Oceansat-2 and RAMA buoy winds: A comparison

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Sea surface vector winds from scatterometers onboard satellites play an important role to make accurate Numerical Weather Prediction (NWP) model analysis over the data sparse oceanic region. Sea surface winds from Oceansat-2 scatterometer (OSCAT) over the Indian Ocean were validated against the Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA) buoy winds to establish the accuracy of OSCAT winds. The comparison of OSCAT winds against RAMA buoy winds for a period of one year (2011) shows that the wind speeds and directions derived from OSCAT agree with RAMA buoy winds. The monthly mean wind speeds from both OSCAT and RAMA buoy show maximum value during the monsoon period as expected. In the complete annual cycle (2011), the monthly mean root mean square differences in the wind speed and wind direction were less than $\sim 2.5 \text{ ms}^{-1}$ and $\sim 20^\circ$, respectively. The better match between the OSCAT and RAMA buoy wind is observed during Indian summer monsoon (June–September). During monsoon 2011, the root mean square differences in wind speed and wind direction were less than 1.9 ms^{-1} and 11° , respectively. Collocation of scatterometer winds against equatorial and off-equatorial buoys clearly brought out the monsoon circulation features. Collocation of Advanced Scatterometer (ASCAT) winds on-board European Space Agency (ESA) MeTop satellite with respect to RAMA buoy winds during monsoon 2011 also showed that the OSCAT wind statistics are comparable with that of ASCAT over the Indian Ocean, and indicates that the accuracy of both the scatterometers over the Indian Ocean are essentially the same.

1. Introduction

Among the three tropical oceans, Pacific, Atlantic and Indian Ocean, the Indian Ocean is unique in that it is blocked at 25°N by the Asian landmass. The Indian Ocean receives heat from the other two tropical oceans, Pacific via the Indonesian Throughflow (Gordon 2001) and exports heat to the Atlantic via the Agulhas Current System (de Ruijter *et al.* 1999). The monsoon circulation, because of the seasonal heating and cooling of the land, sets the wind reversal and intense rainfall over the Indian subcontinent. Since the northern

limit of the Indian Ocean is blocked by the Asian landmass, the currents cannot carry heat from the tropics to the higher northern latitude as in the other oceans. The anomalies in the Indian Ocean climate affect the evolution of El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), rainfall, hurricane activity, the atmospheric circulation of the North Pacific, and western U.S. weather through atmospheric teleconnections (McPhaden *et al.* 2009 and the references therein). However, the lack of potential data over the Indian Ocean limits our knowledge of key potential features of ocean–atmospheric

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coupling and the monsoon circulation. The Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA) buoy network over the Indian Ocean, part of the Tropical Atmosphere Observation (TAO) program helps to fill this data void to a good extent. The RAMA buoy network provides data to validate the scatterometer winds over the Indian Ocean region. The scatterometer wind verification generally rely on the comparison between wind models and the sensor data, or on the inter-comparison with meteorological buoy data (Portabella and Stoffelen 2009; Stoffelen *et al.* 2010; Vogelzang *et al.* 2011; Chakraborty *et al.* 2012).

Oceansat-2 is the second Indian satellite dedicated to ocean research, a continuity of the operational services of Oceansat-1 with high application potentials. The Oceansat-2 was launched from Satish Dhawan Space Centre, Sriharikota on 23rd September, 2009, using Polar Satellite Launch Vehicle (PSLV-C14). It has three payloads: (i) Ocean Colour Monitor (OCM), (ii) Ku-band Pencil Beam Scatterometer (OSCAT) developed by Indian Space Research Organization (ISRO), and (iii) Radio Occultation Sounder for Atmosphere (ROSA) developed by the Italian Space Agency. The mission goal of Oceansat-2 is to provide wind speed measurements of $4\text{--}24\text{ ms}^{-1}$, with an accuracy of 2 ms^{-1} , and direction, with an accuracy of 20° . The scatterometer, a Ku-band pencil beam sensor similar to that onboard QuikSCAT satellite, provides surface vector winds over global oceans with a two-day repeativity. Singh *et al.* (2011) illustrated the impact of the assimilation of OSCAT surface winds in WRF.

