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Multifractal analysis of fluorescence Lidar time series of Black Sea waters

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The multifractal characteristics of the fluorescence signals from the surface Black Sea waters are analyzed using the structure function method. The fluorescence Lidar system was used to estimate in real time the distribution of dissolved organic matter and chlorophyll *a* during a 2007 spring campaign. The chlorophyll time series presents clear multifractal characteristics, while the dissolved organic matter presents a monofractal character. Various time series collected in the Constanta harbor area present the same general characteristics with small differences observed in the values of the exponent β but they all are restricted to the range between pink and red noise. The monofractal character is independent of the analyzed component demonstrating that the observed fluctuations are a property of the seawater itself.

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1. Introduction

The problem of variability of the environmental conditions, usually characterized as noise has considerable impact on the ecosystem structure stability and the conservation of individual species [1-3]. Differences in the relative importance of high and low-frequency variability can have wide-ranging consequences because population dynamics of individual species are known to be dominated by low-frequency fluctuations therefore they tend to be reddish. In other words, the spectral analysis of population variability shows a predominance of the low-frequency fluctuations [4]. An interesting result was presented by Cohen [5] who showed that the most important 8 nonlinear models for population dynamics lead to results in contradiction with this observation. They all generate spectral densities of chaotic trajectories that are neither white nor reddened but are notably blue with increasing power at higher frequencies. A direct conclusion of this result could be the necessity of a development of the models to take into account the environment fluctuations and might be considered as demonstrating the determinant role of the medium conditions on population dynamics.

Based on hypotheses related to the previous observation, Lermusiaux [6] recently presented a model based on Wiener/Brownian processes and white Gaussian noise meant to estimate the uncertainties and predict the main aspects of ocean dynamics.

In previous studies on the water fluctuations of various parameters the measurements were performed either in a fixed point (or a reduced number of fixed points) as function of time [7] or with a long chain of detectors placed equally spaced that can also be dragged over a long distance [8]. We propose a novel type of measurement that can be used to study the fluctuations of seawater components, the fluorescence Lidar.

Lidar is the acronym of Light Detection and Ranging, representing active remote sensing systems [9]. This technique is used for water and mostly for atmosphere sensing in real time, with high vertical resolution [10]. Scattering, Raman, absorption or fluorescence are the detection methods usually used on lidars to select the key signals and components. On aquatic medium measurements it is important to monitor the organic pollution level, which can be properly detected with a fluorescence Lidar system [11].

The humic acids, proteins, hydrocarbons and phytoplankton represent the organic compounds on water. The dissolved organic matter (DOM), nitrogen and phosphorus are the nutrients on the water body, used by phytoplankton to grow. During spring time the nutrients are present mostly on the surface water and support the phytoplankton blooming.

The chlorophyll *a* is an indicator of phytoplankton and biomass presence on shallow waters [12]. High levels of chlorophyll are not an imminent danger, but the persistence of these for a long time can become a problem. The annual chlorophyll concentration is evaluated, representing an indicator of water quality and status.

The fluorescence Lidar time series describe the evolution of the water compounds in a timeframe. Obviously, these real signals contain noise and fluctuations. For such signals, with non-stationary dynamics, the structure function analysis is the appropiate method to identify the type of noise and correlation factors.

The aim of the paper is to obtain the non-stationary information from fluorescence Lidar data recorded on Romanian Black Sea using the structure function analysis.

Laser excitation of ocean water chlorophyll *a* fluorescence was recently used in a different set-up [13].

2. Area of investigations and methods

The analyses of Romanian part of Black Sea were done during spring time, a period of year with important biological activity [14]. During the cruise a large phytoplankton blooming was observed. The signals acquired on Constanta harbor, a presumably highly polluted zone were used for further analysis.

Fluorescence measurements were performed with FLS-S Lidar, which is based on dye laser pumped by excimer laser and multi-channel registration of spectra. The Lidar positioned onboard of the research vessel send a laser beam to a mirror, which deflects the radiation on the water and collected the returned signal from the water column (

Fig. ***1***). The distance from the Lidar to the water surface was around 12m. The excitation wavelength used for fluorescence measurements were 308 nm from excimer laser and 460 nm from dye laser. During the experiments the 90mJ excimer laser pulse energy and 15ns pulse width were used.

