Statistics of Surface Wind Effect on Ocean Colour Measured from Space

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Abstract – **As it follows from both theoretical consideration and in-situ experiments, surface wind may significantly affect the ocean colour observed. This happens due to the variances of the surface roughness induced by the wind. The same effect may take place in satellite observations, but its detecting and estimation is usually complicated due to absence of independent information on "true" ocean colour. To overcome this problem a joint processing of optical and passive microwave remote data used for wind speed estimations (synchronous and well collocated) was suggested.**

In present work a previously proposed method for joint processing based on a model of nonlinear factor analysis and tested in numerical simulations was applied to actual remote data of MODIS and AMSR-E instruments for eleven-day interval of measurements in November, 2010. Remotely measured ocean colour was found to be sensitive to surface wind speed estimates. Results of these investigations are presented and discussed.

Keywords: Oceanography, Sea, Radiometry, Mathematics, Statistics

1. INTRODUCTION

The present work is a part of investigation stimulated by hypothesis that optical remote data of the ocean passed through calibration and correction algorithms still contain the remainders of dependence on the surface state. Namely, it was assumed that the effect of small-scale surface roughness can not be totally removed from remote data while can be a source of noticeable nonlinear distortion of the remotely detected colour as it had been shown in series of in-situ experiments (Ermakov et al, 2010). Briefly speaking, ocean colour measured from space may carry information on small-scale surface roughness (or wind speed).

To confirm or disprove this hypothesis some independent measurements of the surface state or wind field are required along with a method to detect and estimate "consistency" of optical remote data to these other measurements. The main problem here is that the wind effect on ocean colour (if any) is expected to be a relatively small, nonlinear function of a-priory unknown form. In (Ermakov et al, 2010) a mathematical model was suggested and a method of joint processing of ocean colour (from optical data) and wind field (from synchronous passive microwave data) was developed and tested in numerical simulations; also, a principal applicability to actual remote data was shown on example of historical SeaWiFS and SSM/I data.

The method applies a statistical approach and hence benefits from the use of as much as possible amount of input data. From this point of view, the SeaWiFS and SSM/I pair of sensors was not the best choice, as their observations were not synchronous and well collocated. The aims of the present work were to determine a better combination of optical and microwave

sensors adequate for the task and to perform first processing of large amounts of actual remote data to investigate capabilities and shortcomings of the method suggested.

The present paper is structured as follows. Section 2 contains a short introduction into the mathematical model and the method of joint processing of the data, and Section 3 characterizes the remote data used. Section 4 describes the joint processing performed. Some results of this processing are discussed in Section 5, followed by conclusion in Section 6.

2. MODEL AND METHOD OF JOINT PROCESSING

The method proposed by the authors and applied in present work requires that the data of optical and microwave measurements are obtained synchronously and are imposed on the same coordinate grid, so that every optical measurement has a matching microwave measurement and vice versa. If this is the case the remote data can be present in the form:

$$\begin{cases} o_i = h(w_i) + c_i \\ m_i = w_i + e_i \end{cases}, \qquad (1)$$

where o_i = characteristic of ocean colour (see Section 3) obtained in the i-th optical measurement
m_i = wind speed estimated from i-th radiometric measurement
w_i = true wind speed
e_i = error of wind speed estimation
c_i = "true" ocean colour
h = unknown (continuous) function

The term $h(w_i)$ in (1) reflects possible wind effect on remotely measured ocean colour. Its introduction doesn't seem a restrictive assumption, since it may be found that $h(w)$ is not statistically distinguishable from 0 if no wind effect actually takes place. At least, an obvious boundary condition is

$$h(0) = 0 \qquad (2)$$

It had been shown (Ermakov et al, 2010) that under particular assumptions a piecewise-linear approximation of $h(w)$ could be evaluated and the remotely measured ocean colour could be decomposed according to (1) into sum of two terms both calculated with relative error approximately equal to that of wind speed estimations. Not to go into details, essentially the derivative of $h(w)$ by w (i.e. ocean colour "sensitivity" $s(w)$ to wind) was approximated at any point w with the regression coefficient of o_i on m_i for those measurements in which m_i values lied in a narrow range $w \pm \Delta w$:

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$$s(w) = h'(w) \approx \lim_{\Delta w \to 0} r(w, \Delta w) \qquad (3)$$

$$r(w, \Delta w) = \sigma_o \rho / \sigma_m$$

where r = sample regression coefficient of o_i on m_i
σ_o = sample standard deviation of o_i
σ_m = sample standard deviation of m_i
ρ = sample correlation of o_i with m_i

Of the known $s(w)$ the $h(w)$ was obtained by integration with boundary condition (2). This is the bottleneck of the algorithm, since integration accumulates errors of $s(w)$ estimates. On one hand, to make piecewise-linear approximation more precise narrower Δw intervals must be selected. On the other hand, the narrower the intervals are the less actual remote data they contain, thus reducing the accuracy of regression. The present work was aiming to investigate the robustness of the algorithm performance for different amounts of remote data, various Δw intervals (segmentations), and different geographical regions.

3. DATA SELECTING AND PRE-PROCESSING

In present work the data of MODIS and AMSR-E instruments of the Aqua mission (NASA, 2002) were used. These instruments share the same spacecraft, so their data are synchronous and well collocated.

3.1 Ocean colour data (MODIS)
The MODIS data are available through the OceanColor web interface, Goddard Space Flight Center, NASA, USA (http://oceancolor.gsfc.nasa.gov/). Two daily products (Aqua MODIS remote sensing reflectance $R_{rs}(443)$ at 443 nm and $R_{rs}(555)$ at 555 nm) were used in present work to calculate a characteristic of remotely obtained ocean colour, o in the form, see (Gordon and Voss, 2004):

$$o = \log_{10}\left(R_{rs}(443) / R_{rs}(555)\right) \qquad (4)$$

The data of resulting daily global fields of ocean colour were collocated with the fields of surface wind speed for further joint processing.

3.2 Wind speed data (AMSR-E)
The AMSR-E data are available through the National Snow and Ice Data Centre, USA (Wentz and Meissner, 2004). They contain (among other products) the wind speed estimations built on the grid of the instrument scans (swaths). The separate swaths of wind fields were merged into daily global fields and collocated with synchronous ocean colour data.

3.3 Selecting and combining data
The daily distributions of ocean colour and wind speed were collected for a test time interval (arbitrary selected) of November, 10 through November 20, 2010. The data were pre-processed and collocated as described above and the daily global data masks were built, which indicated all pairs of collocated valid colour and wind estimations.

Besides, several "regional" masks were introduced. These masks allowed generating data subsets for particular geographic regions. The regions used in the work are listed in Table 1 and presented in Figure 1. With the use of daily validity masks and regional masks and simple disjunction and conjunction

procedures different data subsets were generated, like: one-day Pacific data, decadal Pacific data, one-day Open waters data, decadal Open waters data etc.

Table 1. Regions used to generate data subsets

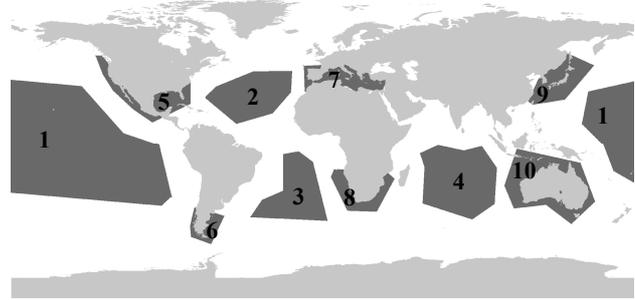| N	Simple region	N	Complex region	
1	Pacific			
2	North Atlantic	I	Open waters	
3	South Atlantic			
4	Indian			Global
5	North America			
6	South America			
7	Europe	II	Coastal waters	
8	Africa			
9	Asia			
10	Australia			

Figure 1. Map of "regional" masks listed in Table 1

The generated subsets of remote data were inputs for the algorithm of joint processing briefly outlined in Section 2. As a result of its application functions of ocean colour sensitivity to wind, $s(w)$, and of wind effect on colour, $h(w)$, see (1, 3), were recovered and compared for different cases of data selecting and various Δw-segmentations.

