International Journal of Remote Sensing
2019, Volume 40, Issue 3, Pages 1120-1147
https://doi.org/10.1080/01431161.2018.1524174
https://archimer.ifremer.fr/doc/00464/57611/

Using sentinel-1A SAR wind retrievals for enhancing scatterometer and radiometer regional wind analyses

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Abstract :

Scatterometer surface wind speed and direction observations in combination with radiometer wind speeds allow to generate surface wind analyses with high space and time resolutions over global as well as at regional scales. Regarding scatterometer sampling schemes and physics, the resulting surface wind analyses suffer from lack of accuracy in areas near coasts. The use of the synthetic aperture radar (SAR) onboard the Sentinel-1A satellite attempts to address the enhancement of surface wind analyses issues. In this study, SAR wind speeds and directions retrieved from backscatter coefficients acquired in interferometric wide (IW) swath mode are used. Their accuracy is determined through comprehensive comparisons with moored buoy wind measurements. SAR and buoy winds agree well at offshore and nearshore locations. The statistics characterizing the comparison of SAR and buoy wind speeds and directions are of the same order as those obtained from scatterometer (Advanced SCATterometer (ASCAT) and RapidScat) and buoy wind comparisons. The main discrepancy between SAR and buoy data are found for high wind speeds. SAR wind speeds exceeding 10 m s–1 tend to be underestimated. A similar conclusion is drawn from SAR and scatterometer wind speed comparisons. It is based on the underestimation of SAR backscatter coefficient (σ°) with respect to σ° estimated from scatterometer winds and the geophysical model function (GMF) named CMOD-IFR2 (Ifremer C band MODel). New SAR wind speeds are retrieved using CMOD-IFR2. The corrected SAR retrievals allow better determination of the spatial characteristics of surface wind speeds and of the related wind components in near-coast areas. They are used for enhancing the determination of the spatial structure function required for the estimation of wind fields gridded in space and time at the regional scale. The resulting wind fields are only determined from scatterometer wind observations in combination with radiometer retrievals. Their qualities are determined through comparisons with SAR wind speeds and directions, and through their application for determination of wind power off Brittany coasts.

1 Introduction

Several scientific studies and operational uses require the knowledge of wind speed and direction at high space and time resolutions over an oceanic basin including nearshore areas. Desbiolles *et al* (2014, and 2016) demonstrated that better characterization of the spatial and temporal patterns of wind drop off expected off west-northern and west-southern African coasts require finer resolution of surface winds. Stammer *et al* (2007) established the spatial and temporal wind resolutions that would meet oceanic and atmospheric requirements. For instance, oceanographic coastal studies require resolutions ranging between 1 km and 10 km for space, and between 1 hour and 3 hours for time. Numerical Weather Prediction (NWP) models may provide wind products with space and/or time gridding meeting the aforementioned requirements. Nonetheless, surface wind analyses determined from remotely sensed data do not allow such high resolutions at global or regional scales. This article is an investigation of how to increase the spatial resolution of satellite wind analyses based on the use of several sources of wind retrievals.

For more than twenty years, scatterometers on polar-orbiting satellites provide valuable information on both wind speed and direction, with good spatial sampling over the global oceans (Bentamy *et al*, 2017). The latest scatterometers such as SeaWinds onboard the QuikSCAT satellite, ASCAT-A/B onboard satellites dedicated to operational meteorology named Metop-A/B satellites, and RapidScat onboard the International Space Station (ISS) provide surface winds with high spatial resolution of 12.5 km. However, this resolution may not meet several study requirements particularly in semi-enclosed seas, coastal regions, marginal ice areas, straits, etc. Furthermore, scatterometer retrieval accuracy is lower in near-shore zones (Pickett *et al*, 2003) that would be affected by land contamination of radar backscatter signals from the large scatterometer footprint, or on the complexity of wind conditions in the coastal zones. For overcoming these limitations and to better characterize surface winds in near coastal regions, scatterometer retrievals could be used in combination with winds retrieved from synthetic aperture radar (SAR). The latter instrument provides wind observations with sub-kilometre resolution over a swath of some hundred kilometres width. Both scatterometer and SAR are active radars measuring the variation of normalised radar cross-section (NRCS) from the wind-roughened sea surface, which is mainly a function of wind condition (speed and direction). Wind retrievals derived from scatterometer and SAR measurements are based on the use of a geophysical model functions (GMF) relating NCRS and wind speed and direction. The usefulness of scatterometer and SAR synergy has been demonstrated in previous studies. For instance Hasager *et al* (2015) used ASCAT and QuikSCAT winds in combination with SAR onboard the Envisat satellite, namely ASAR, for investigating the wind resources for marine renewable energy (MRE) purposes. They showed that the use of scatterometer and SAR wind data lead to finer details in MRE spatial patterns compared to those obtained only from scatterometer winds.

Since early October 2014 through present high spatial wind observations are derived from the latest SAR onboard the Sentinel 1A satellite. These new data would be relevant for investigating the characteristics of surface wind speed and direction spatial variability. The former are required for the determination of finer space and time gridded surface wind, namely surface wind analyses, at regional and/or local scales, based on the use of observations derived mainly from scatterometer data (Bentamy *et al*, 2012). The achievement of this primary study objective requires first the investigation of the inter-comparison of SAR and scatterometer wind retrievals for various oceanic and atmospheric conditions as well as a function of some specific measurement parameters such as incidence and azimuth angles and radar polarization.

2 Data and Methods

2.1 SAR Data

Sentinel-1A was launched in April 2014 and is the first satellite equipped with a SAR in the European Space Agency (ESA) Sentinel constellation. Sentinel-1A SAR data are processed and provided by ESA (https://sentinel.esa.int/web/sentinel/missions/sentinel-1/data-products). The level-2 (L2) ocean product (OCN) has been designed to deliver geophysical parameters related to wind, waves and surface velocity to the users through the Copernicus framework (marine.copernicus.eu*)* . L2OCN product is processed and delivered by ESA. All acquisitions over the ocean are expected to be processed up the Level-2. The ocean wind component of the L2OCN product is available for all acquisition modes. In this study, Sentinel-1A SAR surface winds and the related instrumental and geophysical parameters relied on L2OCN products are also considered. L2OCN products are collected from an archive maintained by the Institut Français pour la Recherche et l'Exploitation de la MER (IFREMER).

In this study, we only use L2OCN products acquired in interofemetric wide (IW) swath mode. IW allows combining a large swath width (250 km) with a moderate geometric resolution (5 m by 20 m). The IW mode images three sub-swaths using Terrain Observation with Progressive Scans SAR (TOPSAR). This technique is expected to ensure homogeneous image quality throughout the swath. Incidence angles range from about (depending to the latitude) 29.1° to 46° and the antenna can operate with four different polarization configurations: VV, HH, VV+VH or HH+HV. Radiometric stability and accuracy are expected to be better than 0.5 dB and 1 dB, respectively.