Sea surface wind products from scatterometers flown onboard satellites play an important role to create accurate Numerical Weather Prediction (NWP) model analysis over the data sparse oceanic region. In this paper, authors attempted to validate the OSCAT wind products with respect to RAMA buoy winds over the Indian Ocean in order to bring out whether the errors in OSCAT derived wind speed and direction are within the mission goal over the Indian Ocean, so that OSCAT wind products can be assimilated in NWP models.

Numerous studies have been reported on the comparison of scatterometer wind observations from different space borne platforms over the Indian Ocean with buoy observations. Goswami and Sengupta (2003) carried out a comparison of QuikSCAT with two buoys in the Indian Ocean and the Root Mean Square Vector Difference (RMSVD) was observed to be 1.4 ms^{-1} for both zonal and meridional components. Goswami and Rajagopal (2003) showed the impact of scatterometer data assimilation in numerical models to improve the weather forecast over India. Satheesan *et al.* (2007)

evaluated the performance of QuikSCAT wind vectors against *in-situ* buoy observations over the Indian Ocean and reported the mean difference in wind speed and wind direction as 0.37 ms^{-1} and 5.8° and the root mean square deviations as 1.57 ms^{-1} and 44.1° averaged over a period of 2000–2003. Sudha and Prasada Rao (2013) compared the OSCAT winds against RAMA buoy (considered 8 buoys) winds over the Indian Ocean and Triangle Trans-Ocean Buoy Network (TRITON) (considered 6 buoys) over the Pacific Ocean and reported that the OSCAT wind speed errors are within the mission goal, but the wind direction errors are higher than the mission goal and the OSCAT wind speeds are relatively more accurate over the Indian Ocean.

In this paper, the OSCAT ocean surface winds over the Indian Ocean were validated against the RAMA buoy (~ 16 buoys) winds for a period of one year, 2011. For a better assessment of the OSCAT winds over the Indian Ocean in comparison to other scatterometer winds available, the ASCAT winds were also compared with respect to RAMA buoy winds during monsoon 2011. Even though there is difference in the configuration and frequency of OSCAT (Ku-band) and ASCAT (C-band), a comparison of two datasets with respect to an independent dataset (RAMA buoy) will give a better evaluation. Four buoys near the equator, four north of equator and eight south of equator were considered in the present study. The data used in this study is described in section 2, followed by the methodology in section 3. The results from the present study are discussed in section 4, and the main findings from the study are concluded in section 5.

2. Data

2.1 Scatterometer data

ISRO reprocessed OSCAT Level-2B (L2B) wind data (version 1.3, released in December 2011) is available through National Remote Sensing Centre (NRSC) (www.nrsc.gov.in). The OSCAT wind vector product generation is based on the algorithms by Gohil *et al.* (2008, 2010). In this study, the performance of ISRO reprocessed OSCAT winds were compared with respect to RAMA buoy winds. National Centre for Medium Range Weather Forecasting (NCMRWF) is regularly assimilating ASCAT wind data from National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service (NOAA/NESDIS) since June 2011 in its global model, T574L64. In this study, ASCAT winds during monsoon 2011 also compared against

RAMA buoy winds. This type of exercise gives a better understanding on the quality of OSCAT winds in terms of other existing scatterometer winds. Figure 1 shows the coverage of OSCAT and ASCAT ocean surface winds received at NCMRWF during different six hourly global model assimilation cycles on a particular day. Figure 1(a) is the scatterometer wind coverage data received

NCMRWF during 00 UTC (00 ± 3 UTC) assimilation cycle on a particular day. Similarly, figure 1(b–d) are the scatterometer wind coverage received at NCMRWF during 06 UTC (06 ± 3 UTC), 12 UTC (12 ± 3 UTC), and 18 UTC (18 ± 3 UTC) assimilation cycles on a particular day. From figure 1, it is clear that both the scatterometers are complementing each other. The orbital

Figure 1. Coverage of OSCAT (red) and ASCAT (green) scatterometer winds available at NCMRWF during different 6 hourly assimilation cycles on a particular day. (a) Centered around 00 UTC (00 ± 3 UTC), (b) centered around 06 UTC (06 ± 3 UTC), (c) centered around 12 UTC (12 ± 3 UTC), and (d) centered around 18 UTC (18 ± 3 UTC).

Figure 2. Locations of RAMA buoys with WMO buoy identification number.

passes of both the satellites over the Indian Ocean is mainly centered on 18 UTC and 06 UTC global model assimilation cycles.

