Validation of a Lagrangian model using trajectories of oceanographic drifters

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ABSTRACT. We compared trajectories of oceanographic drifters and simulations using the Lagrangian model Ichthyop. The drifters data covered the tropical Atlantic Ocean over the period 1992-2008. The model was forced firstly by interannual outputs of the Regional Ocean Modeling System (ROMS) model, and then by the Ocean Surface Current Analysis Real-time (OSCAR) remote-sensing product. We found that the relative error between data and simulations increases with time approximately linearly before leveling out. The results were close for ROMS-Ichthyop and OSCAR-Ichthyop simulations, in accordance with the spatial resolutions of the forcing products that were close ($\frac{1}{3}^\circ$ for OSCAR and $\frac{1}{5}^\circ$ for ROMS). Simulated particles traveled generally significantly lower distances than observed drifters, likely because these spatial resolutions were insufficient to resolve the meso-scale oceanic processes.

RÉSUMÉ. Nous avons comparé les trajectoires des drifters océanographiques avec celles des simulations en utilisant le modèle Lagrangien Ichthyop. Les données des drifters couvraient l'océan Atlantique tropical sur la période 1992-2008. Le modèle Ichthyop a été forcé par les sorties interannuelles du modèle Regional Ocean Modeling System (ROMS) dans un premier temps, et ensuite, par les sorties du produit Ocean Surface Current Analysis Real-time (OSCAR). Nous avons trouvé que l'erreur relative entre les données et les simulations augmentent approximativement linéairement avec le temps avant de se stabiliser. Des résultats proches ont été trouvés entre les simulations ROMS-Ichthyop et OSCAR-Ichthyop, en accord avec les résolutions spatiales des produits de forçage qui sont proches ($\frac{1}{3}^\circ$ pour OSCAR et $\frac{1}{5}^\circ$ pour ROMS). Les particules simulées ont généralement parcouru des distances significativement plus faibles que les drifters observés, probablement parce que ces résolutions spatiales étaient insuffisantes pour résoudre les processus de méso-échelle océaniques.

KEYWORDS : trajectory, drifter, currents, Lagrangian model, tropical Atlantic.

MOTS-CLÉS : trajectoire, drifter, courants, modèle Lagrangian, Atlantique tropical.

1. Introduction

The tropical Atlantic ocean is located between 65°W and 15°E and 10°S and 14°N. It is mainly dominated by the presence of strong currents such as the North Equatorial Counter Current (NECC) and the South Equatorial Current (SEC), and undercurrents such as the Equatorial Under Current (EUC). Model-simulated trajectories obtained from hydrodynamic models are increasingly used to simulate the ocean circulation (Lumpkin et al., 2002) and fish larval trajectories (Koné et al., 2017). Some models use an Eulerian approach and others a Lagrangian approach. The main advantage of the Lagrangian view is the knowledge of the "water particle history" from origin to destination. Useful applications are found in the study of marine pollution (plastic debris) and marine ecology (Lett et al., 2007). As these studies become more frequent, the need to evaluate simulated trajectories increases. The objective of this work is precisely to validate the trajectories simulated by the Lagrangian model Ichthyop using NOAA oceanographic drifters. The Ichthyop model is firstly forced by interannual outputs of the Regional Ocean Modeling System (ROMS) model over the period 1992-2008, and then by the Ocean Surface Current Analysis Real-time (OSCAR) remote-sensing product. The purpose is to make a comparative analysis of the solutions ROMS-Ichthyop and OSCAR-Ichthyop coupled models using the trajectories of in situ drifters as reference.

2. Material and methods

2.1. Oceanographic drifters

The trajectories of near-surface drifters are gathered by the National Oceanic and Atmospheric Administration (NOAA). Drifters are drogued at 15 m depth and are tracked by the Argos satellites. Their positions are given every six hours (Hansen and Poulain, 1996). The data used in this study comprise 278 drifters.

