On The Choice of Space and Time Windows for The Comparison of Altimeter-Derived Sea Surface Wind Speeds With in Situ Measurements

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ABSTRACT The choice of space and time windows is often a puzzling task in the simultaneous comparison of satellite and in situ observations. In this study, numerical simulations are carried out to examine the impacts of instrument noises, geophysical variabilities and the number of data pairs on the determination of an optimal size of space and time windows in the calibration/validation of altimeter-derived wind speeds against buoy measurements. Useful results are obtained which not only provide technical guidelines for future altimeter/buoy wind speed comparisons, but also help to explain some of the past confusions over the problem concerned.

KEY WORDS Altimeter, buoy, wind speed, collocation, simulation.

1. Introduction

It is a common practice in remote sensing that satellite observations be calibrated and/or validated against field measurements. In compiling a collocated satellite/in situ dataset, the choice of space and time windows is very often a puzzling task because of the conflicting requirements involved. On the one hand, large windows are desirable for the inclusion of more collocation data in order to obtain low-variance-correlation statistics. On the other hand, however, small windows are expected for the exclusion of less coincident measurements in order to avoid additional variability due to the inhomogeneous distributions of geophysical parameters. This problem could be more serious when dealing with sensors whose measurements are made on point basis, such as satellite altimeters. Since the overflight of an altimetric satellite rarely coincides with the field measurement in either location or time, the existence of spatial and temporal lags is almost inevitable. Therefore, it is necessary to define some kind of criteria for paring measurements from two independent sources.

As far as the verification of altimeter-derived sea surface wind speed is concerned, the above-mentioned problem has been aware by the altimetric community for many years. Table 1 is a brief summary of the space and time windows used by previous investigators for comparison purposes. In the space domain, the size of the window ranges from 10 km to 150 km; While in the time domain, it varies from 0.5 h to 1.5 h. Obviously, there is a wide consideration among various authors on the definition of data collocation. Attempts have been made by a number of researchers to investigate the influences of window size on the comparison results. Their conclusions, however, are somewhat divided. One argument suggests that the variations of space and time windows do not have a crucial impact on the accuracy of satellite/buoy comparisons (Dobson et al., 1987; Glazman and Pilorz, 1990). In contrast, another argument suggests that reducing the spatial lag persistently improves the agreement of wind speed measurements from altimeters and ocean buoys, while time lags of up to 1 hour do not produce significant changes in the key statistics, such as the RMS difference and the correlation coefficients (Gower, 1996; Hwang et al., 1998). Some of those who favour the second argument further point out that, for future calibration purposes, it is more critical to select in situ measurements that are closer to the satellite tracks while the temporal lag can be relaxed (Hwang et al., 1998).

Before making any comment on the above arguments, it is helpful to recall the major error sources that cause altimeter and buoy estimates of wind speed to differ. These are 1) buoy instrument inaccuracies, 2) altimeter-related uncertainties, 3) spatial separation, and 4) temporal separation. In addition, various means of time and space averaging may also contribute to the difference in the comparison. Keeping in mind these factors, it is somehow less surprise to see the inconsistent conclusions drawn by different authors. As listed in Table 1, the altimeters and buoys employed in previous studies are not the same, the times and locations as well as the marine conditions under which the measurements were taken could also be dramatically different. Diverse conclusions should thus be more or less expected.

In the present work, numerical experiments are carried out to study the influences of the size of space and time windows on the altimeter/buoy wind speed comparisons. As can be seen later on, our simulation results will, to a large extent, help to clarify the observed inconsistencies over the problem concerned.

2. SCHEME and EXPERIMENTS

In this section, the Monte Carlo technique used in the numerical experiments of this study will be described. Considerations on the altimeter and buoy instrument noises as well as the wind speed variability model will be discussed.

2.1. Generation of a Gaussian distribution using Monte Carlo method

It is understood that the error distributions of geophysical measurements usually take the Gaussian form. This is presumably the case for wind speed (Monaldo, 1988). Assuming that $\tilde{x}_1, \tilde{x}_2, \cdots, \tilde{x}_n$ are independent random variables with a uniform probability density function (pdf) between [-1,1], according to the central limit theorem, a Gaussian distribution, $\tilde{y}$, with a variance of σ^2 and a mean value of μ, can be approximated by

$$\tilde{y}_j = \sqrt{\frac{3}{n}}\sigma\sum_{i=1}^{n}\tilde{x}_{ij} + \mu \qquad (1)$$

when *j* gets large and *n* is appropriately chosen. For the case of oceanic wind speed, let $\sigma = 1.0$

Table 1. A partial list of the space and time windows used by previous investigators for altimeter/buoy wind speed comparisons.

