Eulerian and Lagrangian properties of biophysical intermittency in the ocean

Laurent Seuront[1] and François G. Schmitt
CNRS, UMR ELICO, Station Marine de Wimereux, Université des Sciences et Technologies de Lille, France

Received 16 July 2003; accepted 8 January 2004; published 12 February 2004.

[1] Eulerian and Lagrangian characteristics of simultaneously recorded temperature, salinity and phytoplankton biomass time series are investigated over a seasonal cycle. Time series are analyzed in the spectral and multifractal scaling frameworks. We show that passive scalar time series (temperature and salinity) are characterized by scaling laws representative of Eulerian and Lagrangian turbulence. The two different regimes identified are separated by a transition linked to the characteristic scale of turbulent structures of the same size as the boat. While the scaling behavior exhibited by phytoplankton biomass fluctuations is close to the expected passive scalar behavior over Eulerian scales, it is quite far from it over Lagrangian scales. For these scales, the observed scaling behavior exhibits a significant density-dependence, indicative of biological activity. *INDEX TERMS:* 4815 Oceanography: Biological and Chemical: Ecosystems, structure and dynamics; 4568 Oceanography: Physical: Turbulence, diffusion, and mixing processes; 4855 Oceanography: Biological and Chemical: Plankton; 4572 Oceanography: Physical: Upper ocean processes; 4560 Oceanography: Physical: Surface waves and tides (1255). **Citation:** Seuront, L., and F. G. Schmitt (2004), Eulerian and Lagrangian properties of biophysical intermittency in the ocean, *Geophys. Res. Lett.*, *31*, L03306, doi:10.1029/2003GL018185.

1. Introduction

[2] Following the initial proposals to describe scaling laws of turbulent velocity fluctuations in Eulerian and Lagrangian frameworks [*Kolmogorov*, 1941; *Landau and Lifshitz*, 1944], the same has been applied to passive scalar turbulence [*Obukhov*, 1949; *Corrsin*, 1951; *Inoue*, 1952]. These laws have subsequently been generalized using multifractals to take into account the intrinsic intermittent properties of turbulent processes [for a review see *Frisch*, 1995]. Multifractal properties of passive scalar intermittency have been experimentally investigated in the Eulerian framework for the atmosphere [*Schmitt et al.*, 1992, 1996; *Marshak et al.*, 1997; *Cho et al.*, 2001; *Lovejoy et al.*, 2001a] and the ocean [*Seuront et al.*, 1996a, 1999; *Lovejoy et al.*, 2001b]. Fewer results exist for Lagrangian multifractal turbulence: one may find recent laboratory [*Mordant et al.*, 2001, 2002] and oceanic experimental studies [*Seuront et al.*, 1996b] which present direct measurement of particle velocities in a fully turbulent flow and time series of temperature fluctuations, respectively.

[3] In the latter work, time series of temperature and in vivo fluorescence were taken from a drifting platform. They exhibit both Eulerian and Lagrangian regimes for time scales respectively smaller and larger than the characteristic time scale of turbulent structures of the same size as the platform. At small scales, no significant difference has been detected between the scaling and multiscaling behavior of temperature and phytoplankton biomass. This was fully congruent with the hypothesis of a passive behavior of phytoplankton cells. The large-scale fluctuations of temperature corresponded to the theoretical scaling of a Lagrangian passive scalar, and provided the first experimental evidence of Lagrangian multifractality. However, the lack of scaling behavior in phytoplankton data, related to the small number of data points in the series or to biological activity, did not allow to exploring the Lagrangian phytoplankton variability.

[4] We develop and generalize here the previous preliminary results and show how the intermittent distribution of purely passive scalars (temperature and salinity) and phytoplankton biomass, an a priori passive biological tracer, can be characterized in terms of scaling and multiscaling behaviors in Eulerian and Lagrangian frameworks. We study a larger database consisting of 11 high-resolution (2 Hz) time series of temperature, salinity and *in vivo* fluorescence (a proxy of phytoplankton biomass) simultaneously recorded with Sea-Bird 25 Sealogger CTD probe and Sea Tech fluorometer, respectively. The sensors were located at a single depth (10 m) to avoid any smearing and averaging of the signals due to the length of the ship plumbing. To avoid any contamination of the signal by swell and surface waves, the sampling experiments have been conducted under weak wind (<1 m/s) conditions. The dissipative nature of the English Channel also ensures the absence of any stratification, and thus any contamination by internal gravity waves. Time series were recorded during 1 to 5 hours, adrift, monthly and in flood conditions in the coastal waters of the Eastern English Channel from February to December 1996. Energy dissipation and Reynolds number values ranged from $1.8\ 10^{-6}$ to $6.5\ 10^{-4}$ $m^2\ s^{-3}$ and from $7.7\ 10^6$ to $4.7\ 10^7$, respectively.