2.2. OSCAR currents

The OSCAR product provides near real-time ocean surface velocities from different satellites fields (TOPEX / Poseidon (1992- 2002) and Jason (2002-present) (Bonjean and Lagerloef, 2002). OSCAR is a product distributed by NASA's Physical Oceanography Data Center (`http://podaac.jpl.nasa.gov`). Velocities are calculated from quasi-linear equations of motion by combining geostrophy, Ekmann and Stommel formulations and a complementary term to the surface flotation gradient (Bonjean and Lagerloef, 2002). Horizontal velocities are directly estimated from the height of the sea surface, sea surface velocity, surface wind speed, and sea surface temperature. The OSCAR product is on a $\frac{1}{3}^{\circ}$ grid resolution with a 5-day interval.

2.3. ROMS hydrodynamic model

The ROMS hydrodynamic model is three-dimensional, split-explicit based on the hydrostatic balance, incompressibility and Boussinesq hypotheses for solving, primitive equations and also the free surface (Shchepetkin and McWilliams, 2005). The model configuration used here was built over the tropical Atlantic at a horizontal resolution of $\frac{1}{5}^{\circ}$ ($\simeq$ 22 km). The 45 vertical levels of the grid are discretized according to a sigma coordinate system to increase the vertical resolution near the surface. On the surface, the model

is forced with interannual winds derived from atmospheric forcings CFSR (Climate Forecast System Reanalysis). The superficial heat and fresh water fluxes introduced into the model come from the model SODA (Simple Ocean Data Assimilation) version 2. The model has three open borders (North, South and West) and a closed border (East) forced by the outputs of SODA. The outputs of the model are saved every 2 days. Model details and implementations are documented by Djakouré et al. (2014) and Koné et al. (2017).

2.4. Ichthyop Lagrangian model

Ichthyop (Lett et al., 2008) is a tool that simulates Lagrangian particle transport using current fields produced by hydrodynamic models such as ROMS, for applications in physical oceanography and / or in marine ecology. The main applications are the study of the transport processes and their effects on the variability of fish ichthyoplankton recruitment. In the present application, cloud of discrete particles (1000) without mass are released at the observed drifters location. The displacement of each particle is given by the sum of an advective component and a horizontal dispersive component (Peliz et al., 2007). The positions of particles are computed at each time step using the Runge-Kutta 4 forward scheme and saved every six hours (corresponding to the recorded periods of the drifters positions).

2.5. Statistical analysis

The mean position of the particles simulated at each time step is defined as follows:

$$\overline{x}^p(t) = \frac{1}{N}\sum_{i=1}^{N} x_i^p(t) \qquad [1]$$

where t is the time, N is the total number of simulated particles and p is the index of the spatial coordinate (longitude, latitude and depth). Thus, we obtain the barycenter of the simulated particles. The standard deviation is given by

$$\sigma^p(t) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i^p(t) - \overline{x}^p(t))^2} \qquad [2]$$

The relative error measures the separation of two particles or, equivalently, the propagation of a cloud of passive tracers. This index allows to obtain the evolution of the distance between the observation (drifter) and the simulation (barycenter) as a function of time:

$$D(t) = \sqrt{(x_b(t) - x_o(t))^2 + (y_b(t) - y_o(t))^2} \qquad [3]$$

with $(x_b(t), y_b(t))$ and $(x_o(t), y_o(t))$ the coordinates of the simulated particles barycenter and observed drifter at time t, respectively.

Absolute dispersion is defined as the distance to the initial position at each time step:

$$D_0(t) = \sqrt{(x_d(t) - x_d(t_0))^2 + (y_d(t) - y_d(t_0))^2} \qquad [4]$$

where $(x_d(t), y_d(t))$ are the coordinates of the simulated particles barycenter or observed drifter at time t and $(x_d(t_0), y_d(t_0))$ their initial position.

3. Results

3.1. Examples of drifters and simulated trajectories

As a first example, the ROMS-Ichthyop simulation reproduced the path followed by the drifter 55152 quite well, while with the OSCAR-Ichthyop simulation most of the particles were swept away to the east (Figure 1). Here, the initial position of the drifter is close to the divergence zone between the south and north branches of the SEC. A small difference in positioning of this zone between ROMS and OSCAR leads to, in the first case, most particles ended up close to the South American coast, in agreement with the observed trajectory, whereas in the second case, they mostly ended up close to the African coast, at the other end of the basin. As a contrasting, second example, we note that it is the OSCAR-Ichthyop simulation that follows the drifter 13513 trajectory best. With ROMS-Ichthyop, most particles are transported westwards, whereas the drifter goes eastwards (Figure 2) through the NECC. We also note that there is more variability in the trajectories simulated by the ROMS-Ichthyop simulation.