Reference	Satellite	Buoy	Space Window	Time Window
Brown et al. (1981)	GEOS-3	NOAA/NDBC (USA)	110 km	1.5 h
Fedor & Brown (1982)	Seasat	NOAA/NDBC (USA)	80 km	1.5 h
Dobson et al. (1987)	Geosat	NOAA/NDBC (USA)	50, 100, 150 km	0.5 h
Monaldo & Dobson (1989)	Geosat	NOAA/NDBC (USA)	50 km	0.5 h
Glazman & Pilorz (1990)	Geosat	NOAA/NDBC (USA)	0.25°, 1.0°	0.5, 1.0 h
Witter & Chelton (1991)	Geosat	NOAA/NDBC (USA)	50 km	0.5 h
Ebuchi et al. (1992)	Geosat	JMA (Japan)	50, 100, 150 km	0.5, 1.0, 1.5 h
Carter et al. (1992)	Geosat	NOAA/NDBC (USA)	0.25°	1.0 h
Glazman & Greysukh (1993)	Geosat	NOAA/NDBC (USA)	0.5°	0.75 h
Gower (1996)	TOPEX/ Poseidon	AECEC & DFO (Canada)	10, 20, 107 km	0.5 h
Hwang et al. (1998)	TOPEX/ Poseidon	NOAA/NDBC (USA)	10, 50 km	0.5, 1.0 h

m/s and μ=10.0 m/s, the result of Monte Carlo simulation for n=10 and j_{max}=10,000 is shown in Figure 1. The theoretical probability density function of a Gaussian distribution

$$y(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2 \right] \qquad (2)$$

is also superimposed for comparison. The relative difference between the simulated distribution and the theoretical prediction is found to be less than 8.6%, indicating that the pseudo Gaussian distribution generated by Monte Carlo method is a good approximation to the theory.

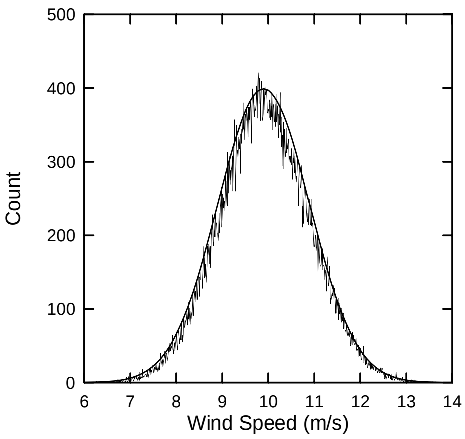


Figure 1. The Gaussian probability density function of wind speed with a variance of σ=1.0 m/s and a mean value of μ=10.0 m/s generated by Monte Carlo simulation (the noisy curve). The number of random samples is 10,000. The theoretical Gaussian probability density function is also superimposed (the smooth curve).

2.2. Simulation scheme

As stated earlier, the factors that complicate altimeter/buoy wind speed comparisons include the instrument noises of both sensors and the spatial and temporal lags in obtaining the measurements. In our simulations, we first consider the impact of space lag together with sensor noises. Time lag can be treated in parallel. For simplicity while without losing generality, we consider a geometry such that the location of a buoy station coincides with that of an altimeter nadir point, which lies on the single ground track entering the collocation window. Assuming that $\tilde{U}_T$ is a random variable which represents the "true" wind speed value at the buoy site, $\tilde{U}_A$ and $\tilde{U}_B$ are the corresponding wind speeds measured by altimeter and buoy respectively, we can then write

$$\left(\tilde{U}_A\right)_n = \left(\tilde{U}_T\right)_n + \left(\tilde{\varepsilon}_A\right)_n \qquad (3a)$$

$$\left(\tilde{U}_B\right)_n = \left(\tilde{U}_T\right)_n + \left(\tilde{\varepsilon}_B\right)_n \qquad (3b)$$

for the nth comparison, where $\tilde{\varepsilon}_A$ and $\tilde{\varepsilon}_B$ are the Gaussian-distributed instrument noises, representing the levels of measurement uncertainties associated with altimeter and buoy, respectively. These uncertainties may result from both the instruments themselves and their operation conditions.