2. Scaling and Multiscaling Laws for Passive Scalar Intermittency

2.1. Eulerian Framework

[5] In fully developed turbulence, scaling laws have been proposed for passive scalar fluctuations in Fourier space [*Obukhov*, 1949; *Corrsin*, 1951]: $E(k) \propto k^{-\beta}$, where $E(k)$ is the spectral density, and k the wave number and the slope β

[1]Also at School of Biological Sciences, Flinders University, Adelaide, Australia.

0094-8276/04/2003GL018185

is close to 5/3. In real space the temperature field θ is studied using the temperature finite difference at scale ℓ, $\Delta\theta_\ell = |\theta(x+\ell) - \theta(x)|$, obeying a scaling law $\Delta\theta_\ell \propto (\chi_\ell)^{1/2} (\epsilon_\ell)^{-1/6}\ell^{1/3}$, where ϵ_ℓ and χ_ℓ are respectively the energy flux and scalar variance flux through scale l. Originally these laws were written using dissipations, but one can also use fluxes. In order to take intermittency into account, these fluxes, which are conserved by the equations of motion, are often considered to cascade from large to small scales, via multiplicative cascades [*Yaglom*, 1966; *Schertzer and Lovejoy*, 1987]. These cascades and their nonlinear interactions are responsible for anomalous scaling exponents of the temperature structure functions: the statistical moments of order q of the increments (q = 1 and 2 for the mean and the variance) obey a scaling law of the form $\langle \Delta\theta_\ell^{\,q}\rangle \propto \ell^{\zeta(q)}$, where $\zeta(q)$ is the structure functions' scale invariant exponent of the temperature field. This function is nonlinear and concave, and characterizes, at all scales, the statistics of the increments. Structure functions must thus be regarded as a generalization of spectral analysis (which is only related to a statistical second order of moment) to higher order of moments. Its nonlinearity is a signature of multifractality (such fields are also called multiaffine, see *Viscek and Barabasi* [1991]): for monofractal processes, such as Brownian motion, the scaling exponents are linear: $\zeta(q) = qH$ where $H = \zeta(1)$ describes the scale dependence of the average fluctuations (H = 1/2 for Brownian motion, H = 1/3 for non-intermittent turbulence). Despite the infinite number of parameters needed to describe the function $\zeta(q)$, it can be conveniently described in the framework of the log-Lévy multifractal model, which corresponds to the stable and attractive classes obtained with continuous multiplicative scaling processes [*Schertzer and Lovejoy*, 1987, 1989]. In this framework the scaling moment function have a precise theoretical shape:

$$\zeta(q) = qH - \frac{C_1}{\alpha - 1}(q^\alpha - q) \quad (1)$$

The parameter C_1 ($0 \le C_1 \le 1$) is the codimension of the mean of the process and thus measures its mean inhomogeneity: the larger this parameter, the more the mean field is inhomogeneous. The Lévy index α ($0 \le \alpha \le 2$) measures the degree of multifractality of the process, i.e. how fast the inhomogeneity increases with the order of the moments. From equation (1) it can be seen that the parameters C_1 and α express a deviation from monofractal behavior: the more concave and nonlinear $\zeta(q)$ is, the more multifractal, or intermittent the related signal. Because of intermittency generated by the two fluxes ϵ_ℓ and χ_ℓ, for passive scalar turbulence, H is expected to be slightly different from the non-intermittent theoretical value of 1/3. This is indeed the case for ocean temperature where H has been estimated as ranging from 0.31 to 0.42 [*Seuront et al.*, 1996a, 1999; *Lovejoy et al.*, 2001b]. The parameter C_1 can be directly estimated using the slope of $\zeta(q)$ around mean values (q = 1): we see from equation (1) that $C_1 = H - \zeta'(1)$. The last parameter characterizes the curvature of the curve, and can be estimated from a best fit for the nonlinear part of the experimental curve. Previous estimates of the parameters α and C_1 have reported values bounded between 0.03 and 0.06, and 1.80 and 1.91 for ocean temperature and salinity, respectively [*Seuront et al.*, 1996a, 1999; *Lovejoy et al.*, 2001b]. These values of α are not far from the lognormal model corresponding to α = 2.