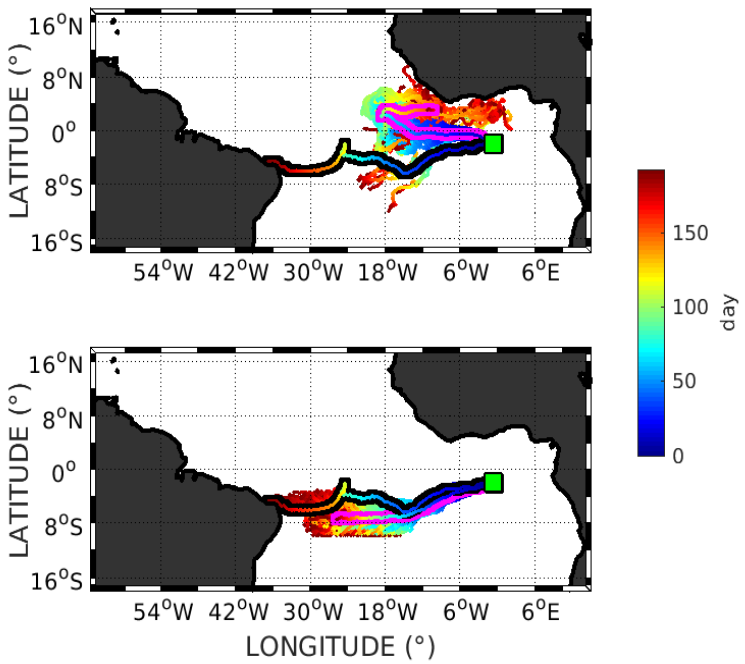

Figure 1. *Trajectories of the NOAA drifter 55152 (black), of the particles simulated using OSCAR-Ichthyop (top) and ROMS-Ichthyop (bottom), and particles barycenter (pink).*

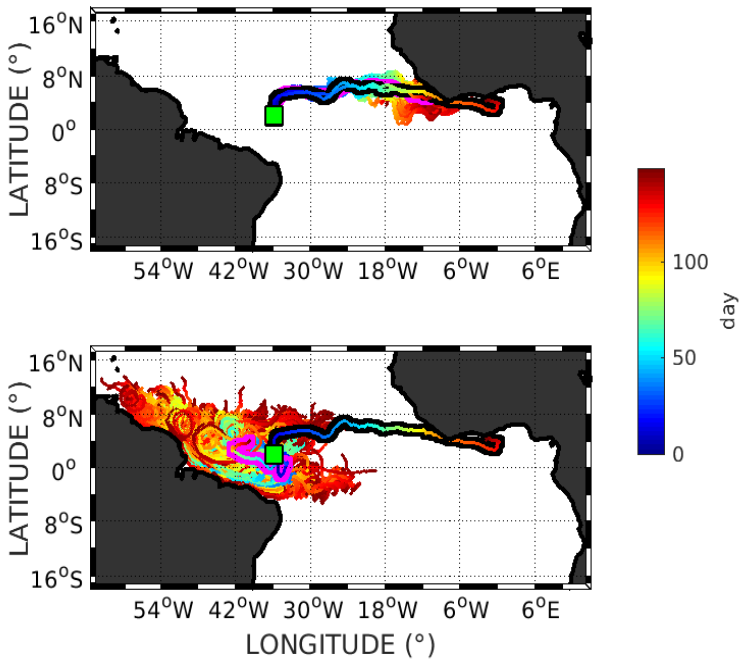

Figure 2. *Same as Figure 1 for NOAA drifter 13513.*

3.2. Comparison of all drifters and simulations

For all 278 NOAA drifters, the error distance between the observed trajectories and those simulated by Ichthyop forced by ROMS or OSCAR are close, increasing linearly with time and then stabilizing around 180 days (Figure 3). The error is slightly larger in the ROMS-Ichthyop simulation. On the other hand, the distances traveled between origin and destination are slightly closer to the observations in the case of that simulation (Figure 4). After 200 days, the drifters are on average more than 2000 km away from their release point whereas the particles in ROMS-Ichthyop are only at 1800 km and those in OSCAR-Ichthyop at 1200 km. The simulated speeds are therefore significantly lower than the observed speeds in both cases.