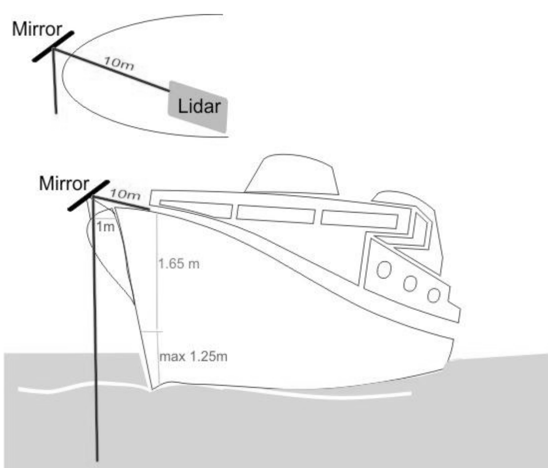


Fig. 1 Research vessel and Lidar set up.

The system was installed on the front of the vessel cabin in order to avoid perturbations on Lidar signal. For the same reason the velocity of the ship was maintained as small as possible. As can be observed on

Fig. ***1*** the laser radiation perpendicular on the water surface had a significant distance from the vessel's stern. In this configuration the waves generated due to vessel movement do not perturbed the Lidar signals. The foremost part of a ship, which generate the waves passes through the same water column excited by the laser beam after the fluorescence signals has been returned and registered.

Typical fluorescence Lidar signals for 308nm and 460nm excitation wavelengths contain DOM and chlorophyll *a* fingerprints and Raman band due to water molecules (Fig. 2).

From the beginning of modern scientific research observation has demonstrated the existence of various irregularities in the natural structures and the behavior of natural systems. To the scientist, unpredictable changes in time of any quantity are known as noise.

The various types of noise most frequently observed in natural or manmade systems are classified as colored noises, by extension of the nomenclature of optical spectroscopy that relates the spectral density to the frequency of oscillation. In the case of noise instead of oscillation frequency the spectral density is related to fluctuation frequency.

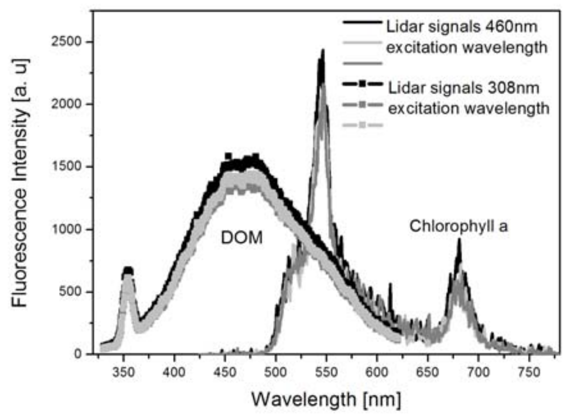


Fig. 2 Typical fluorescence Lidar spectra for chlorophyll and DOM for 308 and 460 nm excitation

The white noise is the most random being characterized by complete absence of correlation from point to point. Its spectral density is a flat line, representing equal amounts of "energy" at all frequencies (like white light). Denoting the spectral density by $S(f)$, this relationship will be written $S(f) \propto f^0$.

Unlike this, the Brownian noise (also known as red or brown noise) is highly correlated. It consists of many more slow (low frequency) than fast (high frequency) fluctuations and the relationship between its spectral density and the frequency is $S(f) \propto f^{-2}$. Formally, the Brownian noise can be generated by numerical integration of the Gaussian white noise. A type of noise present in many domains, from semiconductor devices and fluctuations of voltages across cell membranes to ocean flows is the so called $1/f$ - noise (also known as pink noise), characterized by the spectral density $S(f) \propto f^{-1}$.

In general, the term $1/f$ - noise or colored noise is used to describe any fluctuation whose dependence of the spectral density on frequency is given by $S(f) \propto 1/f^{\beta}$, with the spectral exponent β constant over many decades.

