Regional Studies in Marine Science 14 (2017) 53–62

Contents lists available at ScienceDirect

Regional Studies in Marine Science

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

The Portuguese man-of-war: Gone with the wind

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HIGHLIGHTS

- More than 3,500 Portuguese man-of-war arrived at the Basque coast in August 2010.
- The wind drag velocity was used to estimate their region of origin and routes.
- The region of origin was probably located in the North Atlantic Subtropical Gyre.

ARTICLE INFO

Article history:
Received 4 January 2017
Received in revised form
21 April 2017
Accepted 5 May 2017
Available online 8 May 2017

Keywords:
Bay of Biscay
Physalia physalis
Portuguese man-of-war
SOFT
WRF
Wind

ABSTRACT

The Portuguese man-of-war (*Physalia physalis*) is a siphonophore that lives at the air–water interface of the sea. The wind is the main mechanism controlling its drift. In August 2010, a significant number of individuals of this species arrived at the Basque coast (southeastern Bay of Biscay), causing a great socio-economic impact. Here we investigate the most likely region of origin and routes of these individuals using the Sediment, Oil spill and Fish Tracking model (SOFT). This model was run backwards in time using only the wind drag velocity (i.e., the wind velocity multiplied by a wind drag coefficient) to estimate the drift of these Portuguese man-of-war for one year and taking into account that the final destination was the Basque coast. The wind data were obtained with the Weather Research and Forecasting model (WRF). Six different simulations were carried out with SOFT using the following wind drag coefficients: 0.02, 0.025, 0.03, 0.035, 0.04 and 0.045. The simulation period covered from the end of August 2010 to the beginning of August 2009. After the first eight months of simulation (i.e., at the beginning of January 2010), the virtual Portuguese man-of-war used in SOFT were located near or on the northwest and southwest coasts of France and England, respectively, and in the English Channel, the southern Celtic Sea and the northwestern Bay of Biscay. However, at the end of the simulation period (i.e., at the beginning of August 2009), most of these Portuguese man-of-war were located between the central part of the Bay of Biscay (∼5° W) and the open North Atlantic Ocean (∼35° W), depending on the wind drag coefficient. From these results, we conclude that the region of origin of the Portuguese man-of-war arriving at the Basque coast in August 2010 was probably located in the northern part of the North Atlantic Subtropical Gyre. This conclusion is in agreement with the general wind-driven circulation in the North Atlantic Ocean.

1. Introduction

In 2010, a large number of Portuguese man-of-war (*Physalia physalis*) arrived at the Atlantic and Mediterranean coasts of the Iberian Peninsula and the Canary Islands, threatening the tourism industry, which is a major economic sector in these coastal regions (Prieto et al., 2015). More than 3500 Portuguese man-of-war were collected in the Basque coastal area (southeastern Bay of Biscay) in August 2010. Since then, the number of Portuguese man-of-war has drastically decreased. By mid-July 2011, a few hundred individuals were also collected on some beaches of the Basque coast after several days of intense northerly winds. But in the period 2012–16, only 49 Portuguese man-of-war were recorded.

The Portuguese man-of-war is a pleustonic siphonophore that belongs to the phylum Cnidaria and consists of a complex colony of four types of individual zooids (dactylozooids, tentacles for catching prey and self-defense; gonozooids, for reproduction; gastrozooids, for digestion; and a pneumatophore, a gas-filled float), which cannot survive separately and behave as a single animal (Mapstone, 2014). The Portuguese man-of-war lives in warm tropical and subtropical waters. This species is especially

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http://dx.doi.org/10.1016/j.rsma.2017.05.004

Fig. 1. Portuguese man-of-war (*Physalia physalis*) found on the Basque coast. Photograph by Nagore Zaldua-Mendizabal.

common in the warm waters of the Florida Keys, the Gulf Stream, the Gulf of Mexico, the Caribbean Sea and the Sargasso Sea. An example of the Portuguese man-of-war found on the Basque coast is shown in Fig. 1.

Several attempts have been made to describe the physical behaviour of the Portuguese man-of-war. Iosilevskii and Weihs (2009) studied the hydrodynamics of its trailing tentacles, the interaction between these tentacles and the float, and the actual sailing performance. These authors observed that the Portuguese man-of-war sailed with its float aligned with the wind under strong wind conditions. In 2012, the Department of Security of the Basque Government established an operational protocol for the sighting and tracking of Portuguese man-of-war in the southeastern Bay of Biscay. This protocol was designed by Ferrer et al. (2015) and combines sightings of this colonial organism at sea with numerical models that simulate its drift in the ocean. The initial forecasts of this operational protocol were performed with the Sediment, Oil spill and Fish Tracking model (SOFT), using hourly surface ocean currents and winds obtained with the Regional Ocean Modeling System (ROMS) and the Weather Research and Forecasting model (WRF), respectively. After analysing the drift of eight pop-up satellite tags for fish tracking, Ferrer et al. (2015) suggested that the most straightforward way to estimate the drift of a small floating object is to use a simple empirical model based on the local wind around the moving object.

Prieto et al. (2015) carried out numerical simulations to analyse the probable drift of Portuguese man-of-war from the Atlantic Ocean into the Mediterranean Sea in 2010. They used surface ocean currents and winds obtained with ROMS and from the Advanced SCATterometer (ASCAT) observations, respectively, to estimate this drift. They assumed that each Portuguese man-of-war was transported in the wind direction at 10% of the wind speed. These authors concluded that the 2010 event was an isolated case where a combination of meteorological and oceanographic conditions led to an unusual number of Portuguese man-of-war along the Spanish coast, far from being a permanent invasion. Although some literature is available on the response of the Portuguese man-of-war to physical forcing, little information is available on its life cycle, including growth and reproduction rates, and lifespan.