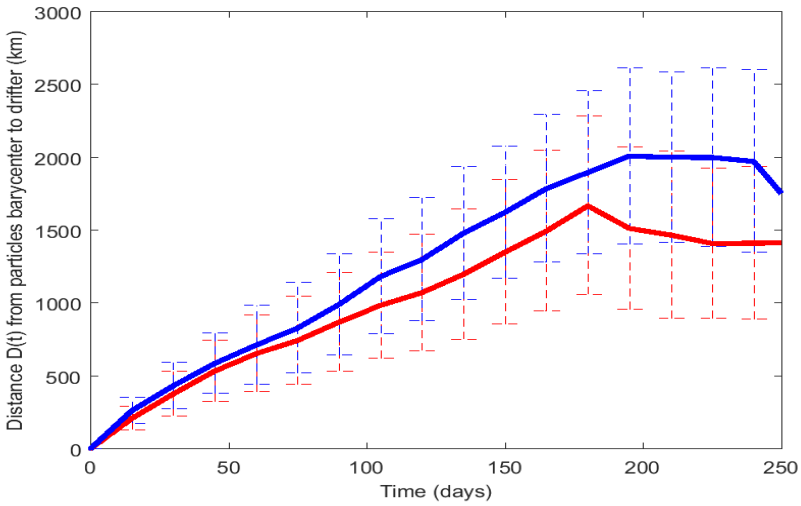

Figure 3. *Distance from the simulated particles barycenter to the observed drifter location over time, averaged for the 278 drifters found in the tropical Atlantic in the 1992-2008 period. Mean (plain) and standard deviation (dash) are in red for OSCAR-Ichthyop and in blue for ROMS-Ichthyop.*

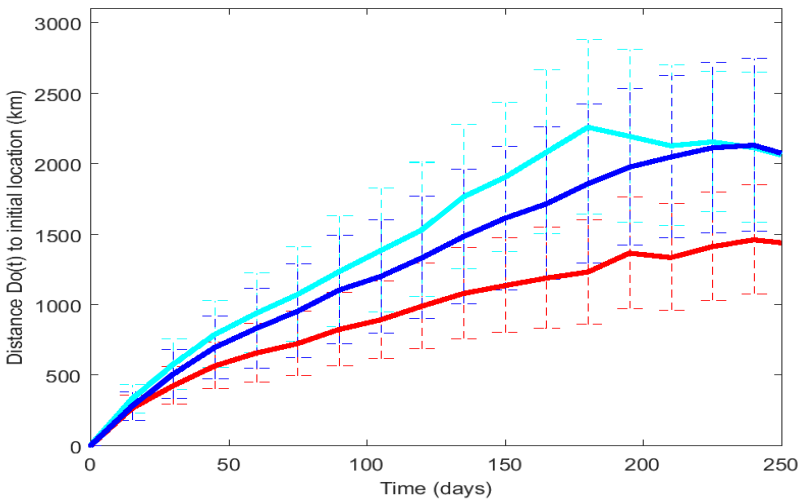

Figure 4. *Distance to initial locations of simulated particles barycenter and observed drifter over time, averaged for the 278 drifters found in the tropical Atlantic in the 1992-2008 period. Mean (plain) and standard deviation (dash) are in red for OSCAR-Ichthyop, in blue for ROMS-Ichthyop, and in cyan for observed drifters.*