4. JOINT PROCESSING OF THE DATA

In order to analyse the robustness of the method of joint processing the main attention was focused on the direct algorithm output, namely, the recovered ocean colour sensitivity to wind, $s(w)$. The estimates of $s(w)$ for different subsets of the remote data were built in range of winds $0 - 17$ m/sec along with their confidence intervals with 95% confidence level.

To investigate regional variations of $s(w)$ the joint processing was performed separately for the region of Open waters and that of Coastal waters (Table 1). Besides, independent processing of some simple regions (e.g., Pacific region) was performed. To investigate the stability of $s(w)$ estimates and the influence of data amount on the output results, the remote data of one-day observations were processed separately, and the total data of eleven-day test interval were processed altogether (for different geographical regions described above).

According to the model (1, 3) colour sensitivity $s(w)$ is assumed to be constant on narrow intervals Δw of wind change. To investigate the robustness of $s(w)$ estimates to choice of these intervals the 4 different Δw-segmentations (S_1, S_2, S_3, S_4) were used to process the data, as listed in Table 2.

Table 2. Δw-segmentations used in joint processing

	Segmentations			
	S_1 intervals	S_2 intervals	S_3 intervals	S_4 intervals
N	min/max (m/sec)	min/max (m/sec)	min/max (m/sec)	min/max (m/sec)
1	0.0/1.1	0.0/2.3	0.0/1.8	0.0/2.9
2	1.1/2.3	2.3/4.6	1.8/2.9	2.9/5.2
3	2.3/3.4	4.6/6.8	2.9/4.1	5.2/7.5
4	3.4/4.6	6.8/9.1	4.1/5.2	7.5/9.8
5	4.6/5.7	9.1/11.4	5.2/6.4	9.8/12.0
6	5.7/6.8	11.4/13.7	6.4/7.5	12.0/14.3
7	6.8/8.0	13.7/15.9	7.5/8.6	14.3/17.0
8	8.0/9.1	15.9/17.0	8.6/9.8	-
9	9.1/10.2	-	9.8/10.9	-
10	10.2/11.4	-	10.9/12.0	-
11	11.4/12.5	-	12.0/13.2	-
12	12.5/13.7	-	13.2/14.3	-
13	13.7/14.8	-	14.3/15.5	-
14	14.8/15.9	-	15.5/17.0	-
15	15.9/17.0	-	-	-

The Δw-segmentations consisted of different number of intervals, at least 7 (S_4), at most 15 (S_1) which covered in total the wind range of 0 – 17 m/sec. The S_2 segmentation merged every two intervals of the S_1 segmentation into one (apart from the last one). So did the S_4 segmentation with respect to the intervals of the S_3 segmentation. The boundaries of S_1 and S_3 intervals did not match (except for the utmost ones).

Based on recovered $s(w)$ functions, some $h(w)$ functions were also evaluated in order to investigate possible wind effect on the remotely obtained ocean colour, see (1). For better visualization $h(w)$ were calculated as percentage of average of colour values, o_i, used in these estimations, see (1, 3).

5. DISCUSSION OF RESULTS

An example of recovery of ocean colour sensitivity to wind, $s(w)$ for the Pacific region (see Table 1) is presented in Figure 2. Open circles are the estimates of $s(w)$ for different days in the test time interval (November, 10 – November, 20, year 2010). In this example the S_1 segmentation was used, and estimates of $s(w)$ are plotted in the middle of corresponding Δw intervals.
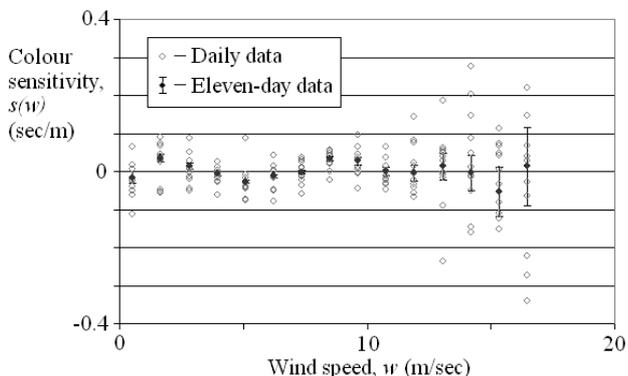

Figure 2. Colour sensitivity to wind, Pacific region

It can be seen that one-day $s(w)$ estimates have a significant variance and are located around zero. However, the estimates for the whole eleven-day test interval indicated in Figure 2 by solid circles with error bars (confidence intervals with 95%

confidence level) show that $s(w)$ is nonzero function at least at $w < 10$ m/sec. Namely, it is significantly positive at about 2 m/sec and 9 m/sec, and negative at about 5 m/sec.

