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Variation that can be expected when using particle tracking models in connectivity studies

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ABSTRACT

Hydrodynamic Ocean Circulation Models and Lagrangian particle tracking models are valuable tools e.g. in coastal ecology to identify the connectivity between offshore spawning and coastal nursery areas of commercially important fish, for risk assessment and more for defining or evaluating marine protected areas. Most studies are based on only one model and do not provide levels of uncertainty. Here this uncertainty was addressed by applying a suite of 11 North Sea models to test what variability can be expected concerning connectivity. Different notional test cases were calculated related to three important and well-studied North Sea fish species: herring (*Clupea harengus*), and the flatfishes sole (*Solea solea*) and plaice (*Pleuronectes platessa*). For sole and plaice we determined which fraction of particles released in the respective spawning areas would reach a coastal marine protected area. For herring we determined the fraction located in a wind park after a predefined time span. As temperature is more and more a focus especially in biological and global change studies, furthermore inter-model variability in temperatures experienced by the virtual particles was determined. The main focus was on the transport variability originating from the physical models and thus biological behavior was not included. Depending on the scenario, median experienced temperatures differed by 3 °C between years. The range between the different models in one year was comparable to this temperature range observed between modelled years. Connectivity between flatfish spawning areas and the coastal protected area was highly dependent on the release location and spawning time. No particles released in the English Channel in the sole scenario reached the protected area while up to 20% of the particles released in the plaice scenario did. Interannual trends in transport directions and connectivity rates were comparable between models but absolute values displayed high variations. Most models showed systematic biases during all years in comparison to the ensemble median, indicating that in general interannual variation was represented but absolute values varied. In conclusion: variability between models is generally high and management decisions or scientific analysis using absolute values from only one single model might be biased and results or conclusions drawn from such studies

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need to be treated with caution. We further concluded that more true validation data for particle modelling are required.

1. Introduction

Major questions in marine biology and habitat conservation have always been: where do species come from, where do they go to, how are marine habitats, nurseries and spawning areas connected, how do environmental factors influence marine animals and what kind of environment do different species experience (e.g. Caley et al., 1996; Christensen et al., 2008; Siegel et al., 2008; Jakobsen et al., 2009). In oceanography, marine chemistry and risk assessment, the tracing of water masses, chemicals, pollutants, lost cargo or castaways has motivated the development and improvement of ocean circulation models (OCMs) (Hackett et al., 2006). Indeed, these models are vital to understand complex environments where observations are scarce, available samples are patchily distributed, sampling is too expensive or other tools and methods are simply not existent. Thus OCMs and especially Lagrangian particle tracking modules linked to the OCMs have become more and more used in marine and larval biology since the earliest model drift studies performed e.g. by Bartsch et al. (1989) or later Heath et al. (1997) and van der Veer et al. (1998). Where larvae in these early approaches have been treated generally as "passive" particles different shades of complexity have since then been included and now mimic behavior like selective tidal transport or stage related vertical distribution pattern (Fox et al., 2006; van der Molen et al., 2007; Bolle et al., 2009; Savina et al., 2010; Lacroix et al., 2013), physiology (Daewel et al., 2008; Kühn et al., 2008; Fiksen and Jørgensen, 2011; Daewel et al., 2011a, 2011b) or mortality (see review by Peck and Hufnagl, 2012). With respect to the connectivity criterion of marine protected areas, OCMs and Lagrangian models have recently been used to also advice spatial planning and management in different regions (Delpeche-Ellmann and Soomere, 2013; Munroe et al., 2014; Engie and Klinger, 2007; Koeck et al., 2015). Coastal and shallow areas, are often used by several species as juvenile nursery area while eggs are generally spawned further offshore or in different locations. There is a general interest in understanding how many eggs or larvae are able to reach these coastal nurseries, which would provide valuable information to understand recruitment variability and ecosystem functioning.