The change of a Brownian variable $V(t)$, $\Delta V(t) = V(t_2) - V(t_1)$ is related to the time interval $\Delta t = t_2 - t_1$ by the scaling law $\Delta V \propto \sqrt{\Delta t}$. An extension of this relationship to the various colors of noise is written $\Delta V \propto \Delta t^H$, where the scaling parameter H, also known as the Hurst exponent takes values in the range $0 < H < 1$. Due to the fractional values of H, the quantities whose fluctuation is characterized by this scaling behavior are known as fractional Brownian motion (noise).

For scalar variables $V(t)$, as the ones considered in this study, the relationship between the spectral exponent and the Hurst exponent is $\beta = 2H + 1$. The scaling property of the fractional Brownian motion also known as self – affinity can be characterized by a fractal dimension D related to the scaling parameter by the simple relationship $D = 2 - H$.

3. Structure functions formalism for multifractal study

The study of fluctuations has been an important direction of research for a long time and has received a strong impetus in the context of nonlinear dynamics.

One of the simplest types of study of fluctuations present in experimental time series is based on the structure functions. If the light intensity back-scattered at a certain position x_i of the ship is denoted $I(x_i)$ then, the succession of the values for a number of positions will be given the conventional name of a "time series". Since the analyzed Lidar time series have stationary increments, a measure of the fluctuations can be obtained by the study of the statistical characteristics of the gradient field

$$|\Delta I(r, x_i)| = |I(x_{i+r}) - I(x_i)|, \quad (i = 0,1,2,\cdots, N-r) \qquad (1)$$

where N is the total number of samples in the series and r is the lag between two successive sampling points (which are equally spaced).

The q-th order structure function is defined by the mean of the q-th power of the gradient field,

$$S(r,q) = \left\langle |\Delta I(r, x_i)|^q \right\rangle = \frac{1}{N-r} \sum_{i=0}^{N-r} |\Delta I(r, x_i)|^q \qquad (2)$$

When the dependence of $\log S(r,q)$ on $\log r$ is linear, the structure functions satisfy the power law

$$S(r,q) \propto r^{\varsigma(q)}. \qquad (3)$$

Usually, the dependence of the slopes on the order is written

$$\varsigma(q) = H(q)q \qquad (4)$$

If $H(q)$ is a constant (independent on q) the time series is monofractal and H is the Hurst exponent. If $H(q)$ is dependent on q, the time series is multifractal (various sections of the series are characterized by different values of $H(q)$).

As early as 1985, colored noise was brought to the attention of the ecologists by Steele 0 who, based on empirical records and some simple models suggested that terrestrial noise is white while marine noise should be brown. A simple argument in support of this difference is based on the following observation. Because water has higher heat capacity than air, large water basins (sea, ocean) should fluctuate in temperature more slowly than does the surrounding atmosphere.

As discussed in the previous section, in white noise the variability (fluctuation amplitude) is the same at all frequencies while, in colored noises it is dominated by frequencies in a certain range, specifically, pink and red noises are dominated by low frequency. Accordingly, marine temperature time series are "redder" than the atmospheric temperature time series. This difference in the character of fluctuations between terrestrial noise and marine noise was further demonstrated in a recent paper 0 based on a wide variety of long term time series of environmental variables.

The spectra were well approximated by the inverse power law $1/f^{\beta}$ and, consistent with previous knowledge, it was found that the terrestrial noise tends to be white $(\beta < 0.5)$ while for the marine environment it tends to be between pink and red $(1 \le \beta \le 2)$. Additionally, it was observed that many spectra of the experimental time series were "flattened" at low frequencies.

4. Results

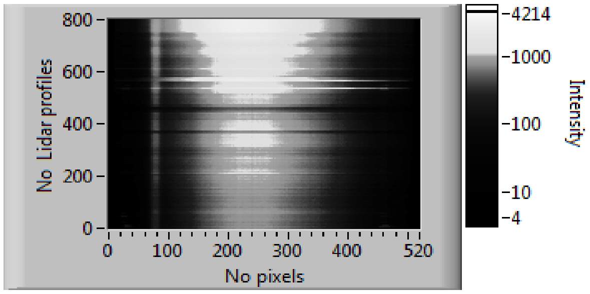
The results of the statistical analysis of time series consisting of Lidar measurements performed along the Black Sea coast are dependent upon the zone under study. We made statistical studies on two time series and different types of behavior were identified.

