference patterns revealed in Figures 6 and 7 are inherent to the characteristics
15 of scatterometer and NWP wind determinations. For instance, model surface wind speeds are
16 earth-relative, whereas scatterometer retrievals are surface-relative. Therefore, surface
17 currents may lead to differences between NWP and remotely sensed wind data (e.g. Quilfen *et*
18 *al*, 2001). Rain impact on scatterometer measurements may also induce a departure from
19 model estimates. Indeed, scatterometer, and especially, radars operating at Ku band such as
20 QSCAT, are rain affected. In the presence of rain, Ku-band backscatter coefficients are
21 affected by the roughening of the sea surface by rain drops and also by scattering and
22 absorption by rain drops in the atmosphere. (Sobieski *et al*, 1999) showed that rain impact on
23 QSCAT retrievals may lead to an overestimation reaching 2m/s in the tropical rainy regions.
24 Another source of the difference between model and scatterometer winds is associated to the
25 atmospheric stability effect. Indeed, NWP wind estimation includes air-sea stratification,
26 whereas scatterometer winds are equivalent neutral wind. Neutral wind speeds are stronger,
27 on average, than stability-dependent wind speeds (e.g. Mears *et al*, 2001). To assess the
28 stability impact, 10m neutral winds are calculated from ERA Interim 10m stability-dependent
29 wind speed, air and sea surface temperatures, and specific air humidity based on the use of
30 COARE3.0 bulk parameterization (Fairall *et al*, 2003). Comparisons between ERA Interim
31 10m neutral and 10m stability-dependent wind speeds are performed for ERS-1, ERS-2,
32 QSCAT, and ASCAT periods (not shown). The mean differences between the two ERA
33 Interim wind speeds are of about 0.20m/s for the four scatterometer periods. It is also found

1 that differences vary as a function of oceanic zone and season. For instance, along north
2 hemisphere western boundary currents, the difference reaches 0.40m/s during winter season.

3 The comparisons of mean wind speed patterns (Figures 6 and 7) are not straightforward
4 due to differences between scatterometer sampling schemes. To assess the impact of sampling
5 schemes, monthly-averaged winds estimated from only CFSR data collocated on one hand
6 with ERS-2/N and on other hand with QSCAT/N during 2000, are compared. It is found (not
7 shown) that differences between the two annual CFSR wind speeds may reach 1m/s,
8 especially at high latitudes where surface wind is more variable. Results shown in Figures 6
9 and 7 indicate that the spatial variability of wind speeds from all scatterometers generally
10 show similar features. Furthermore, they exhibit quite similar magnitudes over the global
11 ocean. For instance, high winds exceeding 10m/s are found in northern (north 50°N) and
12 southern (south 45°S) latitudes. The lowest winds are generally located along the equatorial
13 zones. Mean wind speed biases calculated with respect to CFSR (Figure 6) reveal that the
14 associated patterns are quite similar. Same results are found for bias determined with respect
15 to ERA Interim (Figure 7). For the four scatterometers, about 95% of bias absolute values are
16 lower than 1m/s. Global distributions of both mean differences and STD of ERS-1/N and
17 ERS-2/N are remarkably similar. Similar results are found for QSCAT/N and ASCAT/N and
18 especially for CFSR comparisons. These results are relied on the scatterometer sampling
19 schemes characteristics. On average, the four scatterometer winds tend to be slightly
20 overestimated compared to CFSR and ERA Interim re-analyses. As expected, the four STD
21 spatial distributions exhibit small (lower than 1m/s) and high (great than 2m/s) values in the
22 tropical and high latitude regions, respectively. Both regions are characterized by low and
23 high wind variabilities. Surface winds occurring over extra-tropical regions are known
24 dominated by more dynamic synoptic variability as compared to less variable tropical winds.

25 Although, NWP and scatterometers are in good agreements, significant departures are
26 found at some specific regions. For instance, ERS-1/N winds are underestimated with respect
27 to CFSR estimates (Figure 6b) along south trade wind zone in the Atlantic Ocean. Indeed,
28 mean differences between CFSR and ERS-1/N annual winds are about 0.40m/s, and reach
29 0.80m/s at some locations. Similar difference pattern, even though slightly lower, is found for
30 CFSR and ERS-2/N comparison (Figure 6e). For CFSR and QSCAT/N (Figure 6h) as well as
31 for CFSR and ASCAT/N (Figure 6k) comparisons do not lead to any significant patterns of
32 wind differences along south Atlantic trade wind area. These specific difference patterns are
33 also depicted from ERA Interim and scatterometer comparisons (Figure 7b, e, h, and k).
34 However their magnitudes are lower. These results suggest that CFSR and somehow ERA-

1 Interim south Atlantic trade winds decrease from 1992 through 2011.

2 Noticeable differences are depicted along the three ocean equatorial areas.
3 Scatterometer monthly winds are overestimated with respect to NWP estimates. The highest
4 departures are found for ASCAT and especially for QSCAT/N. These equatorial difference
5 patterns are more pronounced for ERA-Interim comparisons. For instance, mean difference
6 between ERA-Interim and QSCAT/N may reach 2m/s. Such difference behaviors along the
7 equator may partly rely on impact of rain (non detected through quality control procedure),
8 especially for QSCAT/N, current on scatterometer retrievals, and of stability (see above).
9 However, such impacts cannot account for the total differences between ERA Interim and
10 scatterometer winds along equatorial zones. Indeed, these equatorial differences are not found
11 for CFSR and scatterometer comparisons (Figure 6). The former exhibit lower difference
12 values. Somewhat high discrepancies between ERA Interim and scatterometer winds are also
13 depicted along western boundary current regions. ERS-1/N, ERS-2/N, and QSCAT/N winds
14 are slightly overestimated compared to ERA Interim. These patterns are not found for ERA
15 Interim and ASCAT/N and for CFSR and scatterometer comparisons.

16

17 **4.2 Long time series**

18 In section above, the consistency of scatterometer retrievals has been assessed through
19 the spatial differences versus CFSR and ERA Interim analyses. Such consistency would be
20 further assessed through the investigation of long time series of surface wind speeds derived
21 from scatterometers and NWP over ocean basins or at some locations of interest.

22 Figures 8 and 9 show time series of yearly-averaged wind speeds estimated from
23 available monthly-averaged collocated CFSR and scatterometer. and from ERA Interim and
24 scatterometer data, respectively. They also show annual mean wind speeds calculated from 6-
25 hourly CFSR and ERA Interim analyses (dashed lines). They are calculated for five oceanic
26 zones : Northern high-latitudes (50°N – 70°N), Northern mid-latitudes (20°N-40°N), tropical
27 (10°S – 10°N), Southern mid-latitudes (40°S-20°S), and Southern high-latitudes (70°S –
28 50°S). Changes of mean values associated with changes of remotely sensed data sources are
29 related in part to the sampling scheme issues. Indeed, annual means derived from CFSR
30 (**Figure 8**) as well from Era Interim (Figure 9) show small change over time, except for the
31 period beyond 2009, and along southern high latitudes (Figure 8e and 9e). But, stronger
32 changes are present in the time series derived from the collocated data, including
33 discontinuities associated with changes of satellites, thus associated with sampling schemes.

1 Noticeably, similar discontinuities are present in scatterometer wind averages emphasizing
2 again the sampling impacts. Obviously, changes in annual wind speeds estimated from ERS-
3 1/N and ERS-2/N are related to the sampling issues because similar changes are depicted for
4 the collocated CFSR and ERA Interim data. Similar results are found for ERS-2/N and
5 QSCAT/N, except at tropical zone (Figure 8c and 9c). Annual winds calculated from
6 QSCAT/N over the tropics tend to be overestimated due to rain impact. Although, QSCAT/N
7 and ASCAT/N yearly mean values are close during overlapping period (2008 – 2009), a slight
8 overestimation (resp. underestimation) of QSCAT/N with respect to ASCAT/N are found in
9 tropical and midlatitude areas (resp. northern and southern high latitudes). The latter meet the
10 results shown in (Bentamy *et al*, 2011), and in (Grotsky *et al*, 2012). However, one should
11 notice that departure between QSCAT/N and ASCAT/N mean values do not exceed 0.20m/s.

