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Turbulence characteristics inferred from time-lagged satellite imagery of surface algae in a shallow tidal sea

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ABSTRACT

A pair of time-lagged satellite images of surface algae in the Great Barrier Reef lagoon is used to investigate characteristics of the horizontal velocity field at a spatial resolution as small as 4 m. A distinctive feature is the occurrence of surface patches that are relatively clear of algae and which grow in size. These patches are interpreted as resulting from the horizontally diverging motion associated with boils. The surface divergence in such boils can be as large as $\sim 0.01\ s^{-1}$, as deduced directly from the imagery. Overall, root-mean-squared values of divergence, vorticity, and strain rate are 45, 58, and 170, respectively, when normalized by the Coriolis parameter. By observing the algae and its fluid environment simultaneously, the analysis thus provides a glimpse of how underlying hydrodynamic processes help shape the distribution of surface algae — under the calm winds that favor the formation of dense surface aggregations.

1. Introduction

Flow turbulence occurring on the continental shelf and in shallow seas affects the dispersion of pollutants and the distribution of sediment and algae, and contributes to the replacement of surface waters from depth (Nimmo Smith et al., 1999; Thorpe et al., 2008). Originating in the shear layer at the seabed (Steele et al., 2016), turbulence is carried upward through the water column in intermittent bursts, which can sometimes be detected visually as clouds of re-suspended sediment (Nimmo Smith et al., 1999). In weakly stratified water, bursts impinge on the sea surface to produce boils — patches of horizontally diverging motion in which any floating material is forced radially outwards.

In this note, we investigate whether the effects of such macro-scale turbulent motion can be detected in the fine-scale distribution of surface algae. The study area (Fig. 1a) lies within the Great Barrier Reef lagoon, a shallow (~ 30-m deep) tidal sea located between the Australian mainland and outer reefs. The dataset we examine is of an unusual kind, as it consists of an along-track “stereo” pair of multispectral images from the WorldView-3 satellite (DigitalGlobe, Inc.). A sub-scene from one of the pair is shown in Fig. 1b. Such stereo, or time-lagged, data are typically used to construct digital elevation models of land features, so using such imagery to investigate oceanographic phenomena is a novel application. The high spatial resolution of the imagery coupled with a typical time lag of about one minute between the first and second views of a scene allow a detailed portrayal of the velocity field provided a suitable passive tracer is present in the water (Delandmeter et al., 2017; Marmorino et al., 2017). In addition, because different spectral bands penetrate to different depths within the water column, it is possible to differentiate the distribution of surface material such as floating algae from that of deeper suspended material.

2. Approach

2.1. Satellite data

Satellite data were collected on 5 March 2015 at $t_1 = $ 00:03:51 UTC and $t_2 = $ 00:04:42 UTC. The time difference between the two images is thus $\Delta t = t_2 - t_1 = 51$ s. The available wavelength bands include eight visible to near-infrared bands (see Table 1), each with a nominal ground sample distance (GSD) at nadir viewing of 1.24 m, and one panchromatic band having a GSD of 0.31 m. Spatial resolution after resampling to a uniform UTM map grid is 2-m pixels for bands 1–8 and 0.5-m pixels for the panchromatic data. The RGB image shown in Fig. 1b portrays bands 6, 3, and 2. (To see the entire image scene go to https://browse.digitalglobe.com/imagefinder/, then click on “Catalog”, and enter 1040010008249A00.) Band 6, which is the “red edge” band, senses radiation at wavelengths of 706–746 nm, corresponding to a penetration depth in pure water of about 0.75 m (Table 1). Red edge refers to the abrupt increase in near-infrared reflectance from vegetative cellular structure. The orange coloration in Fig. 1b results from the red-edge component and thus indicates areas where dense aggregations of algae are floating at, or very near, the sea surface. Bands 2 and 3

