Progress in Oceanography 156 (2017) 154–173

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Pelagic effects of offshore wind farm foundations in the stratified North Sea

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A R T I C L E I N F O

Article history:
Received 8 February 2017
Received in revised form 4 May 2017
Available online 12 July 2017

Keywords:
Offshore wind farms
TRIAXUS ROTV
Offshore structures
Pelagic environment
Chlorophyll
North Sea

A B S T R A C T

A recent increase in the construction of Offshore Wind Farms (OWFs) has initiated numerous environmental impact assessments and monitoring programs. These focus on sea mammals, seabirds, benthos or demersal fish, but generally ignore any potential effects OWFs may have on the pelagic ecosystem. The only work on the latter has been through modelling analyses, which predict localised impacts like enhanced vertical mixing leading to a decrease in seasonal stratification, as well as shelf-wide changes of tidal amplitudes. Here we provide for the first-time empirical bio-physical data from an OWF. The data were obtained by towing a remotely operated vehicle (TRIAXUS ROTV) through two non-operating OWFs in the summer stratified North Sea. The undulating TRIAXUS transects provided high-resolution CTD data accompanied by oxygen and chlorophyll-*a* measurements. We provide empirical indication that vertical mixing is increased within the OWFs, leading to a doming of the thermocline and a subsequent transport of nutrients into the surface mixed layer (SML). Nutrients were taken up rapidly because underwater photosynthetically active radiation (PAR) enabled net primary production in the entire water column, especially within submesoscale chlorophyll-*a* pillars that were observed at regular intervals within the OWF regions. Video Plankton Recorder (VPR) images revealed distinct meroplankton distribution patterns in a copepod-dominated plankton community. Hydroacoustic records did not show any OWF effects on the distribution of pelagic fish. The results of a pre-OWF survey show however, that it is difficult to fully separate the anthropogenic impacts from the natural variability.

1. Introduction

In 2015 offshore wind power installations represented 24% of the annual EU wind energy market, and the number of new installations continues to increase (Corbetta et al., 2016). As of the summer of 2016 a total of 3344 offshore wind turbines in 82 wind farms across 11 European countries were fully connected to the grid, providing a combined capacity of 11,538 MW (Pineda and Ruby, 2016). The German strategic goal of 80% renewable energy supply by 2050 is partly based on the production of offshore wind energy within the German Exclusive Economic Zone (EEZ (EEG, 2014)). Germany has the largest installed wind power capacity (45 GW) in the EU, and installed 6 GW in 2015 alone, of which 38% were offshore (Corbetta et al., 2016). In the German EEZ 18 wind farm projects with a total of 1285 turbine foundations are either approved, in operation or under construction (BSH, 2015). The political objective (EEG, 2014) of an installed offshore wind power capacity of 15 GW by 2030 will lead to a further advance of offshore wind farm (OWF) development at greater distances from the coast to mitigate environmental impacts and changes in the characteristic landscape.

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http://dx.doi.org/10.1016/j.pocean.2017.07.003

As part of the approval procedure for OWFs in the German EEZ, potential adverse impacts of the planned facilities on the marine environment have to be assessed through an Environmental Impact Assessment (EIA). The German EIA standard (StUK4; BSH, 2013) only considers ecosystem components that have conservation relevance, i.e. demersal fish, benthos, birds, and marine mammals. The investigation or monitoring of the potential effects of OWFs on the pelagic ecosystem is not mandatory. Thus, only a limited number of studies have analysed OWF effects on the pelagic ecosystem, and even fewer include field measurements. One such study, at the OWF alpha ventus (45 km off the coast at a water depth < 30 m), measured oceanographic parameters and currents at a fixed station. The distribution of pelagic fish was also monitored with a horizontally oriented hydroacoustic system (Krägefsky, 2014). The observations revealed that during August 2007 pelagic fish, most likely mackerel, had their highest abundances within 100 m of underwater construction sites (Schröder et al., 2013).

Most other studies have been analytical and modelling studies, whose results suggest OWFs induce changes in vertical water column dynamics and subsequently key biological processes. In one of the first studies on OWF impacts on upper ocean hydrography, Broström (2008) analytically showed that the extraction of energy from the wind creates an upwelling/downwelling dipole in the surface mixed layer through divergence in the Ekman transport. Broström (2008) concluded that water surface wind stresses at a speed of 5–10 m s^{-1} may generate vertical water velocities exceeding 1 m day^{-1} and that the generated upwelling is able to affect the ambient ecosystem. Nerge and Lenhart (2010) simulated an artificial OWF within a three-dimensional model of shelf sea dynamics (Backhaus, 1985; Pohlmann, 1996, 2006). They confirmed the creation of an upwelling/downwelling dipole using a more realistic meteorological forcing and concluded that an OWF could have the potential to alter the seasonal development of tidal fronts, but they did not consider subsequent ecological impacts. Field measurements to assess potential OWF impacts on nutrient dynamics, plankton distribution and production have not yet been conducted.