12 Further investigation of remotely sensed data consistency as well as of comparison
13 between satellite and NWP are performed at some specific locations for monthly time scales.
14 Figures 10 and 11 show time series of monthly-averaged wind speeds estimated from
15 collocated scatterometers and CFSR, and from scatterometers and ERA Interim, respectively.
16 They are shown at locations supposed representing different surface wind characteristics
17 associated with North Atlantic (59°N11°W), Gulf stream (41°N66°W), the Mediterranean
18 Sea (41°N6°E), equatorial (0°N10°W), and Bay of Bengal (15°N90°E) temporal wind
19 patterns. Furthermore, moored buoy measuring winds are also available at these specific
20 locations or nearby. They would be valuable for triplet buoy / scatterometer / NWP
21 collocation analysis.

22 At the north Atlantic location (Figure 10a and 11a) , both scatterometer and NWP wind
23 speeds exhibit very similar wind patterns. The two types of wind sources lead to the expected
24 robust seasonal variation of surface wind speed. Most of maximum and minimum winds
25 occur during north hemisphere winter (December, January, February (DJF)) and summer
26 (June, July, August (JJA)), respectively. However, one should notice that the inter-annual
27 variability is significant. Despite of sampling scheme impact, the four scatterometer retrievals
28 are consistently higher than CFSR as well as than ERA Interim wind estimates.

29 The scatterometer as well as NWP wind speed variabilities at the Atlantic northwest
30 location (Figures 10b and 11b) illustrate the typical annual features of surface wind occurring
31 in the midlatitude of the North Atlantic and the Pacific Oceans. They are mainly characterized
32 by a robust seasonal variability where the maximum and minimum occur in winter and
33 summer seasons, respectively. The month to month variability derived from scatterometer and

1 NWP agree well. However, one should notice that departure found between ERA Interim and
2 ERS-1/N during the period 1992 through 1994 is higher than that depicted from ERS-1/N and
3 CFSR comparison.

4 At the location of Gulf of Lion in the Mediterranean Sea (Figure 10c and 11c),
5 scatterometer and NWP winds reveal similar month to month variabilities characterized by a
6 seasonal features. The highest and lowest winds occur during winter and summer seasons.
7 Due to sampling issues, monthly estimated from collocated NWP, ERS-1/N, and ERS-2/N
8 data are more variable. Monthly scatterometer winds are consistently higher than ERA Interim
9 estimates (Figure 11c), while no systematic bias is found out from CFSR comparisons (Figure
10 10c). The comparisons of monthly winds derived from buoys moored in Gulf of Lion (buoys
11 WMO61001 (43.3°N7.8E) and WMO61002 (42.1°N4.7°E)) and scatterometers (QSCAT/N
12 and ASCAT/N) do not reveal any overestimation of scatterometer estimates (not shown).

13 Time series of wind speeds at equatorial site (Figure 10d and Figure 11d) reveal less
14 robust seasonal variability. The wind variability is more characterized by large interannual
15 patterns. Even though NWP and scatterometer exhibit quite similar variabilities, the month to
16 month agreement is quite poor compared to previous sites. This is mostly pronounced for
17 ERS-1/N and ERS-2/N. Furthermore, due to wind speed distribution along the equatorial
18 region, the departure between ERA Interim and the four scatterometer winds is further
19 highlighted. Better results are drawn from CFSR and scatterometer wind time series
20 comparisons. The latter are similar to those obtained from the comparisons of monthly winds
21 estimated from PIRATA buoy (0°N, 10°W) and from scatterometers (ERS-2/N, QSCAT/N,
22 and ASCAT/N).

23 The wind speed variations obtained at location in the bay of Bengal of the Indian Ocean
24 (Figures 10e and 11e) exhibit a major peak occurring in summer season and related to the
25 Indian monsoon season, while a second weaker peak occurs mostly in January when the
26 region experiences winter weather conditions. The difference between the two peaks indicates
27 that the climate in this region is overwhelmingly controlled by the monsoon. Although, ERA
28 Interim winds are slightly underestimated (Figure 11e), their comparisons to scatterometer are
29 of same order that found for CFSR.

30 **5. Summary and discussion**

31 Twenty years of scatterometer measurements and wind retrievals are investigated to
32 assess the consistency between the various satellite missions. This study is a continuation of

1 those previously set up to assess the comparisons of scatterometer winds derived from
2 ASCAT and QSCAT (Bentamy et al, 2012 and Grodsky et al, 2012), and from ERS-2 and
3 QSCAT (Bentamy et al, 2013). It aims at the characterization of the source of errors yielding
4 to significant differences between scatterometer retrievals and reference data, and at the
5 correction of systematic biases between scatterometer missions.

6 In this study focuses on the four scatterometers missions: ERS-1 (March 1992 – May
7 1996), ERS-2 (March 1996 – January 2001), QSCAT (July 1999 – November 2009), ASCAT
8 (April 2007 – March 2011), which represent more than two decades of the global ocean
9 winds. The study investigates the long-term consistency of the scatterometer missions. For
10 such purpose, bias corrections found for QSCAT and ASCAT and detailed in (Bentamy *et al*,
11 2012, Grodsky *et al*, 2012) are applied without any further investigations. These datasets are
12 referred as QSCAT/N and ASCAT/N. The results drawn from (Bentamy et al, 2013) dealing
13 with the assessment of ERS-2 and QSCAT are used as guideline for further investigation of
14 ERS-2 winds and then for ERS-1.

15 The wind speed retrieval consistency is mainly based on the use of collocated moorings
16 and scatterometer data. Similar space and time collocation procedure is applied for the four
17 scatterometers. The analysis of collocated data clearly shows that the source of WNF ERS-1
18 and ERS-2 wind underestimation with respect to buoys is related in part with the backscatter
19 coefficient bias. This bias characterizes the mean differences between measured (σ_m^0) and
20 expected (σ_e^0 , estimated from buoy wind and Cmod5.n GMF) backscatter coefficients. ERS-1
21 and ERS-2 backscatter coefficient biases do not exhibit similar behavior as a function of σ°
22 and incidence angle ranges. For each ERS beam and each incidence angle bin, a relationship
23 relating difference of σ_e^0 and σ_m^0 as a function of σ_m^0 is determined and used for backscatter
24 coefficient correction. This approach has a serious shortcoming issues. Indeed, moorings
25 have a limited geographical coverage and the associated reported and collocated atmospheric
26 and oceanic conditions are not representative well of for global conditions, especially at high
27 latitudes where buoys are almost missing. However over the global ocean, it is found that
28 corrected ERS-2 NRCS compare better with ERS-2 UWI NRCS (assumed well calibrated)
29 than uncorrected NRCS.

30 The corrected ERS-1 and ERS-2 NRCS are used for reprocessing wind velocity based
31 on CMOD5.n GMF. As expected, the new ERS-1 and ERS-2 winds (referred as ERS-1/N, and
32 ERS-2/N) exhibit better comparisons with independent mooring data not used for the

1 correction procedure. Indeed, both mean and STD characterizing buoy and ERS-1/N and buoy
2 and ERS-2/N are reduced significantly. They of same order that found for QSCAT/N and
3 ASCAT/N.

4 The determination of ERS-1/N , ERS-2/N, QSCAT/N, and ASCAT/N retrievals over
5 global ocean and from March 1992 through March 2011, leads to further investigations of
6 consistency at global and regional scales and as a function of time. The four remotely sensed
7 data sources show very similar spatial and temporal patterns in agreement with the main
8 known wind distributions. The main discrepancies are found along the equatorial areas where
9 ERS-1/N and ERS-2/N winds are slightly higher than QSCAT/N and ASCAT/N. The study of
10 the long-term wind speed time series, do not show any step change associated with the change
11 of scatterometer. The differences between two scatterometer winds, operating at same dates,
12 rely on their space and time sampling schemes

13 These new datasets derived from “calibrated” scatterometer measurements for a period
14 exceeding 20 years would be useful for several studies aiming at the characterization of long-
15 term of surface parameters such as wind stress, wind stress curl, latent and sensible heat
16 fluxes at various spatial and temporal scales. We do believe they provide a better resource for
17 such studies, which are ongoing research.

18
19

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1 Tables

Table 1: Summary of scatterometer characteristics.