Due to overfishing of certain stocks and the increasing anthropogenic influence on the ecosystem, several conservation zones, national parks and protected areas have been established in the past (Habitats Directive, 92/43/EEC from 21 May 1991). The largest one in the North Sea is related to fishing activities: the so called "plaice box" (Fig. 1). This area was established in 1989 (Pastoors et al., 2000) and closed to larger fishing vessels. The main aim of the "plaice box" was to protect flatfish nurseries and juvenile areas, although the benefits have been discussed controversially in the past (see Beare et al., 2010 and references therein).

Recently, the increasing number of areas designated to offshore wind energy generation has challenged marine spatial planners (Douvere and Ehler, 2009; Berkenhagen et al., 2010; Jaques et al., 2011) and the influence of introducing new concrete habitats and closing the designated areas to fishing activity is currently examined concerning the ecological and economic consequences (Boehlert and Gill, 2010; Lindeboom et al., 2011). Fish might get attracted by those areas or remain in their close proximity as soon as they pass them. Thus they would be protected as no fishing is allowed inside these areas. Additionally benthic invertebrates might settle on the hard substrates as soon as they reach the concrete structures. The amount of spat, eggs and larvae transported to and from these wind farms can so far best be analyzed taking the currents around these structures into account.

For the North Sea several OCMs which are suitable for such studies exist (a collection of those used in this study and the respective literature is summarized in Table 1). Some of these models have been developed independently, while some are related and were built upon originally similar equations, parameterizations and grid structures. However, the latter have with time diverged, as the focus of research changed and the models were used to investigate different questions. Thus diversity among models is high, as is the system they are used in and the questions they address. Each of the models performs reasonably

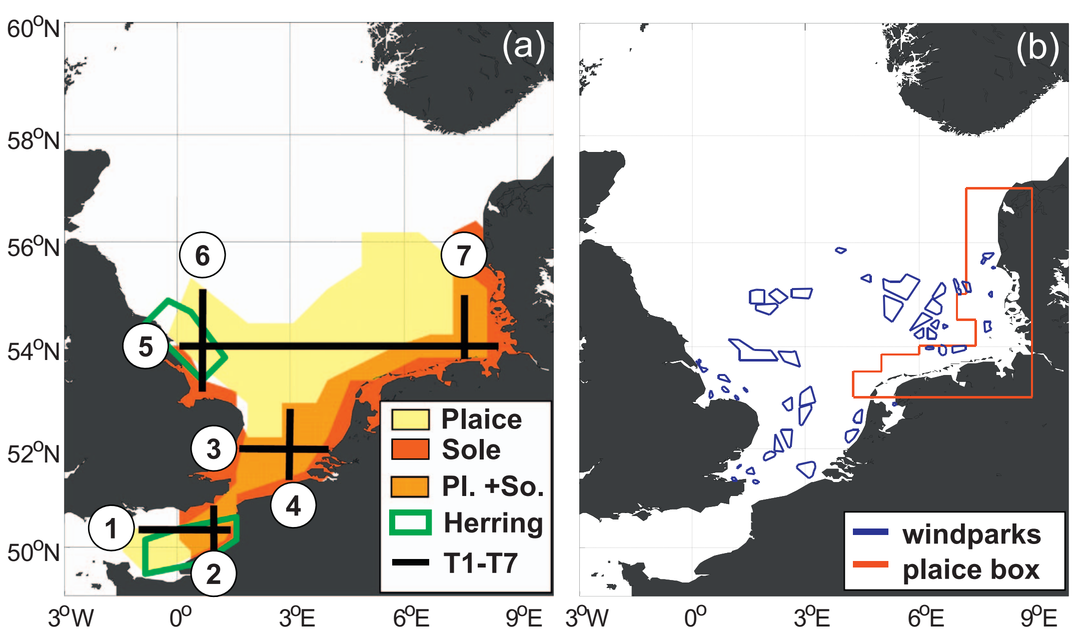

Fig. 1. Left: Spawning areas of plaice (yellow), sole (red), overlapping areas (orange) and herring (green line) in the southern North Sea. Black lines indicate transects T1–T7 defined in Table 2. Right: Location of the plaice box (red) and planned, authorized or fully commissioned wind park areas (blue) in the North Sea. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)