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Distribution of bioluminescent organisms in the Mediterranean Sea and predicted effects on a deep-sea neutrino telescope

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Abstract

The density of bioluminescent organisms was measured using an ISIT camera profiler in the eastern and western Mediterranean, from the subsurface layer to the seafloor; in the Ligurian, Tyrrhenian, Ionian, Adriatic Seas and the Strait of Sicily, including neutrino telescopes sites at ANTARES and NESTOR. A west–east gradient in the density of bioluminescent animals in deep water (1500-2500m) was observed, with the average density in the Ligurian (ANTARES) Sea (0.65 ± 0.13 m^{-3}) an order of magnitude greater than the E Ionian (NESTOR) Sea (0.06 ± 0.04 m^{-3}). Additionally, an exponential relationship was found between the density of near–bed bioluminescence (0-400mab) and depth, with greatest divergence from the trend at the extreme west and easterly sites. For small scale effects we applied flash kinetics of bioluminescent organisms to map the bioluminescent field around a sphere; we predict most light emission downstream of an optical module.

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1. Introduction

Bioluminescence is the light produced by living organisms. It is a widespread phenomenon in the oceans, with up to an estimated 90% of deep sea animals capable of luminescing [1]. Bioluminescence is often produced by organisms as a self defense mechanism in response to perceived threats. This can

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include contact or close-contact with objects, such as submerged structures. The threshold shear force required to generate bioluminescence in a copepod, one of the most abundant deep-sea animals, has been measured as that generated by a flow of $5.5 \pm 3.4 mm.s^{-1}$ [2]. Water currents impinging on deep-sea structures can trigger this behaviour in advected organisms.

In this paper we describe the vertical and horizontal distribution of deep-sea bioluminescent animals in the Mediterranean Sea and discuss their interaction with deep-sea telescopes.

2. Profiling technique

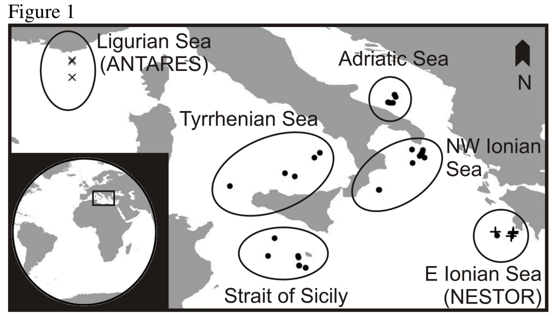
To determine the density of bioluminescent animals (m^{-3}) a rectangular mesh (Area: 0.38 x 0.5m; Pitch: 8 x 16mm) was traversed vertically through the water column, at velocities 0.4 – $0.88 m.s^{-1}$. As travel velocity exceeds threshold values, animals are stimulated to luminesce as they impact on or pass through the mesh. The stimulated luminescence was recorded using a downward looking ultra low light ISIT video camera (OE1325: Kongsberg Simrad, UK, faceplate sensitivity 5 x 10-6 Lux or 10^{-4} $mW.m^{-2}$ at 1m at λ = 470nm), focused on the mesh. The camera was powered and controlled autonomously via a custom built control system (Oceanlab, UK). This system may be mounted on a free-fall lander [3] or lowered on a wire on a CTD frame [4], with both systems capable of maintaining a known, constant descent velocity. Counts of bioluminescent events, each corresponding to a single animal, were determined during replay of the video. From the descent velocity and the area of the mesh, the density of bioluminescent animals was calculated.

3. Study area

The Mediterranean Sea (MS) is characterised as oligotrophic (low nutrient; low productivity), although there is spatial variation within the area such that the western Mediterranean experiences higher surface productivity than the eastern Mediterranean basin [5][6] All areas are subject to seasonal and interannual variation of surface productivity, with greater variation in the west compared to the east [7]. Production in surface layers is subsequently exported into deeper water [8].