Scatterometer	Period	Cycle	Frequency	GMF	L2b version	WVC	Agency
ERS-1	Aug 1991 – Mar 1992	3 days	C-band (5.3GHz, 5.7 cm)	CMODIFR2	WNF2	50km ²	IFREMER
	Apr 1992 – Dec 1993	35 days					
	Dec 1993 – Apr 1994	3 days					
	Apr 1994 – Mar 1995	168 days					
	Mar 1995 – May 1996	35 days					
ERS-2	Apr 1995 – Jan 2001	35 days	C-band (5.3GHz, 5.7 cm)	CMODIFR2	WNF2	50km ²	IFREMER
	Apr 1995 – Jun 2011	35 days		CMOD5.n	UWI	25km ²	ESA
QuikSCAT	Jul 1999 – Nov 2009	4 days	Ku-band (13.4GHz, 2.2 cm)	KU_Model	V2	25km ²	JPL
ASCAT	Oct 2006 – Present	29 days	C-band (5.3GHz, 5.7 cm)	CMOD5.n	V1	25km ²	EUMETSAT

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Table 2: Statistical comparison results of collocated 10m wind speeds and direction from NDBC buoys and scatterometer ERS-1, ERS-2, QSCAT, and ASCAT products. Bias is defined as mean difference between buoy and scatterometer winds (in this order). Std, bs, ρ , and ρ^2 indicate standard deviation, regression symmetrical coefficient, scalar correlation coefficient, and vector correlation coefficient. The latter varies between -2 and +2.

	Wind Speed				Wind Direction		
	Bias (m/s)	STD (m/s)	bs	ρ	Bias (deg)	STD (deg)	ρ^2
ERS-1 WNF	0.42 (-0.06)	1.36 (1.10)	1.02 (1.00)	0.92 (0.94)	-4	19	1.84
ERS-2 WNF	0.70 (-0.15)	1.41 (1.09)	1.01 (1.02)	0.93 (0.95)	-5	18	1.86
ERS-2 UWI	0.13	1.31	0.99	0.93	-2	38	1.33
QSCAT	-0.01	1.21	0.99	0.94	-4	21	1.85
ASCAT	0.15 (0.10)	1.21 (1.26)	1.00 (1.01)	0.94 (0.94)	0	18	1.90

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Table 3: Statistical comparison results of collocated 10m wind speeds and direction from Tropical (TAO, PIRATA, RAMA) buoys and scatterometer ERS-1, ERS-2, QSCAT, and ASCAT products. Bias is defined as mean difference between buoy and scatterometer winds (in this order). Std, bs, ρ , and ρ^2 indicate standard deviation, regression symmetrical coefficient, scalar correlation coefficient, and vector correlation coefficient. The latter varies between -2 and +2.

	Wind Speed				Wind Direction		
	Bias (m/s)	STD (m/s)	bs	ρ	Bias (deg)	STD (deg)	ρ^2
ERS-1 WNF	0.77 (0.26)	1.23 (0.99)	0.99 (0.95)	0.90 (0.91)	-9	19	1.64
ERS-2 WNF	0.88 (0.12)	1.32 (0.91)	1.01 (0.99)	0.90 (0.92)	-10	20	1.68
ERS-2 UWI	0.46	1.12	0.95	0.90	0	31	1.24
QSCAT	0.19	0.95	0.96	0.91	1	16	1.74
ASCAT	0.45 (0.32)	1.02 (1.01)	0.95 (0.94)	0.91 (0.90)	-3	15	1.78

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1 **Figures**

2 **Figure 1:** C-band model power coefficient A_0 from observed scatterometer backscatter
3 coefficients (eq. 2) versus its predicted values from Cmod5.n GMF and collocated buoy
4 winds. Red, blue, and green colors dots indicate A_0 values associated to inner- (mid beam θ of
5 18°), middle- (θ of 27°), and outer- (θ of 45°) swaths, respectively.

6 **Figure 2:** Differences between expected and measured backscatter (uncorrected – dashed,
7 corrected - solid) coefficients as a function of the incidence angle.

8 **Figure 3:** Mean Differences between ERS-2 UWI and ERS-2 WNF backscatter coefficients
9 (uncorrected – dashed, corrected - solid) as a function of the incidence angle.

10 **Figure 4:** Time series of monthly differences between NDBC buoy and scatterometer wind
11 speeds. Full and dashed lines indicate running bias and bias \pm STD, respectively.

12 **Figure 5:** Time series of monthly differences between Tropical (TAO, PIRATA, RAMA)
13 buoy and scatterometer wind speeds. Full and dashed lines indicate bias and bias \pm STD,
14 respectively.

15 **Figure 6:** Annual mean scatterometer wind speeds (1st column), mean (2nd column) and STD
16 (3rd column) differences (CFSR minus scatterometer). First, second, third, and fourth rows
17 show statistics for ERS-1/N, ERS-2/N, QuikSCAT, and ASCAT/N, respectively.

18 **Figure 7:** Annual mean scatterometer wind speeds (1st column), bias (2nd column), and STD
19 (3rd column) differences ERA Interim minus scatterometer wind speeds. First, second, third,
20 and fourth rows are related to statistics estimated for ERS-1/N, ERS-2/N, QuikSCAT, and
21 ASCAT/N, respectively.

22 **Figure 8:** Annual mean wind speed estimated from available monthly averaged collocated
23 scatterometer (ERS-1/N, ERS-2/N, QSCAT, ASCAT/N) and CFSR data. They are calculated
24 for the period March 1992 – March 2011, and for latitudinal oceanic zones: a) $50^\circ\text{N} - 70^\circ\text{N}$;
25 b) $20^\circ\text{N} - 40^\circ\text{N}$; c) $10^\circ\text{S} - 10^\circ\text{N}$; d) $40^\circ\text{S} - 20^\circ\text{S}$; and e) $70^\circ\text{S} - 50^\circ\text{S}$. CFSR_Scatt (thin
26 black line) indicate CFSR data collocated with scatterometer retrievals, whereas CFSR
27 (dashed black line) indicates annual winds calculated from all CFSR data.

28 **Figure 9:** Annual mean speed estimated from available monthly averaged collocated
29 scatterometer (ERS-1/N, ERS-2/N, QSCAT, ASCAT/N) and ERA Interim data. They are
30 calculated for the period March 1992 – March 2011, and for latitudinal oceanic zones: a)
31 $50^\circ\text{N} - 70^\circ\text{N}$; b) $20^\circ\text{N} - 40^\circ\text{N}$; c) $10^\circ\text{S} - 10^\circ\text{N}$; d) $40^\circ\text{S} - 20^\circ\text{S}$; and e) $70^\circ\text{S} - 50^\circ\text{S}$.
32 ERAI_Scatt (thin black line) indicate ERA Interim data collocated with scatterometer
33 retrievals, whereas ERAI (dashed black line) indicates annual winds calculated from 6-hourly
34 analyses.

35 **Figure 10:** Time series of monthly-averaged wind speeds estimated from collocated
36 scatterometer (ERS-1/N, ERS-2/N, QSCAT, ASCAT/N) and CFSR data. They are shown for
37 five locations which coordinates are indicated in the top/leftcorner of each panel.