At this point, we introduce a space variability model of wind speed, V. It is defined as the expected RMS difference between two wind speeds separated by a given distance. The altimeter-measured wind speed of the mth neighboring sample with respect to the buoy site can be expressed as

$$(\tilde{U}_A)_{mn} = (\tilde{U}_T)_n + (V)_m + (\tilde{\varepsilon}_A)_n \qquad (4)$$

Consider a space window which contains M altimeter measurements, the averaged wind speed is then given by

$$(\tilde{U}_A(M))_n = \frac{1}{M}\sum_{m=1}^{M}\left[(\tilde{U}_T)_n + (V)_m + (\tilde{\varepsilon}_A)_n\right] \qquad (5)$$

We further assume that the wind speed variability model, V, has several possible modes (denoted by index l) corresponding to different oceanic conditions, while the altimeter noise (i.e., the altimeter-measured wind inaccuracy), $\tilde{\varepsilon}_A$, has several possible levels (denoted by index *J*) corresponding to various generations of altimeters, Equation (5) becomes

$$(\tilde{U}_A(I,J,M))_n = \frac{1}{M}\sum_{m=1}^{M}\left[(\tilde{U}_T)_n + (V(I))_m + (\tilde{\varepsilon}_A(J))_n\right] \quad (6)$$

Ultimately, we examine the influence of the window size, *M*, under given conditions of *V*(*I*) and $\tilde{\varepsilon}_A$ (*J*) through the following quantity,

$$D^2(I,J,M,N) = \frac{1}{N}\sum_{n=1}^{N}\left[(\tilde{U}_A(I,J,M))_n - (\tilde{U}_B)_n\right]^2 \quad (7)$$

where *N* is the total times of simulation. Inserting Equations (3b) and (6) into (7), yields,

$$D^2(I,J,M,N) = \frac{1}{N}\sum_{n=1}^{N}\left\{\frac{1}{M}\sum_{m=1}^{M}\left[(\tilde{U}_T)_n + (V(I))_m + (\tilde{\varepsilon}_A(J))_n\right] - \left[(\tilde{U}_T)_n + (\tilde{\varepsilon}_B)_n\right]\right\}^2 \quad (8)$$

2.3. Numerical experiments

Before starting the numerical experiments, the values of the four parameters in Equation (8), *I, J, M* and *N*, must be properly selected, as they will, to a large extent, determine the validity and representativeness of the simulation results.

According to Monaldo (1988), the expected RMS differences between two wind speed estimates separated by a given distance or a given time appear to have a logarithmic form. The following wind speed variability models are employed in the space and time domain, respectively,

$$V^s(I) = I \times \ln(x/150+1) \quad (9a)$$

$$V^t(I) = I \times \ln(t/1.5+1) \quad (9b)$$

where *x* and *t* are spatial and temporal separations in kilometer and hour, respectively. The graphical illustrations of Equations (9a) and (9b) with *I*=0,1,2,3,4 (m/s) are presented in Figure 2. It is obvious that a greater *I* is associated with a higher wind speed variation.

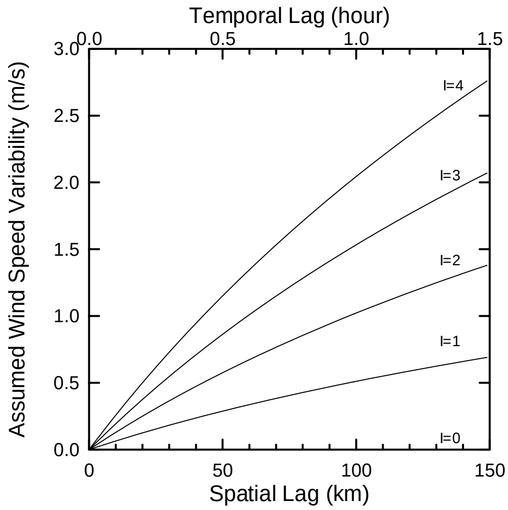


Figure 2. The assumed wind speed variabilities as functions of spatial and temporal lags for various *I*s (in m/s).