In the L2OCN product, the 10m ocean surface winds are derived from normalised radar cross section (NRCS) using the geophysical model (GMF) called CMOD-IFR2 (Bentamy *et al*, 1999) and a priori wind information from ECMWF (0.125°, 3 hours). Indeed, SAR is a single fixed antenna instrument and cannot rely on rotating antenna or several fixed antenna to get both wind speed and direction. This under-constrained inverse problem is usually solved by using a priori wind information from scatterometer acquisitions (Monaldo *et al*, 2004) or wind direction directly extracted from the image. Indeed, in particular situations, the ocean surface wind can induce boundary layer rolls which are aligned with the wind direction (Koch, 2004; Wackerman *et al*, 1996). However such streaks are not always present and/or detectable in SAR images. To date, these two methods are not realistic in the context of an operational service. This leads to the use of ECMWF atmospheric model. To retrieve the ocean surface wind, radar parameters and a priori wind information are combined into a Bayesian scheme, described in Kerbaol (2007); Mouche *et al* (2012) and Alpers *et al* (2015), where the cost function to be minimized is shown in Mouche *et al* (2012) as equation (2). It aims at the retrieving surface wind speed and direction from the SAR normalised radar cross section (also named backscatter coefficients). The procedure is known as inversion and ambiguity removal.. Full details can be found in Mouche *et al* (2012). The procedure is applied wind cell by wind cell. For instance, wind speed at 10m height is estimated at each SAR cell through the following inversion:

$$w_{10} = (\mathrm{CMOD})^{-1}(\theta, \chi, \sigma^0) \quad (1)$$

Where w_{10} is the ocean surface wind speed at 10m height, θ is the incidence angle, χ is the radar look direction relative to the wind direction, σ^0 is the normalised radar cross section. CMOD indicates the geophysical model function (GMF) relating surface wind and backscatter coefficient. It is the updated CMOD-IFR2 (Bentamy *et al*, 1999; Mouche *et al*, 2012). The procedure based on (eq. 1) enables fast computation of the solution but is very sensitive to any calibration issue. SAR winds are assumed estimated as equivalent neutral winds (ENW) at 10m height.

Although SAR wind retrievals are available for VV and HH polarization, only VV related winds are used throughout the paper. Indeed, during the study period, more than 98% of total available and valid data are associated with VV polarization.

2.2 ASCAT

The two Advanced SCATterometers ASCAT-A and ASCAT-B on board the ESA's polar-orbiting Metop-A and Metop-B satellites are used in this study. ASCAT-A and ASCAT-B are identical radars. During the study period (January 2015 – December 2016) the satellites operate simultaneously on the same orbit of 09:30 (local time) equator crossing, but with a phase delay of 48.93 minutes. Scientific and technical documentation related to ASCAT physical measurements as well as to ASCAT derived products may be found at the EUMETSAT web site http://www.eumetsat.int/Home/Main/Publications/Technical_and_Scientific_Documentation/Technical_Notes/ and at the SAF OSI web site http://www.knmi.nl/scatterometer/. Metop-A and Metop-B are in circular orbits (near synchronous orbit) for a period of about 101 minutes, at an inclination of 98.59° and at a nominal height of 800 km with a 29-day repeat cycle. Both ASCAT scatterometers have two swaths 550 km wide, located on each side of the satellite track, separated by 700 km. They operate at 5.3 GHz (C band). Radar fore-beam and aft-beam antennas point at 45° and 135° to each side of the satellite track, respectively. The mid-beam antennas points at 90°. The ASCAT beams measure NRCSs with vertical polarization, radar cross sections, σ^0. These data represent a dimensionless property of the surface, describing the ratio of the effective echoing area per unit area illuminated. The fore and aft-beams provide backscatter coefficient measurements at incidence angle varying between 34° and 64°. The mid-beams provide σ^0 measurements at incidence angles varying between 25° and 53°. ASCAT wind retrievals are obtained from σ^0 measurements through an inversion procedure based on the use of a GMF namely CMOD5.n (Hersbach, 2009).

ASCAT-A and ASCAT-B wind data are obtained from the EUMETSAT Satellite Application Facility Ocean Sea Ice (SAF/OSI). They are processed by the Royal Netherlands Meteorological Institute (KNMI). The ASCAT-A and ASCAT-B swath datasets used in this study are referenced as ASCAT coastal level 2b (L2b). ASCAT wind retrievals are provided at wind vector cells (WVC) of 12.5 km×12.5 km. There are 42 WVCs across the two-swaths of each scatterometer. Data include wind retrievals as well as backscatter coefficients measured over ocean and several associated fields at each valid WVC.

2.3 RapidScat

The latest National Aeronautics and Space Agency (NASA) scatterometer RapidScat mounted on the International Space Station (ISS) operated from 20 September 2014 through 22 August 2016. RapidScat is quite similar to QuikSCAT scatterometer (JPL, 2006). RapidScat is a K_u-band (13.4 GHz, 2.1 cm) rotating antenna with two emitters: the H-pol inner beam at incidences angle θ=49° and V-pol outer beam at θ=56°. Regarding the ISS altitude, ranging between 375 km and 435 km, and its inclination of 51.6°, RapidScat inner- and outer-swaths are of 900 km and 1100 km, respectively. RapidScat L2b products, involving wind speed and direction retrievals, are from NASA Jet Propulsion Laboratory (JPL) / Physical Oceanography Distributed Archive Active Center (PODAAC). They are processed based on same method used for QuikSCAT V3 processing (Fore et al, 2014). Briefly, RapidScat swath data are binned into WVCs of 12.5×12.5 km^2. RapidScat winds are derived from backscatter using the empirical QSCAT-1 GMF (JPL, 2006) together with a Maximum Likelihood Estimator, which selects the most probable wind solution. To improve wind direction in the middle of the swath where the azimuth diversity is poor, the Direction Interval Retrieval with Threshold Nudging algorithm is applied.

Due to its shorter wavelength K_u-band scatterometers are more sensitive to impacts of rain than longer wavelength C-band scatterometers. Sobieski *et al.* (1999) have shown that rain may decrease the transparency of the atmosphere, thus reducing backscatter, causing an underestimation of wind speed. The opposite effect develops in response to surface ripple generation by raindrops and scattering off raindrops, both of which lead to overestimation of winds (Weissman *et al*., 2002). Rain flags are provided with the RapidScat data set to mark rain detection. The RapidScat datasets include rain corrected and uncorrected wind retrievals (JPL, 2006). Only rain corrected RapidScat data are used throughout this study.

2.4 Moorings

To characterize the quality of SAR surface wind speed and direction retrievals , moored buoy measurements including wind speeds and directions (or associated zonal and meridional wind components) sea surface temperature (SST), air temperature, and significant wave height (when available) are used in this study. They are obtained from the Météo-France and U.K. MetOffice (MFUK), the National Data Buoy Center (NDBC), and from the Spanish Ente Publico Puertos del Estado network (EPPE). They are moored off European seas (MFUK), off US coasts (NDBC), and along Spanish coasts (Figure 1). All buoy data used in this study are reported on the hour and represent 8-minutes averages. Buoy winds are measured at specific anemometer heights varying between 3 and 6m. Hourly buoy measurements of wind velocity, sea surface and air temperatures, and humidity are converted to 10m neutral wind using the COARE3.0 algorithm (Fairall *et al.* , 2003).

2.5 Collocation

2.5.1 Mooring collocation

The procedure collocation between sources with different spatial and temporal sampling schemes is a challenging task. For instance, buoy data represent time averaged winds at a single location, while satellite winds are instantaneous spatially averaged winds.