The analysis of eleven-day data for the whole Open waters region (regions 1–4 in Table 1) reveals this pattern more clearly. The $s(w)$ estimates with their confidence intervals were calculated from these data using the segmentations S_1, S_2, S_3, S_4. The results are presented in Figure 3.
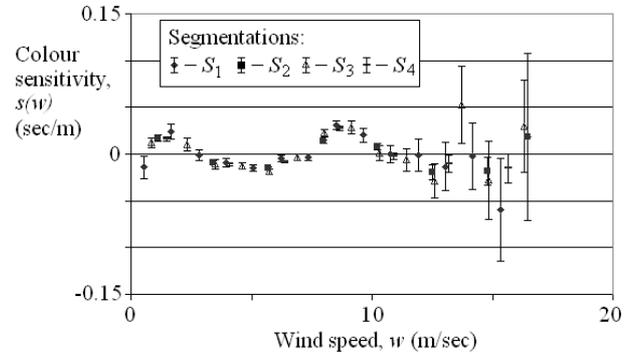

Figure 3. Colour sensitivity to wind, Open waters

It can be seen that $s(w)$ estimates obtained with the use if different segmentations are in good consonance with each other, and the estimates obtained for wider Δw intervals (segmentations S_2 and S_4) have much narrower confidence intervals.

The analysis of eleven-day data for Coastal waters revealed a significantly different pattern of $s(w)$ estimates. These estimates are presented in Figure 4.
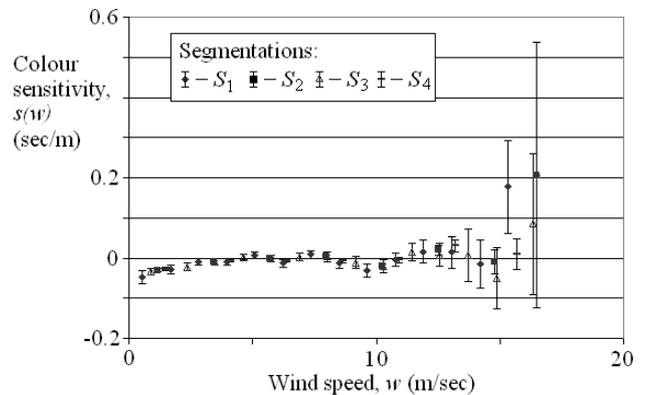

Figure 4. Colour sensitivity to wind, Coastal waters

It can be seen, that for coastal waters, the $s(w)$ function is significantly negative or close to 0 at $w < 10$ m/sec. The estimates made for different Δw-segmentations are in good consonance with each other.

Based on calculations of ocean colour sensitivity to wind, $s(w)$ the corresponding $h(w)$ functions (estimates of wind effect on ocean colour) were obtained as percentage of average of colour values observed, see (1, 3). An example of recovered wind effect function, $h(w)$ estimated from eleven-day data for the Open waters region is presented in Figure 5. The four lines in Figure 5 correspond to the four different Δw-segmentations used.
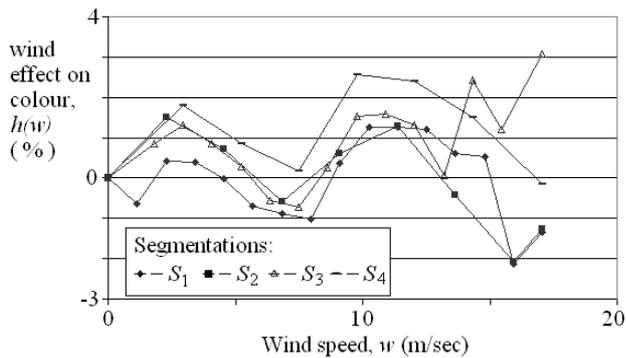
Figure 5. Wind effect on colour, Open waters