4. Discusion

The trajectories simulated by the Lagrangian model Ichthyop forced by the OSCAR satellite product or by the ROMS hydrodynamic model is globally satisfactory to the extent that the main currents of the tropical Atlantic region are obtained. However, differences due to vortices, areas of divergence and variability in each of the considered regions can have significant consequences in terms of simulated drifting trajectories. Despite good results obtained by one or the other forcing product for some drifters (Figs 1 and 2), on average the simulated particles barycenter and observed drifter trajectories differed significantly. Averaged over all 278 drifters in our studied domain, the distance between particles barycenters and drifters was 1600 km for OSCAR-Ichthyop and 1800 km for ROMS-Ichthyop after 180 days (Figure 3), the same order of magnitude as the value of 229 km after 20 days obtained by Price et al. (2006). We found that this error distance increased approximately linearly with time, like in many other studies (LaCasce and Ohlmann, 2003). We also found that the velocities of simulated particles were lower than those of drifters, as in other circulation models (Doos et al., 2011), likely related to the insufficient spatial resolution used for forcings ($\frac{1}{5}^{\circ}$ grid for ROMS and $\frac{1}{3}^{\circ}$ for OSCAR). It is clear that at such resolutions, mesoscale structures such as eddies are not represented correctly. Recent works such as Jorda et al. (2014) detail the importance of including mesoscale currents as forcing factor, especially in areas of strong currents. They showed that these currents should be selected at the highest possible frequency because the changes in their frequency can have a significant impact on the modeled trajectories. Similarly, Doos et al. (2011) showed that a good agreement between the simulated speeds and drifters speeds can be obtained provided sufficiently fine resolutions in space and time are used. Regarded time, frequencies we used (2 days for ROMS and 5 days for OSCAR) may also be insufficient to account for oceanic variability. It is also often pointed that low values of simulated velocities can come from the coarse resolution of the field atmospheric winds (McClean, 2002). Indeed, atmospheric forcing is often taken at 2 m in height and not at the surface of the ocean which can cause differences at the level of modeled results. The effect of drifter slip is also poorly simulated in forcing atmospherics, leading to lower particle dynamics (Edwards et al., 2006). These limitations point to the need to develop higher resolution solutions, which will be done in future work by using the capacity of ROMS of embedding smaller but higher resolution (child) grids within larger but lower resolution (parent) domain (Debreu et al., 2012; Djakouré et al., 2014).

5. References

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Appendix 1

We did not proceed to model calibration in our work but performed a sensitivity analysis of our results to model parameters. As an example, in appendices 1 and 2 we show the results obtained for Figure 3 and Figure 4 when simulations are performed without the horizontal dispersive component (Figure 5 and Figure 6) and with release of particles in the neighborhood (disc of 50 km with/without diffusion and of 200 km radius R, Figure 7 and Figure 8) of observed drifters, as opposed to with horizontal dispersive component and release of particles at the exact drifters location in the main text. We essentially found the same results, showing the robustness of those presented in the main text.

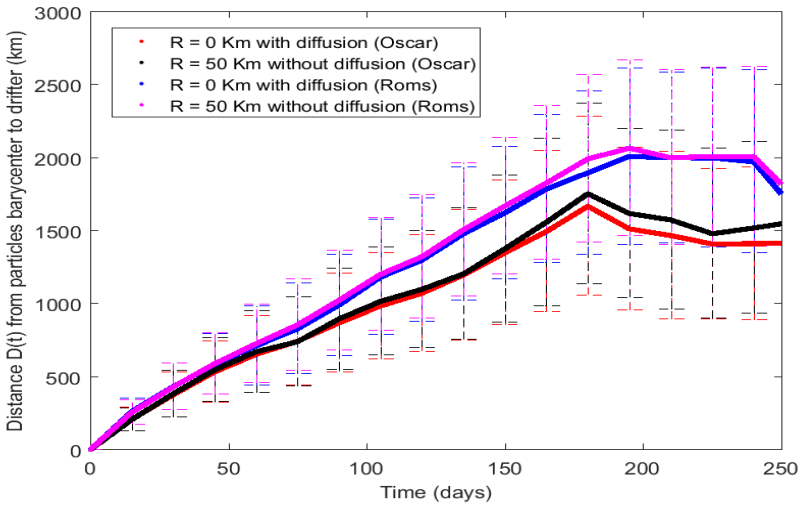

Figure 5. *Distance from the simulated particles barycenter to the observed drifter location over time, averaged for the 278 drifters found in the tropical Atlantic in the 1992-2008 period.*

