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Detecting small–scale horizontal gradients in the upper ocean using wavelet analysis

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ABSTRACT

Mesoscale and submesoscale eddies and fronts in the upper ocean are often closely coupled with biogeochemical processes. Improved instrumentation provides high–resolution data in both the horizontal and vertical capturing this large range of scales (1–100 km), but novel analysis methods are still needed to take full advantage of this advancement. A new method using wavelet analysis is therefore proposed to identify the horizontal scales at which biophysical interactions occur, defined by concurrent fluctuations in temperature and phytoplankton patchiness. The method is applied to temperature and chlorophyll–a fluorescence data measured in the North Sea's German Bight during early spring using a towed undulating vehicle. The wavelet analysis identified the scale and location of individual features characterized by horizontal gradients of temperature and chlorophyll–a fluorescence. Applied to multiple transects, the method can also retrieve the statistics of relevant biophysical scales in a particular region. The combined analysis of seven transects suggests that physical and biogeochemical tracers tend to align at scales of 3–15 km in the German Bight, highlighting the likely relevance of submesoscale processes in this region. In general, the proposed wavelet analysis method is shown to be a robust tool for the analysis of biophysical interactions across a range of scales.

1. Introduction

Coastal oceans are the most productive oceanic regions yet face particularly high external pressures due to large human populations, agricultural and industrial runoff, ship traffic, and offshore industry such as wind farms and oil drilling. In addition, coastal regions may be severely impacted by the effects of climate change (Field et al., 2015). In order to predict, mitigate and adapt to these pressures, an improved understanding of the functioning of complex coastal ocean ecosystems is essential (Weisberg et al., 2015). In particular, recent studies suggest the need to understand the role of submesoscale to mesoscale physical processes as drivers of biogeochemical processes, thus influencing the abundance and distribution of phytoplankton, zooplankton and higher trophic levels (e.g., Bost et al., 2009; Grados et al., 2012; Lévy and Martin, 2013; Bertrand et al., 2014; Rutterford et al., 2015).

The German Bight region of the North Sea is a prime example of such a complex coastal ocean system (Fig. 1) that has been influenced by human activity for centuries. It is characterized by the large freshwater input of the Elbe River and some smaller rivers (van Leeuwen et al., 2015), a strong tidal exchange with the intertidal mudflats of the Wadden Sea (Flöser et al., 2011; Van Beusekom et al., 2012) and river mouth estuaries, shallow water depths (<50 m), and a highly variable stratification (van Leeuwen et al., 2015). In addition, the region experiences significant change, such as the installation of extensive offshore wind farms and the effects of climate change. These effects include increasing surface water temperature (Wiltshire et al., 2010) and a rise in regional sea level (Albrecht et al., 2011). A greater understanding of biophysical connections will help to improve the design and interpretation of regional monitoring programs and observation systems, including fish observatories, and the setting of baselines for comparing water properties before and after the installation of offshore wind farms. Although phytoplankton patchiness has been a topic of interest for decades in the North Sea (e.g., Mackas and Boyd, 1979; Horwood, 1981), connections to the physical drivers of this patchiness are still unclear, as it is not trivial to identify links between phytoplankton patchiness and physical processes.

A recent review by Lévy et al. (2012) highlighted this difficulty, specifically the shortcomings of traditional measurement and analysis methods to cover a broad range of scales. Traditional