38 **Figure 11:** Time series of monthly-averaged wind speeds estimated from collocated
39 scatterometer (ERS-1/N, ERS-2/N, QSCAT, ASCAT/N) and ERA Interim data. They are
40 shown at five locations which latitudes and longitudes are indicated at top/left of each panel.
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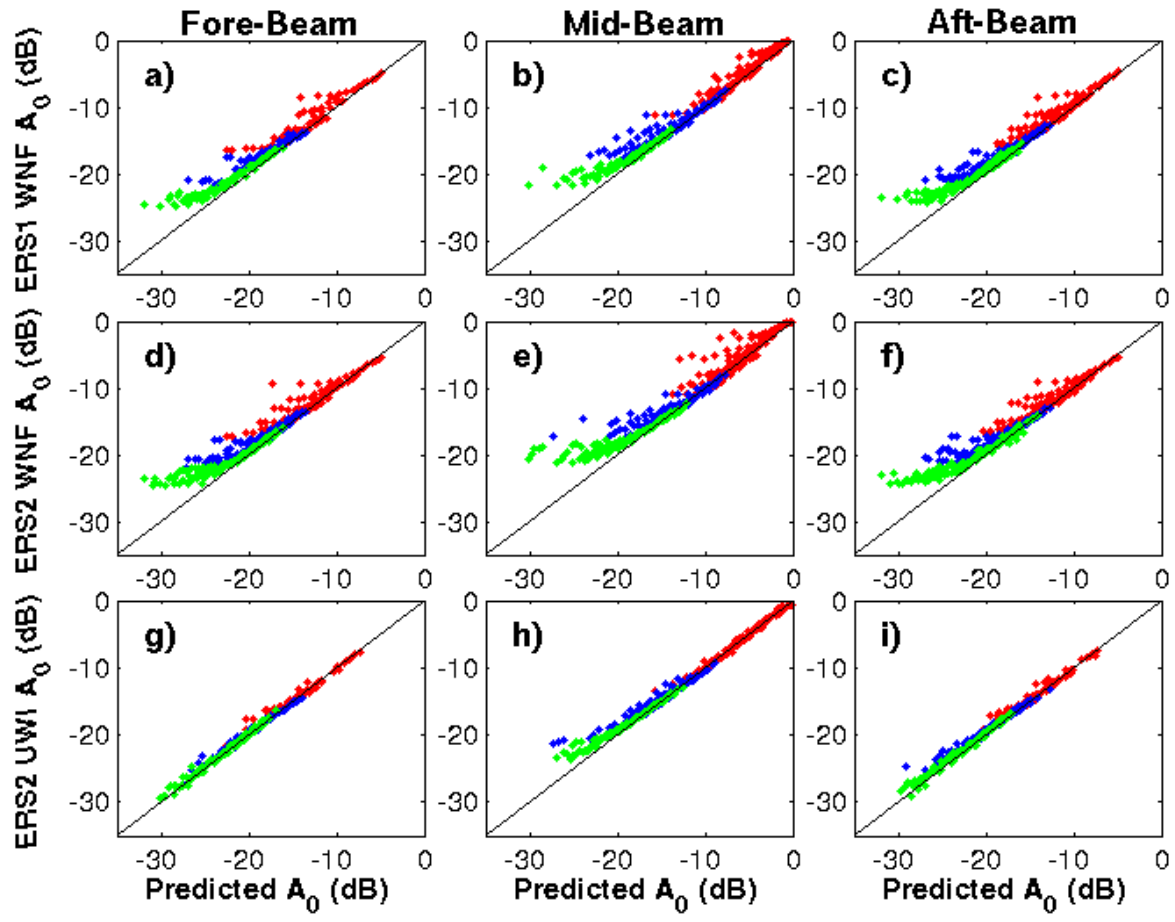


Figure 1: C-band model power coefficient A_0 from observed scatterometer backscatter coefficients (eq. 2) versus its predicted values from Cmod5.n GMF and collocated buoy winds. Red, blue, and green colors dots indicate A_0 values associated to inner- (mid beam θ of 18°), middle- (θ of 27°), and outer- (θ of 45°) swaths, respectively.

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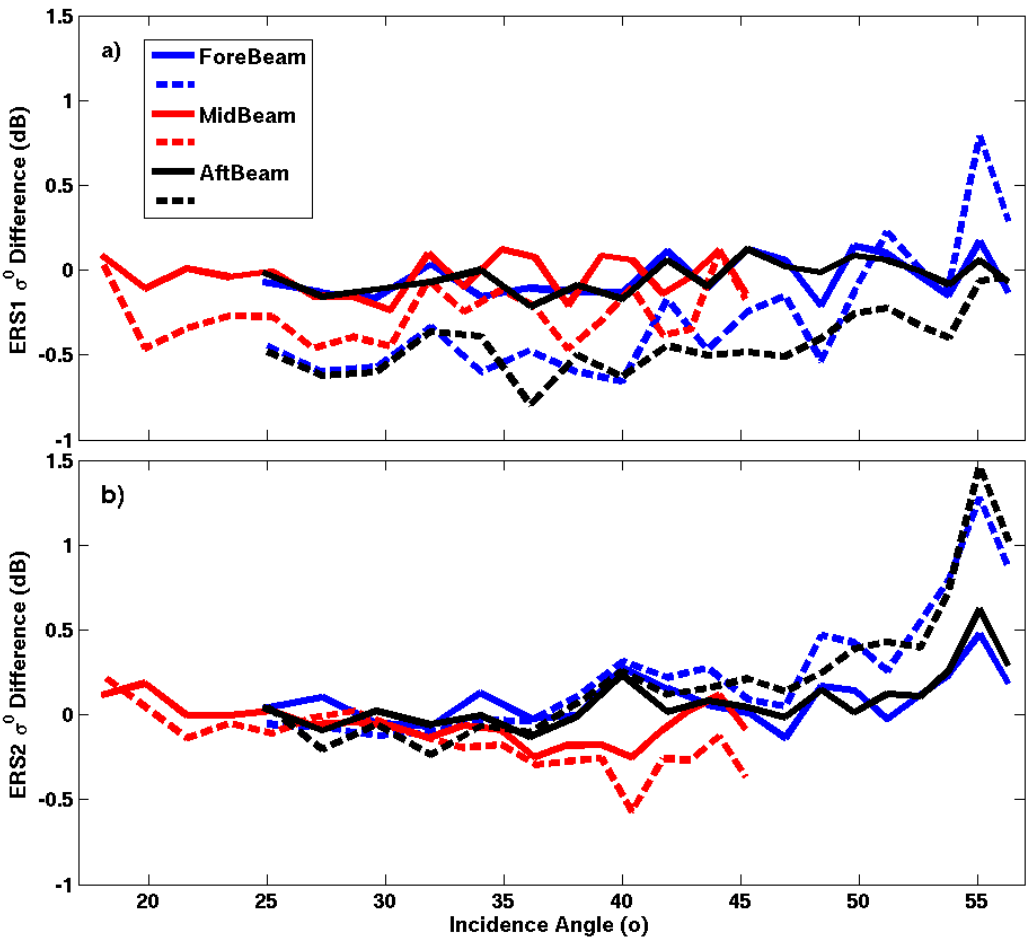


Figure 2: Differences between expected and measured backscatter (uncorrected – dashed, corrected - solid) coefficients as a function of the incidence angle.

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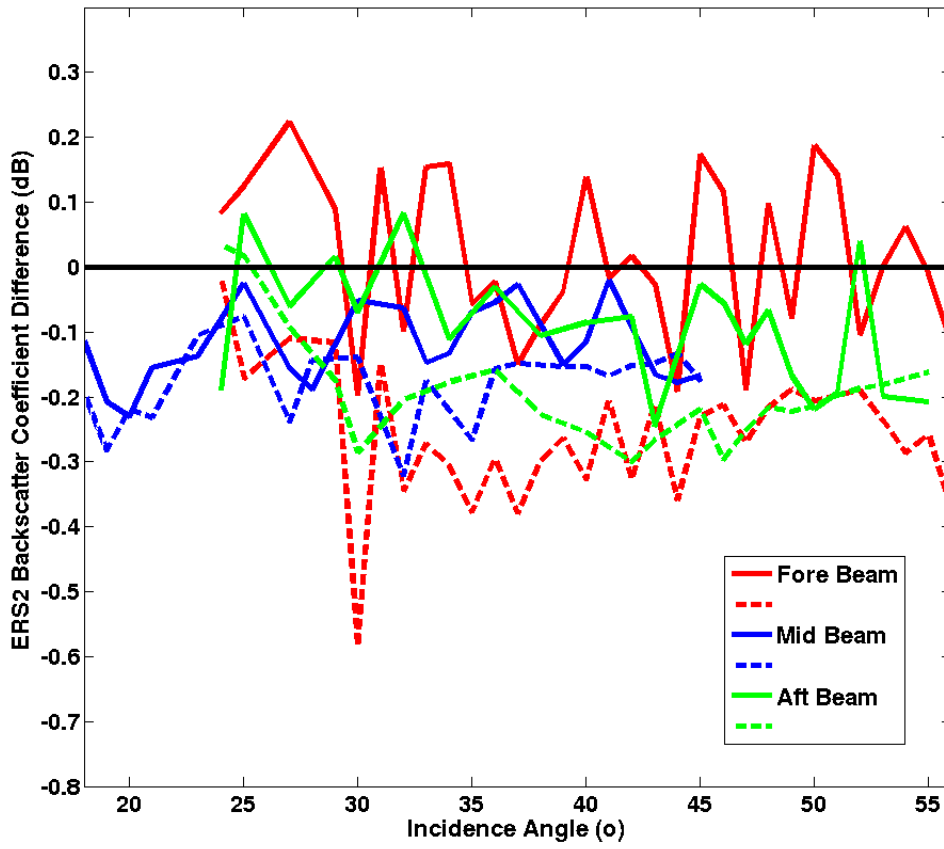


Figure 3: Mean Differences between ERS-2 UWI and ERS-2 WNF backscatter coefficients (uncorrected – dashed, corrected - solid) as a function of the incidence angle.

