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The dispersal of phytoplankton populations by enhanced turbulent mixing in a shallow coastal sea

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ABSTRACT

A single tidal cycle survey in a Lagrangian reference frame was conducted in autumn 2010 to evaluate the impact of short-term, episodic and enhanced turbulent mixing on large chain-forming phytoplankton. Observations of turbulence using a free-falling microstructure profiler were undertaken, along with near-simultaneous profiles with an in-line digital holographic camera at station L4 (50° 15′ N 4° 13′ W, depth 50 m) in the Western English Channel. Profiles from each instrument were collected hourly whilst following a drogued drifter. Results from an ADCP attached to the drifter showed pronounced vertical shear, indicating that the water column structure consisted of two layers, restricting interpretation of the Lagrangian experiment to the upper ~25 m. Atmospheric conditions deteriorated during the mid-point of the survey, resulting in values of turbulent dissipation reaching a maximum of 10^{-4} W kg^{-1} toward the surface in the upper 10 m. Chain-forming phytoplankton >200 μm were counted using the data from the holographic camera for the two periods, before and after the enhanced mixing event. As mixing increased phytoplankton underwent chain breakage, were dispersed by advection through their removal from the upper to lower layer and subjected to aggregation with other suspended material. Depth averaged counts of phytoplankton were reduced from a maximum of around 2050 L^{-1} before the increased turbulence, to 1070 L^{-1} after, with each of these mechanisms contributing to this reduction. These results demonstrate the sensitivity of phytoplantkon populations to moderate increases in turbulent activity, yielding consequences for accurate forecasting of the role played by phytoplankton in climate studies and also for the ecosystem in general in their role as primary producers.

1. Introduction

Turbulence, be it generated at the surface or by internal processes, may have a controlling influence on the movement and distribution of phytoplankton, acting to keep non-motile phytoplankton in suspension (Jumars et al., 2009). This is particularly relevant in shallow coastal seas, where the majority of energy associated with tidal activity is dissipated. Turbulence can also act against stratification to mix nutrients across density gradients, so turbulent patches within the thermocline may impact on bloom dynamics by acting as sites of enhanced primary productivity (Sharples et al., 2001; Steinbuck et al., 2009).

Investigating the impact that turbulence has on individual populations of phytoplankton is not straightforward, and would typically be conducted in laboratory microcosms. Within these idealised environments our understanding of the response of phytoplankton to turbulence has been advanced considerably, including examining the influence upon nutrient uptake (Romero et al., 2012), community composition and size (Arin et al., 2002), and the influence of varying levels of turbulence itself (Cozar and Echevarria, 2005). Similar investigations in the field are uncommon, typically due to the limitation of an uncontrolled environment or the absence of appropriate instrumentation to tackle the problem. Often, destructive techniques are used to sample the water column, which can readily damage phytoplankton giving misleading information on biomass or size (Gallienne and Robins, 2001). Non-destructive methods such as laser transmissometry are beginning to prove popular (Rzadkowolski and Thornton, 2012), although it is unclear how well the statistics gained from these instruments translate to the characteristic size and shape of phytoplankton in the marine environment.

Image analysis has been shown to be a useful non-destructive method for analysing phytoplankton in situ (Stemmann and Boss, 2012; Zarauz et al., 2009). Methods such as digital photography allow some indication of the organisms under study, though the resulting image resolution may be considered impractical for a more comprehensive analysis of particle type. The emerging technology of holographic imaging offers detailed images of suspended particles under a range of conditions, generating particle statistics such as size and number density

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without the need to disturb particles from their natural environment (Graham and Nimmo Smith, 2010; Graham et al., 2012). The work presented here utilises holographic imaging for all observations of phytoplankton.

The aim of this paper is to investigate the response of a phytoplankton community to short-term, enhanced turbulent mixing at station L4 in the Western English Channel. L4 may be regarded as typical of the shallow shelf system of the United Kingdom. Whilst exhibiting seasonal stratification, this site is prone to frequent bouts of increased mixing from inclement weather systems (Groom et al., 2009). As such, L4 is well suited to providing an insight into phytoplankton dynamics when exposed to differing types of physical forcing.

2. Methods

2.1. Survey location

Station L4 resides approximately 10 km south of Plymouth at 50° 15′ N 4° 13′ W where the water depth is around 50 m with a seabed predominantly consisting of sand (Fig. 1). Long-term data exist for temperature and salinity at L4, along with a wealth of information on phytoplankton and zooplankton. With the proximity to the coast, and also to the outflow of freshwater from the local rivers, the L4 site forms a central part of the Western Channel Observatory (WCO). The long-term data indicates that the site is well-mixed during the winter, before the onset of thermal stratification in spring that is maintained through to the autumn months. The stratified water column has an average difference in temperature of 2 °C between the upper and lower layers (Fishwick, 2008). The site is characterised by a dominant semi-diurnal tide, experiencing a maximum range of over 5 m that generates currents of 0.5–0.6 m s^{-1} at the surface.