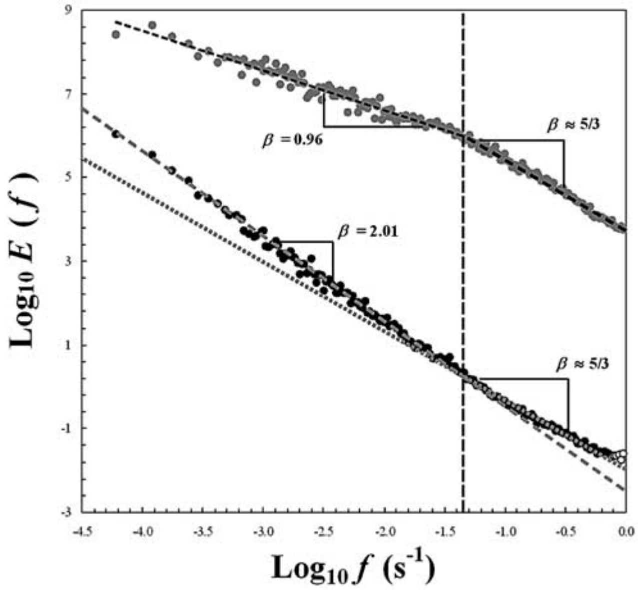

Figure 1. The power spectra $E(f)$ of the fluorescence (grey dots; (*fluorescence unit*)^2 s^{-1}) and the temperature (black dots; K^2 s^{-1}) time series, shown in a log-log plot. The high frequency open dots have not been included in the regression analysis.

2.2. Lagrangian Framework

[6] In the Lagrangian framework, as one follows the motion of an element of fluid, the previous scaling relations are to be expressed as functions of time lag τ and the corresponding finite differences are written $\Delta\theta_\tau = |\theta(t+\tau) - \theta(t)|$. Lagrangian scaling laws have been proposed for passive scalars for over fifty years [*Inoue*, 1952], in the form $\langle\Delta\theta_\tau^2\rangle \propto \bar{\chi}\tau$, where $\bar{\chi}$ is the dissipation of passive scalar variance, assumed here to be homogeneous. Intermittency can be introduced [*Novikov*, 1989, 1990] with the assumption of a Lagrangian cascade for passive scalar flux written as $\chi_\tau \propto \Delta\theta_\tau^2/\tau$, which is still conserved on average by the equations of motion ($\langle\chi_\tau\rangle = \bar{\chi} = k$, where k is a constant). This Lagrangian passive scalar variance flux generates intermittency and multifractal statistics for the Lagrangian passive scalar fluctuations:

$$\langle(\Delta\theta_\tau)^q\rangle \propto \tau^{\zeta(q)} \quad (2)$$

The Lagrangian scale invariant moment function $\zeta(q)$ is still nonlinear and concave, but the peculiarity here is that there is no intermittency correction for the second moment ($\zeta(2) = 1$) corresponding to an exactly -2 power spectrum $E(f) \propto f^{-2}$, where f is the frequency. The difference in spectral slope can then be used to identify Lagrangian and Eulerian regimes in our oceanic data. This function can be written as: $\zeta(q) = q/2 - K(q/2)$, where $K(q)$ is the scaling moment function characterizing the intermittency of the passive scalar flux, and since $K(1) = 0$ it can be written in the log-Lévy model as $K(q) = \frac{C_\chi}{\alpha-1}(q^\alpha - q)$. Based on the analysis of a single temperature time series, the parameters

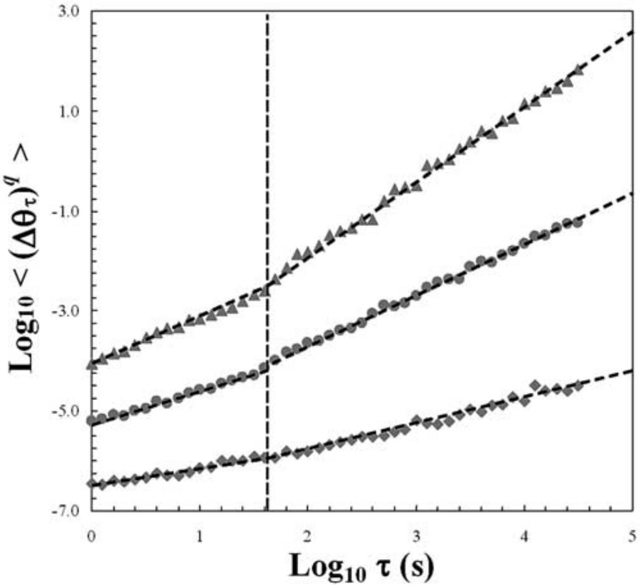

Figure 2. The temperature structure functions, $\langle|\Delta\theta\tau|^q\rangle$ versus τ in log-log plots for q = 1, 2 and 3 (from bottom to top). The straight lines indicate the best power law fit over each range of scales for each value of q. The Lagrangian exponents verify $\zeta(1) = 0.5$ and $\zeta(2) = 1$.