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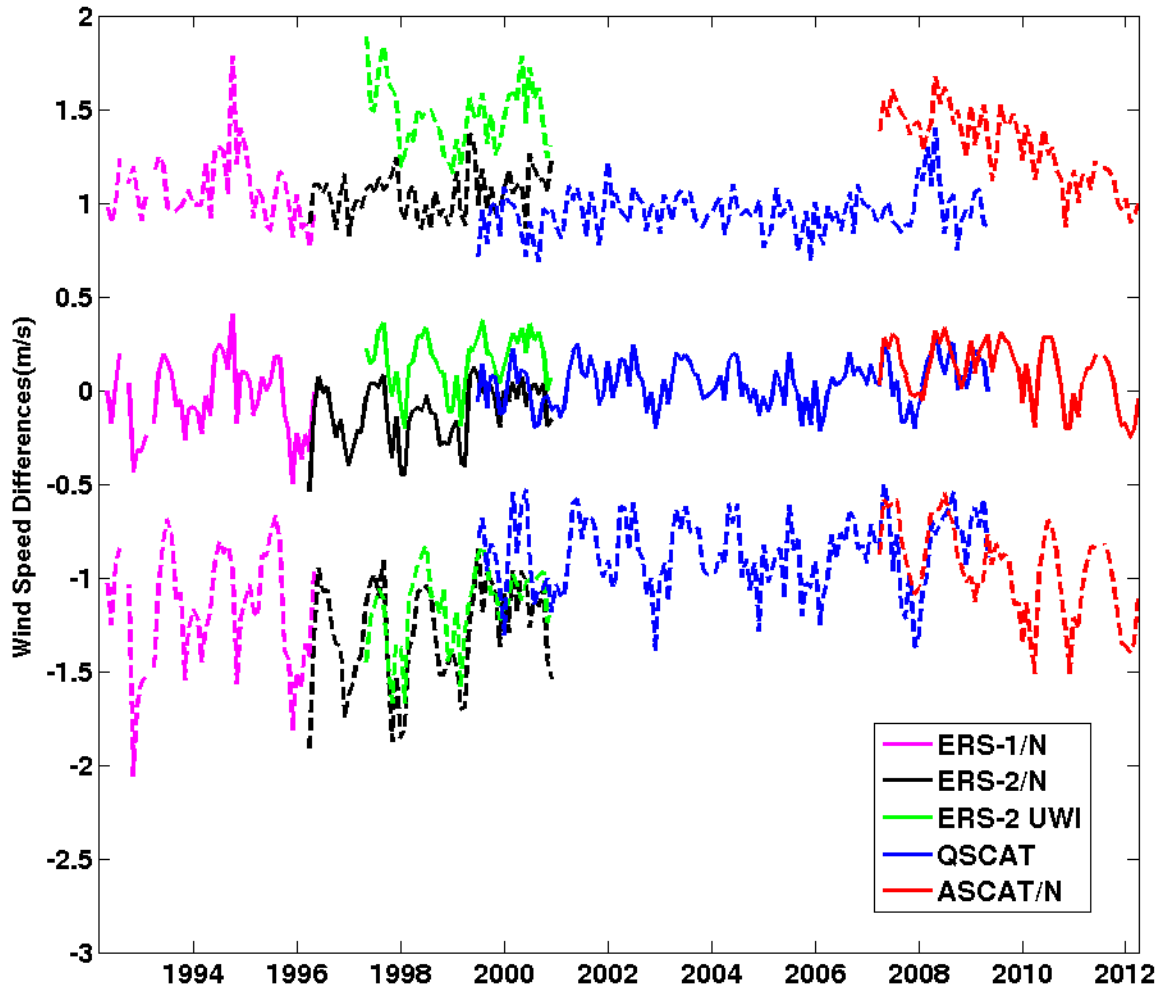


Figure 4: Time series of monthly differences between NDBC buoy and scatterometer wind speeds. Full and dashed lines indicate running bias and bias±STD, respectively.

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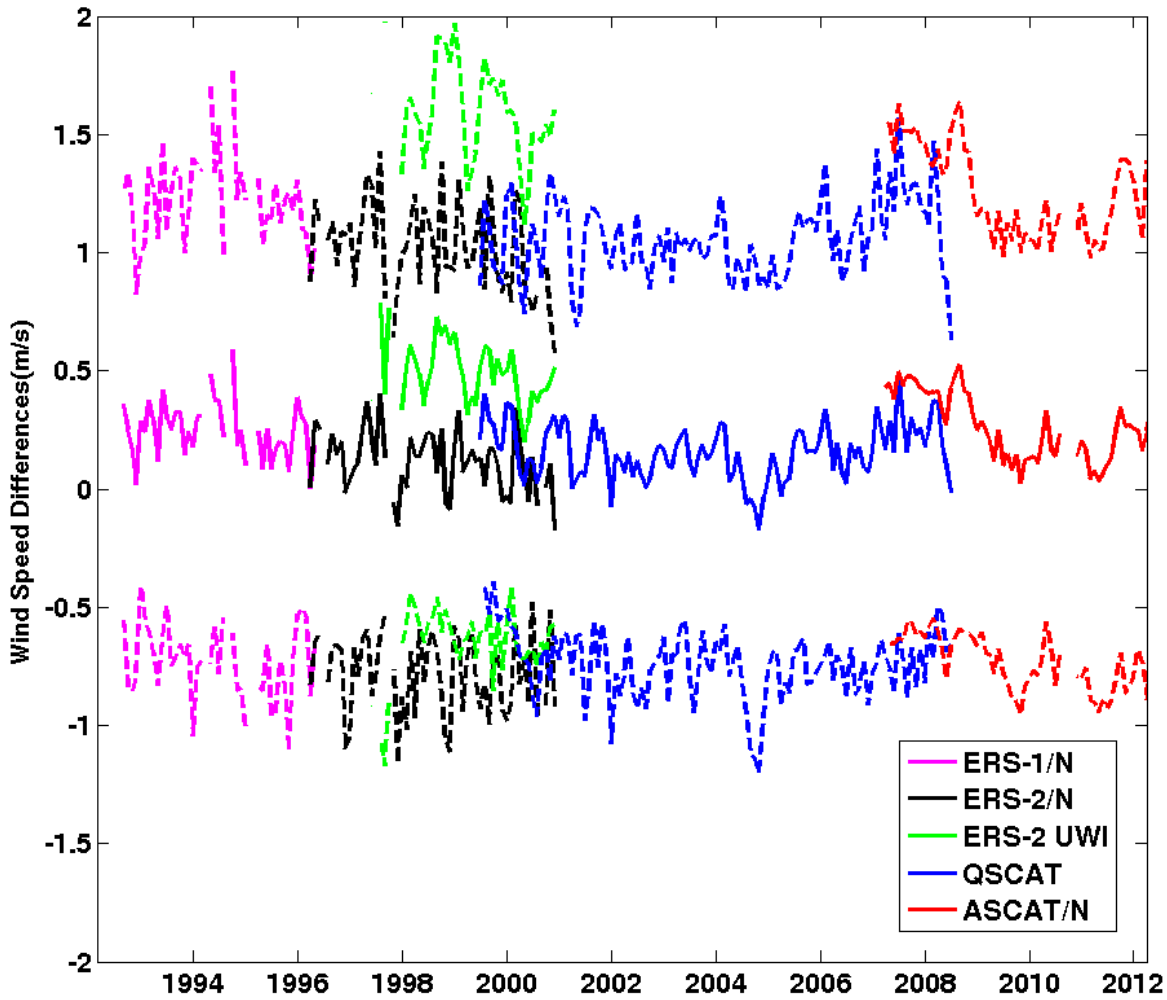


Figure 5: Time series of monthly differences between Tropical (TAO, PIRATA, RAMA) buoy and scatterometer wind speeds. Full and dashed lines indicate bias and bias±STD, respectively.