As far as parameter *J* is concerned, values of 1.2 m/s, 0.8 m/s, 0.4 m/s and 0.0 m/s are chosen to represent the decreasing noise levels of the past, present and future altimeters. For parameter *M*, we consider a changeable window size varying from 0 to 150 km in space and from 0 to 1.5 h in time, which, to our knowledge, covers the maximum space and time windows used by previous investigators (see Table 1). For parameter *N*, we will first make some initial tests on its effectiveness (see the next section), then, taking into account both the statistical confidence and the computational cost, a fixed value of *N*=10,000 will be used.

With the four parameters defined above and the simulation scheme described earlier on, the numerical experiments can now proceed with a variety of combinations of *I*, *J*, *M* and *N*.

3 RESULTS AND DISCUSSIONS

3.1. Influence of the Number of Collocation Data

The first experiment is designed to examine the relationship between the expected RMS difference of altimeter/buoy wind speed estimates and the number of collocation data used in the comparison. Consider a simple case with *I*=*J*=*M*=0, meaning that the wind field is uniform, the altimeter is perfect and only the sample at the buoy site is included.

Thus, the only source of error comes from the buoy. Selecting σ_B=1.0 m/s and μ_B=10.0 m/s for $\tilde{\varepsilon}_B$, the simulated D^2 as a function of N is shown in Figure 3. As can be clearly seen from this figure, the RMS difference of wind speed decreases monotonically as the number of data pairs increases. It is known from the theory of statistics that

$$(\sigma_B)_N = \frac{\sigma_B}{\sqrt{N}} \qquad (10)$$

By overlaying the numerically simulated and theoretically predicted results at the bottom of Figure 3, the excellent agreement becomes immediately visible. This agreement serves as a direct verification on the validity of our numerical scheme.

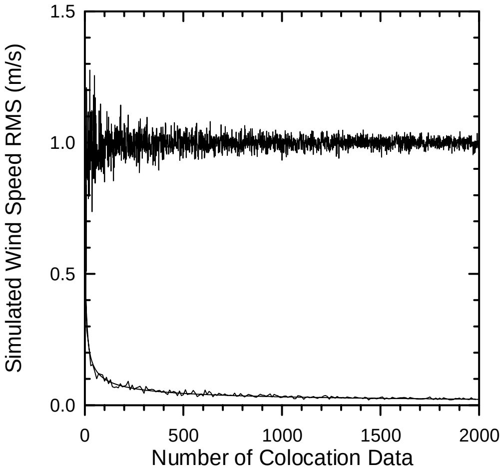
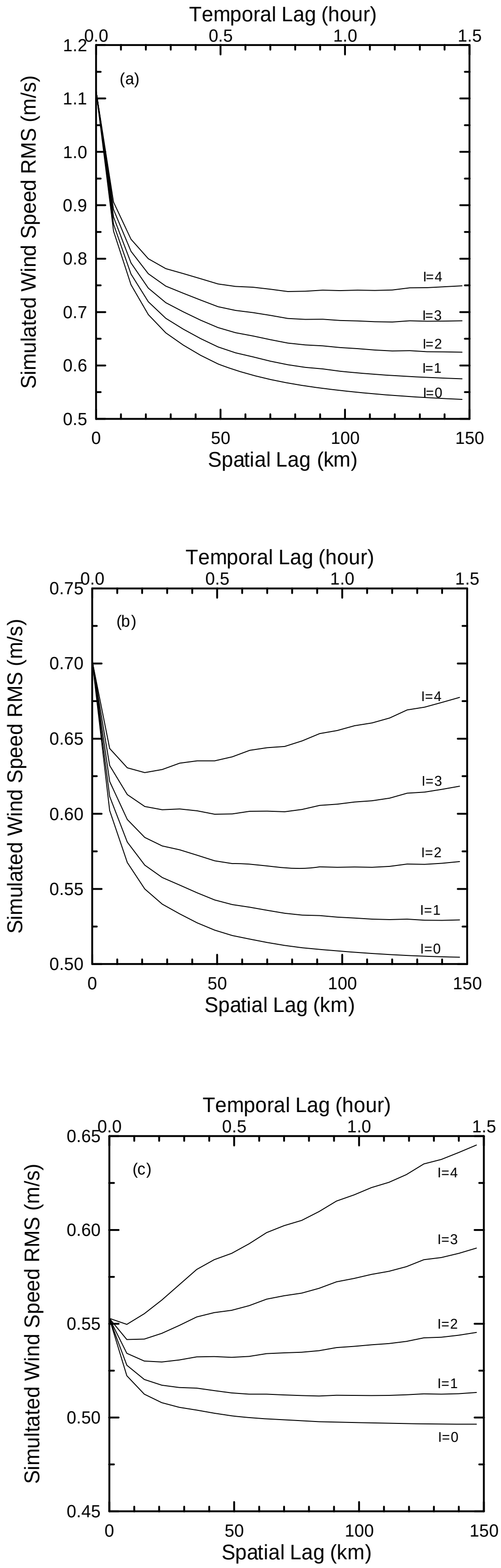