α and C_χ have been estimated as $C_\chi = 0.05 \pm 0.01$ and $\alpha = 1.80 \pm 0.05$ [*Seuront et al.*, 1996b].

3. Eulerian and Lagrangian Intermittency of Temperature, Salinity and Phytoplankton Fields

[7] The previous spectral and multiple-scaling framework is applied to the temperature, salinity and in vivo fluorescence time series. They exhibit a mixed scaling behavior with two scaling tendencies (Figures 1–2). The Lagrangian scaling regime is clear. For high frequencies the Eulerian regime is only developed over a decade. Nevertheless, an Eulerian $-5/3$ slope is roughly compatible with the observations. The change in behavior occurs for frequencies f ranging from 0.02 to 0.11 Hz, associated with characteristic time scales T_0 ranging from 9 to 54 seconds. Using the mean tidal drift observed during each experiment, bounded between 0.3 and 1.5 ms^{-1}, the corresponding spatial transition scales are estimated as 12.1 ± 1.6 m. These length scales cannot be distinguished from the size of the ship used during the sampling experiment, i.e. 12.5 m. For time scales larger than T_0, the spectral slope of temperature and salinity are close to the Lagrangian value -2. For smaller time scales, β is close to $-5/3$, interpreted as an Eulerian slope, through the use of Taylor's hypothesis to relate time variations to spatial variations. This confirms that for time scales larger than the characteristic time scale of eddies of the size of the ship, the inertia of the ship becomes negligible and the measurements are done following the flow, in a Lagrangian framework. These results confirm and generalize the preliminary results obtained by *Seuront et al.* [1996b] from a single time series of temperature and fluorescence. For a small drifting buoy, such as those used by *Abbott and Letellier* [1998], a break should also be observed at spatial scales corresponding to $\sim$1 m assuming that the sampling frequency f is significantly larger than t^{-1}, where t is the time scale of 1 m size turbulent eddies. While temperature and salinity spectral exponent are quite constant (between 1.68 and 1.72), fluorescence power spectra are fluctuating between 1.66 and 1.75. The Lagrangian spectral exponents estimated for temperature and salinity (values of 2.01 and 2.00) are fully congruent with the theoretical prediction. However, the Lagrangian fluorescence spectral exponents exhibit a significantly different behavior, with a wide range of observed values ranging from 0.58 to 1.37 depending on the time series considered.

[8] In order to investigate the origin of the specific behavior of fluorescence fluctuations, we conducted a correlation analysis between the observed spectral exponent and the properties of the water column during the sampling experiments in terms of temperature, salinity and phytoplankton biomass. Eulerian and Lagrangian fluorescence spectral exponents appeared (i) independent of the surrounding physical properties, and (ii) significantly related to the phytoplankton concentration, suggesting a biological, density-dependent control of phytoplankton biomass variability.

[9] These observations are specified by the results of the multifractal analysis. The clear nonlinearity of the exponents $\zeta(q)$ demonstrates the multifractal character of temperature, salinity and fluorescence variability (Figure 3). The differences (not shown) between $\zeta_\theta(q)$, $\zeta_S(q)$ and $\zeta_F(q)$ confirm the slightly non-passive character of Eulerian fluctuations of phytoplankton biomass and the clearly non-passive character of Lagrangian ones. Finally, the multifractal parameters estimated for temperature and salinity are the following: $H = 0.39$, $C_1 = 0.043$ and $\alpha = 1.75$ for the Eulerian range of scales, and $C_\chi = 0.056$ and $\alpha = 1.86$