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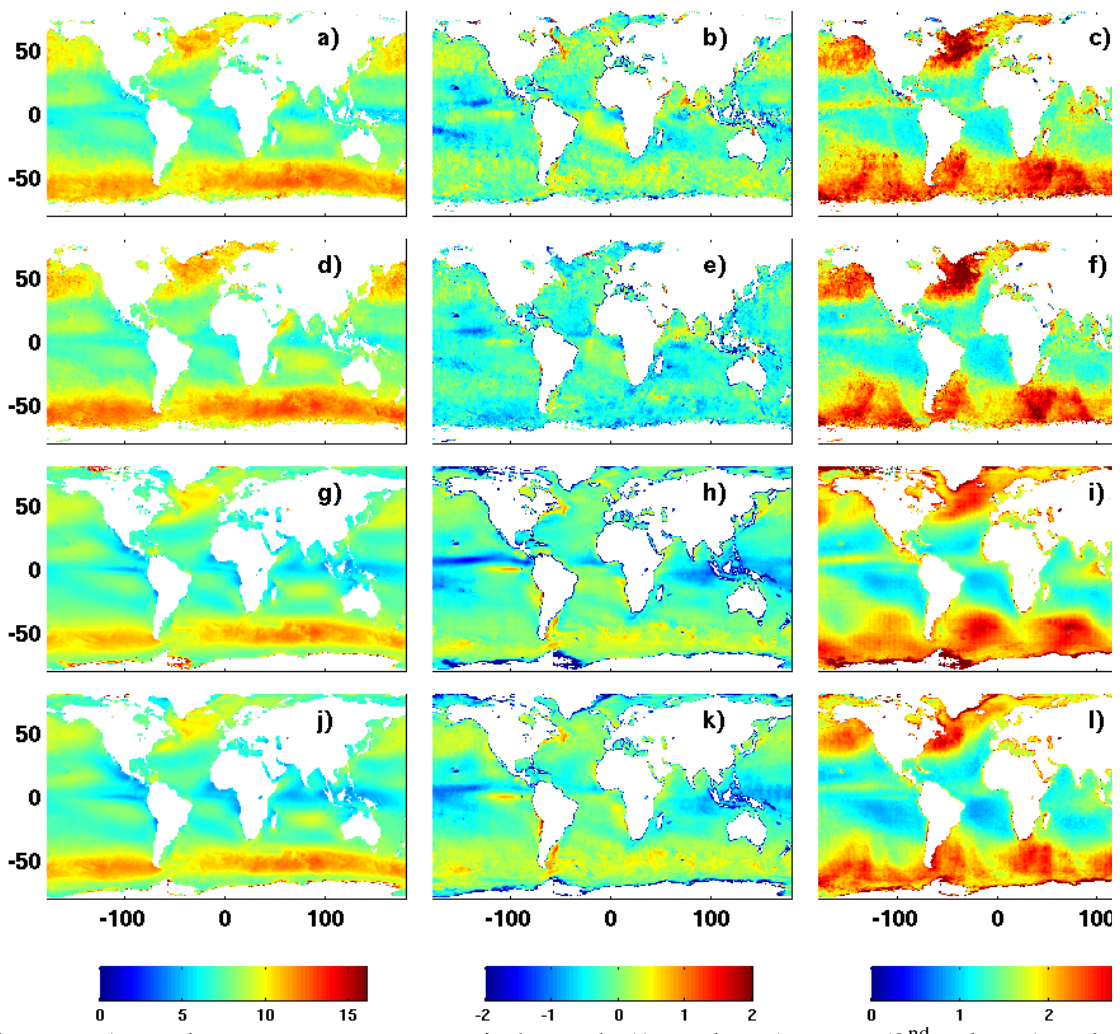


Figure 6: Annual mean scatterometer wind speeds (1st column), mean (2nd column) and STD (3rd column) differences (CFSR minus scatterometer). First, second, third, and fourth rows show statistics for ERS-1/N, ERS-2/N, QuikSCAT, and ASCAT/N, respectively.

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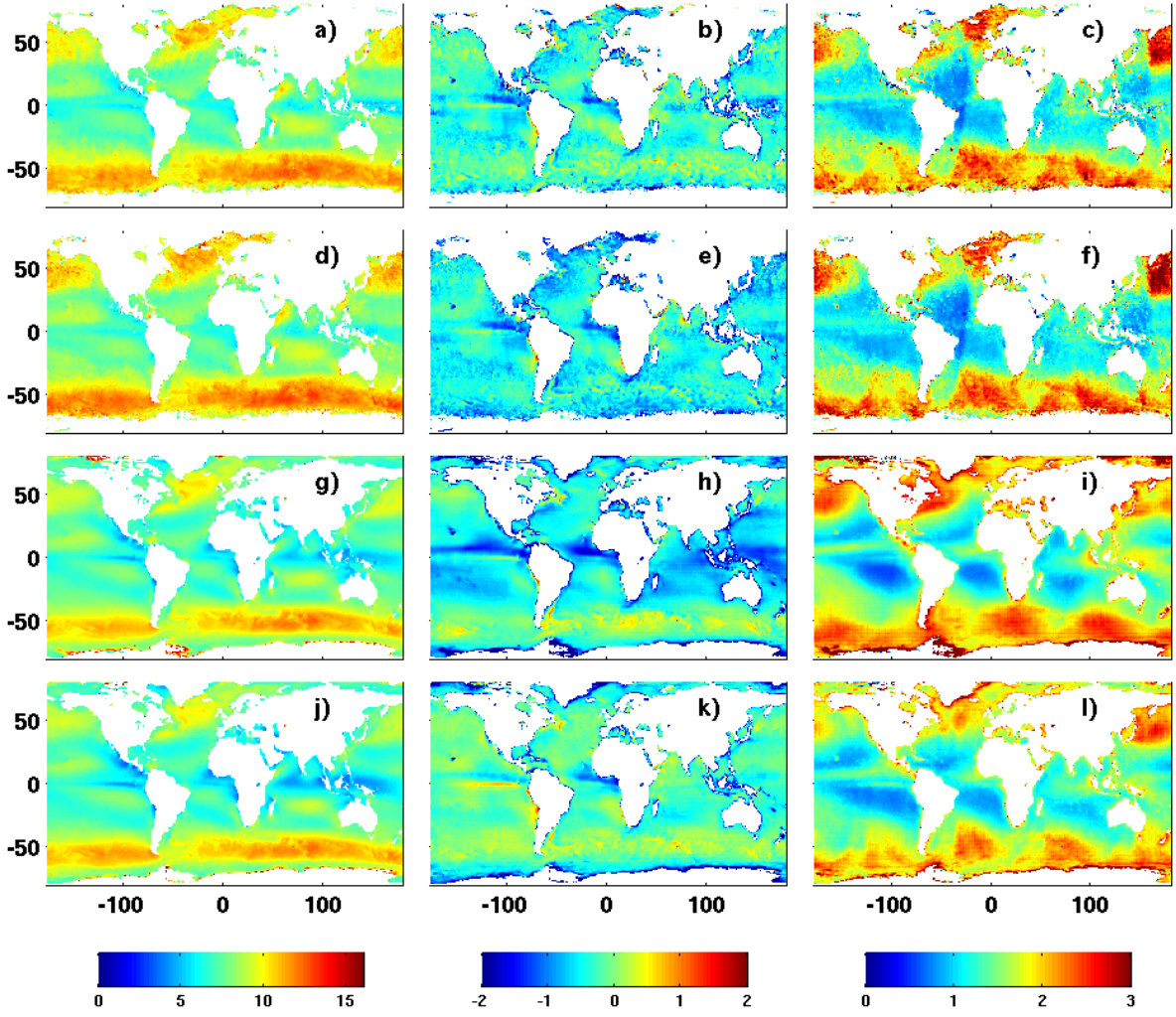


Figure 7: Annual mean scatterometer wind speeds (1st column), bias (2nd column), and STD (3rd column) differences ERA Interim minus scatterometer wind speeds. First, second, third, and fourth rows are related to statistics estimated for ERS-1/N, ERS-2/N, QuikSCAT, and ASCAT/N, respectively.