Here we investigate the most likely region of origin as well as the routes of the Portuguese man-of-war arriving at the Basque coast in August 2010. Using SOFT, we test the hypothesis that the region of origin of these Portuguese man-of-war was located in the North Atlantic Subtropical Gyre (NASG). The NASG is one of the five major oceanic subtropical gyres. The currents that compose the NASG include the Gulf Stream in the west, the North Atlantic Current in the north, the Canary Current System in the east and the North Equatorial Current in the south (Laiz et al., 2012; Putman and He, 2013). The Sargasso Sea, the only sea without a land boundary, is located entirely within the NASG. This sea stretches from roughly 70° W to 40° W and from 20° N to 35° N. The general ocean surface circulation in the NASG is shown in Fig. 2(a). The results obtained from this study will increase our predictive capability for future events and will enable us to develop effective management strategies to avoid economic losses in the affected coastal areas.

2. Methods

The region of origin and routes of the Portuguese man-of-war arriving at the Basque coast in August 2010 were estimated using SOFT. This Lagrangian particle tracking model is mainly designed for marine applications. In this model, the method used for the movement of particles (i.e., sediments, oil spills, eggs and larvae, jellyfish, Portuguese man-of-war, etc.) is based on the fourth-order Runge–Kutta scheme (Benson, 1992). Ferrer et al. (2015) carried out a calibration of this model using eight trajectories from pop-up satellite tags for fish tracking. The results of this calibration showed that the wind is the main mechanism controlling the tag drift following the equation:

$$\mathbf{U}_D = C_D \cdot \mathbf{U}_{WRF} = C_D \cdot U_{WRF} + C_D \cdot V_{WRF} \quad (1)$$

where $\mathbf{U}_D = (U_D, V_D)$ is the drift velocity, $\mathbf{U}_{WRF} = (U_{WRF}, V_{WRF})$ is the wind velocity at 10 m height obtained with WRF and C_D is the wind drag coefficient. WRF is a next-generation mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting needs. A detailed description of this model can be found in Skamarock et al. (2005). To estimate the drift of the Portuguese man-of-war, we used Eq. (1) with the hourly wind fields provided by MeteoGalicia (meteorological agency of Galicia) for 2009 and 2010. The coverage of the WRF model domain used by MeteoGalicia in its operational system is shown in Fig. 2(b). The spatial resolution of the grid is 36 km.

The C_D values used by Ferrer et al. (2015) in their numerical simulations ranged from 0.001 to 0.04. On average, the best fit between the modelled and observed trajectories was obtained when a C_D value of 0.018 was used. However, C_D must be estimated for each specific floating object. For example, a C_D value of 0.03 is commonly applied to estimate the surface drift of oil spills (Fallah and Stark, 1976; Wu, 1983). Following Ferrer et al. (2015), we used different wind drag coefficients in our simulations with SOFT to investigate the routes of the Portuguese man-of-war. In total, six values were used: 0.02, 0.025, 0.03, 0.035, 0.04 and 0.045.

Two virtual Portuguese man-of-war were released every day in August 2010 (at midday and midnight) at a distance of ∼10 km from the Basque coast (see location in Fig. 2(b)). Although little information exists on the life cycle of the Portuguese man-of-war, most experts believe that the lifespan of this colonial organism is approximately one year and its reproduction takes place in autumn. For this reason, each virtual Portuguese man-of-war was moved backwards in time using SOFT for one year. Therefore, the simulation period covered from the end of August 2010 to the beginning of August 2009. The results obtained from the end of August to the beginning of January 2010 (first part of the simulation period) were plotted separately from those obtained from the end of December to the beginning of August 2009 (second part of the simulation period). The purpose of this was to identify the existence of differences between these two parts of the simulation period.