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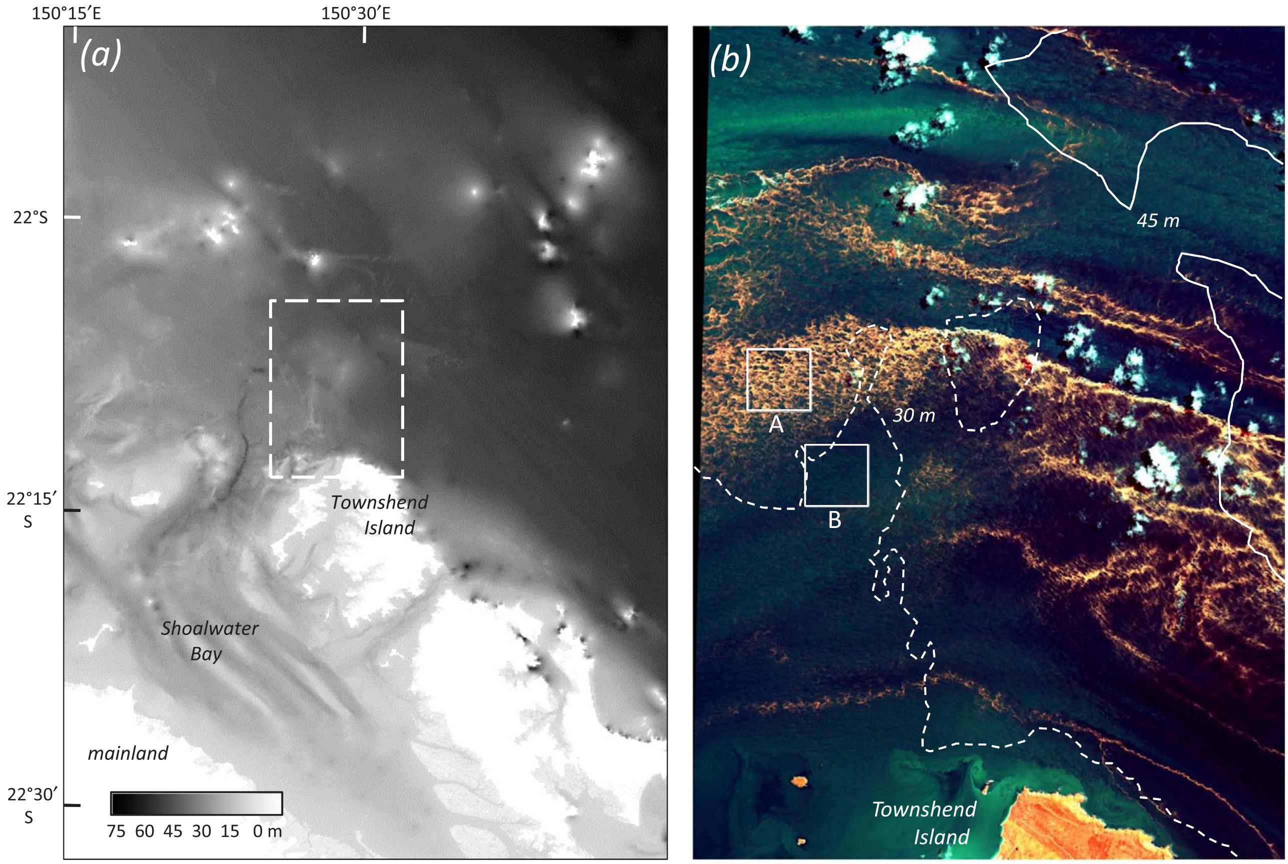

Fig. 1. (a) Study area bathymetry (Beaman, 2010); scale shows depth in meters. (b) Sub-scene of WorldView-3 imagery (DigitalGlobe, Inc.) collected on 5 March 2015 in the area of the dashed rectangle in (a). Orange-colored water areas derive from the red-edge spectral band and indicate aggregations of algae. Areas A and B, each 1 km × 1 km in extent, are examined in Section 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Wavelength bands for the WorldView-3 sensor. Right-most column is the band-averaged penetration depth based on the inverse attenuation coefficient for pure water; value for the panchromatic band is an estimate based on the published spectral response function for the sensor.

Band		Wavelength [nm]	c^{-1} [m]
1	Coastal	400–452	86.79
2	Blue	448–510	58.01
3	Green	518–586	17.03
4	Yellow	590–630	4.37
5	Red	632–692	2.61
6	Red edge	706–746	0.75
7	Near-infrared-1	772–890	0.33
8	Near-infrared-2	860–1040	0.07
Pan	Panchromatic	450–800	8.6

(blue and green wavelengths) penetrate much farther into water than the red-edge band, and can provide information from deeper within the water column, or from the bottom itself in some areas. White areas in Fig. 1b are cumulus clouds. Because of parallax, the location of a cloud in one view of the scene is considerably different in the other; the net effect being that the total area contaminated by clouds is approximately doubled when both images are considered together. Two areas for detailed analysis were thus chosen from a relatively cloud-free part of Fig. 1b: area A, located within a dense algal aggregation; and area B, located nearby but outside the dense aggregation. Because the panchromatic band has higher spatial resolution, it will be used to estimate the velocity field; but, because of its wide spectral response, some attention is needed as to what the data portray. That will be discussed in Section 3.1.

2.2. Environmental background

The algae depicted in the imagery are most likely the cyanobacteria *Trichodesmium* spp., as it is common to the study area and the only algae to form locally large-scale, dense surface aggregations (Furnas, 1992; McKinna et al., 2011; McKinna, 2015). Extensive aggregations of *Trichodesmium* are favored in warm water and during extended periods of calm winds. In our case, daily-mean surface water temperatures in the lagoon were consistently above 27 °C and southeast winds (measured at Middle Percy Island: 21°40' S, 150°16' E) were less than 3 m s^{-1} for 10 h prior to the satellite overpass. There were no nearby measurements of stratification, but the water column in the lagoon is typically well mixed (Furnas, 1992; Wolanski, 1994). Mean water depth is 33.6 m in area A (29.4 m in area B), and the seabed has an irregular roughness with root-mean-square (rms) amplitude of 2.3 m. Currents are primarily tidally forced, and results from a numerical hydrodynamics model (www.climate.be/slim) show that the tidal current ellipse in the study area is highly elongated in the east-west direction. At the time the imagery was collected the tide was nearing the end of flood, so the flow direction can be expected to be westward; and sea level was about 1.5 m above the mean, so the total water depth would have been 35.1 m in area A (30.9 m in B).

2.3. Deriving velocity from the imagery

Currents are derived from the image pair using a normalized cross-correlation algorithm (Tseng et al., 2012), which is implemented as a particle-image-velocimetry (PIV) "plugin" to the ImageJ processing and analysis package (Schneider et al., 2012). In this algorithm an $n \times n$ pixel-sized interrogation window in the t_1 image is compared against a