2.2 RAMA buoy data

The Tropical Moored Array Programs consist of three different TAO Buoy Arrays. They are TAO/TRITON in the Pacific, Prediction and Research Moored Array (PIRATA) in the Atlantic, and RAMA in the Indian Ocean. Since from implementation, the high quality time series data from these moored arrays improved the understanding and prediction of climate variability and climate change (McPhaden *et al.* 2009). The measurements on the RAMA surface floats include the meteorological parameters like air temperature, relative humidity, and wind velocity at a height of 3–4 m above the mean sea level (MSL). Daily averages of all data and several hourly samples per day of most meteorological variables are transmitted to shore in real time via Service Argos. These data placed on the Global Telecommunication System (GTS) for use in operational weather, climate and ocean forecasting (McPhaden *et al.* 2009). As of now, around 16 moorings are included in the RAMA Buoy Array (<http://odis.incois.gov.in/Insitu/Rama-Buoy-Graph.jsp>), and figure 2 shows the locations of these buoys with the World Meteorological Organization (WMO) buoy identification number and also described in table 1. NCMRWF is getting the three hourly RAMA buoy data through GTS. NCMRWF archived RAMA buoy data during 2011 is used to compare the scatterometer winds. Figure 3 shows the monthly count

Figure 3. Monthly count of Rama buoy reports (observations) received at NCMRWF in 2011.

of RAMA buoy reports (observations) received at NCMRWF in 2011. It has to be noted from figure 3 that the maximum number of RAMA buoy reports are received during monsoon (checked for other years as well, not shown here). The difference in the monthly count of RAMA buoy reports may be due to vandalism or improper maintenance.

3. Methodology

OSCAT data downloaded from NRSC and the RAMA buoy data received at NCMRWF through GTS were used in this study. Apart from the above two datasets, ASCAT winds from NOAA/NESDIS during monsoon 2011 was also used to compare the quality of OSCAT winds in terms of scatterometer winds from other space-borne platforms. Since the scatterometer winds over the ocean surface are provided at 10 m neutral stability height, the RAMA buoy winds which are reported at 3 m height is converted to 10 m to conform to the universally accepted standard level. Even though the RAMA buoys are having temperature and humidity sensors in addition to the wind sensor, most of the time, the humidity information is not available in GTS data. Thus an empirical logarithmic profile method suggested by Peixoto and Oort (1992) is used to convert the 3 m buoy winds to 10 m level. If the wind speed at 3 m and 10 m are $W_s(3\text{ m})$ and $W_s(10\text{ m})$ respectively, then

$$W_s(10\text{ m}) = W_s(3\text{ m}) \frac{\ln(Z/Z_0)}{\ln(Z_{ref}/Z_0)},$$

Table 1. WMO buoy identification number and locations of RAMA buoy.

WMO buoy identification number	Location
14041	7.95°S 55.05°E
14042	12.03°S 54.99°E
14043	12.19°S 67.21°E
14046	16.0°S 55.0°E
23001	0.12°N 80.55°E
23003	1.50°S 80.52°E
23004	0.03°N 89.85°E
23005	1.58°N 90.10°E
23006	3.98°N 89.60°E
23007	8.03°N 88.99°E
23008	11.93°N 89.90°E
23009	14.98°N 89.92°E
23010	3.98°S 80.51°E
53005	8.01°S 80.46°E
53006	12.0°S 80.52°E
53009	11.87°S 93.31°E

where $Z = 10$ m, $Z_{\text{ref}} = 3$ m and $Z_0 = 1.52 \times 10^{-4}$. The limitation of this method is that atmospheric stability and the ocean roughness are not taken into account.

The logarithmic profile method and the Liu method (developed at JPL by Liu and Tang (1996), (http://airsea-www.jpl.nasa.gov/publications/lkb_code.html)) were applied to buoy data in a comparison of SSM/I series of satellite wind and buoy wind by Mears *et al.* (2001). The Liu method as opposed to the logarithmic profile method, evaluates the atmospheric stability in the computation of wind speed to a standard height. Z_0 which is the roughness length depends on the roughness of the ocean surface and thus on the wind (stress). Portabella and Stoffelen (2009) reported that $\ln(10/Z_0)$ values vary between 13 (for low Z_0) and 9 (for high Z_0). From their study, Mears *et al.* (2001) concluded that using a correction factor, the difference in the results of the logarithmic profile method compared with the Liu approach may be compensated. These investigators also state that the errors induced, excluding atmospheric stability, are small in comparison to other errors, related to the satellite's measurements. To account for the lack of temperature and humidity data, buoy wind has been converted to 10 m height using the minimal error profile method (Peixoto and Oort 1992). This method requires only the wind speed at the reference height, not the stability parameters (Caballero *et al.* 2005).