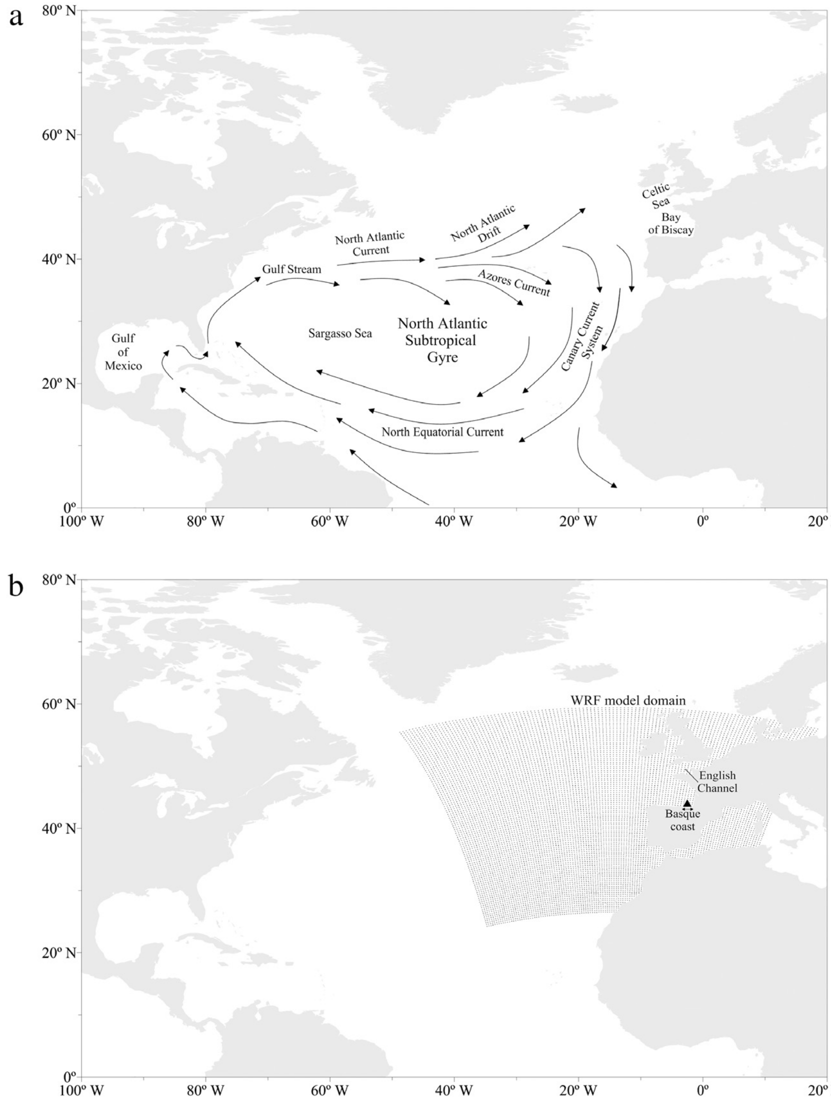

Fig. 2. (a) General surface ocean circulation in the North Atlantic Subtropical Gyre, adapted from Putman and He (2013). (b) Oceanic grid points of the WRF model domain. The black triangle indicates the initial location (near the Basque coast) of the virtual Portuguese man-of-war used in SOFT.

3. Results

In total, 62 trajectories of Portuguese man-of-war were obtained in each simulation, starting near the Basque coast. The trajectories obtained with SOFT using C_D values of 0.02, 0.025 and 0.03 are shown in Fig. 3, while those obtained using C_D values of 0.035, 0.04 and 0.045 are displayed in Fig. 4. The end points of these trajectories are shown in Figs. 5 and 6. The trajectories of the second part of the simulation period (Figs. 3(b), (d), (f), 4(b), (d) and (f)) start at the end points of the trajectories of the first part of the simulation period (Figs. 5(a), (c), (e), 6(a), (c) and (e)).

During the first part of the simulation period and with C_D values of 0.04 and 0.045, the routes of the virtual Portuguese man-of-war released near the Basque coast covered a large area, including the northwest and southwest coasts of France and England, respectively, the English Channel, the southern Celtic Sea and the northwestern Bay of Biscay (Fig. 4(c) and (e)). The drift of these Portuguese man-of-war occurred between 43.36° N and 52.22° N and between 0.67° W and 13.24° W with a C_D value of 0.045 (Fig. 4(e)). However, this drift was confined to a smaller geographical area with a C_D value of 0.02. In this latter case, the drift occurred between 43.43° N and 48.01° N and between 2.31° W and 5.01° W (Fig. 3(a)).

During the second part of the simulation period, there was a change in the drift direction of our virtual Portuguese man-of-war due to a change in the wind direction. At the end of the simulation period, most of these Portuguese man-of-war were located in the open North Atlantic Ocean, although some of them were located near or on the northwest and southwest coasts of France and England, respectively (Figs. 5(b), (d), (f), 6(b), (d) and (f)). The region of origin of these Portuguese man-of-war was located in the eastern and central parts of the North Atlantic Ocean, between 15° W and 35° W, with a C_D value of 0.045 (see Fig. 6(f)), but it was located in the central and western parts of the Bay of Biscay, between 5° W and 11° W, with a C_D value of 0.02 (see Fig. 5(b)). From these results, we can conclude that, on average, our virtual Portuguese mar-of-war drifted east-northeastwards from the beginning of August to the end of December 2009, and then drifted southeastwards from the beginning of January to the end of August 2010. They drifted from the open North Atlantic Ocean to the Basque coast.

For the virtual Portuguese man-of-war released on 31 August 2010 at midday, we analysed the drift and wind velocities from the end of August 2009 to the end of August 2010 along the trajectory obtained using a C_D value of 0.045 (Fig. 7). This Portuguese man-of-war was located at 41.16° N and 35° W on the last simulation