2.2. Physical measurements

Measurements utilising an array of instruments were undertaken on the 22nd September 2010 aboard the *RV Plymouth Quest*, during spring tides. The experiment formed part of a set of surveys detailed in (Cross et al., 2013), though much of the method is reproduced here for clarity. All instruments were deployed in a Lagrangian reference frame whilst following a drifter drogued by a holey sock positioned at 3–12 m. Within the drifter-drogue assembly, a 600 kHz Acoustic Doppler Current Profiler (ADCP) was fixed within a neutrally-buoyant submersible at an approximate depth of 20 m. The ADCP sampled at 2 s intervals with a bin size of 0.5 m, with the depth of the first good bin at 21 m. The device was fixed in a downward-looking position and was able to resolve the level of current shear present for the lower part of the water column. The vessel relocated to the drifter each hour, and measurements were obtained whilst the drifter was no further than 100 m from the ship. A free-fall microstructure profiler, the ISW Wassermesstechnik MSS-90, was utilised to observe the turbulent velocity shear. The number of profiles taken during each hour ranged from 6 to 8. The MSS-90 contains a number of sensors including optical backscatter (OBS), a fluorometer and conductivity, temperature and depth (CTD) probe. The dissipation rate of turbulent kinetic energy was estimated from the small-scale shear and assuming isotropy is defined as:

$$\varepsilon = 7.5\nu\left\langle(\partial u/\partial z)^2\right\rangle, \quad (1)$$

where v is the kinematic viscosity, which in seawater takes the value of about 10^{-6} m^2 s^{-1}, and $\partial u/\partial z$ represents the spatial derivative of the horizontal current component, u, in the vertical direction, z. The angled brackets denote a suitable time average, and the units of turbulent dissipation are given in W kg^{-1}. MSS-90 profiles begin at a depth of 5 m, due to the potential for contamination from the motion of the boat induced by wave activity (Lozovatsky et al., 2006). The MSS-90 samples at a rate of 1024 Hz with a typical fall speed of 0.5 m s^{-1}. Such high frequency measurements allow for great confidence in the estimate of ε. Common to the use of these instruments, the error associated with each measurement is around $\pm 50\%$ (Rippeth and Inall, 2002; Simpson et al., 1996). It should be noted that with moderate turbulence generating values for ε of around 10^{-6} W kg^{-1}, such as would be observed at L4, it is readily shown that the uncertainty with each measurement is low (e.g. (Prandke, 2005)).

2.3. Holographic camera

An in-line digital holographic imaging system, the holocam, was also deployed. The holocam is mounted on a steel frame along with a CTD,

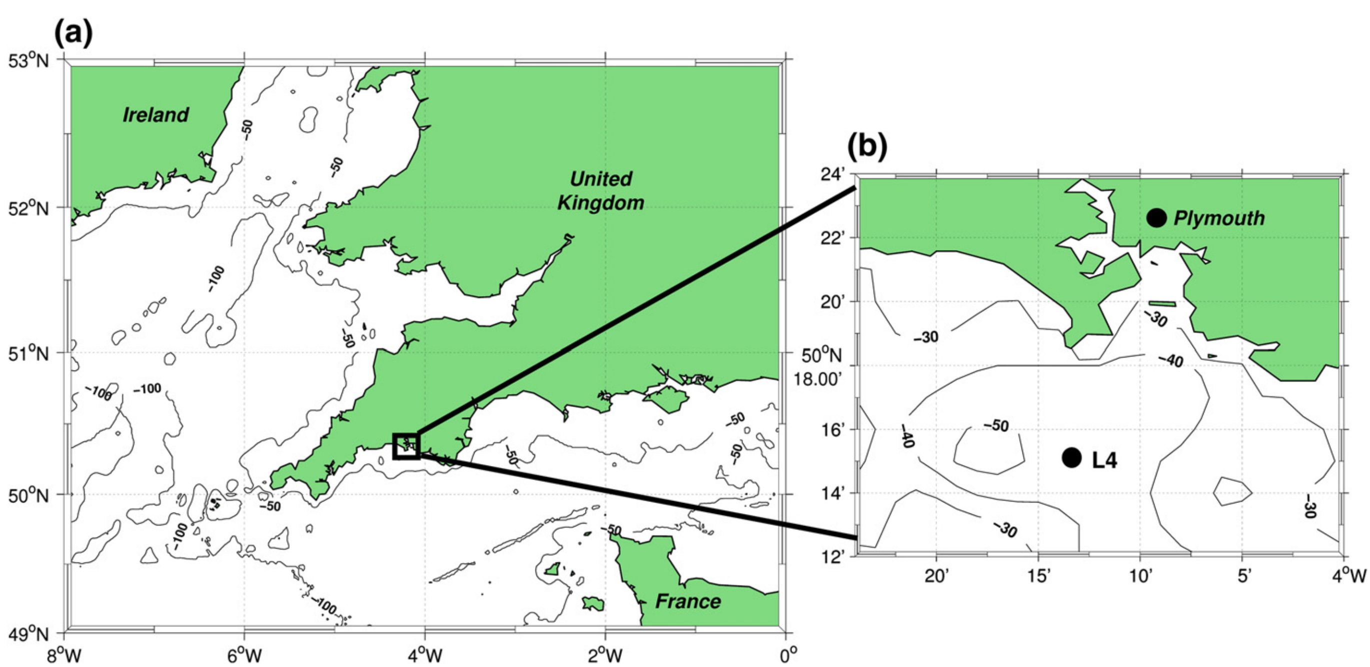

Fig. 1. Map of the southern part of the United Kingdom (a) with exploded section noting the location of Station L4, approximately 10 km south of Plymouth (b).