The harbors area and signals presented some features and characteristics that can be identified by multifractal analysis. Fig. 3 a) is an example of the lidar time series recorded on 29 April 2007, on Constanta harbor using 308nm excitation wavelength. The first band around pixel number 90 is the Raman signal due to the water column and the second band is the DOM fluorescence intensity. The time series is composed actually from individual fluorescence spectra as in

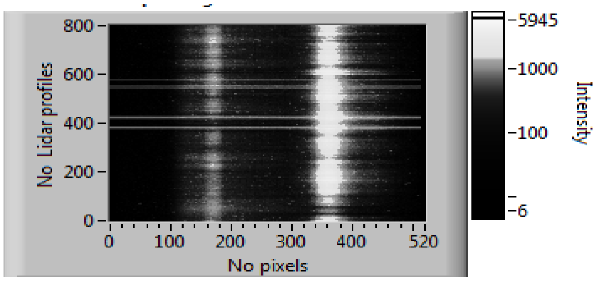
Fig. ***2*** measured successively after a few seconds.

Fig. 3b) is an example of Lidar time series recorded on 29 April 2007, on Constanta harbor using 460nm excitation wavelength. First band around pixel number 180 is the Raman signal due to the water column and the second one is the chlorophyll *a* fluorescence intensities.

For multifractal analysis a single time series corresponding to the maximum fluorescence intensity of chlorophyll *a* or DOM was extracted. The variation of concentrations is represented in around 800 points.



a)



b)

Fig. 3 a) Time series Constanta –DOM; b) Time series Constanta –Chlorophyll.

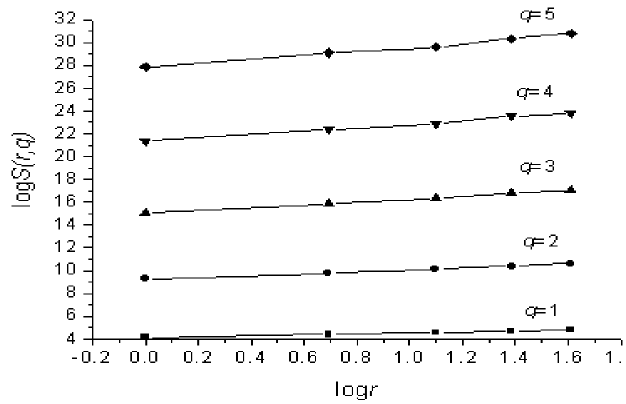
We shall first consider the spectrum analysis and the structure function study performed on the Constanta-DOM. The dependence of the various moments of the statistics between up to q=5 are presented in Fig. 4a. We observe that the dependence of the structure functions on the delay in a log-log plot is very close to linear for values of the order q as large as 5. This shows that the structure functions satisfy the power law

$$S(r,q) \propto r^{\varsigma(q)} \tag{5}$$

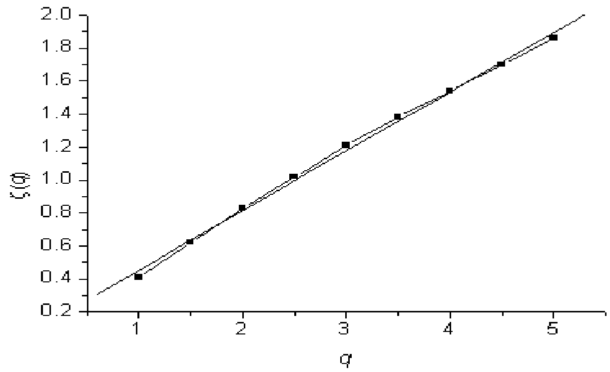
The slopes $\varsigma(q)$ of the lines are increasing nearly linearly with q. Since $S(r,0)=0$, the power $\varsigma(q)$ is 0 for $q=0$ and the dependence can be written

$$\varsigma(q) = qH(q) \tag{6}$$

where, in this case, $H(q)$ is very close to a constant known as the Hurst exponent. The slight nonlinearity of the dependence $\varsigma(q)$ presented in Fig. 4b is unlikely to be a sign of multifractality because it can easily have been caused by the reduced length of the time series. In this graph the interval between successive values of q is 0.5.



a



b

Fig. 4 a) Linear dependence of the structure functions on the delay r and power exponent q for the Constanta-DOM time series; b) the slopes of the graphs in a) versus q.