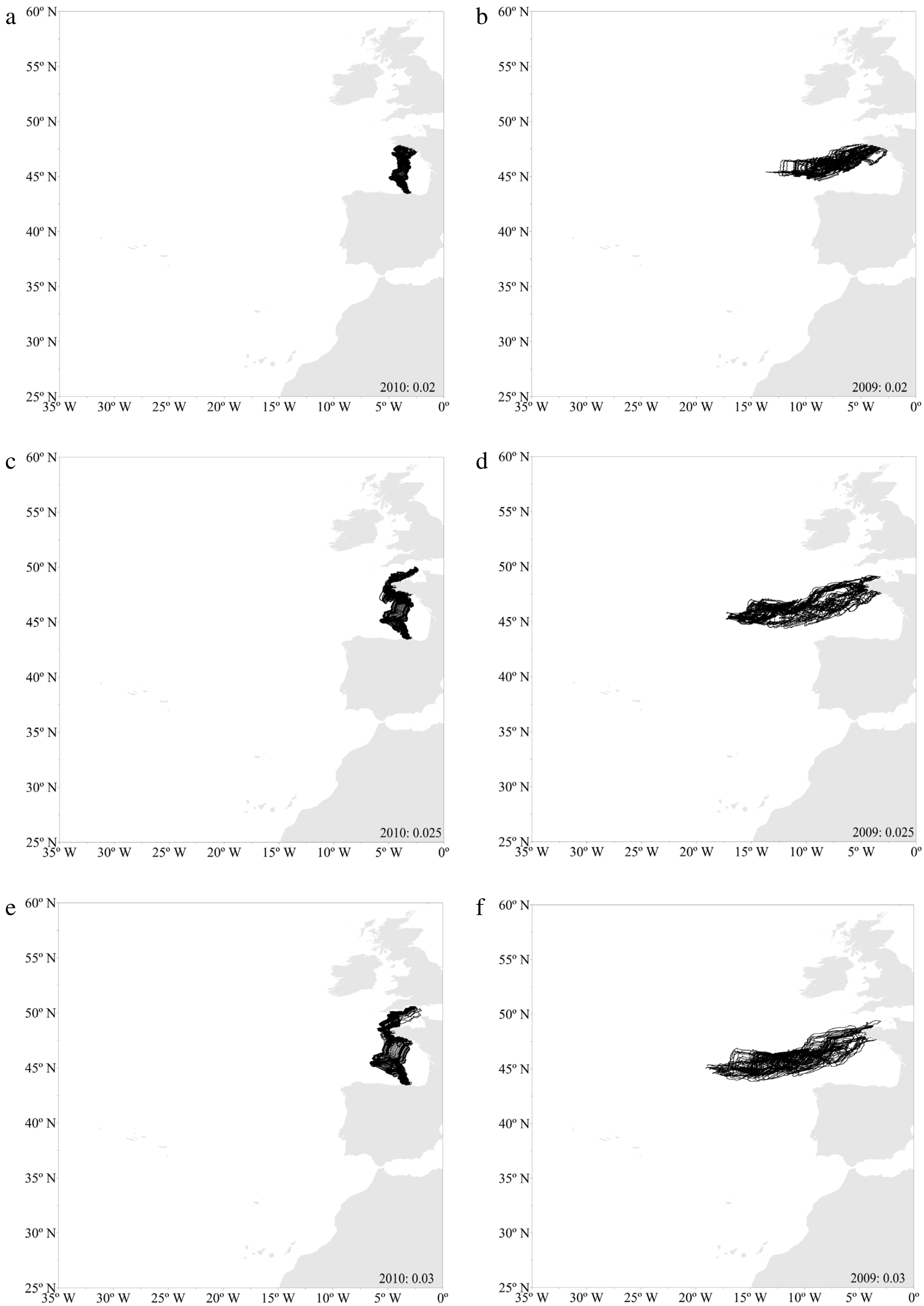

Fig. 3. Trajectories of 62 Portuguese man-of-war obtained with SOFT using the following wind drag coefficients: (a, b) 0.02; (c, d) 0.025; and (e, f) 0.03. The results obtained from the end of August to the beginning of January 2010 (a, c, e) are plotted separately from those obtained from the end of December to the beginning of August 2009 (b, d, f).

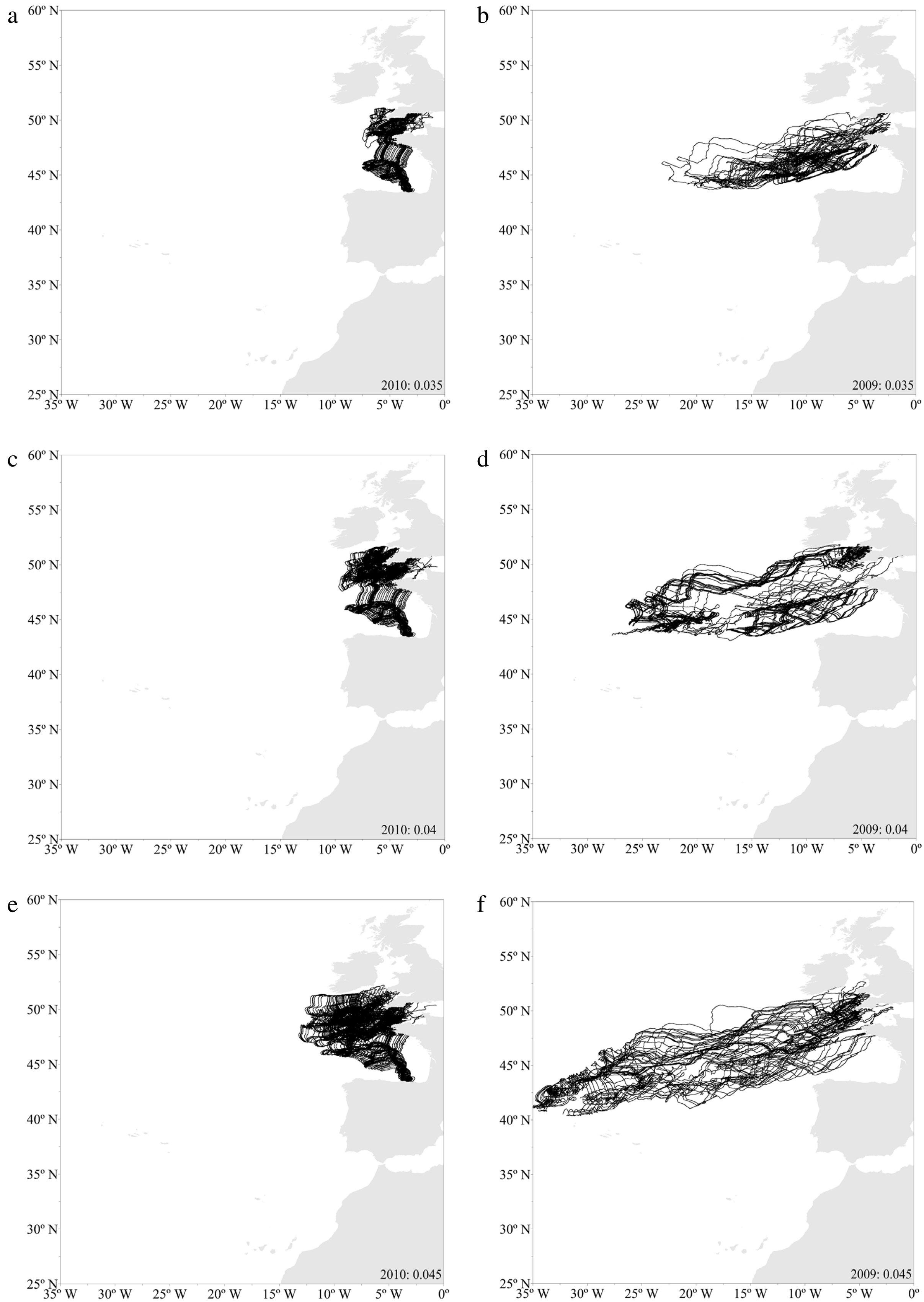

Fig. 4. As in Fig. 3, but using the following wind drag coefficients: (a, b) 0.035; (c, d) 0.04; and (e, f) 0.045.