The scatterometer winds were collocated with the buoy winds only if they were spatially within a box of $0.25^\circ \times 0.25^\circ$ and temporally within 60 minutes. It has also taken into account that each buoy wind was considered only once for collocation within the above spatial and temporal resolution. To ensure that the correct scatterometer wind was selected, the collocated pair was retained only if the difference in the direction between buoy wind and scatterometer wind was less than 60° . Since the mission goal of Oceansat-2 is to provide wind speed measurements of $4\text{--}24 \text{ ms}^{-1}$, the buoy winds whose magnitude below 4 ms^{-1} were not considered for collocation owing to the difficulty of the scatterometer sensor in measuring directions for low wind speeds. Vogelzang *et al.* (2011) and Chakraborty *et al.* (2012) show that the accuracy of buoy winds and scatterometer winds are similar, i.e., the width of their error distribution functions is similar. Throwing the low buoy winds away has the side effect of rejecting negative error realizations more abundantly than positive error realizations for the buoys, but not for the scatterometer, which obviously causes bias. This is, truncation of the buoy error distribution on the negative side, and will increase mean buoy winds relative

to the scatterometer winds. In this study, similar threshold has also been applied to the scatterometer winds as well.

Statistical parameters like mean scatterometer wind speed, mean buoy wind speed, speed bias between the scatterometer wind speed and buoy wind speed, root mean square component differences, such as RMSVD for wind speed and root mean square difference (RMSD) for wind direction, and the number of collocated winds were estimated for every month. The statistical parameters are calculated as follows:

$$\text{Scatterometer wind speed} = \sqrt{Su^2 + Sv^2} \quad (1)$$

$$\text{Buoy wind speed} = \sqrt{Bu^2 + Bv^2} \quad (2)$$

$$\text{Speed bias} = \frac{\text{Scatterometer wind speed} - \text{Buoy wind speed}}{\text{Buoy wind speed}} \quad (3)$$

$$\text{Vector difference (VD)} = \sqrt{(Su - Bu)^2 + (Sv - Bv)^2} \quad (4)$$

$$\text{RMSVD} = \sqrt{\frac{\sum VD^2}{N}} \quad (5)$$

$$\text{RMSD} = \sqrt{\frac{(Swd - Bwd)^2}{N}}, \quad (6)$$

where N is the number of collocation (NC) points, Su is the zonal component of scatterometer wind in ms^{-1} , Sv is the meridional component of scatterometer wind in ms^{-1} , Bu is the zonal component of buoy wind in ms^{-1} , and Bv is the meridional component of buoy wind in ms^{-1} . Swd and Bwd are the scatterometer wind direction and the buoy wind direction, respectively. The error characteristics of the scatterometer winds with respect to the buoy winds along the equator, and over off-equator are also calculated.

Mean monthly vector plots of observed scatterometer winds were generated for monsoon 2011 to see whether the scatterometer winds can capture the low level jet (LLJ), and cross equatorial flow, the lower atmospheric circulations associated with monsoon. Mean vector plots of scatterometer winds are generated by binning the scatterometer winds into $5^\circ \times 5^\circ$ boxes. Density plots of wind speed, and wind direction were generated for the collocated scatterometer winds and RAMA buoy winds

Figure 4. Mean monthly vector plot of OSCAT winds during monsoon 2011. (a) June, (b) July, (c) August and (d) September 2011.

Figure 5. Similar to figure 3, but for ASCAT winds.