Deployments were conducted at 36 stations on 4 cruises to the MS between January 2004 and May 2007: in the Ligurian (all ≤70km to ANTARES site), Tyrrhenian, Adriatic, NW Ionian, E Ionian (all ≤55km to NESTOR site) Seas, and the Strait of Sicily (Fig. 1). Unfortunately, it was not possible to sample at the NEMO sites (Catania Bay and Capo Passero).

Figure 1



ISIT-CTD profiler and ISIT free-fall lander deployment sites in the Mediterranean Sea: (×) January & May 2004; (•) October 2006 (*RV Meteor* M70-1); (+) May 2007 (*RV Aegaeo*)

4. Distribution of bioluminescence across the Mediterranean Sea

Profiles were grouped into regions within the MS, as indicated in Figure 1. Bioluminescent (BL) density values were averaged over the depth ranges: 500-1500, 1500-2500, 2500-3500 and >3500m.

Within the shallowest depth range (500-1500m) the Adriatic was found to have the highest BL density ($2.51 m^{-3}$), followed by the Ligurian Sea (1.65). The Tyrrhenian and the NW Ionian Seas were found to have the same BL density (1.53) at this depth, followed by the Strait of Sicily (1.44). The lowest value was seen in the E Ionian Sea (0.3). Deeper in the water column (1500-2500m), the Ligurian and the Tyrrhenian Seas, both in the western basin, were found to have the highest densities (0.65 and 0.40 m^{-3}, respectively). The NW and the E Ionian (NESTOR) Sea regions, both within the eastern basin, were found to have the lowest BL densities (0.21 and 0.06 m^{-3}, respectively) at these depths.

Table 1

Depth range (m)	500 - 1500	1500 - 2500	2500 - 3500	> 3500
Region	**Mean density of bioluminescent sources ± 1 stdv (m^{-3})**			
Adriatic Sea (n=5)	2.51 ± 0.41	-	-	-
Ligurian Sea (ANTARES) (n=5)	1.65 ± 1.18	0.65 ± 0.13	-	-
Tyrrhenian Sea (n=5)	1.53 ± 0.53	0.40 ± 0.34	-	-
NW Ionian Sea (n=9)	1.53 ± 0.79	0.21 ± 0.18	-	-
Strait of Sicily (n=7)	1.44 ± 0.71	-	-	-
E Ionian Sea (NESTOR) (n=5)	0.30 ± 0.29	0.06 ± 0.04	0.04 ± 0.05	0.02 ± 0.04

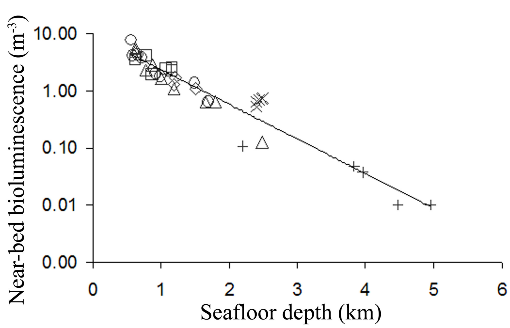
Mean density of bioluminescent sources ± 1 stdv (m^{-3}) in the Mediterranean Sea with profiles grouped into regions indicated (n = number of profiles). Mean values of the density of bioluminescent sources for the depth ranges: 500-1500, 1500-2500, 2500-3500 & >3500 m.

Only the E Ionian Sea (NESTOR) region extended to depths greater than 3500m where the BL density decreased to 0.02 m^{-3}. The data show a west-east gradient in deep water BL densities across the MS, with higher values in the west.

5. Variation of near-bed bioluminescence with seafloor depth

BL density values were averaged over 0-400 metres above bottom (mab) at 32 sites (4 of 36 deployments not sufficiently deep) within the Mediterranean Sea (Fig 2).