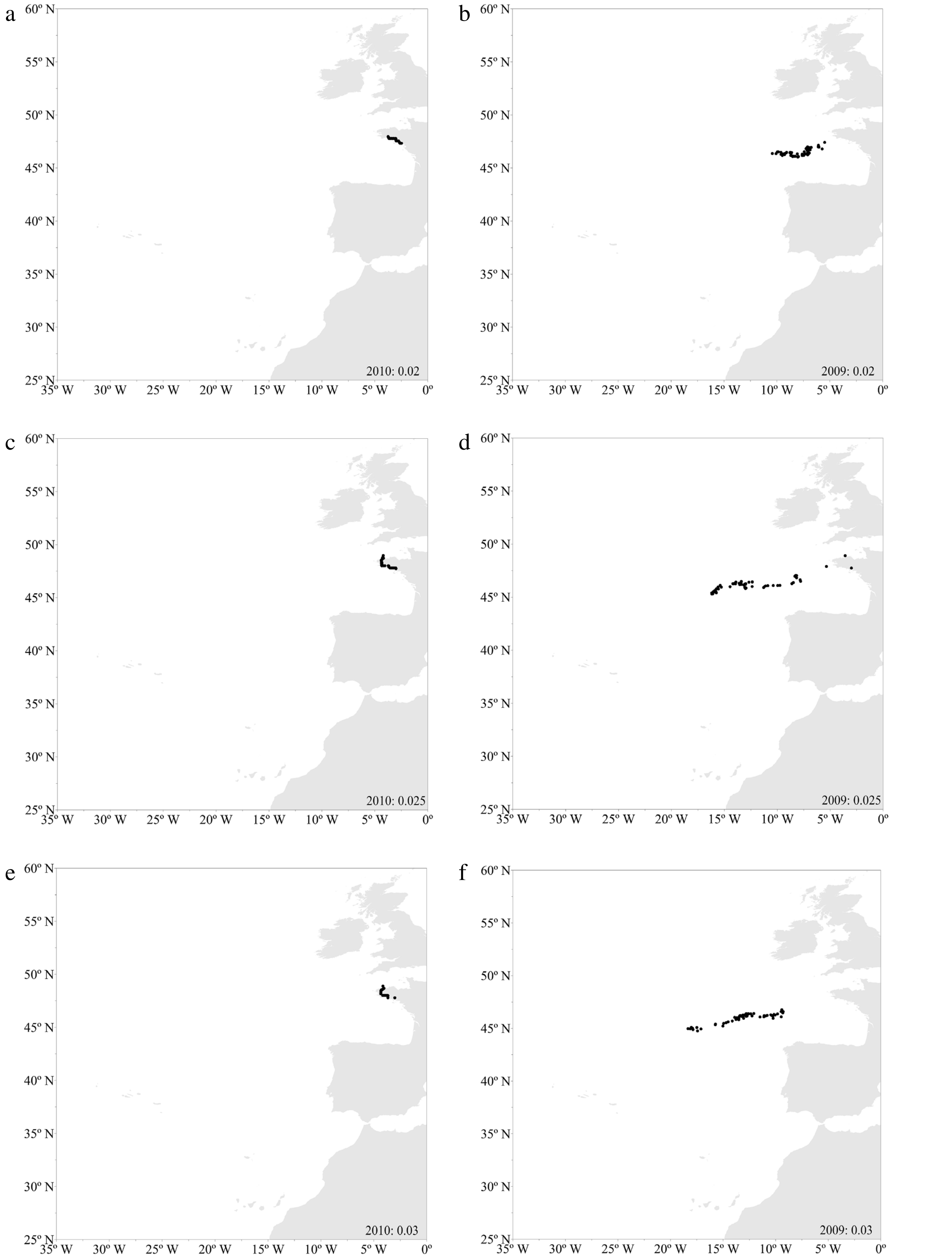

Fig. 5. End points of the trajectories obtained with SOFT using the following wind drag coefficients: (a, b) 0.02; (c, d) 0.025; and (e, f) 0.03. The results obtained at the beginning of January 2010 (a, c, e) are plotted separately from those obtained at the beginning of August 2009 (b, d, f).