Figure 3. The simulated RMS deviations of altimeter-measured wind speed as a function of the number of collocation data, N (the noisy curve at the bottom). A Gaussian pdf with σ=1.0 m/s and μ=10.0 m/s is employed in the simulation. A theoretical Gaussian pdf with the same properties is superimposed for comparison (the smooth curve at the bottom). The original biases of the simulated wind speed around the mean are also plotted as a function of N with an offset of 1 m/s.

3.2. Influence of the Altimeter Noise Level

In order to test the impact of altimeter error on the choice of an optimal window size, we assume that there are four generations of altimeters whose instrument noises are at J=1.2, 0.8, 0.4, 0.0 (m/s). Their corresponding relationships of simulated wind speed RMS with respect to spatial and temporal lags are plotted in Figures 4(a)-(d), respectively. Within each family, five modes of the wind speed variability model, corresponding to I=0, 1, 2, 3, 4 (m/s), are applied.



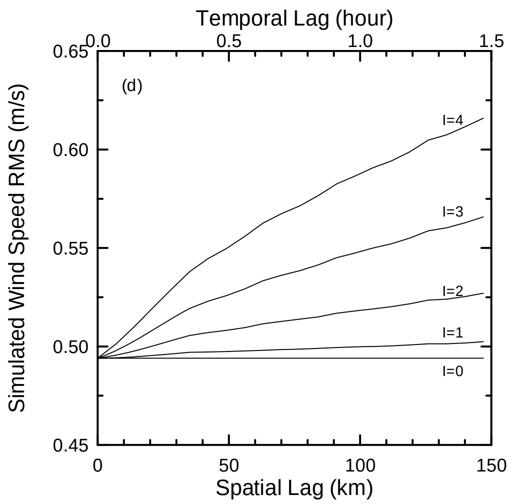


Figure 4. The simulated RMS deviations of altimeter-measured wind speed as functions of spatial and temporal lags for a) *J*=1.2 m/s, b) *J*=0.8 m/s, c) *J*=0.4 m/s, and d) *J*=0.0 m/s. A buoy instrument noise of 0.5 m/s is employed in the simulation and the number of samples is 10,000 for each curve.

The series of plots demonstrate a general trend that the optimal size of space and time windows decreases constantly with the noise level of altimeters. Figures 4(a) and 4(d) represent two extreme cases. Figure 4(a) shows that, when the accuracy of altimeter instrument is very poor, large space and time windows up to 150 km and 1.5 h, or more, are needed in order to include a greater number of samples so that the random noises of the measurements can be reduced (see Figure 3). Conversely, if the altimeter itself is error free, the ideal treatment is of course to compare directly the satellite and buoy measurements at the same time and location. The inclusion of extra samples with any spatial or temporal lag will inevitably introduce additional RMS variability (Figure 4(d)). For those altimeters with intermediate noise levels (which are likely to be the reality for the present time), the situation is more complicated. The optimal size of the window could vary from 0 to 150 km in space and from 0 to 1.5 h in time, depending on the competition of the wind speed variability and the altimeter noise level (Figures 4(b) and 4(c)).

3.3. Influence of the Wind Speed Variability

Now let us focus on Figures 4(b) and 4(c), which can be reasonably related to the cases of Geosat and TOPEX/Poseidon, respectively. Fortunately, we are able to find some previous studies by Glazman and Pilorz (1990), Ebuchi et al. (1992) and Gower (1996) who performed qualitative or quantitative analyses of the impacts of window sizes on the comparison results using real Geosat and TOPEX/Poseidon altimeter data in conjunction with the US, Japanese and Canadian buoy data. These give us the opportunity to check the validity and applicability of our simulation results.