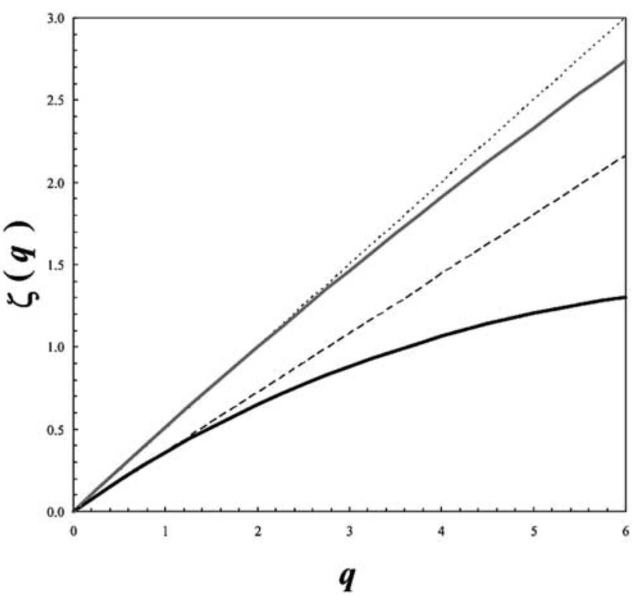

Figure 3. Empirical values of $\zeta_\theta(q)$ for Eulerian (black curve) and Lagrangian (grey curve) temperature fluctuations, compared to the non-intermittent linear cases, $\zeta_\theta(q) = qH$ (dotted line) and $\zeta_\theta(q) = q/2$ (dashed line), corresponding to non-intermittent Eulerian and Lagrangian turbulence. The nonlinearity of the empirical curves indicates multifractality.

for the Lagrangian range of scales. These values are fully compatible with previous results [*Seuront et al.*, 1996a, 1996b, 1999; *Lovejoy et al.*, 2001b]. Alternatively, the parameters estimated for Eulerian fluorescence are on average similar to those of temperature and salinity (H = 0.39, C_1 = 0.043 and α = 1.75), but they exhibit a higher variability, with a significant positive correlation with phytoplankton concentration. Over the Lagrangian regime, since the spectral slopes do not show an exactly -2 value, it seems clear that the Lagrangian turbulent passive scalar theoretical framework does not apply, and we use the general expression (1). For this range of scales, the mean of the estimated multifractal parameters of fluorescence are very specific (H = 0.26, C_1 = 0.34 and α = 1.61) and are clearly dependent on the phytoplankton concentration, especially for H, which decreases from 0.47 to 0.03 when the latter increases from 1 to 6 μgl^{-1}.

4. Conclusions

[10] We have interpreted temperature, salinity and phytoplankton fields recorded adrift in the Eastern English Channel from February to December 1996 in the framework of Eulerian and Lagrangian turbulence, separated by a time scale intrinsically linked to the size of the ship used to collect the data. Our results show that Eulerian and Lagrangian scaling and multiscaling properties of temperature and salinity are very similar and fully compatible with the behavior of purely passive scalars, and preliminary results obtained from ocean temperature sampled in the same area. We also provided evidence of the specific behavior of phytoplankton over Eulerian and Lagrangian regimes. The variability and the subsequent correlations of the Eulerian/Lagrangian scaling and multiscaling properties of fluorescence with phytoplankton concentrations indicate (i) a non-passive behavior of phytoplankton, and (ii) a density-dependent control of phytoplankton distribution in relation to the biological seasonal cycle. The scaling and multiscaling laws of passive scalars and phytoplankton are closer in the Eulerian than in the Lagrangian framework.

[11] The specific nature of Lagrangian phytoplankton distribution may open perspectives in zooplankton ecology. Zooplankton predators indeed perceive their preys from a Lagrangian perspective. The distribution of preys is crucial for predators, because food availability changes depending on its distribution. According to our results, phytoplankton distribution is less intermittent when concentration is high. Low intermittency means a smoother and more regular distribution of particles, and high intermittency means rough, fragmented and a more apparently "random" distribution. When a predator can remotely detect its surroundings, intermittent prey distributions would be more beneficial, especially if they correspond to high food density as suggested here. In contrast, when a predator has no detection ability, non-intermittent prey distributions may be relatively better, as available food quantity or encounter rate becomes proportional to the searched volume as intermittency increases.

[12] **Acknowledgments.** We thank two referees for their useful comments and suggestions on an earlier version of this work. Thanks are extended to R. Waters for improving the language.