Figure 2



Plot of density of near-bed (0-400m above bottom) bioluminescence (BL_{NB}) (m^{-3}) with seafloor depth (D_{SF}) (km) in the: Tyrrhenian (◊); Adriatic (□); NW Ionian (Δ) Seas; Strait of Sicily (○); NESTOR (+); and ANTARES (×) sites

The density of near-bed bioluminescence (BL_{NB}) (m^{-3}) was found to have the following exponential relationship (R^2 = 0.92) with seafloor depth (D_{SF}) (km):

$$BL_{NB} = 9.5e^{(-1.4D_{SF})} - 0.01 \qquad (1)$$

This relationship allows a prediction to be made at any seafloor depth within the MS. Accordingly, a BL density of 0.06 m^{-3} is predicted at the proposed NEMO depth of 3.5km. However, variation from this trend is seen: values from the most westerly sites (ANTARES) exceed the predicted value, while values from the easterly Ionian sites lie on or below the trend line. We suggest this variation is related to regional differences in exported surface production.

6. Animal / telescope interactions

Rates of naturally occurring (spontaneous) bioluminescence are reported to be very low [9], understood to be the result of avoidance of incurring high energy cost light production by organisms. Bioluminescent flashes experienced in the vicinity of neutrino telescopes are likely the result of the stimulation of organisms as they impinge on these sub-sea structures.

Assuming all animal-optical module (OM) impacts result in a BL flash, Priede et al. [10] predict a linear relationship between the rate of flashes and both the BL density, ρ (m^{-3}), and the water current velocity, v ($m.s^{-1}$). Also, the flash rate is dependent on the diameters of the OM sphere, $Ø_{sphere}$ (m), and the animal $Ø_{animal}$ (m):

$$Impacts.s^{-1} = \pi\left(\frac{\phi_{sphere}}{2} + \frac{\phi_{animal}}{2}\right)^2 \times v \times \rho \qquad (2)$$

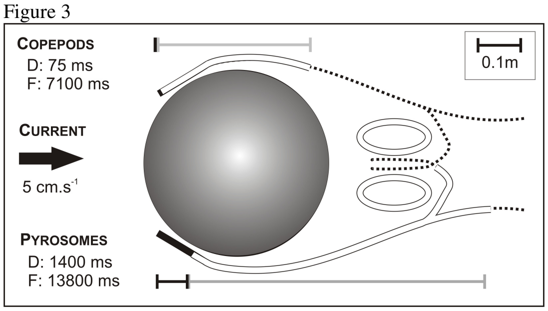
6.1. Bioluminescent field around an optical module

Bioluminescent animals can be grouped into three accepted size categories of marine plankton [11]: mesoplankton (0.2-20mm); macroplankton (20-200mm); and megaplankton (200-2000mm). Flash characteristics vary widely, but common to most species is a delay after stimulation, followed by a rapid rise in the intensity of light emitted and by a slower decay. Using published values of flash timing we can conceptualise the BL field around an OM. This is illustrated by a copepod (mesoplankton) (Flash delay - 75ms; duration – 7100ms) [12][13] and a pyrosome (megaplankton) (Flash delay – 1400ms; duration – 13800ms) [14]. Assuming a sphere (OM) in a water flow of 5cm.s^{-1} we can translate the flash timing of an organism, stimulated on the upstream side, into distance travelled around the sphere's contour (Fig. 3).

Bioluminescent animals have been shown to be able to re-bioluminesce until exhaustion [13]. Eddies formed in the wake may provoke restimulation of bioluminescence through shear stresses and causing interactions among entrained animals (e.g. collisions; and photic stimulation from nearby flashes [15]).

We predict more light to occur on the downstream side of an OM than the upstream side.

Figure 3



Hypothetical BL field produced around a sphere (43cm) by a copepod and a pyrosome advected by a current of 5cm.s^{-1} Delay (D) (▬); Flash duration (F) (▭); Mean flow (⋯)

7. Conclusions

From in-situ measurements we find a west-east gradient in the density of deep–sea bioluminescent animals in the water column with highest values in the west (ANTARES) and lowest values in the east (NESTOR), probably reflecting differences in regional biological productivity. An exponential relationship in the density of near-bed bioluminescence to depth was determined within the MS. However, seasonal and interannual variations in surface productivity are reported throughout the MS [17] and are expected to influence densities of bioluminescent animals within the different regions. A higher sampling frequency would be required to assess such fluctuations at potential telescope sites.

Acknowledgments

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