Paskyabi et al. (2012) showed that the dipoles are sensitive to wind stress, wave forcing and the size of the OWF, and have a tendency to become asymmetric with time. Simulations showed that the winds and wind-driven waves passing a large OWF generate downstream eddies of a similar size as the OWF and their time scale is up to several days (Paskyabi and Fer, 2012). Ludewig (2015) used a 3D hydrodynamic model with realistic atmospheric forcing to show that a small OWF with 12 turbines could affect the upper ocean dynamics within 100 km on the leeside and that the upwelling/downwelling cells could have a diameter of 15 km. In addition to wind-wake effects, underwater structures may impact the local hydrodynamics.

Lass et al. (2008) measured enhanced mixing downstream of a pile in an estuarine flow in the Baltic Sea. While the simulations of Paskyabi et al. (2012) had eddies the size of an OWF, Lass et al. (2008) observed enhanced mixing and eddies with a characteristic diameter of the monopile and a frequency corresponding to a von Kármán vortex street (see also Grashorn and Stanev, 2016). Rennau et al. (2012) applied a numerical model to assess monopile induced mixing in a dense bottom current, representative of the western Baltic Sea. They calculated an additional vertically integrated positive buoyancy production in an area on the order of 10 monopile diameters. However, the impact of structure-induced mixing due to realistic wind farm distributions was rather low, with a typical decrease in the bottom water salinity in the range of 0.1–0.3. Most recently, Cazenave et al. (2016) applied a 3D unstructured grid model (FVCOM) to focus solely on the impact of the physical presence of the turbine monopiles. In a mixed or stratified eastern Irish Sea, the effects of 242 wind turbine monopiles from 7 OWFs were explicitly described within the tidal current regimes from January and May 2011. The spatial resolution increased from 2.5 m to 10 km with distance from the monopiles. A resulting 5% reduction of horizontal maximum current speed was found within a radius of 1 km, i.e., approximately 250 times the monopile diameter. Monopiles were found to increase local vertical mixing within a radius of only 200 m, but an OWF was found to have a 5–15% impact on stratification in May 2011, affecting an area approximately 80,000 times larger than the footprint of its 162 monopiles. In contrast, Carpenter et al. (2016) concluded that OWFs are expected to have very little impact on large-scale stratification at the current capacity in the North Sea. Their study used order of magnitude estimates of mixing and advection time scales, and compared their results for water bodies with OWFs to natural stratification variability. However, if development continues as predicted, the impact of OWFs could become significant at the OWF scale and at the southern North Sea scale. As concluded by Clark et al. (2014), observational studies on the bio-physical impacts of OWFs on the pelagic ecosystem are still missing, yet they are necessary to validate model results. Therefore, we provide for the first empirical results from a bio-physical survey of two OWFs in the North Sea during the summer stratification period. As a follow-up to previous theoretical and modelling investigations, the key objective of the survey was to provide initial empirical indication of potential OWF foundation effects on:

1. ambient hydrography
2. local nutrient concentrations
3. light availability and primary production
4. zooplankton and pelagic fish distribution.

A high-speed remotely operated towed vehicle (ROTV) TRIAXUS system was deployed to identify potential impacts of wind turbine foundations. As the OWFs were not operating, the results only consider the effects of the interactions of the foundations with tidal and wind driven currents. We covered an area within approx. 20 km of the OWFs and obtained high resolution abiotic and biotic data, including temperature, chlorophyll-a fluorescence, nutrients, and the abundance and distribution of plankton and pelagic fish. Particle drift modelling was conducted to hindcast the trajectories of the sampled water bodies and calculate OWF contact times. In addition, the observations were compared with model predictions and with hydrographic measurements conducted during a previous summer cruise, before the OWFs were built.

2. Material & methods

2.1. Surveys

Field measurements were conducted during a summer cruise (HE429, July 19–24, 2014) with the RV Heincke. The two OWFs that were surveyed, Global Tech I (GTI) and BARD Offshore 1 (BARD), are located at a water depth of around 40 m in the German EEZ, and a distance of approx. 100 km offshore. Both OWFs had 80 wind power plants installed, GTI has tripod foundations and BARD has tripile foundations. The turbines were not in operation and the rotors were not turning, i.e., any observed effects are solely attributed to the foundations and changes in the wind field due to the static presence of the piles, turbines and rotors.

On the 14th of July 2010, two years before construction of the OWF GTI, the RV Heincke made a North-South ROTV transect through the area. The then recorded ScanFish ROTV data therefore provides a baseline to get indications of any potential OWF effects.