Table 2. *Statistical parameters of OSCAT and RAMA buoy wind speed for 2011.*

Month	Mean OSCAT WS (ms^{-1})	Mean buoy WS (ms^{-1})	Speed bias (ms^{-1})	RMSVD (ms^{-1})	Number of collocations
January	7.52	7.84	-0.32	1.75	32
February	6.56	7.26	-0.69	1.80	19
March	6.13	7.29	-1.16	2.46	15
April	6.90	6.73	0.16	2.67	12
May	6.74	7.37	-0.62	1.72	23
June	8.58	9.23	-0.64	1.75	27
July	8.96	9.12	-0.16	1.86	30
August	7.42	7.74	-0.32	1.55	45
September	6.54	7.01	-0.46	1.81	32
October	6.17	6.16	0.14	2.31	13
November	5.42	5.29	0.12	2.10	8
December	7.31	7.44	-0.12	2.45	10

Table 3. *Statistical parameters of OSCAT and RAMA buoy wind direction for 2011.*

Month	Mean OSCAT wind direction (degrees)	Mean buoy wind direction (degrees)	Speed bias (degrees)	RMS (V)D (degrees)	Number of collocations
January	103.68	104.19	-0.54	10.53	32
February	60.27	51.38	9.41	11.85	19
March	63.0	67.33	-4.33	15.80	15
April	168.44	174.50	-6.05	14.47	12
May	226.91	220.00	6.91	11.17	23
June	223.80	220.00	3.80	10.67	27
July	212.35	210.92	1.48	8.84	30
August	194.43	196.41	-2.13	10.11	45
September	172.18	171.13	1.09	10.21	32
October	158.16	154.58	3.28	18.86	13
November	132.21	133.57	-1.35	18.01	8
December	120.50	125.50	-5.00	15.92	10

Figure 6. Monthly mean OSCAT (bubbled) and RAMA buoy (continuous) wind speed (ms^{-1}) for 2011.

Figure 7. Similar to figure 5, but for wind direction (degrees).

for monsoon 2011. Density plots are generated by plotting the number of scatterometer winds corresponding to different RAMA buoy winds. These types of plots generally used to identify the errors associated with different wind speed range.

Validation of scatterometer surface winds (both OSCAT and ASCAT) were limited to one year, because the validation results are encouraging and the errors in wind speed and wind direction are observed to be within the mission goal, and the assimilation of these scatterometer winds showed positive impact in global NWP models (Prasad *et al.* 2013). OSCAT and ASCAT have complementing orbital passes, and the ascending and descending orbital data of both the satellites over the Indian Ocean is segregated everyday during the study period. It is noted that the ascending and descending passes of both the satellites over the Indian Ocean is centred on 18 UTC and 6 UTC assimilation cycles of global models. It was noted

that the maximum OSCAT surface winds were available around 06 UTC and in this study the descending orbital pass data was used for collocation for both the scatterometers, however in the scatter plots both descending and ascending orbital passes data during monsoon 2011 were shown.

4. Results and discussion

Before comparing the scatterometer winds with RAMA buoy winds, the scatterometer observations were analysed to ensure that these observations could capture the atmospheric circulations on an average scale. Mean monthly vector plots of scatterometer winds were generated during monsoon 2011. One of the salient features of the monsoon circulation is LLJ. LLJ has its origin in

Table 4. *Statistical parameters of OSCAT and equatorial RAMA buoy wind speed/direction for 2011.*

Month	Mean OSCAT ws/wd ($\text{ms}^{-1}/\text{degree}$)	Mean buoy ws/wd ($\text{ms}^{-1}/\text{degree}$)	RMSVD/RMSD ($\text{ms}^{-1}/\text{degree}$)	Number of collocations
January	6.40/283.0	7.14/276.66	1.08/6.33	3
February	4.90/209.0	4.59/220.0	0.95/11.0	1
March	Nil	Nil	Nil	Nil
April	7.30/273.6	6.16/286.6	3.99/23.0	3
May	8.69/271.0	8.63/250.0	3.16/21.0	1
June	6.50/242.5	7.32/231.6	1.70/10.83	6
July	6.09/215.3	7.92/206.6	2.15/8.66	3
August	5.06/161.3	5.80/166.8	1.44/10.75	16
September	5.83/158.3	6.34/155.0	1.91/10.78	14
October	5.78/168.0	6.05/166.6	1.44/11.6	6
November	5.03/197.6	5.60/183.3	2.24/21.0	3
December	7.25/308.0	5.44/300.0	3.60/8.00	2

Table 5. *Statistical parameters of OSCAT and north equatorial RAMA buoy wind speed/direction for 2011.*