For each SAR image, all valid buoy measurements occurring within 30 minutes of SAR overpass time are selected. Based on the use of the temporal matchup data, all SAR pixels located within 12.5 km of buoy location are selected. Regarding the SAR spatial resolution (of about 30m), several SAR pixels may be collocated with same buoy measurement for a given date. Figure 2 illustrates an example of SAR wind speed image collocated with NDBC buoy (WMO 44005) moored at 43°.19N and 69°.16W for SAR pass of 3 October 2015 10:48 UTC. RegardingSentinel-1A sampling scheme leading to data availability at selected oceanic areas, only data from a few buoys are collected with SAR for the period January 2015 through December 2016.

The determination of matchups of buoy and scatterometer (ASCAT and RapidScat) data is achieved based on the use of 12.5 km and 30 minutes for the spatial and temporal criteria, respectively. No further averaging is performed.

For comparison buoy and remotely sensed data purposes, several methods would be used. For instance, comparison of buoy with SAR or scatterometer WVCs in which the buoy lies, comparison of buoy and the weighted average of the closest (in space) remotely sensed data occurring at buoy location, or comparison of buoy and averaged data estimated from retrievals occurring within 12 km from buoy location. Even though the two methods provide quite similar comparison results (shown hereafter), the second method tends to be more appropriate. The former is used in this study.

2.5.2 SAR and scatterometer collocation

For SAR and scatterometer comparisons, all ASCAT and RapidScat data occurring over the same area within 3 hours of SAR imaging time are selected. The collocation time criteria is selected based on the investigation of the autocorrelation of surface wind time series derived from each buoy with a time lag varying between 1 hour and 3 hours. It results in autocorrelation values exceeding 0.94 and mean differences lower, in absolute value, than 0.005 m s^{-1}. For the period January 2015 – December 2016, the time separation between SAR and ASCAT is less than 1 hour, laying between 1 hour and 2 hours, and higher than 2 hours accounts for 6.6%, 33.3%, and 60.1% of total collocated SAR and ASCAT data, respectively. The associated SAR and RapidScat time separation intervals are 47.8%, 32.9%, and 19.3%.

SAR and scatterometer winds are available with various space sampling grids. To assess the spatial criteria required for SAR and scatterometer collocation, we first investigate the spatial scales of SAR and scatterometer wind speed and associated components at some selected oceanic regions. The spatial scales are determined based on the use of correlations between wind time series occurring at two locations spatially separated by Δx (in km) and Δy (in km) along longitudinal and latitudinal axes, respectively. For instance, Figure 3 shows the SAR and scatterometer wind speed spatial structures estimated as two dimensional space lagged autocorrelations at five selected oceanic zones cantered on 43°N-4°E, 42°N-5°E, 40°N-6°E, 36°N-3°W, 36°N-7°W, from valid observations occurring from January 2015 to December 2016. The location selection stems from the high number of SAR and scatterometer data available at these areas and is required for significant statistics calculation. The first four locations are in the western Mediterranean Sea. The first through third locations are in the Gulf of Lion home of the Mistral wind conditions. The fourth and fifth locations are in the Alboran Sea and near Gibraltar strait both characterised by Levanter and Vendeval wind conditions. Only autocorrelation values calculated with a sampling length exceeding 30 are shown in Figure 3. The results found for SAR and scatterometer wind speeds are similar for the five zones.

The horizontal as well as vertical spatial significant scales at 95% confidence level do not exceed 100 km. During the study period (January 2015 – December 2016), the smallest horizontal and vertical significant scales for SAR and ASCAT are found at 36°N-7°W (Figures 3 i and j) and are lower than 12.5 km and 25 km, respectively. Such spatial pattern relied on the geographical location close to Gibraltar strait and to Vendeval wind characteristics (occurring mainly during October-November and February-March periods) both leading to strong variability of local winds. The largest SAR and scatterometer horizontal scales are depicted at 40°N-6°E and are about of 75 km and 100 km, respectively. The vertical structures at this location exhibit lower scales not exceeding 50 km for both SAR and ASCAT winds. At locations further north (42°N-5°E (Figures 3c and d) 43°N-4°E

(Figures 3a and b)) the latitudinal scales (about 50 km) tend to be higher than longititudinal ones (less than 37 km). These locations are impacted by north-northwest cold and dry Mistral wind condition. The latter blows in the Gulf of Lion and may reach the African coasts.

The results provided above suggest that spatial criteria for SAR and scatterometer collocation should be less than 25 km. In this study 12.5 km spatial separation is chosen.

3 Local comparison results

The statistics characterizing ASCAT and RapidScat scatterometer wind speed and direction accuracies, determined through comparisons with buoy wind data, would be found in several publications (e.g (non exhaustive): Bentamy *et al* 2008, Verspeek *et al*, 2010, Ebuchi, 2011 and 2015, Bentamy *et al*, 2017). At our best knowledge, no similar publications are available for Sentinel-1A SAR IW wind vector accuracy. Previous studies investigated the comparisons of the preceding C-band SAR wind retrievals and buoy wind measurements. For instance (Yang *et al*, 2011) assessed the quality of Envisat SAR wind retrievals through comprehensive comparisons with offshore NDBC buoy winds. However, the processing schemes of Satinel-1A and Envisat SAR winds are different. For instance, they do not use the same GMF, which may have significant impact on SAR wind speed and direction retrievals. The main topic is to assess the accuracy of the three remotely sensed wind data using same in-situ references available over the same period. The matchup procedures are used for the collocation of SAR as well as scatterometer retrievals with moorings MFUK, NDBC, and EPPE data available for the period January 2015 through December 2016. They lead to thousands of collocated data sets satisfying the aforementioned space and time criteria. The analysis (not shown) of buoy and remotely sensed collocated winds indicates that the discrepancies increase according to spatial distance separating the two sources. For buoy comparison purpose, only closest in space remotely sensed data of buoy locations are selected. The main statistical parameters characterizing buoy and satellite wind speed and direction comparisons are estimated for all matchups including all buoy collocated data, and for each buoy network. For the study period (January 2015 – December 2016), most of data are drawn from NDBC collocation data sets. Indeed, the sampling length of collocated NDBC (Figure 1a) data is 2216, and drops to 349 for MFUK and EPPE (Figure 1b) collocated data. The collocation between buoys and scatterometers leads to better sampling lengths. Indeed, collocated data are found for almost all buoys (Figure 1 blue cross symbols). To assess the comparisons between statistical results obtained for SAR and scatterometers, only statistics estimated for buoys collocated with the three radars are used here. Table 1 shows the comparison results derived from collocated NDBC and remotely sensed data. Similar results are obtained for MFUK and EPPE comparisons. The statistical parameters shown in Table 1 are mean difference (bias), root mean square wind speed difference (RMS), symmetrical regression coefficient associated to wind speed comparisons (b_s), wind speed scalar correlation coefficient (ρ), standard deviation of wind direction difference (SD), and wind direction vector correlation coefficient (ρ^2). The latter varies between -2 and +2. The three remotely sensed wind sources are highly correlated with in-situ data. For wind speed, correlation coefficients and symmetrical regression coefficients exceed 0.90 and close to unity, respectively. Vector correlation coefficients, aiming at the estimation of the degree to which two vector series co-vary with each other, are higher than 1.70. It should be noted that surface wind experiences high variability at the NDBC locations of interest. For instance, during the study period buoy wind speed and direction SD are about 4 m s^{-1} and 60°, respectively. Based on the correlation parameters, statistically significant at the 95% confidence level, the wind patterns observed at the mooring sites are well captured by the three satellite wind sources.. The best statistical results are obtained for both ASCAT and buoy wind speed and direction comparisons. The former meet the previous ASCAT validation results (Bentamy *et al*, 2008; Verspeek *et al*, 2010). The statistical results obtained for RapidScat and shown in Table 1 are slightly lower than those obtained by Ebutchi (2015). The latter are derived from a larger collocated RapidScat and buoy database. This result suggests that RapidScat accuracy would be buoy location dependent. Indeed, as shown in Figure 1, buoys used in this study are mainly located near coasts. Although SAR validation results (Table 1) are obtained from quite limited collocated data sampling, they are of the same orderas those obtained for RapidScat, but lower than those associated with ASCAT. For instance, the results related to SAR wind direction rely on ambiguity removal issue (Mouche *et al*, 2012). Selecting the closest SAR wind direction to buoy data leads to a significant improvement of SAR wind direction statistics. The wind direction SD and vector correlation drops to 22° and increases to 1.73, respectively.