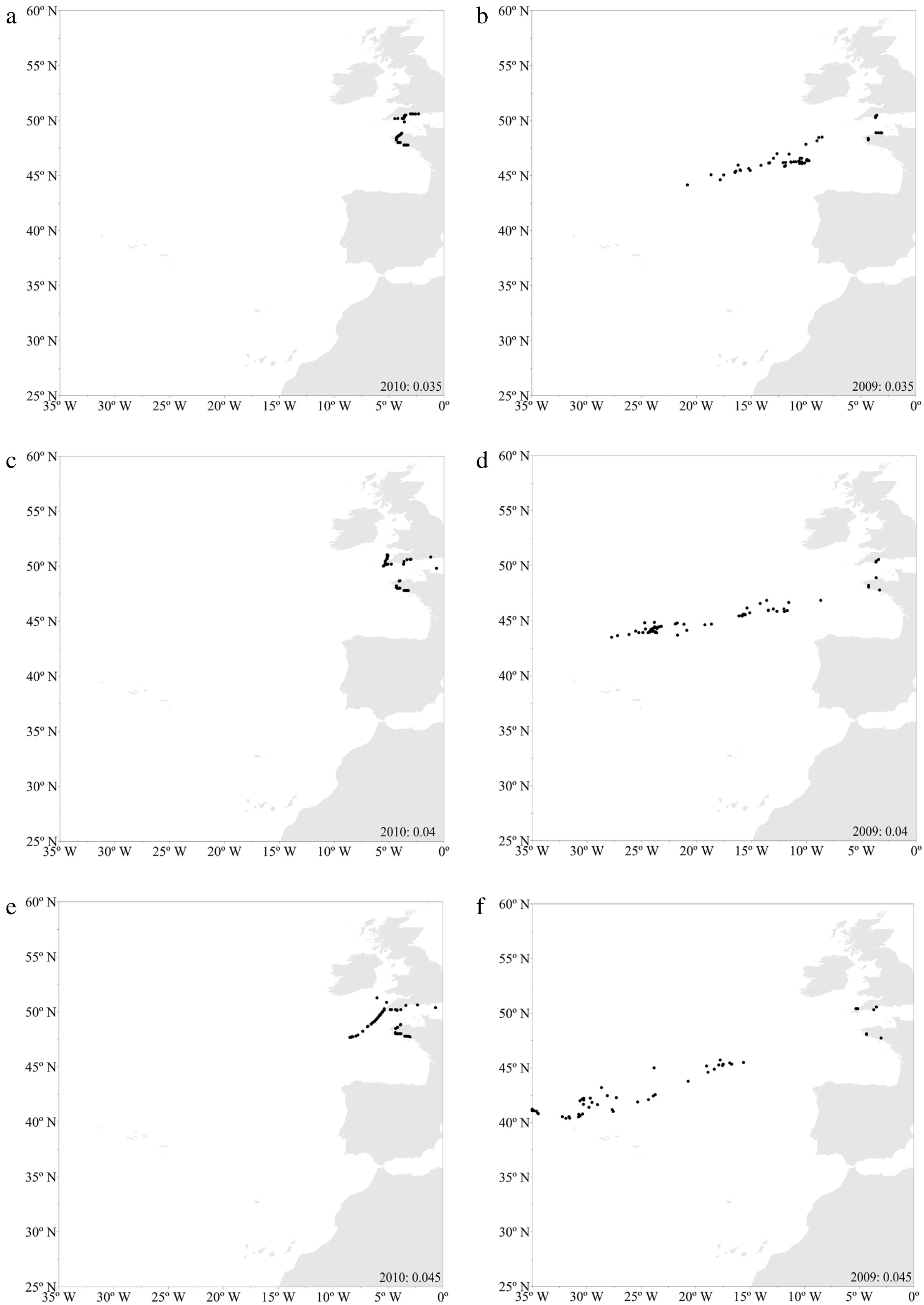

Fig. 6. As in Fig. 5, but using the following wind drag coefficients: (a, b) 0.035; (c, d) 0.04; and (e, f) 0.045.

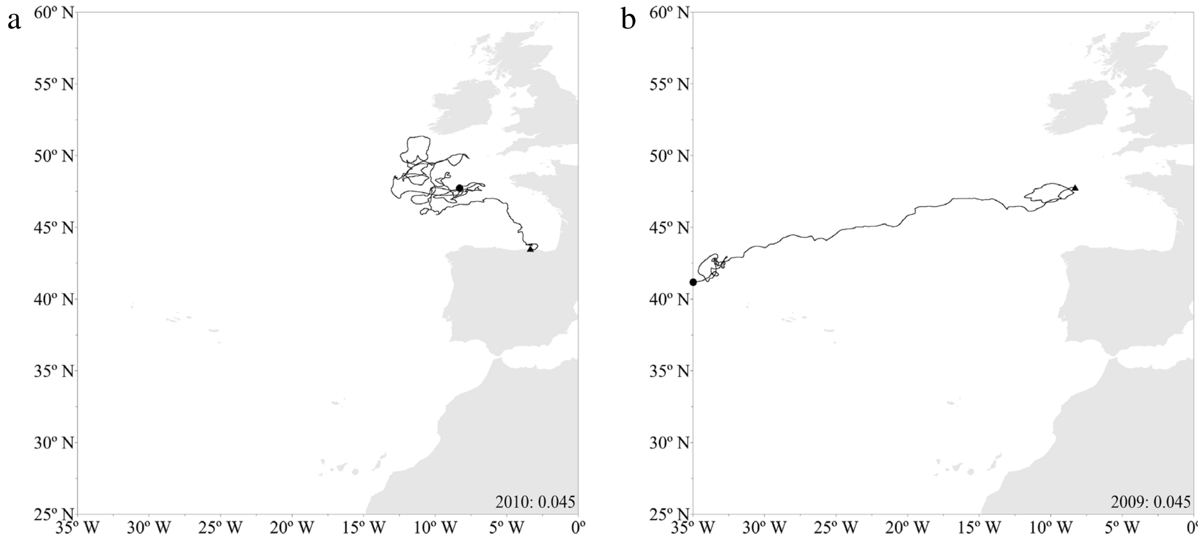

Fig. 7. Trajectory of the Portuguese man-of-war released on 31 August 2010 at midday, obtained with SOFT using a wind drag coefficient of 0.045: (a) from the end of August (black triangle) to the beginning of January 2010 (black circle); and (b) from the end of December (black triangle) to the end of August 2009 (black circle).

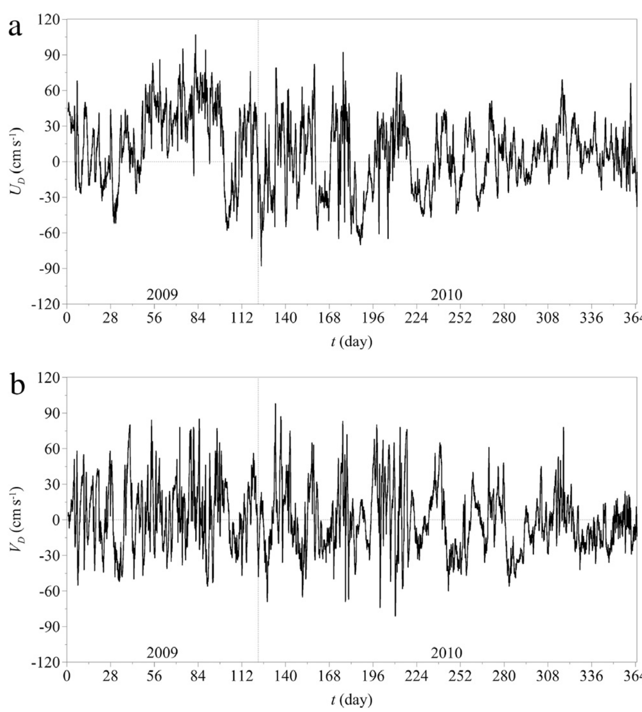

Fig. 8. Drift velocity along the trajectory shown in Fig. 7, from the end of August 2009 to the end of August 2010: (a) zonal component, U_D; and (b) meridional component, V_D.