This dynamics of the fluctuations can be very well simulated as fractional Brownian motion (fBm) with the Hurst exponent $H = 0.34$, as shown by Fig. 5.

In order to obtain a similar range of values for the structure functions, the computed values of the fBm time series were multiplied by a convenient constant such that the two time series (experimental and simulated) would have similar values of their means.

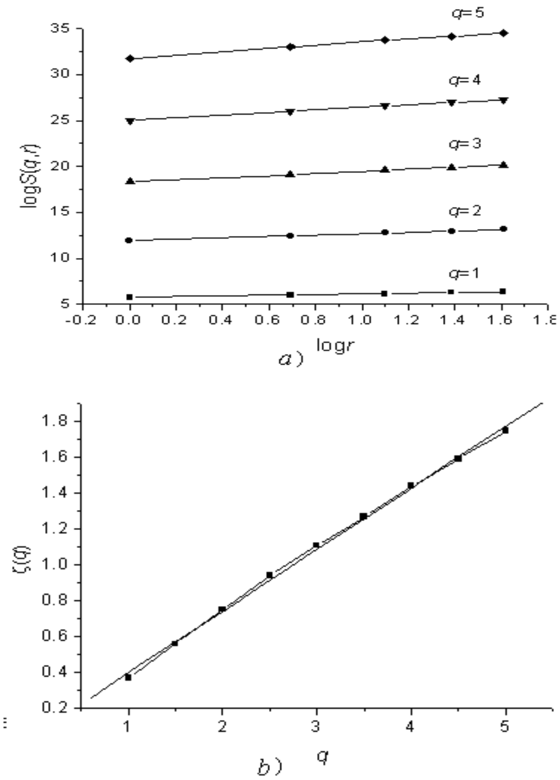


Fig. 5 a) Linear dependence of the structure functions on the delay r and power exponent q for the simulated fBm time series; b) the slopes of the graphs in a) versus q.

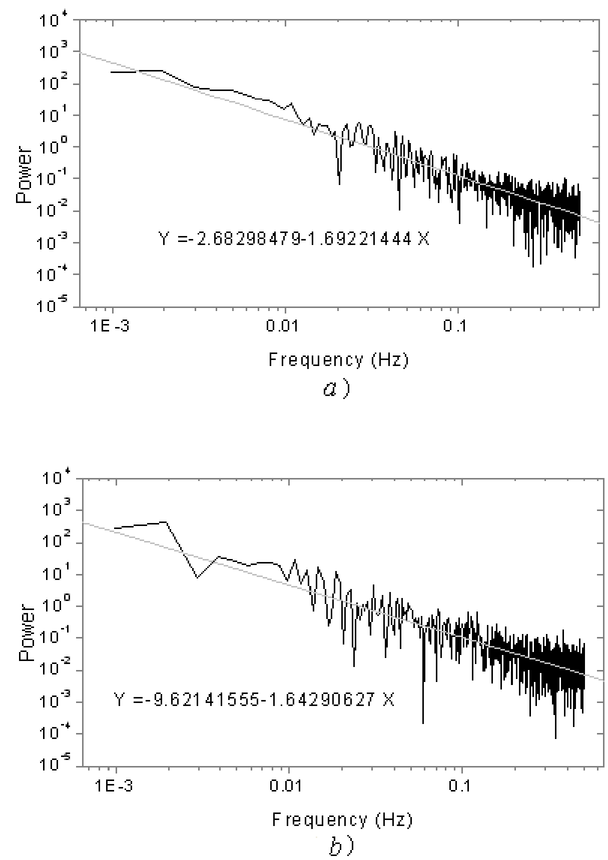


Fig. 6 a) Spectrum for the experimental time series; b) Spectrum for the computed fBm time series.

