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Can lagrangian models reproduce the migration time of European eel obtained from otolith analysis?

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ABSTRACT

European eel can be found at the Bay of Biscay after a long migration across the Atlantic. The duration of migration, which takes place at larval stage, is of primary importance to understand eel ecology and, hence, its survival. This duration is still a controversial matter since it can range from 7 months to > 4 years depending on the method to estimate duration.

The minimum migration duration estimated from our lagrangian model is similar to the duration obtained from the microstructure of eel otoliths, which is typically on the order of 7–9 months.

The lagrangian model showed to be sensitive to different conditions like spatial and time resolution, release depth, release area and initial distribution. In general, migration showed to be faster when decreasing the depth and increasing the resolution of the model.

In average, the fastest migration was obtained when only advective horizontal movement was considered. However, faster migration was even obtained in some cases when locally oriented random migration was taken into account.

1. Introduction

The European eel (*Anguilla anguilla*, Linnaeus, 1758) is a migratory species that starts its journey at the Sargasso Sea towards the European shelf (Kleckner and McCleave, 1988; Schmidt, 1923; Tesch, 1977) and undergoes one of the longest marine larval migrations (> 6000 km). The worldwide decline in eel population (Dekker et al., 2003), observed over the last decades makes mandatory to understand the duration of migration across the Atlantic.

The Gulf Stream is the main current involved in the dispersion of eel larvae after hatching. The current, which is part of the North Atlantic subtropical gyre, is formed in the eastern part of the Gulf of Mexico, flows through the Straits of Florida and continues along the east coast to Cape Hatteras where it flows away from the continent (Cornillon, 1992). Approximately, at 50°W, the Gulf Stream is split into several branches. The largest one, which is known as the North Atlantic Current, reaches the west coast of Europe and later turns north. The second branch turns south-eastwards to form the Azores Current to finally return and circulate into the subtropical gyre (Brown et al., 2001; Tomczak and Godfrey, 2003).

Considerable effort has been devoted to determine the migration duration of European eel larvae using different methods with estimations ranging from months to years. Thus, based on growth curves, Boëtius and Harding (1985) found a duration of around 1.5 yr. van Utrecht and Holleboom (1985) estimated a migration time ranging from 2 to 6 years using the macrostructure of eel otoliths. Based on the microstructure of eel otoliths, Lecomte-Finiger (1992) and Arai et al. (2000) established a migration of 7–9 months, while Kuroki et al. (2008) suggested a duration of 11 months. Finally, calculations based on lagrangian model also provided a wide range of values. Kettle and Haines (2006) obtained a minimum migration time of about 2 yr, Bonhommeau et al. (2009) concluded that it would be necessary 10 months and 3 days for European eel larvae to cross the Atlantic Ocean and Blanke et al. (2012) obtained a minimum migration time of 285 days. For a complete review of the different methods and the duration of migration of Atlantic eel larvae the reader is referred to Bonhommeau et al. (2010). In summary, estimations range from months to years and the question remains open.

The aim of this study is to determine whether or not the duration of migration obtained from the analysis of the microstructure of eel otoliths could be reconciled with the minimum migration time provided by numerical models. The sensitivity of lagrangian models to different conditions (spatial and time resolution, release depth and initial distribution) and to migration strategies was analyzed. Different migration strategies were considered: (1) passive migration (particles were horizontally advected by currents at a fixed depth); (2) passive migration in

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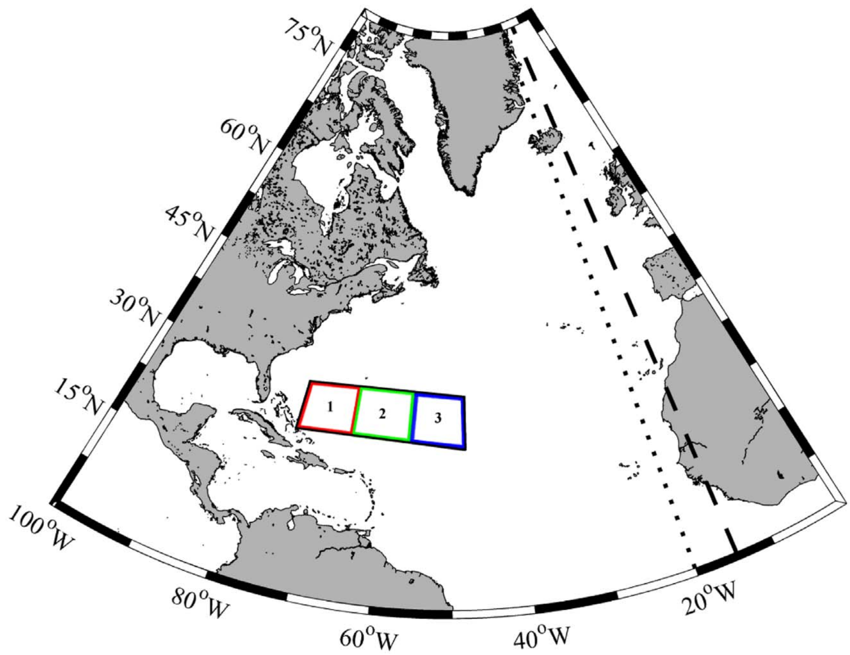