The mean wind speed differences related to NDBC (Table 1) and to MFUK and EPPE (not shown) comparisons indicate that SAR winds are slightly underestimated, whereas ASCAT and especially RapidScat tend to be overestimated. Excluding low buoy wind speeds (<3 m s^{-1}) that would introduce artificial error in buoy and remotely sensed wind comparisons (Freilich, 1997), the bias of SAR, ASCAT, and RapidScat are of 0.31 m s^{-1}, 0.05 m s^{-1}, and -0.46 m s^{-1}, respectively. Investigating mean difference between buoy and remotely sensed wind speeds as a function of buoy wind speed ranges (not shown), indicate that SAR winds tend to be consistently underestimated for wind speed exceeding 6 m s^{-1}. The main departure contributing to the overestimation of RapidScat is found for high buoy wind speeds exceeding 10 m s^{-1}.

The mean direction differences (Table 1) do not show significant systematic biases. The lowest bias is for ASCAT, while for SAR and RapidScat biases are both negative and lower than 4°. The computation of wind direction biases for buoy wind speeds higher than 3 m s^{-1}, does not change significantly the bias results.

The comparisons between buoy wind measurements and retrievals are also investigated using the root mean square (RMS) parameter. The latter is calculated as the square root of the variance of the residuals from collocated buoy time series. It is an indicator of the extent to which the remotely sensed winds differ from the buoy measurement statistically. The largest and the lowest for both wind speed and direction are found for RapidScat and ASCAT, respectively. The analysis of difference between buoy and remotely sensed data as a function of wind speed ranges, indicate that significant improvement is achieved for RMS wind direction error estimated for buoy winds higher than 3 m s^{-1}. They do not exceed 20°. Changes in RMS wind speed differences exhibit quite limited changes for buoy high winds (>12 m s^{-1}), accounting for less than 10% of collocated data, except for SAR for which it exceeds 2 m s^{-1}. Investigations of buoy and satellite wind differences are also performed for near and off coasts locations. Near costs wind speed and direction would be highly variable at both small spatial and temporal scales. For instance, the highest variability indicator of surface winds, estimated as scatter coefficient (ratio of SD versus mean), of each NDBC wind time series occurring during study period (January 2015 – December 2016) are drawn from buoys located near shore (<25 km from shorelines) and reach 70% for wind speed, and exceed 80% for absolute values of zonal and meridional components. The statistics aiming at the characterization of buoy and remotely sensed winds are poorer for near coast buoy comparisons. Indeed, for SAR, RMS differences (resp. correlation coefficient) of wind speed, zonal, and meridional components are 2.40 m s^{-1} (resp. 0.75), 3.09 m s^{-1} (0.75), and 2.97 m s^{-1} (0.57), respectively. Whereas, for buoys located 40 km from shorelines, these parameters are 1.79 m s^{-1} (resp. 0.86), 2.93 m s^{-1} (0.75), and 2.58 m s^{-1} (0.81). Similar results are found for RapidScat. Indeed, RMS differences between nearshore buoy and RapidScat exceed 2 m s^{-1} for wind speed and 3 m s^{-1} for zonal and meridional wind components. Such differences of statistics estimated for nearshore and offshore are not found for ASCAT and buoy comparisons. RMS differences (resp. correlation coefficients) associated to nearshore buoy and ASCAT comparisons are of 1.67 m s^{-1} (resp. 0.92), 2.37 m s^{-1} (0.88), 1.99 m s^{-1} (0.90) for wind speed, zonal and meridional components, respectively.

4 Regional comparison results

The results derived from buoy and remotely sensed wind comparisons are used to assess the inter-comparisons between Sentinel-1A SAR IW and scatterometer retrievals. Based on the space and time collocation criteria, SAR and scatterometer collocated data are found off US Atlantic and Pacific coasts, European Seas, Mediterranean Sea, off Morocco Atlantic coasts, and off South Africa coasts. The comparison between scatterometers and SAR are first investigated through the spatial distributions of the statistical parameters such as bias, SD, RMS difference, and sampling length. Figure 4 illustrates examples showing the distributions of RMS differences of ASCAT minus SAR wind speeds estimated from collocated data occurring during the study period (January 2015 – December 2016). No systematic regional dependency is depicted. Similar results are drawn from RapidScat and SAR comparisons. High RMS values may occur in off-coast areas such in the Mediterranean Sea (Figure 4a) as well as in near coasts such as in south-west of Hawaiian Islands (Figure 4e). Differences are mainly due to dominating wind conditions. For instance, the difference pattern shown in the western Mediterranean Sea in an area between south Spain and North Africa and associated with RMS values exceeding 3 m s^{-1}, is related to high wind conditions. Indeed, collocated ASCAT winds exhibit time means and SD, estimated at each grid point, exceeding 13 m s^{-1} and 5 m s^{-1}, respectively.

Figure 5 illustrates examples of comparisons obtained from all valid SAR and ASCAT, and SAR and RapidScat matchups. The number of collocated ASCAT and SAR, and RapidScat and SAR determined for the period January 2015 – December 2016 are 346845 and 168599, respectively. The comparisons shown for wind speeds and wind directions lead to good agreements between scatterometer and SAR wind retrievals. The ASCAT and SAR coefficient correlations are 0.97 for wind speed, and 1.84 for wind direction. For RapidScat and SAR these correlation coefficients are 0.92 and 1.78, respectively. The results related to ASCAT and SAR wind speed comparisons (Figure 5) meet those found in Monaldo *et al* (2016). However, the latter reference indicates a mean difference between ASCAT and SAR wind speeds is of -1.12 m s^{-1}. In this study, it is 0.28 m s^{-1}. Such difference in mean difference of wind speeds from ASCAT and SAR would be related to wind conditions characterizing each dataset and to collocation procedure used in each study. For instance, (Monaldo *et al*, 2016) wind speed results were derived from a shorter period (10 January to 30 June, 2015) of collocated data.