The similarity is still more evident if the spectra of the two time series are considered. Fig. 6 shows side by side the two spectra. The closeness of their slope (of their color) is a strong argument in support of our hypothesis. As well known 0, in the case of monofractal time series, the spectral exponent β is related to the Hurst exponent according to the equation

$$\beta = 1 + \varsigma(2) = 1 + qH \qquad (7)$$

which is well satisfied by the computed values of β shown on Fig. 6: experimental time series $\beta = 1.69$ and the computed fBm time series $\beta = 1.64$.

The same type of behavior was identified for all the time series obtained by measurements performed in the neighborhood of the Constanta for the fluorescence backscattered light by DOM. The fact that the experimental values obtained for Constanta-DOM are very similar to the other time series corresponding to DOM, demonstrates that the monofractal character is independent of the analyzed component and that the observed fluctuations are a property of the seawater itself.

Various other time series collected in the same zone in different days present the same general characteristics with small differences observed in the values of the exponent β but they all are restricted to the range between pink and red noise.

The situation is considerably different for measurements performed in the same environment for chlorophyll. The time series presents clear multifractal characteristics. Fig. 7 shows the spectrum of the Constanta-Chlorophyll time series. It clearly presents different slopes over different spectral ranges, as suggested by the line segments that approximate the average value of the slope for the respective zone.

For low frequency, up to $8 \cdot 10^{-2}$ Hz, the spectral exponent has the same value $\beta \approx 1.67$ as for the DOM spectrum while for frequency in excess of this value, $\beta \approx 1.24$. For the highest frequency range (above 0.2Hz) β is still lower, approaching the value $\beta = 0$ characteristic of white noise.

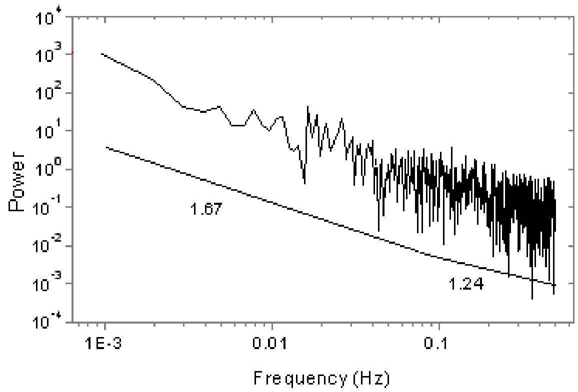


Fig. 7. Spectrum of the Constanta-Chlorophyll showing two different slopes.

This change in β is reflected in the structure function analysis presented in Fig. 8. The dependence of the slope of the curves $\ln S(q,r)$ versus $\ln r$ shown on the bottom of Fig. 8 is not linear. In this case, eq. (6) can be satisfied only if H is a function of the order of the structure function, $H = H(q)$. As before, for the sake of clarity of perception, in Fig. 8 *a*) only the graphs for integer values of q are presented.

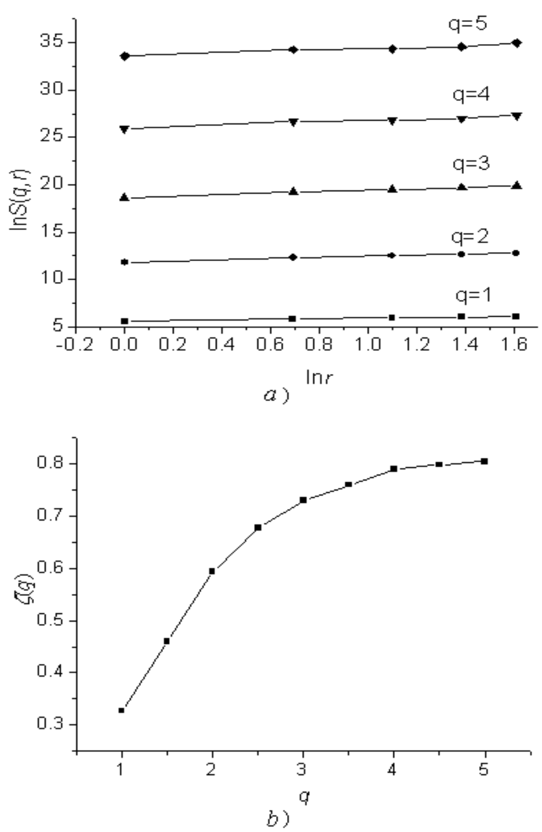


Fig. 8 Structure function analysis for Constanta-Chlorophyll.