Fig. 1. Area under scope. Map of the North Atlantic Ocean and the release area (black rectangle) in the Sargasso Sea divided in 3 subareas (1-red, 2-green and 3-blue, in the electronic version). Dotted and dashed line represent the 20°W and 15°W meridians respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the horizontal with diel vertical migration, where particles were located at 50 m during nighttime and 300 m during daylight; (3) migration with added random walk that can be fully random or locally oriented following currents.

Vertical displacement due to currents was not considered due to the inaccuracy of models to calculate velocities in Z direction. This approach is quite common in most of the lagrangian models.

2. Methods

2.1. Velocity field

Numerical simulations were run over the entire North Atlantic Ocean (see Fig. 1). Particles were released at the Sargasso Sea (black rectangle, Fig. 1).

The velocity components U, V were retrieved from the HYbrid Coordinate Ocean Model (HYCOM) + Navy Coupled Ocean Data Assimilation (NCODA) Global 1/12° Reanalysis database version GLBu0.08/expt_19.1 (http://hycom.org/data/glbu0pt08/expt-19pt1). HYCOM uses the NCODA system for data assimilation (Cummings, 2005; Cummings and Smedstad, 2013). The database includes several variables as sea surface elevation, salinity, water temperature, eastward and northward water velocity. Each velocity component is characterized by three indices (i, j, k) that determine the grid point. The horizontal resolution of HYCOM GLBu0.08/expt_19.1 is 1/12° × 1/12°, with a vertical resolution of 40 levels ranging from 0 to 5000 m. Data covers the period 08/01/1995 to 12/31/2012 with a recording time step of 3 h.

2.2. Lagrangian model

Simulations were run using a lagrangian model to track the dispersion of particles in the North Atlantic Ocean. The main features of the lagrangian model are described in Gomez-Gesteira et al. (1999) and Díaz et al. (2008). In the base case, an initial interparticle spacing of 0.06° × 0.06° was considered. Approximately 50,000 particles were initially released in an area (23–30°N; 48–72°W) located in the Sargasso Sea at each numerical experiment. The release area was chosen to fit the spawning area of the European eel larvae (Schmidt, 1925, 1932; Schoth and Tesch, 1982; van Ginneken and Maes, 2005). Three subareas (1-red, 2-green and 3-blue, see Fig. 1 in the electronic version) were defined to analyze the influence of the initial position on further dispersion. The release date (April) was chosen to fit the spawning period of the European eel larvae, which mainly occurs from March to June with a peak in April (Schmidt, 1922, 1923, 1925). Following previous research (Bonhommeau et al., 2009), each numerical experiment was run for a period of 18 months recording the position of particles every day. As we mentioned above different migration strategies were considered: i) particles were uniformly distributed at five depths covering the mixed layer (surface, 50 m, 100 m, 150 m and 200 m) with an advection-driven movement in the horizontal direction and without vertical movement; ii) the movement was advection-driven in the horizontal direction and a diel vertical migration (DVM) was implemented considering a daylight depth of 300 m and a nighttime depth of 50 m. This active behavior has been observed for wild European eel larvae (Castonguay and McCleave, 1987; Jespersen, 1942; Schmidt, 1925; Tesch, 1980); iii) passive migration with added random walk, assuming a constant depth, particles were allowed to move following the current plus an additional random walk.

Previous research has fixed different limits to succeed in crossing the Atlantic. Kettle and Haines (2006) considered the finishing line at 25°W, Bonhommeau et al. (2009) at 20°W and Blanke et al. (2012) at 15°W. Here we have considered both 20°W and 15°W for comparison purposes.

Following previous research (Cowen et al., 2000; Bonhommeau et al., 2009; Rudorff et al., 2009), chemical or biological processes such as mortality were not implemented in the model since the goal of the study is to analyze the minimum duration of migration, not the real amount of European eel larvae that has succeeded in crossing the North Atlantic Ocean.

The time step (Δt) was calculated to meet the CFL (Courant–Friedrichs–Lewy) criterion (Pacariz et al., 2014), based on the fact that the time step must be smaller than the time spent by a particle to go over a grid point (1/12°).

2.3. Interpolation process

When a particle was located at a certain point, neither the time nor the position coincided with the particular instant and node where the HYCOM GLBu0.08/expt_19.1 velocities were recorded. Therefore, an interpolation process was carried out both in time and in space.

First, for particle p, the vertical grid point was identified as the