The statistics estimated for wind speed comparisons indicate bias and RMS differences are 0.26 m s^{-1} and 1.34 m s^{-1}, respectively, and the bias and RMS estimated for RapidScat and SAR difference are 0.59 m s^{-1} and 1.51 m s^{-1}, respectively. Results shown in Figure 5 highlights significant departures found for high scatterometer wind speeds exceeding 18 m s^{-1}. The former tend to be more pronounced for RapidScat and SAR comparisons. The investigation of scatterometer and SAR wind speed comparisons are performed as a function of scatterometer and SAR wind speed ranges. They are illustrated by red and magenta dashed lines in the wind speed panels (Figure 5) indicating the mean wind speed averages estimated for scatterometer and SAR 1 m s^{-1} wind speed bins. SAR tends to be underestimated compared to scatterometer retrievals for all wind speed ranges exceeding 10 m s^{-1}. These results indicate that the systematic overestimation of SAR wind speed, compared to ASCAT retrievals, underlined in Monaldo *et al* (2016) (should be considered with caution. Although the sampling of high wind exceeding 18 m s^{-1} are quite low (lower than 1% of total collocated data), SAR wind speed underestimation associated with these wind ranges may reach or exceed 1 m s^{-1}. Further investigations of SAR and scatterometer wind comparisons are performed as a function of SAR incidence angles (not shown) for various scatterometer wind speed bins. The associated results do not yield any significant dependency of scatterometer and SAR wind speed differences on incidence angle.

Wind direction comparisons of SAR retrievals versus ASCAT as well as RapidScat exhibit good agreement (Figure 5). The associated biases (Scatterometer minus SAR), RMS differences, and vector correlations are of 2°, 30°, and 1.70, respectively. These statistics exhibit significant dependency on wind speed conditions (not shown). For instance for wind speed (scatterometer or SAR) lower than 3 m s^{-1}, RMS differences exceed 40°, while for wind speed higher than 6 m s^{-1}, RMS differences are 20°. For low wind speed conditions, wind direction experiences high space and time variability leading to significant departures between scatterometers and SAR mainly related to the collocation criteria. In addition to wind speed range dependency, scatterometer and SAR wind direction differences are investigated with respect to SAR incidence angles. No systematic dependence on the incidence angle is found for the residual wind directions.

The wind speed and direction comparisons shown above indicate that the difference between scatterometer and SAR are mainly due to wind speed conditions. The main sources leading to differences between scatterometer and SAR winds would be related to the procedure used for retrieving SAR winds (e.g. Mouche *et al*, 2012) from backscatter coefficient measurements. The latter includes direct (GMF) and inverse (retrieving procedure) issues. The quality of SAR wind retrievals would be assessed through the comparisons of measured (σ_m^0)) and expected backscatter coefficients (σ_e^0). The latter are estimated based on the use of the updated (Mouche *et al*, 2012) and standard CMOD-IFR2 (Bentamy *et al*, 1999) GMF forced by collocated ASCAT wind speed and direction. Figure 6 shows examples of σ_m^0 and σ_e^0 as a function of ASCAT wind speed and for three ASCAT wind direction ranges, associated with upwind, downwind, and crosswind cases, and three incidence angle bins. Both simulated backscatter coefficients track very well σ_m^0 for all selected wind directions and incidence angles. Better comparison results are found for ASCAT winds lying between 4 m s^{-1} and 12 m s^{-1}, whereas the lowest results are depicted for high winds. For winds exceeding 14 m s^{-1}, the measured backscatter coefficients σ_m^0 tend to be underestimated compared to the measuredσ_e^0. Regarding the procedure used to retrieve SAR winds, based on the minimization of root mean square difference between measured and predicted backscatter coefficients (Mouche *et al*, 2012), SAR wind speed retrievals would be underestimated for high wind conditions. Therefore, the enhancement of SAR and ASCAT wind speed comparison, especially for high winds, requires the reduction of difference between σ_m^0 and σ_e^0 The latter is achieved through a linear regression analysis of and σ_m^0 and σ_e^0 for each SAR incidence angle 1° bins. Various regression analyses would be used to determine the linear relationship between measured and predicted σ^0 (e.g. Bentamy *et al*, 2011). However, one should notice that both σ_m^0 and σ_e^0 have their own uncertainties, neither measured nor expected σ^0 can be selected as a reference ('ground truth') for the analysis (e.g. Bentamy *et al*, 2013). Indeed, both sources have errors related to scatterometer wind and SAR backscatter coefficient measurements. Additional errors are related to the procedure of estimation of σ_e^0 and to the spatial and temporal separations between SAR and scatterometer data. In this study, the symmetrical regression analysis, also called the reduction of major axis is used (e.g. Trauth , 2007; Bentamy *et al*, 2011). It aims at the minimization of the distances separating regression fit and both, σ_m^0 and σ_e^0. Outliers, detected through the application of robust regression algorithm (Street *et al*, 1988), are excluded. The collocated data are split into two subsamples, which are randomly selected. The first subsample (67% of collocated data) is used to determine the regression slope and intercept coefficients, whilst the second subsample is utilized for the validation. Although the original and corrected backscatter coefficients are quite close, some differences are depicted for some wind speed and incidence angle ranges. For instance, for wind speeds of 12 – 15 m s^{-1} and incidence angles of 32° – 44°, the difference between corrected. σ_m^0 and σ_e^0 is lower than the difference between original . σ_m^0 and σ_e^0 by a factor of 20%.

The corrected σ_m^0 are used to retrieve a new SAR wind speed aiming mainly at the improvement of SAR and ASCAT wind speed comparisons, especially at high wind conditions. A simple method t o reduce departure between SAR and scatterometer winds is to apply CMODIFR2 (Bentamy *et al*, 1999) assuming that SAR wind direction is bias-free. This latter assumption is supported by Table 1 and Figure 5. It significantly simplifies and speeds up wind speed calculations. The resulting wind speed is referred to as the new ERS, or ERS/N. It is determined by minimizing the following cost function:

$$J(w,\chi) = (\sigma_m^0 - \sigma_e^0(w,\chi))^2 \qquad (2)$$

where *w* is the new wind speed, χ is the wind direction relative to antenna azimuth (known from SAR data), σ_e^0 is the simulated backscatter coefficients estimated from CMODIFR2 GMF. For each SAR WVC, the new wind speed retrieval determined from (eq. 2) based on the use the original SAR wind speed as the first guess for minimization of (eq. 2).

Figure 7 shows an example of high surface wind speed conditions occurring on 28 November, 2015 17:29:15 UTC over a geographical zone of the western Mediterranean Sea (Figure 7a). Wind speed retrievals are from ASCAT-B (Figure 7b), occurring 2 hours and half later than SAR time, SAR original data (Figure 7c), and from the reprocessed SAR winds (Figure 7d). The three retrievals exhibit very similar wind patterns with much higher spatial resolution from the two SAR data sets. The main change between original and reprocessed SAR wind speeds for high wind speeds (>18 m s^{-1}) occurring north of Gulf of Lyon and related to the wind event named "Mistral Intramontane". The reprocessed SAR winds lead to better comparison with ASCAT retrievals. Similar improvements also result from \comparison between the reprocessed SAR and scatterometer RapidScat wind retrievals (not shown). The statistics, characterizing the comparison of scatterometer and SAR data, calculated from all wind speed conditions are similar for original and reprocessed SAR winds. The main change is found for mean difference between RapidScat and SAR, calculated for scatterometer wind speed exceeding 12 m s^{-1}. It drops from 0.62 m s^{-1} (bias related to original SAR) to 0.07 m s^{-1} (bias related to the reprocessed SAR winds).