The work by Ebuchi et al. (1992) is based on the analysis of 437 data pairs from Geosat altimeter and JMA (Japan Meteorological Agency) buoys. It is found in their results that a minimum RMS value occurs when the wind speeds are averaged between 50-100 km in space or 1-1.5 h in time (see Table 1 of Ebuchi et al. (1992)). In the space domain, the RMS values of the two side windows (0-50 km and 100-150 km) are both higher than the middle one: 2.15 m/s and 2.59 m/s compared to 1.98 m/s. This result violates the conclusion that reducing the spatial lag will persistently improve the agreement of wind speed measurements from altimeters and buoys (Hwang et al., 1998). But it supports our simulation result by coinciding with the situation between *I*=2 and *I*=3 in Figure 4(b), which represents a moderate oceanic condition. The behavior of time window in the results of Ebuchi et al. (1992) is also somewhat surprising, as the two windows with smaller temporal lags (0-0.5 h and 0.5-1.0 h) both exhibit higher wind speed RMS values compared to the window of 1.0-1.5 h: 2.25 m/s and 2.31 m/s versus 2.18 m/s. This result also goes against the common illusion that a smaller window size usually leads to a better agreement. But again, it appears to fall into our simulation prediction between *I*=1 and *I*=2 in Figure 4(b), which may correspond to a relatively calm sea.

In another attempt by Glazman and Pilorz (1990), two space windows (0.25° and 1.0°) and two time windows (0.5 h and 1.0 h) are used. They conclude that the reduced spatial and temporal separations between a buoy and a satellite footprint only result in a small reduction in the observed scatter. We believe that this statement is, in a sense, representative as far as Geosat altimeter is concerned. Since the majority of the measurements might be taken under moderate oceanic conditions as represented by *I*=2 in Figure 4(b), which almost shows a horizontal trend beyond 50 km and 0.5 h.

Finally, we turn to a more recent work by Gower (1996) who compares 452 pairs of TOPEX and buoy wind speeds. He uses three sizes of space window in his analysis, i.e., 107 km, 20 km and 10 km, and finds that the RMS scatter reduces constantly with the window size from 2.05 m/s to 1.76 m/s. A similar trend can be found in our simulation result. In fact, the curve with *I*=3 in

Figure 4(c) might be a good representation of Gower's case. This result implies that with the new generation of more accurate altimeters, the RMS deviation is likely to be dominated by local wind effect. Consequently, the optimal window size might be significantly reduced in both space and time.

4 SUMMARY AND IMPLICATIONS

As a summary of this work, the recommended sizes of space and time windows under various options of *I* and *J* are presented in Table 2.

The following points should be stressed based on Table 2. 1) For altimeter/buoy wind speed calibration/validation, there usually exists an optimal window size within which the RMS scatter is minimal. Under normal circumstances, this size may vary from 0 to 150 km in space and from 0 to 1.5 h in time. The exact value for each case depends on the noise levels of buoy and altimeter instruments, as well as the actual spatial and temporal variabilities of wind speed. It could be misleading to draw any general conclusion on the relationship between the size of the optimal window and the level of comparison agreement. 2) For the present generation of altimeters such as TOPEX/Poseidon, it would be ideal if a space window of 10-20 km and a time window of 0.1-0.2 h could be used. However, such small windows usually lead to an insufficient number of data pairs, which, in return, give rise to an increase in random error. The eventual choice is always a compromise between the size of window and the number of data. But as time goes on, the volume of collocation data will expand constantly, hence, becomes a less severe constraint on the choice of windows in the future. 3) The questions raised in this study may be generalized to altimeter-derived sea level and significant wave height, or even to other geophysical parameters derived from space-borne radiometers, scatterometers and synthetic aperture radars. In this context, the results obtained here may serve as a technical guideline when satellite and in situ measurements are compared over the ocean.

Table 2. The recommended sizes of space/time windows for various combinations of *I* and *J*.

J, *I* (m/s)	0	1	2	3	4
0	—	0 km/0 h	0 km/0 h	0 km/0 h	0 km/0 h
0.4	>150 km/1.5 h	80 km/0.8 h	20 km/0.2 h	10 km/0.1 h	10 km/0.1 h
0.8	>150 km/1.5 h	140 km/1.4 h	100 km/1.0 h	50 km/0.5 h	20 km/0.2 h
1.2	>150 km/1.5 h	150 km/1.5 h	150 km/1.5 h	130 km/1.3 h	80 km/0.8 h

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