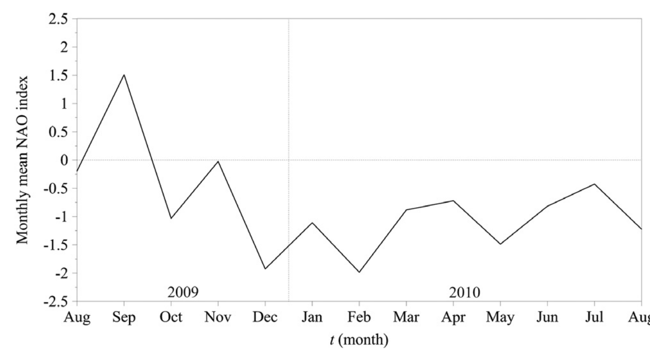

Fig. 9. Monthly mean NAO index from August 2009 to August 2010.

day. The zonal and meridional components of its drift velocity, U_D and V_D, respectively, are displayed in Fig. 8. The maximum values of U_D and V_D ranged between 85 cm s^{-1} and 107 cm s^{-1}. The mean values of these components were higher in the second part of the simulation period (21 cm s^{-1} and 5 cm s^{-1}, respectively) than in the first part (2 cm s^{-1} and −2 cm s^{-1}, respectively), reflecting the aforementioned change in the drift direction. The distance travelled by this Portuguese man-of-war from the open North Atlantic Ocean to the Basque coast was about 11,800 km.

Regarding the maximum values of U_{WRF} and V_{WRF} along the trajectory shown in Fig. 7, these ranged between 68 and 86 km h^{-1}. The mean values of U_{WRF} and V_{WRF} were higher in the second part of the simulation period (17 km h^{-1} and 4 km h^{-1}, respectively) than in the first part (2 km h^{-1} and −2 km h^{-1}, respectively), showing a change in the wind direction. This change can also be analysed using the monthly mean NAO (North Atlantic Oscillation) index provided by the US National Oceanic and Atmospheric Administration (Fig. 9). The NAO index measures the strength of the westerly winds blowing across the North Atlantic Ocean between 40° N and 60° N (Greatbatch, 2000). When this index is high (low), the westerly winds are stronger (weaker) than normal. Its mean value was −1.08 in the first part of the simulation period and −0.33 in the second part. The minimum and maximum values occurred in February 2010 (−1.98) and September 2009 (1.51), respectively. On average, the trajectories of our virtual Portuguese man-of-war were characterised by northwesterly winds in the first part of the simulation period and west-southwesterly winds in the second part.

Clearly, our findings indicate that the region of origin of the Portuguese man-of-war is very large, especially in longitude, and its location is strongly dependent on the C_D value: the higher the wind drag coefficient, the farther the region of origin. Therefore, the selection of an appropriate wind drag coefficient is crucial for a successful estimation of this region. Obviously, the presence of obstacles along the routes of the Portuguese man-of-war, such as islands and coasts, also plays a fundamental role.

4. Discussion

The hypothesis that the region of origin of the Portuguese man-of-war arriving at the Basque coast in August 2010 was located in the NASG is reasonable. The general surface ocean circulation in the

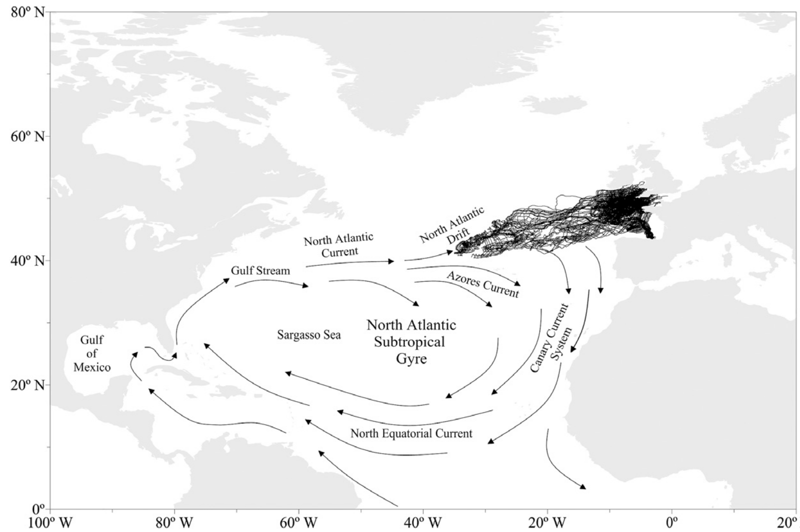

Fig. 10. Trajectories of 62 Portuguese man-of-war obtained with SOFT using a wind drag coefficient of 0.045, from the beginning of August 2009 to the end of August 2010. The general surface ocean circulation in the North Atlantic Subtropical Gyre is also shown.

North Atlantic Ocean supports this hypothesis (Fig. 2(a)). The North Atlantic Current is a warm ocean current that continues the wind-driven Gulf Stream northeast. West of Continental Europe, it splits into two major branches: the North Atlantic Drift and the Azores Current. The North Atlantic Drift continues north along the coast of northwestern Europe, while the Azores Current goes southeast and its easternmost branch turns southwards to feed the Canary Current System.