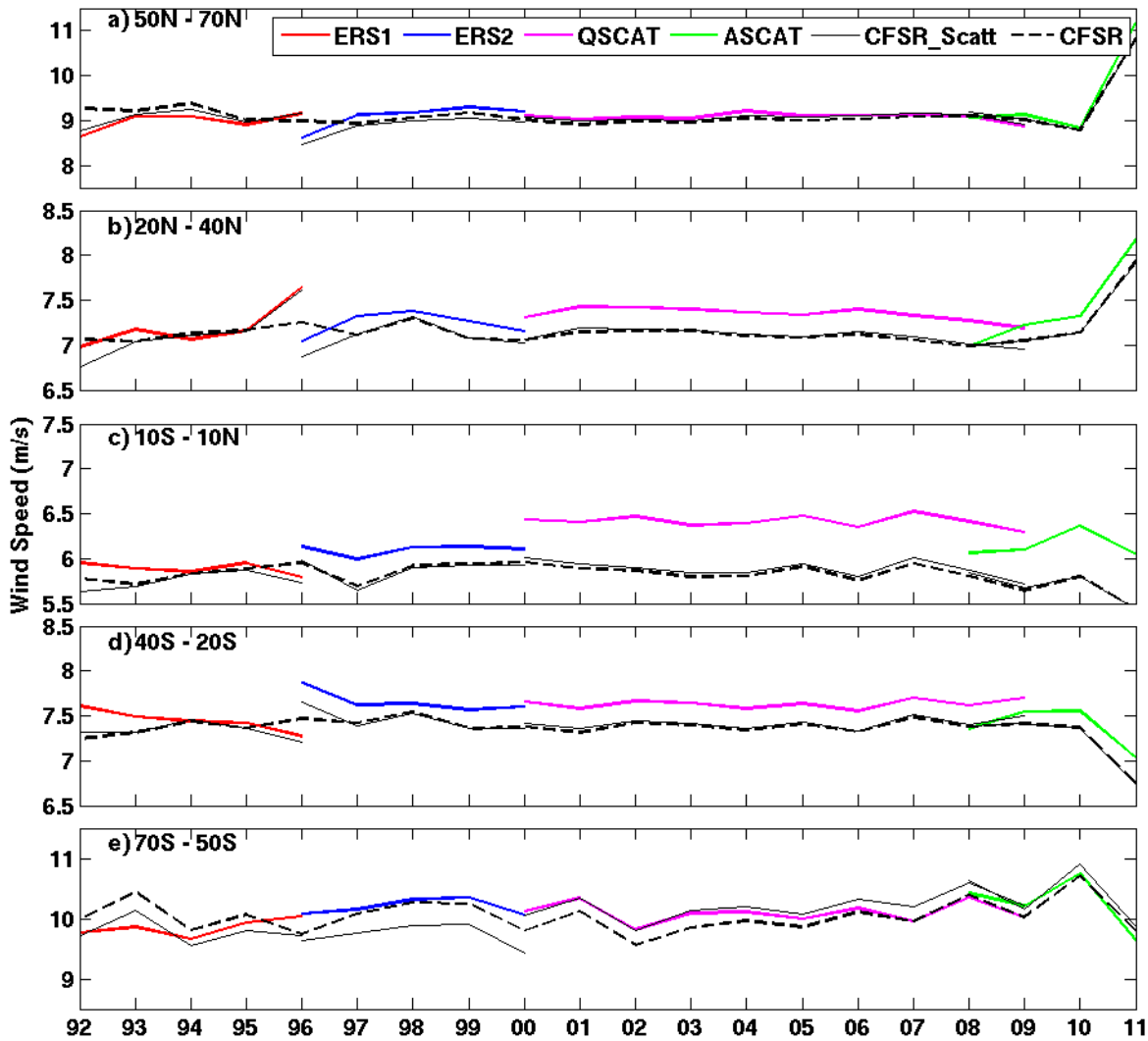


Figure 8: Annual mean wind speed estimated from available monthly averaged collocated scatterometer (ERS-1/N, ERS-2/N, QSCAT, ASCAT/N) and CFSR data. They are calculated for the period March 1992 – March 2011, and for latitudinal oceanic zones: a) 50°N – 70°N; b) 20°N – 40°N; c) 10°S – 10°N; d) 40°S – 20°S; and e) 70°S – 50°S . CFSR_Scatt (thin black line) indicate CFSR data collocated with scatterometer retrievals, whereas CFSR (dashed black line) indicates annual winds calculated from all CFSR data.

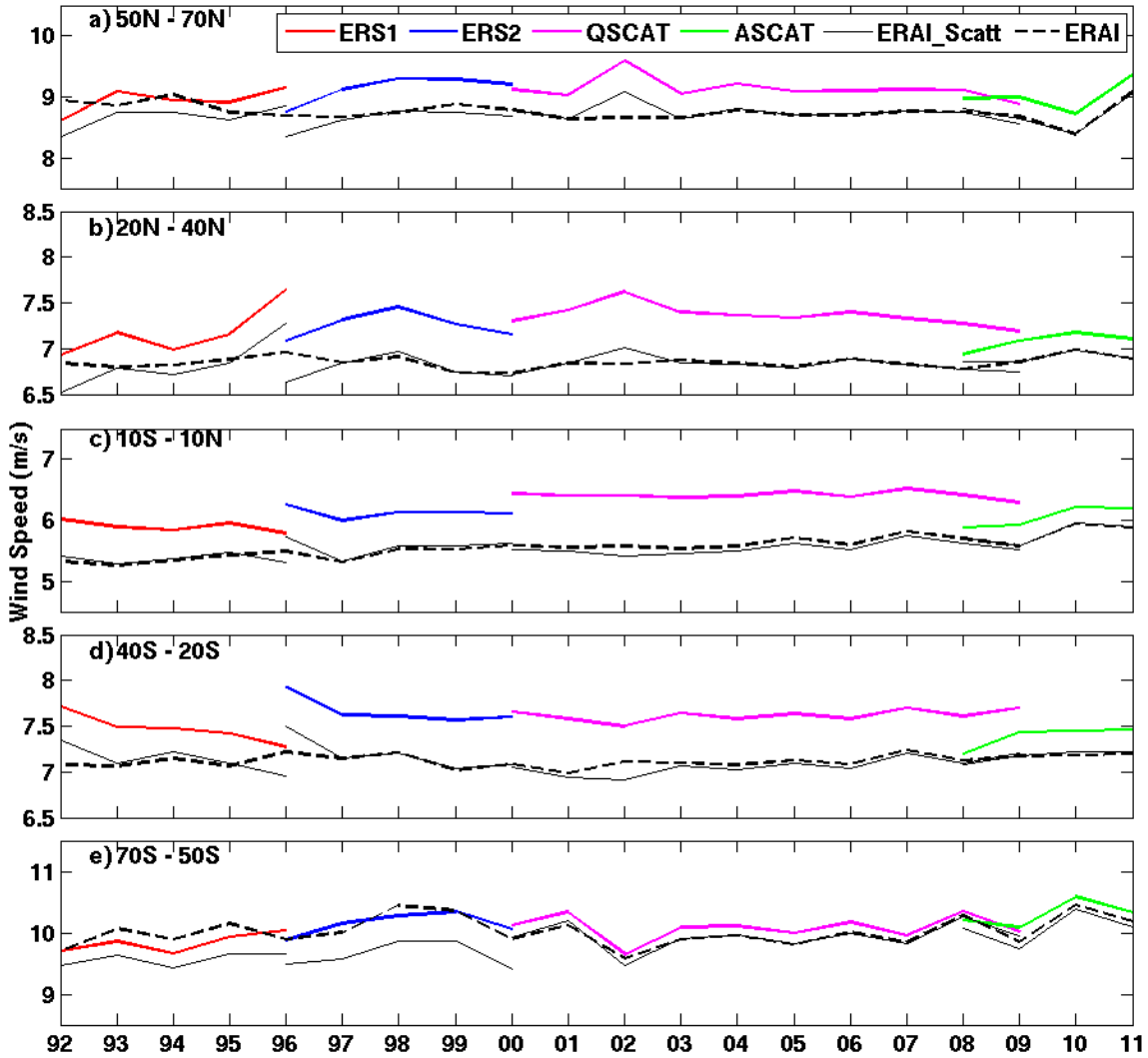


Figure 9: Annual mean speed estimated from available monthly averaged collocated scatterometer (ERS-1/N, ERS-2/N, QSCAT, ASCAT/N) and ERA Interim data. They are calculated for the period March 1992 – March 2011, and for latitudinal oceanic zones: a) $50^{\circ}\text{N} - 70^{\circ}\text{N}$; b) $20^{\circ}\text{N} - 40^{\circ}\text{N}$; c) $10^{\circ}\text{S} - 10^{\circ}\text{N}$; d) $40^{\circ}\text{S} - 20^{\circ}\text{S}$; and e) $70^{\circ}\text{S} - 50^{\circ}\text{S}$. ERAI_Scatt (thin black line) indicate ERA Interim data collocated with scatterometer retrievals, whereas ERAI (dashed black line) indicates annual winds calculated from 6-hourly analyses.