To assess the quality of the new SAR retrievals, comparisons are performed with mooring winds based on the use of buoy and SAR collocated data (see section above). The results are shown in Figure 8 for NDBC and MFUK buoy networks (Figure 1). Although the statistics, provided in each panel, are close to those obtained for the original SAR wind speed retrievals (Table 1), the results depending on the reprocessed SAR exhibit lower bias and variability. The main improvements are found for high wind conditions. For buoy wind speed exceeding 12 m s^{-1}, the reprocessed wind retrievals leads to a reduction of buoy and SAR mean difference by a factor of 22%.

5 Enhancement of regional surface wind analyses

Several studies have shown that scatterometer wind observations lead to a significant improvement in the determination of regular wind field in space and time , named wind analyses, over the global ocean or over a specific oceanic basin (e.g. Bentamy *et al*. (1996; 1998 ; 2011), Perrie *et al* (2002), Royle *et al*. (1999), Tang and Liu (1996)). For instance IFREMER wind analyses are calculated from ASCAT retrievals using the kriging method with external drift (Bentamy *et al*, 2012). The analysis method requires the knowledge of the spatial and temporal structure functions. The latter is determined from scatterometer wind observations. To improve the determination of the spatial structure function over some specific areas of interest, SAR winds are used. Indeed, SAR data allows the investigation of surface wind variability at scales smaller than 12.5 km (scatterometer WVC spatial grid).

5.1 Wind analysis determination: Brittany case

Based on SAR wind retrievals available for the study period (January 2015 – December 2016), structure functions (γ) (eq. 3 - 4), known as variogram for kriging methods, are estimated along Brittany coasts (Northwest of France). γ Illustrates the behaviour of covariance between two variable values occurring at two locations and times separated spatially and temporally by δ_{h} and δ_{t}, respectively. The kriging method is described by Bentamy *et al* (1996) and Bentamy *et al* (2012).

$$\boldsymbol{\gamma} = \boldsymbol{c}(0,0) - \boldsymbol{c}(\delta_{\mathrm{h}}, \delta_{\mathrm{t}}) \quad (3)$$

Where:

$$\boldsymbol{c}(\delta_{\mathrm{h}},\delta_{\mathrm{t}}) = \mathrm{cov}(\boldsymbol{x}(m_i,t_i),\boldsymbol{y}(m_i,t_j)) \quad (4)$$

cov indicates covariance between observation vectors occurring at location m_i *and* m_j which are δ_{h} (spatial lag in km) apart, and at times t_i and t_j which time separation *is* δ_{t} (temporal lag in hour*)*

Exponential model (eq. 5) is used for fitting the structure function:

$$\gamma(\delta_h, \delta_t) = a(1 - \exp\left(-\frac{\delta_h + c\delta_t}{b}\right)) \quad (5)$$

a and *b* are named sill and variogram range, respectively. a indicates variogram values associated with γ value when correlation between variables becomes not significant. Parameter *b* and *c* indicates spatial and temporal lags beyond where no significant spatial and temporal structures are drawn (Bentamy *et al*, 1996), respectively. They indicate the distance (in km) and time (in hour) at which the variogram reaches 95% of the sill values.

Regarding SAR spatial and temporal sampling schemes, only spatial structure are investigated. Therefore, variograms γ are determined from SAR winds (wind speed, zonal component, and meridional component) occurring over same swaths ($\delta_t = 0$).

The investigation of the spatial structures of surface winds from SAR are performed through the analysis of variogram parameters *b* estimated from SAR wind speeds (Figure 9a), zonal wind component (Figure 9b), and meridional component (Figure 9c). As expected, the spatial structure scales tend to increase from near the coast towards offshore locations. The lowest and highest values of the spatial structure scales exceed 10 km and 100 km, respectively. Wind speed and wind vector components have significant regional spatial patterns. For instance regions located northeast of Brittany exhibit low spatial scales related to wind variability characterizing the English Channel (La Manche in French). Spatial scales estimated for regions located west of 4.5°W (47.5°N-49°N) exhibit high values due to prevalent westerlies.

Variogram parameters *a* and *b*, estimated from SAR data, are thus used in combination with *c* parameter (eq. 5) determined from scatterometer wind data (Bentamy *et al*, 2012) to enhance the wind field analysis at regional scale (Brittany region). The wind analyses are calculated from ASCAT and RapidScat retrievals in combination with wind speed retrievals from Special Sensor Microwave Imager (SSM/I) radiometers onboard F16 and F17 satellites. The method aiming at the calculation of such “blended” wind field is described in (Desbiolles *et al*, 2017). The former are estimated as 6-hourly averaged winds, associated with synoptic time epochs (00h:00, 06h:00, 12h:00, and 18h:00 UTC), with a spatial grid of 0.125° in longitude and latitude. One should notice that SAR wind retrievals are not used in the calculation of wind field analyses. Figure 10 illustrates an example of wind fields analyses calculated for day 2 January 2016. It shows the spatial variability of wind speed and direction associated with each time epoch, and also the spatio-temporal variability depicted between the four epochs. For this study one year (1 January – 31 December 2016) of 6-hourly wind field analyses are calculated.

5.2 Wind analysis quality

The quality of the 6-hourly wind field analyses is tested through comparisons with corrected SAR wind speed and direction retrievals collocated in space and time (section 4). More specifically, the first collocated step is the selection of valid SAR data and wind field analyses occurring within 3 hours from each other. The second step aiming at the depiction of the selected SAR retrievals and 6-hourly analyses located within 12.5 km. The SAR collocated data are linearly interpolated at wind field cell (0.125°×0.125°) centre. Figure 11 shows the geographical distributions of SAR and 6-hourly wind field matchups. It indicates that distribution of the collocated sampling length is not random. It mainly relies on the characteristics of the SAR sampling scheme. Better matchup lengths are found in the western area, where SAR samples more frequently, than in eastern area of Brittany. Furthermore, the sampling length does not mean that all samples are fully independent. Indeed, some samples might be associated with the same synoptic weather situation. The lowest sampling lengths are depicted along Brittany in near shore zones where they do not exceed 20 per cell (0.125°×0.125°).

Based on the use of all valid collocated data, the mean difference (bias) between SAR and wind field wind speeds and directions are of -0.10 m s^{-1} and 0.70°, respectively. The associated standard deviations are 1.35 m s^{-1} and 12°, while the associated scalar correlation for wind speed and vector correlation for wind direction are 0.94 and 1.88, respectively. These statistics are of the same order that was found for SAR and scatterometer retrieval comparisons (Figure 5).

Further investigations of SAR and wind analyses are performed under various criteria. For instance, Figure 12 shows comparison results determined as a function of SAR wind speed ranges (Figure 12 a), b), and c)) and of distance from the Brittany coastlines (Figure 12 d), e), and f)). The mean differences and the associated standard deviations are calculate from collocated data binned in 1 m s^{-1} intervals of SAR wind speeds, and in 10 km bins distance between coastlines and collocated matchup locations. Regarding the mean difference (heavy black line) and the associated standard deviation (shaded grey area) values (Figure 12a), no significant difference is found for SAR wind speeds ranging between 3 m s^{-1} and 12 m s^{-1}.