Month	Mean OSCAT ws/wd ($\text{ms}^{-1}/\text{degree}$)	Mean buoy ws/wd ($\text{ms}^{-1}/\text{degree}$)	RMSVD/RMSD ($\text{ms}^{-1}/\text{degree}$)	Number of collocations
January	7.57/71.56	8.02/74.37	1.71/10.15	25
February	6.61/56.00	7.34/46.66	1.81/11.64	18
March	6.13/63.00	7.29/67.33	2.46/15.80	15
April	5.92/170.00	5.15/172.50	3.11/20.00	4
May	6.71/229.90	7.44/223.80	1.68/10.76	21
June	9.11/235.26	9.93/233.66	1.60/9.38	16
July	9.26/213.67	9.30/212.80	1.78/8.56	25
August	8.77/218.52	9.07/219.56	1.44/8.27	23
September	6.93/225.81	7.72/230.62	1.26/8.07	9
October	5.90/140.00	5.15/165.00	3.23/33.00	2
November	4.83/60.33	4.41/76.66	1.51/16.33	3
December	7.22/57.37	7.79/67.50	2.27/19.12	8

the south Indian Ocean north of the Masacarence High as an easterly current. It crosses the equator in a narrow longitudinal belt close to the east African coast as southerly current and then turns into Arabian Sea as a westerly current. LLJ transports the moisture from the Indian Ocean to the Indian landmass. Joseph and Raman (1966) and Findlater (1966) first pointed out the existence of Monsoon Low Level Jet (MLLJ) over peninsular India. Figures 4 and 5 show the vector plots of OSCAT and ASCAT winds during monsoon 2011 over the oceanic region surrounding India and the neighbouring landmass. Both OSCAT and ASCAT winds clearly depict the important features of the Indian summer monsoon circulation, such as the cross-equatorial flow along the East African coast, the LLJ and associated peak winds over the Arabian Sea, relatively calm winds a few degrees of latitudes on either side of the equator and easterly trade winds of southern hemisphere. Sathiyamoorthy *et al.* (2012) also reported these

kinds of monsoonal features in OSCAT surface winds.

Tables 2 and 3 show the monthly mean wind speed and wind direction statistics of OSCAT winds with respect to the RAMA buoy winds for different months in 2011. These tables describe the mean OSCAT wind speed/direction, mean buoy wind speed/direction, the bias, the RMSVD/RMSD and the number of collocated winds. It was noted that the buoy measured mean speed was always higher than that of OSCAT. It suggests that the OSCAT winds have a slow (negative) bias with respect to buoy winds over the Indian Ocean. Figure 6 shows the monthly mean wind speed from the OSCAT and RAMA buoy for 2011. It is obvious from figure 6 that the buoy wind speed is always higher than that of OSCAT wind speed. The monthly mean RMSVD in wind speed was observed to be below 2.5 ms^{-1} . It was also noted that during Indian summer monsoon period, the RMSVD (1.9 ms^{-1}) reduced significantly. The

Table 6. Statistical parameters of OSCAT and south equatorial RAMA buoy wind speed/direction for 2011.

Month	Mean OSCAT ws/wd (ms^{-1} /degree)	Mean buoy ws/wd (ms^{-1} /degree)	RMSVD/RMSD (ms^{-1} /degree)	Number of collocations
January	8.25/273.50	8.21/260.00	2.76/13.50	4
February	Nil	Nil	Nil	Nil
March	Nil	Nil	Nil	Nil
April	7.50/115.80	8.05/128.00	2.01/12.19	5
May	5.40/120.00	4.59/110.00	1.18/10.00	1
June	9.85/126.40	9.71/134.00	2.16/13.00	5
July	8.35/160.50	6.61/165.00	2.10/9.50	2
August	7.38/143.33	6.82/133.33	2.23/15.00	6
September	7.14/135.88	7.50/137.77	1.81/8.37	9
October	6.61/138.80	6.37/130.00	3.19/25.60	5
November	6.80/126.00	6.39/135.00	2.98/15.00	2
December	Nil	Nil	Nil	Nil

Table 7. Statistical parameters of OSCAT and ASCAT with respect to RAMA buoy winds during monsoon 2011.

