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Turbid wakes associated with offshore wind turbines observed with Landsat 8

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ABSTRACT

In the last decade, the number of offshore wind farms has increased rapidly. Offshore wind farms are typically constructed in near-shore, shallow waters. These waters can be highly productive or provide nursery grounds for fish. EU legislation requires assessment of the environmental impact of the wind farms. The effects on hard and soft substrate fauna, seabirds and marine mammals are most frequently considered. Here we present Landsat-8 imagery that reveals the impact of offshore wind farms on suspended sediments. Turbid wakes of individual turbines are observed that are aligned with tidal currents. They are 30–150 m wide, and several km in length. The environmental impact of these wakes and the source of the suspended material are still unclear, but the wake size warrants further study. The underwater light field will be affected by increased suspended sediments and the turbid wakes could significantly impact sediment transport and downstream sedimentation. The question of whether such features can be detected by other remote sensors is addressed by a theoretical analysis of the signal:noise specification for the Operational Land Imager (OLI), the Enhanced Thematic Mapper Plus (ETM+), the Advanced Very High Resolution Radiometer (AVHRR/3), the Moderate-Resolution Imaging Spectroradiometer (MODIS), the Spinning Enhanced Visible and Infrared Imager (SEVIRI), the Flexible Combined Imager (FCI) and the Multispectral Instrument (MSI) and by a demonstration of the impact of processing OLI data for different spatial resolutions.

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1. Introduction

The first offshore wind farm was opened by Denmark in 1991, and consisted of 11 turbines with a combined capacity just under 5 MW (EWEA, 2011). For the next ten years, the construction of offshore wind farms was sporadic and limited to small-scale projects. After 2001, the installed capacity in Europe increased rapidly and by the end of 2012, 55 offshore wind farms were operational in Europe, with more than 1600 turbines and a total capacity just less than 5 GW, or 90% of the world total (EWEA, 2013). The United Kingdom had a 59% share in the European capacity, or over half of the world total, provided by 870 turbines on 20 farms (EWEA, 2013). This includes the two largest operational farms in the world: the London Array (630 MW) and the Greater Gabbard (504 MW). Both are located in the southern North Sea (SNS), as is in fact more than 40% of the world's offshore wind farm capacity: the combined nameplate capacity of seven farms in Belgian and UK waters is almost 2.2 GW (Table 1). There are currently five wind farms in and around the Thames estuary, two of which will be studied in more detail in this paper: the London Array and Thanet. Both have a large number of turbines supported by steel monopiles 4–7 m in diameter, piled up to 40 m in the seafloor (LORC, see reference in Table 1). In the EU, offshore wind farm projects are subject to the directives on Strategic Environmental Assessment (SEA, 2001/42/EC) and Environmental Impact Assessment (EIA, 85/337/EEC and amendments). Environmental surveying carried out before, during, and after construction allows for mitigation of adverse effects of wind farms.

Mapping of surface Suspended Particulate Matter concentration (SPM), also called Total Suspended Matter (TSM), has been routinely made using data from dedicated wide-swath ocean color instruments such as Orbview-2/SeaWiFS, Aqua/MODIS and ENVISAT/MERIS (e.g. Gohin, 2011; Nechad, Ruddick, & Park, 2010; Ouillon et al., 2008; Van der Woerd & Pasterkamp, 2004). These instruments offer a good compromise between revisit time (approx. daily at 50°N) and spatial resolution (ranging between 0.25 and 4 km). Marine reflectance in a single red channel can be used to reliably retrieve a wide range of SPM concentrations in the SNS (Nechad, Alvera-Azcaràte, Ruddick, & Greenwood, 2011; Vanhellemont, Greenwood & Ruddick, 2013). While few sensors are designed for ocean color, other satellite-borne passive optical instruments with a red and near-infrared channel have also been used for SPM mapping. Generally they have a lower quality than e.g. MODIS and MERIS, due to their lower signal-to-noise ratio, but are used when a higher spatial (e.g. Doxaran, Froidefond, Lavender, & Castaing, 2002; Mertes, Smith, & Adams, 1993) or temporal (Neukermans et al., 2009) resolution is required. Even before the ocean color era, passive imagers were used for turbidity mapping (e.g. Amos & Alföldi, 1979; Rouse &

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Table 1
Seven wind farms in the southern North Sea, listed by nameplate capacity.
Source: Lindoe Offshore Renewables Centre, LORC, Offshore Wind Farms Map, http://www.lorc.dk/offshore-wind-farms-map/list, accessed 2013-10-14.