The difference found for low wind speed ranges (<3 m s^{-1}) is due to asymmetrical distribution of collocated data about the one-to-one line, which does not mean systematic underestimation of SAR with respect to wind analyses (e.g. Freilich, 1997). The discrepancy found for high wind speed ranges (>13 m s^{-1}) is due to the spatial and temporal collocation issues. Indeed, SAR high winds are instantaneous observations at high spatial resolution, whereas wind analyses are 6-hourly averages estimated over a cell of 0.125°square. The wind direction residual (Figure 12b) is almost zero and shows no systematic dependence on SAR wind speed ranges exceeding 3 m s^{-1}. The high variability of wind direction associated with low wind speed condition (<3 m s^{-1}) leads to an increase in the standard deviation of SAR and wind analysis wind direction differences. Difference results shown in Figure 12d and Figure 12e indicate that no significant dependence on distance from the coastlines is discernible.

5.3 Characteristics of surface wind speed distribution

The results shown above allow the use of 6-hourly surface wind analyses for better characterizing surface wind speed distributions at local scales. The latter would be, for instance, of interest for the studies aiming at the characterization of wind power. One advantage of using wind analyses is the enhancement of the space and time sampling including coastal areas.

Most studies aiming at the investigation of wind speed distributions, assume that the former would be approximated by the Weibull distribution (e.g. Justus et al, 1976, Bentamy *et al*, 2014) defined as:

$$f(w) = 1 - \exp\left(-\left(\frac{w}{a}\right)^c\right) \quad (6)$$

w denotes the wind speed derived from 6-hourly wind analyses.

a is a scaling parameter expressed in m s^{-1}, and *c* is a dimensionless shape parameter. They would be determined by various methods yielding small deviations between weibull curves. Here, the method named moment method is used. The mean (μ) and the variance (σ^2) of Weibull distribution are calculated as a function of the Weibull parameters

$$\mu = a\Gamma(1/c + 1) \text{ and } \sigma^2 = a^2(\Gamma(2/c + 1) - \Gamma^2(1/c + 1)) \quad (7)$$

Γ is the gamma function

Using the above equations the Weibull parameters are determined as following:

$$c = (\sigma/\mu)^{-1.086} \text{ and } a = \mu/\Gamma(1/c + 1) \quad (8)$$

The significant of the Weibull distribution fitting is determined through the comparison between the quantiles of the observations and the Weibull distribution at each grid. The quantiles differences are estimated for the probabilities 0.25, 0.50, 0.75, 0.90, and 0.95. The spatial distributions (not shown) of differences do not show any significant patterns including at near coastal areas. The difference between distribution medians associated with each probability are -0.09 m s^{-1}, -0.17 m s^{-1}, 0.01 m s^{-1}, 0.49 m s^{-1}, and 0.18 m s^{-1}, respectively. However, larger differences reaching or exceeding 1 m s^{-1} are found for probability 0.90 and 0.95. Weibull fitting tends to underestimate the higher winds frequencies. For probabilities 0.50 and 0.75, 90% of differences are within 0.50 m s^{-1}.

The main spatial and seasonal wind speed characteristics are illustrated in Figure 13. It shows the spatial distribution of Weibull parameters a and c estimated for winter (December-January-February (DJF)), spring (March-April-May (MAM), summer (June-July-August (JJA)), and fall (September-October-November (SON)) 2016. The main prevailing regional scales of surface wind speed are depicted in the spatial distributions of the Weibull scaling parameter a (Figures 13 a), b), c), and d)). The seasonal variation of the spatial distribution of scaling parameter a meet the seasonal variation of wind occurring along Brittany coasts. The highest and lowest a values are depicted in winter season (Figure 13a), mainly due to the westerlies, and in summer season (Figure 13d), respectively. Significant spatial variations of parameter a are also found for each season. For instance, there is a factor of 100% between a values estimated offshore and nearshore. Furthermore, a exhibits significant spatial variation along Brittany coasts. These specific spatial variations are more pronounced in the southern area underlining the usefulness of high spatial and temporal resolutions of surface wind. Such high space ad time resolutions are also needed for investigating the spatial and temporal variations of shape parameter c (Figure 13 e), f), g) h)). Indeed c exhibits significant spatial and seasonal variations. For instance, in winter season (Figure 13e) the highest values are mostly found in northern areas, suggesting narrow wind speed distributions, whereas in southern regions c exhibits lower values leading to a larger spread in wind occurring during this seasons. The temporal change in c spatial distribution assesses the significant changes in wind speed distributions according to season. Furthermore, it is found (not shown) that the spatial and temporal variations of both Weibull parameters a and c are enhanced according to wind conditions. For instance in the winter season of 2016 and for conditions of westerlies, accounting for about 40% of total winter data, the spatial patterns of a are quite similar to those shown in (Figure 13a), but with enhanced amplitude of 10%. The associated patterns of shape parameter indicate that wind speed distributions are narrower in both north and south zones.

6 Summary and Conclusion

The newest high resolution wind speeds and directions retrieved fromSentinel-1A SAR measurements are investigated. The main goal of the study is to underline the ability of SAR winds for enhancing the determination of the surface wind analysis (regular wind fields in space and time) at regional scale and especially in near coastal areas. The wind analyses are calculated mainly from scatterometer winds in combination with radiometer data.

In this study only SAR data occurring from January 2015 to December 2016 and retrieved from backscatter coefficients in interofemetric wide (IW) mode are used. The accuracy of SAR wind speed and direction retrievals is first investigated through comprehensive comparisons with buoy data derived from various NDBC, MFUK, and EPPE mooring networks. The buoy winds are also used to estimate the main statistics characterizing the accuracy of wind speed and direction retrieved from ASCAT-A/B and RapidScat scatterometer and available over the aforementioned SAR period. All remotely sensed wind data show quite similar results. They compare well to buoy data and do not exhibit any systematic errors. For instance RMS values of SAR and scatterometer wind speeds and directions are of about 1.30 m s^{-1} and 20°, respectively. The main departure between buoy and remotely sensed wind data are found for SAR retrievals collocated with high buoy wind speeds exceeding 10 m s^{-1}. Scatterometer wind retrievals do not lead to such behaviour for high wind conditions. The underestimation of SAR high winds also result from the comparisons with ASCAT-A/B and RapidScat data. Such discrepancy relies on the underestimation of SAR backscatter coefficients (σ_{m}^{0}) compared to σ^0 calculated from scatterometer winds based on the use of GMF CMOD-IFR2 (σ_{e}^{0}). Regarding the procedure used for SAR wind retrieval, the underestimation of SAR wind speed results from the underestimation of σ_{m}^{0}. To achieve the main goal of the study, SAR winds are reprocessed based on the use of GMF CMOD-IFR2. The validation of the new retrievals, through the comparison with buoy data, shows better results of SAR retrievals for high wind conditions.