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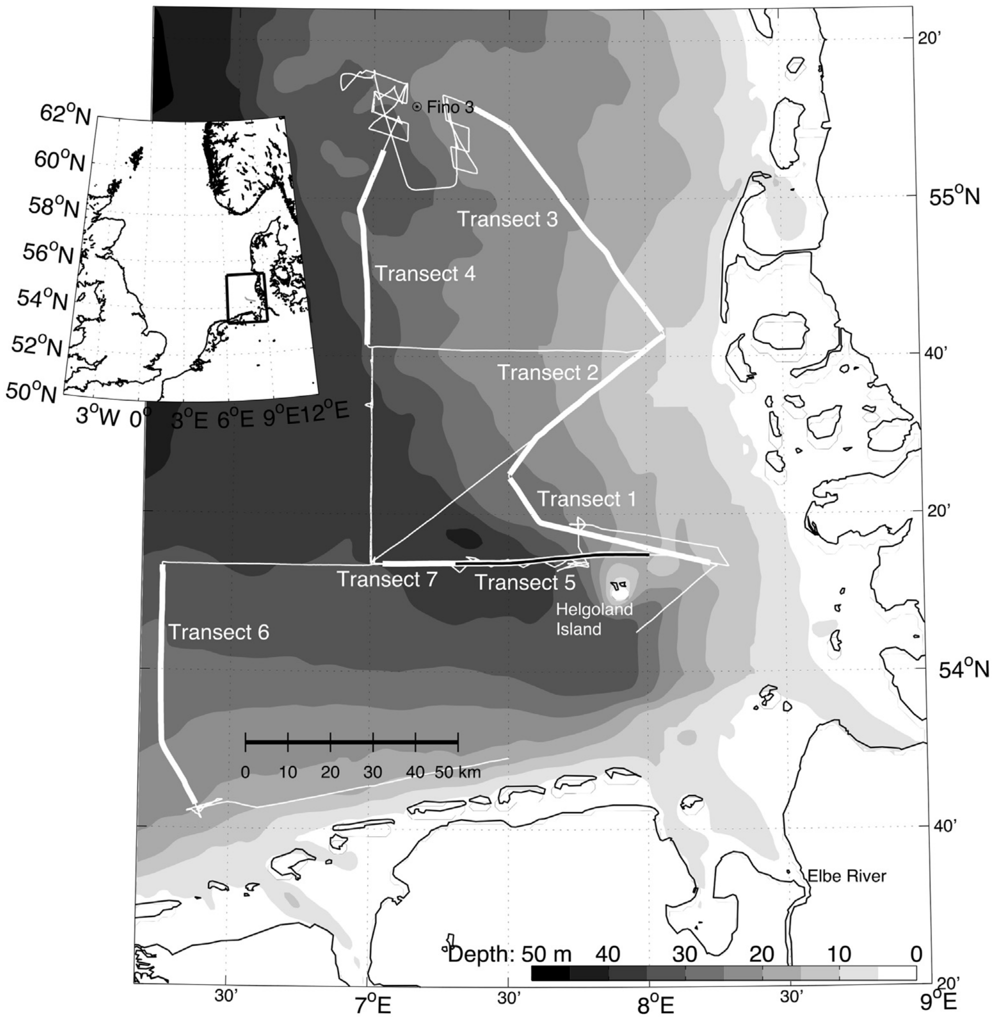

Fig. 1. Map of the German Bight in the southeastern North Sea, showing the cruise track of the RV *Heincke* during the 6–day campaign in April 2013 (thin white line). The thick white lines and the black line show the location of the transects, as labeled. Transects 5 (black line) and 7 follow nearly the same path, but on different days. Filled contours show the bathymetry. The inset shows a map of the North Sea with a black square marking the boundaries of the main plot.

oceanographic measurement methods, such as surveys with CTD (conductivity, temperature, depth) profiles produce highly resolved data in the vertical, but cannot properly capture processes with small horizontal scales, such as submesoscale eddies, fronts, and filaments with length scales of $O(0.1)$ km to $O(10)$ km (Buckingham et al., 2016). However, recent studies suggest that submesocale processes play an important role in the downscaling of the ocean's energy (e.g., Capet et al., 2008; Poje et al., 2014), contribute to the subduction of organic carbon (Omand et al., 2015), and are zones of elevated concentrations of phytoplankton and zooplankton (e.g., Lévy et al., 2001; Shulman et al., 2015), as well as fish, sea birds, and marine mammals (e.g., Bertrand et al., 2014; Lowther et al., 2014). Submesoscale features may therefore be an important driver of phytoplankton patchiness through (1) horizontal and vertical advection of phytoplankton cells, (2) an increase in the vertical transport of nutrients to the photic zone, or (3) a combination of the two (Lévy et al., 2001, 2012; Shulman et al., 2015).

A typical traditional analysis of spatial scales compares the spectral slopes of biological tracers with physical tracers known to control biological variability. The method assumes that for scales at which the two tracers have the same spectral slope, it is likely that the same process controls their variability. However, this type of analysis is difficult to interpret and the slope is not a reliable indicator of flow structure, potentially producing misleading results (Armi and Flament, 1985).

Novel measurement and analysis methods are therefore needed to properly capture horizontal variability in the coastal ocean across a wide range of scales, and in particular at small spatial scales. Therefore, the goal of this study was to develop a method capable of identifying the horizontal scales at which biophysical interactions may occur, defined hereafter as concurrent fluctuations in temperature and phytoplankton patchiness. Measurements were obtained with a towed–undulating system, measuring physical and biogeochemical variables at $O(100)$ m horizontal and $O(1)$ m vertical resolutions. The measured data were analyzed using wavelet analysis to identify scales that may be relevant to biophysical interactions. Applied to a spatial signal, wavelet analysis determines the spatial variability of the signal's spectra, as well as the coherence and phase relationship between two signals. Wavelet analysis of coastal and ocean data is a relatively new field, but its applicability continues to grow (e.g., Hodges and Rudnick, 2006; Winder and Cloern, 2010; Grados et al., 2012; Bertrand et al., 2014).

Using the German Bight of the North Sea as a test case, the study aims to answer the following questions: Does the data show significant horizontal variability in physical and biogeochemical tracers? Can wavelet analysis be used to identify the horizontal