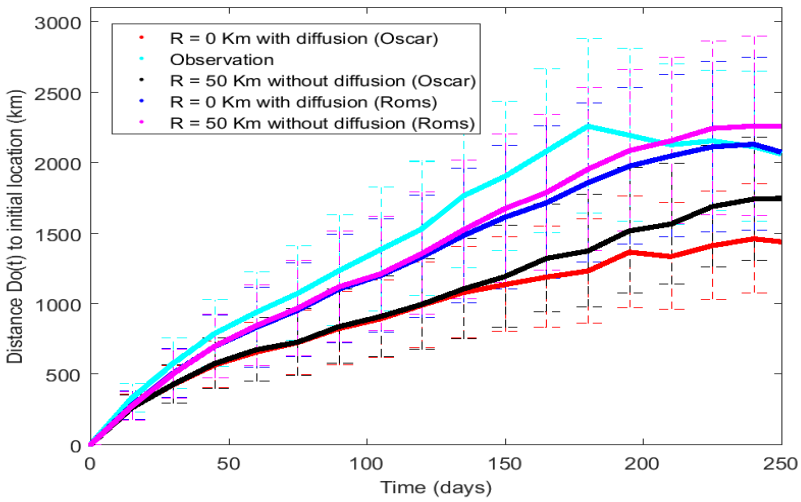

Figure 6. *Distance to initial locations of simulated particles barycenter and observed drifter over time, averaged for the 278 drifters found in the tropical Atlantic in the 1992-2008 period.*

Appendix 2

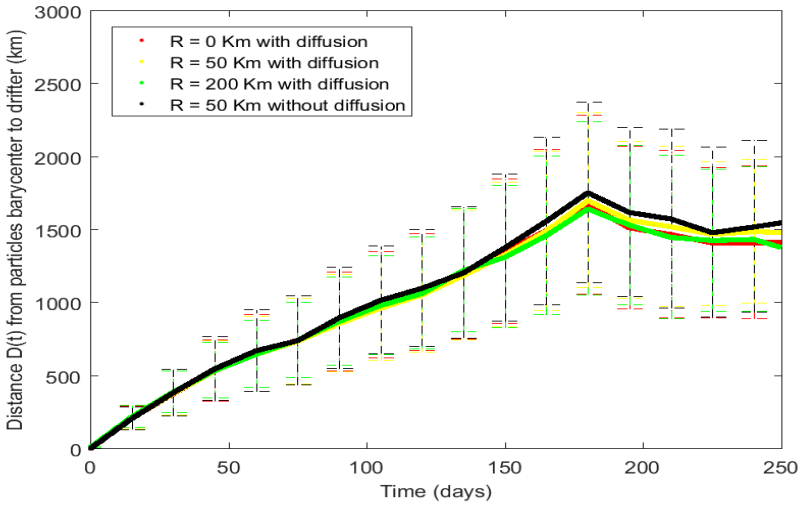

Figure 7. *Distance from the simulated particles barycenter (OSCAR) to the observed drifter location over time, averaged for the 278 drifters found in the tropical Atlantic in the 1992-2008 period.*

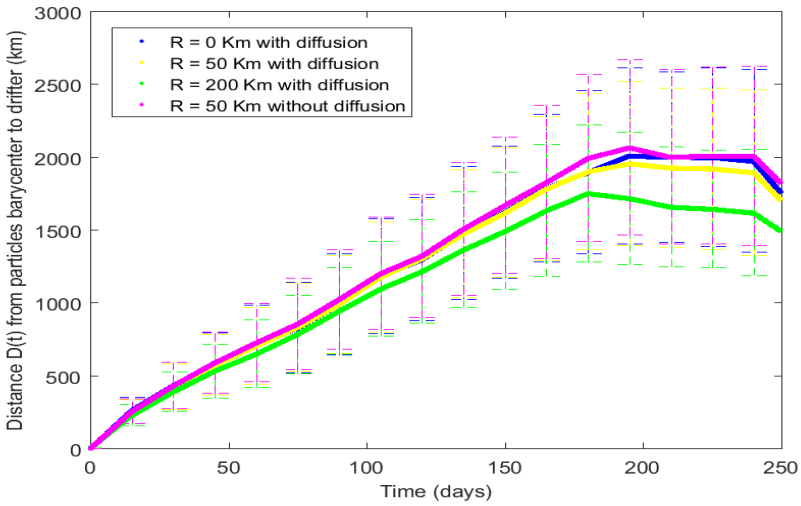

Figure 8. *Distance from the simulated particles barycenter (ROMS) to the observed drifter location over time, averaged for the 278 drifters found in the tropical Atlantic in the 1992-2008 period.*