The results obtained with a C_D value of 0.02 go against our initial hypothesis. In this case, the region of origin was located in the central and western parts of the Bay of Biscay after running the model backwards in time for a year. However, the findings obtained with a C_D value of 0.045 support the initial hypothesis. In this latter case, the region of origin was located in the eastern and central parts of the North Atlantic Ocean. The weights and float lengths of the Portuguese man-of-war arriving at the Basque coast did not exceed 60 g and 20 cm, respectively. Therefore, the drift obtained with a C_D value of 0.02 should be similar to the one observed by Ferrer et al. (2015) using pop-up satellite tags (∼40 g in weight). However, recent data obtained with small surface drifting buoys (not shown) seem to indicate that C_D values higher than 0.04 could be more appropriate to estimate the drift of the Portuguese man-of-war, especially under strong wind conditions. For example, Prieto et al. (2015) used a wind drag coefficient of 0.1 in their simulations, together with surface ocean currents, based on the study carried out by Iosilevskii and Weihs (2009).

This study has taken a step in the direction of defining the relationship between the wind and the region of origin of the Portuguese man-of-war. It is important to emphasise that some aspects of the numerical simulations limit the interpretations of our results. Obviously, a higher spatial resolution of the wind model over a larger area of the North Atlantic Ocean would be more appropriate to analyse the drift of this colonial organism. It is also possible, of course, that a numerical model including surface ocean currents may yield different results from those obtained here. However, it would be surprising if these results were entirely different, because, in general, the wind is the main mechanism controlling the ocean circulation in the upper centimetres of the water column. The results obtained by Ferrer et al. (2015) using both surface ocean currents and wind velocities confirm the importance of the wind in the estimation of the trajectory of a partially emerged drifter, such as the Portuguese man-of-war. For this reason, here we focused our effort on a model based only on the wind drag velocity.

Several studies have demonstrated that the effects of winds and waves on surface ocean currents are significant (Ursell, 1950; Longuet-Higgins, 1953, 1960; Hasselmann, 1970; Pollard, 1970; Huang, 1979; Wu, 1983; Jenkins, 1989; Perrie et al., 2003; Tang et al., 2007; Sotillo et al., 2008; Song, 2009; Abascal et al., 2009, 2012). These authors conclude that these effects change the nature of the Ekman layer. More information about the characteristics of this layer can be found in Ekman (1905). Ferrer et al. (2015) summarised the results of some of these studies, showing that the estimation of the drift velocity of a small floating object using a combination of outputs from numerical models (winds, waves and ocean currents) is a very difficult task. For example, the comparisons between predicted and observed trajectories carried out by Sotillo et al. (2008) and Abascal et al. (2009, 2012) in the Bay of Biscay and in the northwestern coastal area of Spain confirm the complexity of the problem under study.

The findings obtained using high C_D values suggest that the region of origin of the Portuguese man-of-war is located in the NASG (Fig. 10). Within the NASG, the Sargasso Sea, due to its special characteristics, could probably be a region with a high concentration of Portuguese man-of-war where reproduction takes place. But this is more of an untested hypothesis than a conclusion, because the WRF model domain used here does not cover the Sargasso Sea region. Using mainly the wind drag velocity, the Portuguese man-of-war would drift from the Sargasso Sea and surrounding waters towards different coastal regions, to finally wash up on the shores of America and Europe. It seems reasonable to assume that the C_D value will vary along the lifespan of the Portuguese man-of-war, because there will be a significant increase in the size of this colonial organism. It is also possible that the reproduction of the Portuguese man-of-war takes place along the routes of the parents.

The Portuguese man-of-war occurs in two forms which are mirror images of one another but otherwise identical (Totton and Mackie, 1956; Woodcock, 1956). Under the influence of the wind, it seems that one form (left-handed) moves to the right of the downward direction, and the other (right-handed) to the left. Here we assumed that the Portuguese man-of-war drifts in the wind direction. Therefore, further work should be done to investigate the effect of this dimorphism on the region of origin and routes of the Portuguese man-of-war.

For example, Shannon and Chapman (1983) discussed the distribution of Portuguese man-of-war on 19 beaches around the South Western Cape Province during January 1983. Most of the specimens collected on these beaches were in the 10–40 mm size range. Left- and right-handedness occurred in the approximate ratio 3:2, respectively, and the dimorphism and density appeared to be related to the wind during the period prior to stranding, the presence of warm water inshore and the orientation of the beach and coastline. These authors concluded that the high incidence of Portuguese man-of-war during the summer 1982–83 on the study beaches was unusual and could be indicative of the anomalous meteorological and oceanographic conditions which occurred on a global scale.

In view of the above, our results must be taken with caution. To our knowledge, no previous studies have analysed the region of origin and routes of the Portuguese man-of-war. With our model, we can predict the arrival of this colonial organism along the European coasts. Assuming that its region of origin is located in the NASG, we can carry out numerical simulations and predict its most likely routes from the previous to the next summer. Therefore, we can anticipate and better manage the problem caused by the Portuguese man-of-war in our coastal regions.

5. Conclusions

In August 2010, more than 3500 Portuguese man-of-war arrived at the Basque coast (southeastern Bay of Biscay). Using the Sediment, Oil spill and Fish Tracking model (SOFT), we investigated the most likely region of origin and routes of these individuals. From our results, we conclude that their region of origin was probably located in the northern part of the North Atlantic Subtropical Gyre. A combination of west-southwesterly and northwesterly winds from the beginning of August 2009 to the end of August 2010 seems to be the main cause of this unusual arrival. With SOFT, we can predict the arrival of Portuguese man-of-war along the European coasts. Further research should be conducted to investigate the effect of the dimorphism of this colonial organism on the most likely region of origin and routes.

Acknowledgements

We thank MeteoGalicia for sharing its data, Patrizio Mariani (Technical University of Denmark, DTU Aqua) for his invaluable advice and comments, and Nagore Zaldua-Mendizabal for providing photographic material. This research was supported by the European Union (LIFE LEMA Project, LIFE15 ENV/ES/000252). This paper is contribution no. 817 from AZTI-Marine Research.

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