It is not surprising that the time series for the two seawater components are different, because they have completely different origins. While the DOM signal can be considered as direct measure of the intrinsic seawater fluctuations, the Chlorophyll *a* signal is a measure of the presence of the phyto-plankton, and its amplitude fluctuations are related to specific characteristics of the latter, particularly the blooming degree. It should be observed that, while at low frequencies the characteristics of the fluctuations of the Chlorophyll *a* follow those of the seawater, at high frequency they have specific behaviour. This confirms results of recent previous studies [17,13].

5. Conclusions

The results are in very good agreement with observations carried out using completely different methods and set-up. The main differences between our procedure and more conventional ones are: the observation is performed in situ by remote optical measurement which avoids any substantial contact with the analyzed zone; the time series are obtained by observations carried out at equally spaced points but at different times unlike the previous studies which measured the chosen parameters either at equally spaced points but at the same time or at a specified location but at successive moments. The consistency of our results with conclusions obtained by the more conventional methods can be considered as test for the wide applicability of the method of Lidar fluorescence to the study of marine fluctuations. The variety of the results obtained for different time series generated during the same tranzit (measuring at different wavelengths) excludes the hypothesis that the fluctuations could be a consequence of the turbulence generated by the ship movement.

From a different point of view, this consistency can be considered as a good support for the old Taylor suggestion on “frozen turbulence” according to which the sequence of changes at a fixed point are due to the passage of an unchanging pattern of turbulent motion over that point [18].

Acknowledgements

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References

[1] J. H.Steele, E. W. Henderson, Phil. Trans. R. Soc. Lond. B **343**, 5 (1994)
[2] S. L. Pimm, A. Redfearn, Nature **334**, 613 (1988)
[3] H. Caswell, J. E. Cohen, J. Theor. Biol. **176**, 301 (1995)

[4] D. A. Vasseur, P. Yodzis, Ecology **85**, 1146 (2004)
[5] J. E. Cohen, Nature **378**, 610 (1995)
[6] F. J. Lermusiaux, J. Computational Physics **217**, 176 (2006)
[7] L. Seuront, F. Schmitt, Y. Lagadeuc, D. Schertzer, S. Lovejoy, J. Plankt. Res. **21**, 877 (1999)
[8] P. C. Chu, Chaos, Solitons and Fractals **19**, 275 (2004)
[9] R. Measures, Krieger Publishing Company, Malabar, Florida (1992).
[10] C. Radu, L. Belegante, C. Talianu, D. Nicolae, J. Optoelectron. Adv. Mater., **12**(1), 165 (2010).
[11] J. Vasilescu, L. Belegante, C. Sliwinski, C. P. Cristescu, U.P.B. Sci. Bull., Series A, ISSN 1223-7027, **70**(4), 41, (2008).
[12] S. R. Laney, R. M. Letelier, R. A. Desiderio, M. R. Abbott, D. A. Kiefer, C. R. Booth, Journal of Atmospheric and Oceanic Technology **18(**11), 1924 (2001).
[13] M. J. Doubell, H. Yamazaki, H. Li, Y. Kokubu, J. Plankt. Res. **31**, 1441 (1999)
[14] J. Vasilescu, L. Marmureanu, E. Carstea, C. P. Cristescu, U.P.B. Sci. Bull., ISSN 1223-7027, Series A, accepted 2010
[15] J. H. Steele, Nature **313**, 355 (1985)
[16] H-O. Peitgen, D. Saupe (Editors) The Science of Fractal Images, Springer-Verlag, New York, 1988
[17] K. R. Iversen, R. Primicerio, A. Larsen, J. K. Egge, F. Peters, O. Guadayol, A. Jacobsen, H. Havskum, C. Marrase, J. Plankt. Res. **32**, 197 (2010)
[18] G. I. Taylor, Proc. R. Soc. London A **164**, 476 (1938).

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