References

Abbott, M. R., and R. M. Letellier (1998), Decorrelation scales of chlorophyll A as observed from bio-optical drivers in the California Current, *Deep Sea Res.*, *45*, 1639–1668.
Cho, J. Y. N., et al. (2001), Aircraft observations of boundary layer turbulence: Intermittency and the cascade of energy and passive scalar variance, *J. Geophys. Res.*, *106*, 2199–2210.
Corrsin, S. (1951), On the spectrum of isotropic temperature fluctuations in an isotropic turbulence, *J. Appl. Phys.*, *22*, 469–473.
Frisch, U., (1995), *Turbulence, the legacy of A. N. Kolmogorov*, Cambridge Univ. Press, New York.
Inoue, E. (1952), Turbulent fluctuations in temperature in the atmosphere and oceans, *J. Meteorol. Soc. Japan*, *29*, 246–253.
Kolmogorov, A. N. (1941), The local structure of turbulence in incompressible viscous fluid for very large Reynolds number, *Dokl. Acad. Nauk. SSSR*, *30*, 299–303.
Landau, L. D., and E. M. Lifshitz (1944), *Fluid mechanics* (in Russian), 1st edition.
Lovejoy, S., D. Schertzer, and J. D. Stanway (2001a), Direct evidence of multifractal atmospheric cascades from planetary scales down to 1 km, *Phys. Rev. Lett.*, *86*, 5200–5203.
Lovejoy, S., et al. (2001b), Universal multifractals and ocean patchiness: Phytoplankton, physical fields and coastal heterogeneity, *J. Plankton Res.*, *23*, 117–141.
Marshak, A., et al. (1997), Scale invariance in liquid water distributions in marine stratocumulus. Part II: Multifractal properties and intermittency issues, *J. Atmos. Sci.*, *54*, 1423–1444.
Mordant, N., et al. (2001), Measurement of Lagrangian velocity in fully developed turbulence, *Phys. Rev. Lett.*, *87*, 214–501.
Mordant, N., et al. (2002), Long time correlations in Lagrangian dynamics: A key to intermittency in turbulence, *Phys. Rev. Lett.*, *89*, 254–502.
Novikov, E. A. (1989), Two-particles description of turbulence, Markov property and intermittency, *Phys. Fluids A*, *1*, 326–330.
Novikov, E. A. (1990), The effects of intermittency on statistical characteristics of turbulence and scale similarity of breakdown coefficients, *Phys. Fluids A*, *2*, 814–820.
Obukhov, A. (1949), Structure of the temperature field in a turbulent flow, *Izv. Akad. Nauk. SSSR, Geogr. I Jeofiz.*, *13*, 55–69.
Schertzer, D., and S. Lovejoy (1987), Physical modeling and analysis of rain and clouds by anisotropic scaling multiplicative processes, *J. Geophys. Res.*, *92*, 9693–9714.
Schertzer, D., and S. Lovejoy (1989), Nonlinear variability in geophysics: Multifractal analysis and simulation, in *Fractals: Physical Origin and Consequences*, edited by L. Pietronero, pp. 49–79, Plenum, New York.
Schmitt, F., et al. (1992), Estimations directes des indices de multifractals universels dans le champ de vent et de temperature, *C. R. Acad. Sci., Paris, ser. II*, *314*, 749–754.
Schmitt, F., et al. (1996), Multifractal Temperature and Flux of Temperature Variance in Fully Developed Turbulence, *Europhys. Lett.*, *34*, 195–200.
Seuront, L., F. Schmitt, Y. Lagadeuc, D. Schertzer, S. Lovejoy, and S. Frontier (1996a), Multifractal analysis of phytoplankton biomass and temperature variability in the ocean, *Geophys. Res. Lett.*, *23*(24), 3591–3594.
Seuront, L., et al. (1996b), Multifractal analysis of Eulerian and Lagrangian variability of oceanic turbulent temperature and plankton fields, *Nonlinear Proc. Geophys.*, *3*, 236–246.
Seuront, L., et al. (1999), Universal multifractal analysis as a tool to characterise multiscale intermittent patterns; example of phytoplankton distribution in turbulent coastal waters, *J. Plankton res.*, *21*, 877–922.
Viscek, T., and A.-L. Barabasi (1991), Multi-affine model for the velocity distribution in fully turbulent flows, *J. Phys. A: Math. Gen.*, *24*, L845–L851.
Yaglom, A. M. (1966), The influence of fluctuations in energy dissipation on the shape of turbulent characteristics in the inertial interval, *Sov. Phys. Dokl.*, *11*, 26–29.

L. Seuront and F. G. Schmitt, CNRS, Ecosystem Complexity Research Group, Station Marine de Wimereux, UMR 8013 ELICO, Université des Sciences et Technologies de Lille, France. (laurent.seuront@univ-lille1.fr)