Regarding the spatial resolution of SAR wind data, the characterization of spatial scales of wind speed, zonal, and meridional components are investigated, using the reprocessed SAR winds, over a region of interest (Brittany) including near coast areas. The patterns of the wind scales exhibit significant spatial variability. They vary between 10 km and 100 km depending on geographical locations along Brittany coasts. Such spatial scale results allow for better estimation of the spatial structure function required for the determination of gridded wind fields. The latter are mainly calculated from scatterometer (ASCAT-A/B and RapidScat) retrievals in combination with SSM/I radiometer wind data, with a spatial grid of 0.125° in latitude and longitude and available at synoptic times (00h:00, 06h:00, 12h:00, and 18h:00 UTC). The resulting wind fields show good agreement with collocated SAR wind retrievals (not used in regular wind field calculation) even in near coastal areas.

The method aiming at the estimation of regular, in space and time, wind fields from scatterometer retrievals based on the use of the spatial structure function, determined from SAR data, will benefit various coastal studies requiring high space and time resolution data. For instance, it would be particularly useful for the investigation of available resources for wind power over a dedicated region and at various spatial scales. Nevertheless, these surface analyses would benefit from further improvements. The accuracy of wind field analyses should be investigated through comprehensive comparisons with high quality coastal buoy data. The latter are very few and only available at some specific areas. More investigation of processing, used for retrieving wind speed and direction from SAR measurements, including GMF issues, is expected. Furthermore, finer spatial and temporal resolutions of surface wind analyses should be achieved. The former would be used as an alternative source of surface wind data where in-situ data are not available.

Acknowledgements. The analysis is carried out at Ifremer/LOPS, supported in part by the E.U. INTERREG project named ARCWIND (http://www.arcwind.eu/) . The authors are grateful to ESA, EUMETSAT, CERSAT, JPL, ECMWF, Météo-France, UK MetOffice, NDBC, and PMEL for providing satellite, numerical, and in-situ data used in this study. We would like to thank D. Croizé-Fillon and IFREMER/Cersat Team for providing useful processing tools and support. We would like to thank Pr Katsaros who provided useful and relevant comments on the study and manuscript.

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Tables

Table 1: Statistical comparison results of collocated 10m wind speeds and direction from NDBC buoys and Sentinel 1A SAR IW data occurring during the period 17 June 2015 to 19 March 2016. Bias is defined as mean difference between buoy and scatterometer winds (in this order). SD, b_s, ρ, and ρ^2 indicate standard deviation, regression symmetrical coefficient, scalar correlation coefficient, and vector correlation coefficient, respectively. The latter varies between -2 and +2.

	Length	Wind speed				Wind direction		
		Bias (m s^{-1})	RMS (m s^{-1})	b_s	ρ	Bias (°)	SD (°)	ρ^2
SAR IW	2216	0.22	1.42	0.97	0.93	-5	44	1.57
ASCAT	11739	-0.16	1.24	0.95	0.95	0	35	1.78
RapidScat	13265	-0.69	1.61	1.01	0.92	-3	41	1.56

Figures

Figure 1 : Buoy locations. NDBC (red asterisks symbols) are shown in a) while MFUK (red cross) and EPPE (blue cross) in b) panels. Only buoys providing valid wind data during the period January 2015 – December 2016 are shown.

Figure 2:   Sentinel -1A wind speed (in m s^{-1}) image (Colourbar) collocated in space and time with NDBC buoy (shown as blue asterisks symbol).

Figure 3 : Two-dimensional space lagged autocorrelation estimated from SENTINEL-1A (left column) and ASCAT (right) wind speed retrievals at five oceanic regions centred on 43°N-4°E (panels a and b), 42°N-5°E (c and d), 40°N-6°E (e and f), 36°N-3°W (g and h), and 36°N-7°W (i and j) . Colourbar shows autocorrelation values.

Figure 4: Spatial distributions of the RMS differences of ASCAT and SAR wind speeds estimated from collocated data occurring for the period January 2015 – December 2016. They are estimated over oceanic zones of collocate data availability: a) The Mediterranean Sea and North-east Atlantic (off Morocco, Portugal, and Spain coasts) ; b) North Atlantic; c) North-west Atlantic (off USA coats); d) North-east Pacific (off USA coasts); e) Hawaii; f) off South Africa coasts. Colourbar show RMS difference values in m s^{-1}

Figure 5: Sentinel-1A SAR wind speed (top) and direction versus ASCAT (left column) and RapidScat (right column). Results are shown for all scatterometer and SAR matchups. Colourbar indicate density of collocated data for wind speed and direction bins of 0.20 m s^{-1} and 2 °, respectively. Red and magenta dashed lines, shown in wind speed panels, state for mean wind speed estimated for 1 m s^{-1} ASCAT and SAR IW wind speed bins, respectively. Colourbars show sampling lengths of collocated scatterometer and SAR data.

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Figure 6: Measured σ_{m}^{0} and simulated σ_{e}^{0} SAR backscatter coefficients as a function of ASCAT wind speed. They are shown for three ASCAT wind direction ranges associated to Upwind, downwind, and crosswind cases, and for three SAR incidence angle (θ) ranges (30°, 37°, and 44°). Grey dots indicate σ_{m}^{0}. Red line shows averaged σ_{m}^{0} calculated for 1 m s^{-1} ASCAT wind speed ranges. Blue and black lines indicate σ_{e}^{0} estimated from updated CMODIFR2 and from standard CMODIFR2, respectively.

Figure 7:   Example illustrating the comparison enhancement between SAR and ASCAT surface wind speeds. a) blue colour zone indicates SAR swath occurring on November, 28 2015 17h:29:15 UTC. b) Collocated ASCAT-B wind speed retrievals. c) and d) panels show original and reprocessed SAR wind speed retrievals, respectively. Colorbar show wind speed values in m s^{-1}.

Figure 8:   Comparisons of collocated wind speed of NDBC (left) and MFUK (right) and reprocessed SAR. Statistics shown in each panel indicate mean difference bias (buoy minus

SAR), root mean square difference (RMSD), correlation coefficient (ρ), symmetrical regression slope coefficient (b_s), and intercept (a_s). Bias and RMSD units are $m\ s^{-1}$.

Figure 9: Spatial distribution of variogram parameter *b* (eq 5) indicating the spatial structure scales (in km) calculated from SAR IW wind speed (a), zonal wind component (b), and meridional wind component (c) occurring during the period (January 2015 – December 2016) along Brittany coasts. Colourbar shows *b* values in km.

Figure 10: Example of four wind field analyses estimated from scatterometer (ASCAT and RapidScat) in combination with radiometer SSM/I F16 and F17 for day 2 January 2016 on the four synoptic time epochs 00h:00 (top/left), 06h:00(top/right), 12h:00(bottom/left), and 18h:00 (bottom/right) . Colour indicates wind speed (in $m\ s^{-1}$), while black arrows indicate wind directions (Only one in two wind direction is shown).

Figure 11: Spatial distribution of collocated SAR IW and 6-hourly wind field analysis data length (in colour), determined from data occurring between 1 January and 31 December 2016.

Figure 12: Wind speed (a) and d)) and direction (b) and e)) difference (heavy black lines) as a function of SAR wind speed (left column) and distance from Brittany coastlines (right column). Shaded areas represent one standard deviation associated to the mean difference. c) and d) sow the sampling length according to wind speed and distance ranges, respectively.

Figure 13: Wind speed distributions characteristics estimated from 6-hourly wind field analyses (January 2016 – December 2016) along Brittany coasts. Panels show seasonal (indicated within brackets) variation of the spatial distribution of Weibull parameters *a* (in $m\ s^{-1}$) and *c*, respectively.