All $h(w)$ estimates have the same pattern: local maximum at about 3 m/sec and local minimum at about 8 m/sec. Range of $h(w)$ values (-1.0% – 1.8%) at $w < 8$ m/sec shows that wind may introduce a significant disturbance in ocean colour. However due to uncertainty of $s(w)$ in the range of low winds which is accumulated during integration procedure in $h(w)$ it is impossible to choose the most reliable $h(w)$ realization, as it was discussed above. More reliable (in average) $s(w)$ estimates can be obtained from wider Δw intervals, but wider Δw intervals make piecewise-linear approximation of $h(w)$ less adequate.

In Figure 6 wind effect on colour, $h(w)$ recovered from eleven-day data for Coastal waters region is presented. Again the four lines correspond to the four different Δw-segmentations.
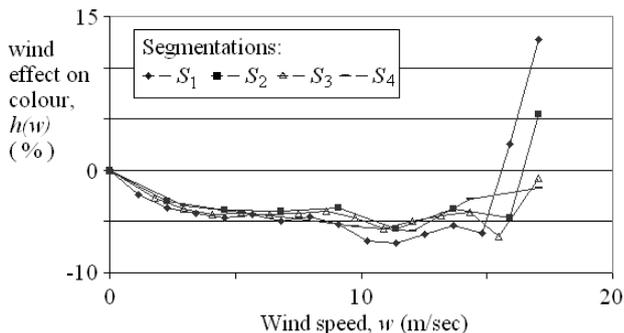

Figure 6. Wind effect on colour, Coastal waters

It can be seen from Figure 6 that the estimates of $h(w)$ for coastal waters are much more consonant with each other than those for open waters. Besides, the absolute values of $h(w)$ are times greater for coastal waters. This may be an indication of the presence of some factor other than surface roughness making a strong connection between optical and microwave remote data for Coastal waters region.

In order to reduce uncertainties in $s(w)$ and $h(w)$ estimations, especially at low wind speeds, larger amounts of remote data must be processed altogether. Figure 7 presents the distribution of total number of pairs of available colour and wind measurements over the Δw intervals of S_1 segmentation from eleven-day data of observations of Open waters region and of Coastal waters region. In a simple assumption that number of available data pairs is inversely proportional to the confidence interval of $s(w)$ estimate, an approximate amount of remote data needed for as confident estimates at low wind speeds as currently obtained for moderate wind speeds can be calculated.
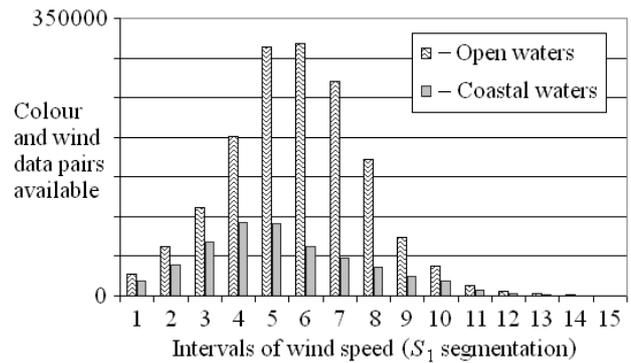

Figure 7. Distribution of remote data available over wind speed

As it follows from Figure 7, approximately 11.5 times more measurements (127 days of observations) are required to accumulate the necessary amount of remote data at low wind speed conditions for Open waters region.

6. CONCLUSION

With the use of previously proposed method for joint processing of remote optical and microwave data an eleven-day amount of actual measurements of MODIS and AMSR-E instruments were processed. It was shown that remotely measured ocean colour contains residual information on the ocean surface state. Colour "sensitivity" to wind speed was found to be significantly different for open (case I) waters and coastal (case II) waters. For more adequate evaluation of surface wind influence on measured ocean colour much larger amount of remote data must be accumulated and processed altogether. In present paper this amount is estimated as approximately 4 months of MODIS and AMSR-E measurements.

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