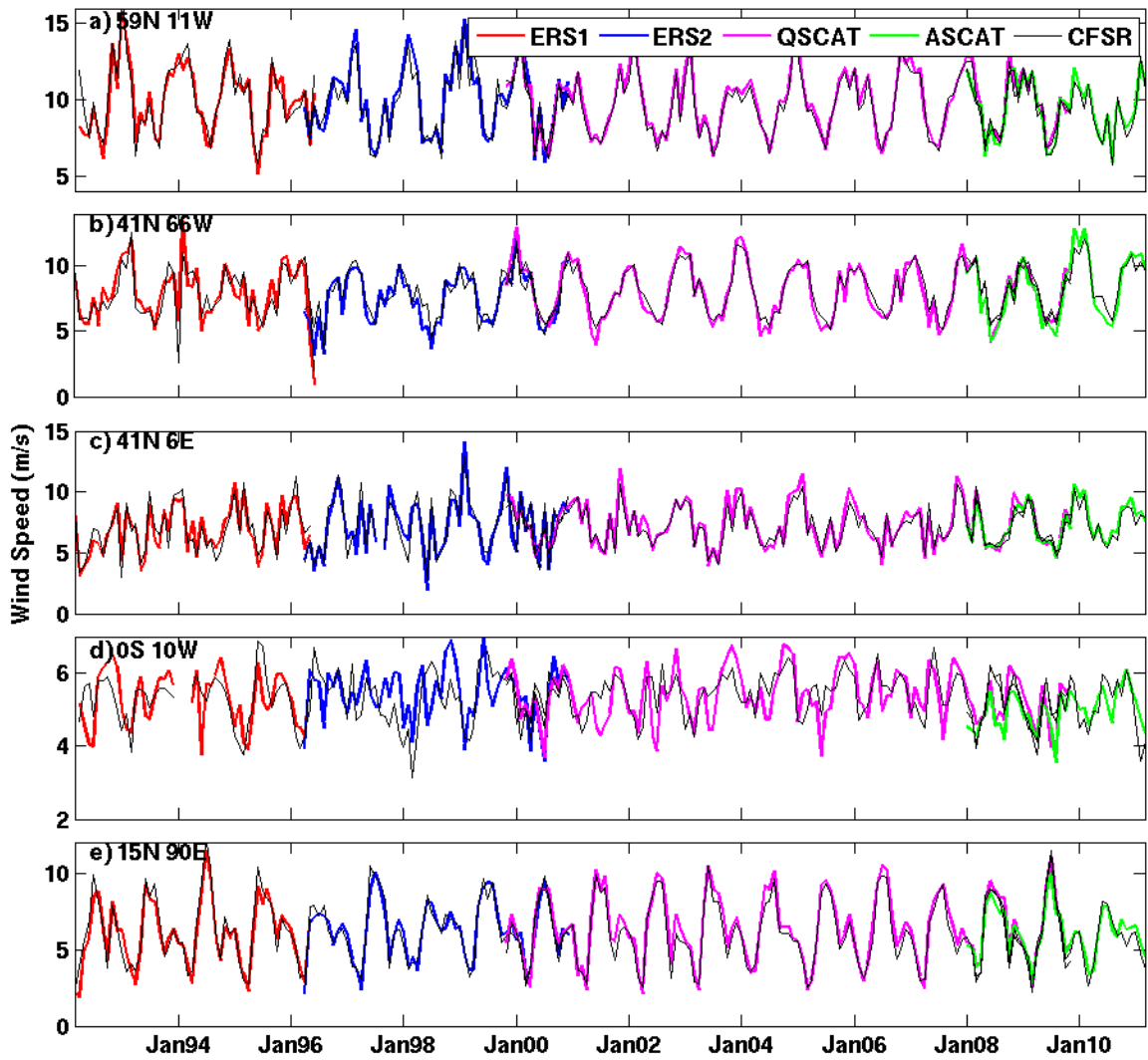


Figure 10: Time series of monthly-averaged wind speeds estimated from collocated scatterometer (ERS-1/N, ERS-2/N, QSCAT, ASCAT/N) and CFSR data. They are shown for five locations which coordinates are indicated in the top/leftcorner of each panel.

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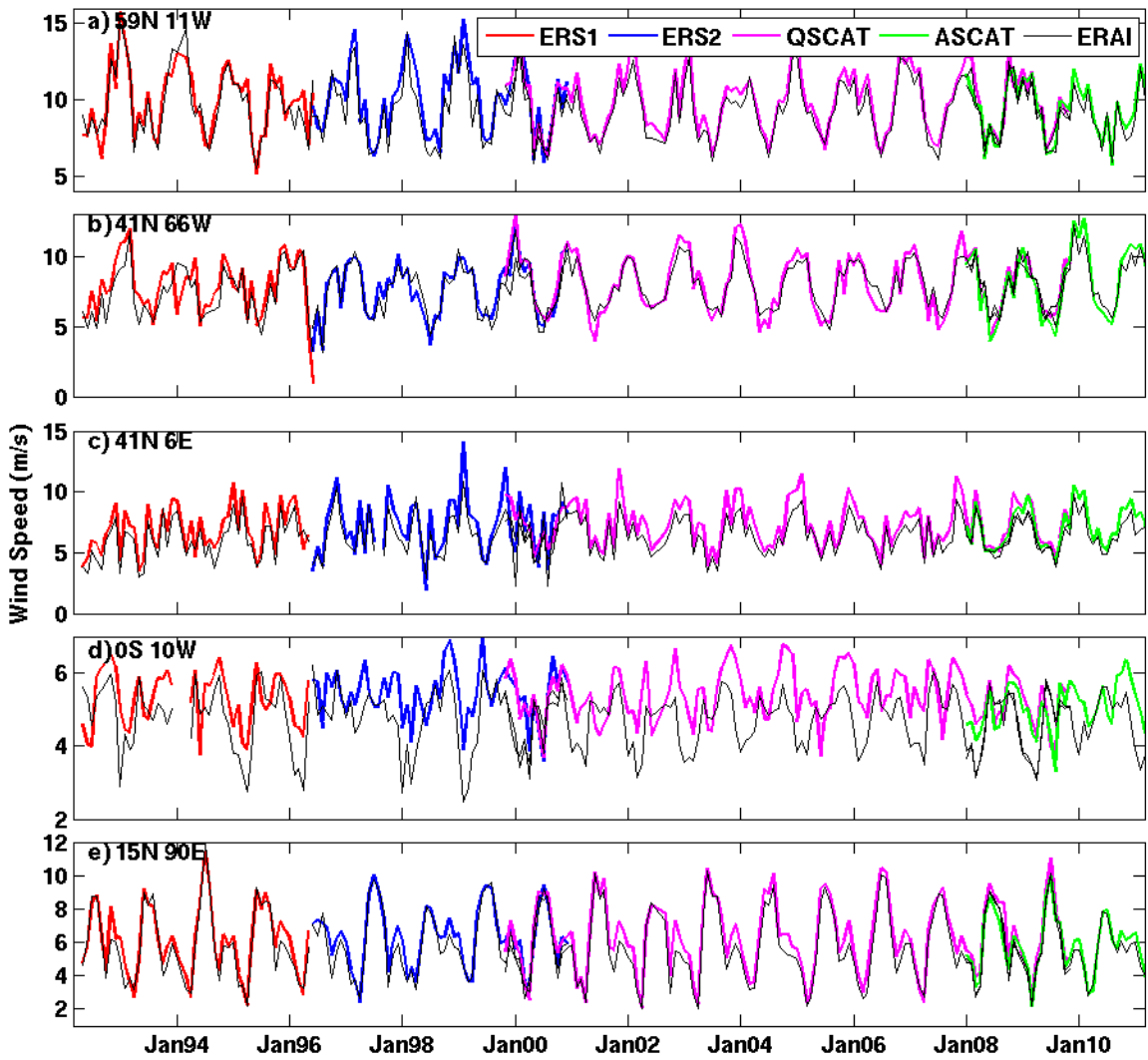


Figure 11: Time series of monthly-averaged wind speeds estimated from collocated scatterometer (ERS-1/N, ERS-2/N, QSCAT, ASCAT/N) and ERA Interim data. They are shown at five locations which latitudes and longitudes are indicated at top/left of each panel.