Parameter	June 2011		July 2011		August 2011		September 2011	
	OSCAT	ASCAT	OSCAT	ASCAT	OSCAT	ASCAT	OSCAT	ASCAT
Mean scat ws	8.58	8.49	8.96	8.51	7.42	8.14	6.54	8.75
Mean buoy ws	9.23	8.67	9.12	8.87	7.74	8.31	7.01	8.79
Speed bias	-0.64	-0.22	-0.16	-0.36	-0.32	-0.17	-0.46	-0.36
RMSVD	1.75	1.90	1.86	1.93	1.55	1.62	1.81	1.82
No. of collocations	27	18	30	32	45	38	32	36
Mean scat wd	223.80	185.04	212.35	159.21	194.43	155.75	172.18	153.90
Mean buoy wd	220.00	187.08	210.92	161.35	196.41	155.04	171.13	158.54
Wd bias	3.80	-2.04	1.48	-2.13	-2.13	0.80	1.09	-4.64
RMSD	10.67	12.14	8.84	11.62	10.11	10.78	10.21	10.80
No. of collocations	27	18	30	32	45	38	32	36

number of collocations also increased during monsoon period. NCMRWF archived RAMA buoy data also showed maximum RAMA buoy reports during monsoon period (figure 3).

From table 3, it is clear that the monthly mean wind direction from OSCAT and buoy were comparable. Figure 7 is similar to figure 6, but for wind direction. The bias and RMSD in wind direction of OSCAT with respect to the buoy winds also showed less value during monsoon, as seen in the wind speed. Tables 4–6 show the monthly mean wind parameters (wind speed and direction) statistics of OSCAT winds against the buoy winds over the equator, north of equator and south of equator respectively for 2011. Over these three

regions, the monthly RMSVD/RMSD in the wind speed/direction was within the mission goal especially during monsoon. Monsoon circulation features like relatively calm winds a few degrees of latitudes on either side of the equator (table 4), strong westerly over the north of equator (table 5) and easterly trade winds of the southern hemisphere (table 6) are noticed both in the scatterometer and buoy winds.

The ASCAT winds were also compared against RAMA buoy winds in addition to the OSCAT winds, during monsoon 2011 in order to assess the performance of OSCAT winds in terms of other scatterometer wind products. The statistics of OSCAT and ASCAT winds with respect to

Figure 8. Density plots of OSCAT wind parameters (wind speed and wind direction) against the corresponding RAMA buoy parameters for monsoon 2011.

Figure 9. Similar to figure 7, but for ASCAT.

RAMA buoy winds during monsoon 2011 were tabulated in table 7. Both the scatterometer winds showed slow (negative) bias with respect to the buoy winds. The root mean squared differences in wind speed and wind direction of both the scatterometer winds with respect to the RAMA buoy winds were within the mission requirement. The numbers of collocated winds from both the scatterometers were also comparable.

Figures 8 and 9 are the density plots of wind speed, and wind direction from OSCAT and ASCAT against RAMA buoy winds for monsoon 2011. In these figures, (a) and (b) represent the wind speed, and wind direction respectively. Wind speeds were segregated into 1 ms^{-1} bins and wind direction to 5° bins. Standard deviation of OSCAT and ASCAT scatterometer wind speed (wind direction) with respect to RAMA buoy winds during monsoon 2011 were 1.03 ms^{-1} (21.47°) and 0.91 ms^{-1} (21.06°), respectively.

5. Conclusions

Sea surface winds from OSCAT over the Indian Ocean are evaluated against the RAMA buoy winds during 2011. Validation of OSCAT winds against RAMA buoy winds during 2011 showed maximum collocations in the Indian summer monsoon season. In general OSCAT winds showed slow (negative) bias with respect to the RAMA buoy winds. The comparisons of scatterometer and buoy winds which are temporally and spatially separated within 60 minutes and 0.25° showed that the wind speeds and directions observed by OSCAT agree with RAMA buoy winds. The monthly root mean square difference in the wind speed and wind direction are approximately in the range of $1.5\text{--}2.5 \text{ ms}^{-1}$ and $15^\circ\text{--}8^\circ$, respectively. Better agreement between the OSCAT and RAMA buoy winds were observed during Indian summer monsoon season with root mean square differences in wind speed and wind direction $\sim 1.5\text{--}1.8 \text{ ms}^{-1}$ and $\sim 11^\circ\text{--}8^\circ$, respectively. Collocation of scatterometer winds against equatorial and off-equatorial buoys clearly brought out the monsoon circulation features. Collocation exercise of ASCAT winds with respect to RAMA buoy winds during monsoon period also showed that the OSCAT wind statistics are comparable with that of ASCAT over the Indian Ocean.

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