Name/phase (Country)	Coordinates	Capacity	Turbines	Depth	Installed
1. London Array/1 (UK)	51.63° N, 1.50° E	630 MW	175	0–25 m	2009–2013
2. Greater Gabbard (UK)	51.88° N, 1.94° E	504 MW	140	24–34 m	2009–2012
3. Thornton Bank/1 + 2 + 3 (BE)	51.55° N, 2.94° E	325 MW	54	12–28 m	2008–2013
4. Thanet (UK)	51.43° N, 1.63° E	300 MW	100	20–25 m	2009–2010
5. Gunfleet Sands (UK)	51.73° N, 1.24° E	172 MW	48	0–15 m	2008–2010
6. Belwind/1 (BE)	51.67° N, 2.80° E	165 MW	55	20–27 m	2009–2010
7. Kentish Flats/1 (UK)	51.46° N, 1.09° E	90 MW	30	5 m	2004–2005
Total		2186 MW	602		

Coleman, 1976; Stumpf & Pennock, 1989). The suitability of the Operational Land Imager on Landsat 8 (L8/OLI) for coastal zone monitoring has been demonstrated using simulated data (Gerace, Schott, & Nevins, 2013; Pahlevan & Schott, 2013).

On imagery with sufficient spatial resolution, large vessels and offshore constructions, such as wind turbines, can be easily distinguished (for example in Fig. 1), as they are highly reflective structures on a dark background (water). In the present study, imagery from Landsat 8 also reveals significant modification of near-surface suspended sediment concentration in the form of turbid wakes extending up to several km downstream of turbines installed offshore of the Thames estuary.

2. Methods

2.1. Study area

The southern North Sea (SNS) is a shallow sea (<50 m) with a sharp gradient of suspended particulate matter concentrations (SPM) from >100 g m^{-3} in the near-shore waters to <0.5 g m^{-3} offshore. Tidal

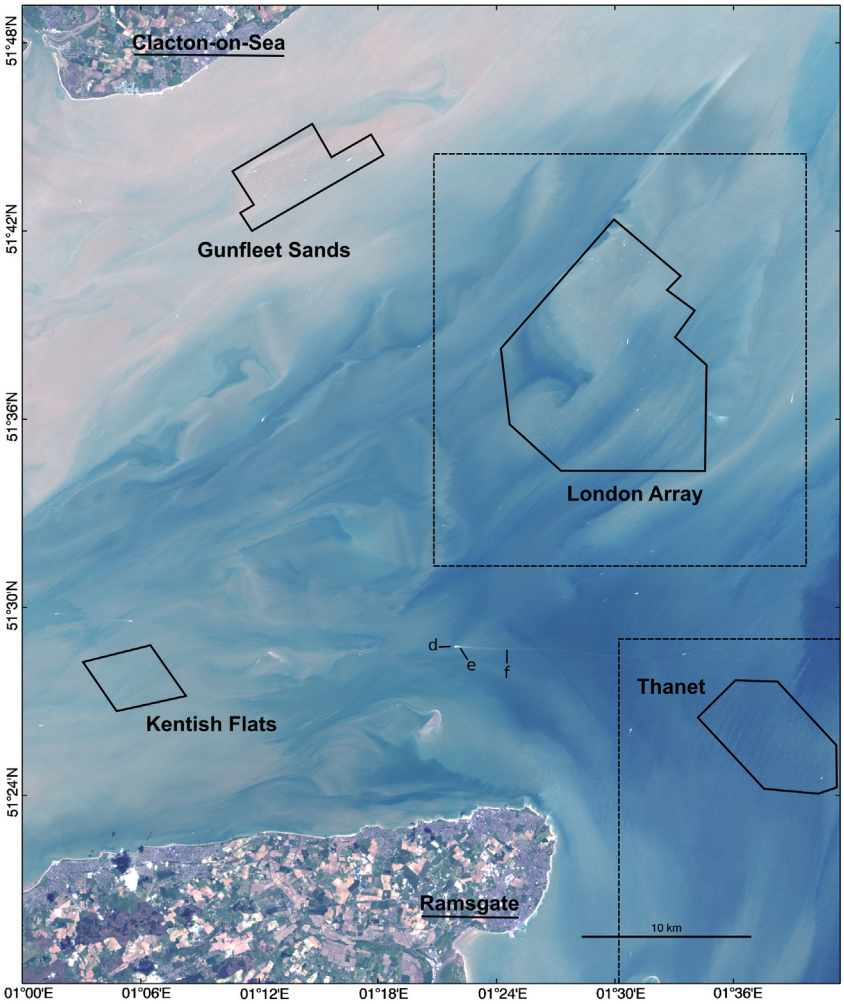

Fig. 1. RGB composite (channels 4-3-2) of a part of the L8/OLI image on 2013-04-28 at 10:54 UTC, showing the suspended sediments (brown-reddish colors) in the Thames estuary. Large ships can be seen as white spots, sometimes with an attached wake. Four wind farms are marked: the London Array, Thanet, Gunfleet Sands and Kentish Flats. Coverage of Figs. 6 and 7 (partially) is shown by the dashed lines. Spectra for points d, e and f are shown in Fig. 5.

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