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Quantification of errors induced by temporal resolution on Lagrangian particles in an eddy-resolving model

Xuerong Qin *, Erik van Sebille, Alexander Sen Gupta

Climate Change Research Centre & ARC Centre of Excellence on Climate System Science, The University of New South Wales, Sydney, Australia

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ABSTRACT

Lagrangian particle tracking within ocean models is an important tool for the examination of ocean circulation, ventilation timescales and connectivity and is increasingly being used to understand ocean biogeochemistry. Lagrangian trajectories are obtained by advecting particles within velocity fields derived from hydrodynamic ocean models. For studies of ocean flows on scales ranging from mesoscale up to basin scales, the temporal resolution of the velocity fields should ideally not be more than a few days to capture the high frequency variability that is inherent in mesoscale features. However, in reality, the model output is often archived at much lower temporal resolutions. Here, we quantify the differences in the Lagrangian particle trajectories embedded in velocity fields of varying temporal resolution. Particles are advected from 3-day to 30-day averaged fields in a high-resolution global ocean circulation model. We also investigate whether adding lateral diffusion to the particle movement can compensate for the reduced temporal resolution.

Trajectory errors reveal the expected degradation of accuracy in the trajectory positions when decreasing the temporal resolution of the velocity field. Divergence timescales associated with averaging velocity fields up to 30 days are faster than the intrinsic dispersion of the velocity fields but slower than the dispersion caused by the interannual variability of the velocity fields. In experiments focusing on the connectivity along major currents, including western boundary currents, the volume transport carried between two strategically placed sections tends to increase with increased temporal averaging. Simultaneously, the average travel times tend to decrease. Based on these two bulk measured diagnostics, Lagrangian experiments that use temporal averaging of up to nine days show no significant degradation in the flow characteristics for a set of six currents investigated in more detail. The addition of random-walk-style diffusion does not mitigate the errors introduced by temporal averaging for large-scale open ocean Lagrangian simulations.

1. Introduction

Understanding the pathways and timescales of oceanic transport for properties, such as mass, heat, salt, nutrients and larvae, is fundamental to many oceanographic applications. One widely used method for investigating these pathways and the connectivity of distinct regions is the use of passive Lagrangian trajectories. This method involves advecting virtual particles within Eulerian velocity fields that have been computed from an ocean-only or coupled climate model through an integration of a two- or three-dimensional velocity field. These integrations can typically be performed efficiently off-line (independent of computing the velocity fields) to significantly reduce the computational resources required.

Typically, the high-frequency velocity output, which is based on one- to five-day averages, is used in Lagrangian analysis to capture the highly chaotic nature of the trajectories, even in laminar velocity fields (Griffa et al., 2004). However, a considerable amount of data storage is required to save such high-resolution fields, often constraining the time span and the domain size that can be simulated and archived. In addition, much of the existing output from ocean models (including the extensive suite of simulations undertaken as part of the Coupled Model Intercomparison Project, CMIP5, Taylor et al., 2012) is only archived as monthly averages. As models obtain an increasingly higher spatial resolution, the storage limitations are likely to persist, leading to the ongoing requirement of compromising the temporal resolution of the output. The low-temporal resolution output is not ideal for Lagrangian analysis. In this study, we quantify the extent to which the Lagrangian simulations deteriorate as the temporal resolution of the velocity fields is degraded through temporal smoothing.

* Corresponding author. Tel.: +61 424110863.
E-mail address: xuerong.qin@unsw.edu.au (X. Qin).

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Certain aspects of the sensitivity of the Lagrangian trajectories to the sampling frequency of the velocity field have been examined in previous studies. For example, Valdivieso Da Costa and Blanke (2004) used a non-eddy-resolving model with a resolution of $2^{\circ} \times (0.9–1.9^{\circ})$ to simulate the annual cycle of the North Atlantic Ocean circulation. When velocity fields with a frequency of 15 h were averaged up to 30 days, the largest errors in the particle travel distance were 2.5–8%. However, the course spatial resolution of the model indicated that important circulation features on scales below ~200 km were not explicitly represented. Iudicone et al. (2002) an ocean general circulation model with a 1/4° resolution to study the evolution of simulated trajectories using one day, monthly and annual surface circulation fields for the Mediterranean Sea. The trajectories were sensitive to the temporal resolution only at small spatial scales and were largely independent of the model details at scales larger than ~100 km. However, of particular importance in this respect are the mesoscale eddies, which play an important role in many physical and biological processes and have an effect on the large-scale dynamics, which these low-resolution models do not fully resolve. Because many of the current Lagrangian studies are performed using the model output from eddy-permitting or eddy-resolving resolutions, typically of 1/4° or less, this study focuses on the velocity fields derived from an eddy-resolving model.

Certain Lagrangian studies using high spatial resolution models have included limited sensitivity tests to evaluate the robustness of their results for the temporal resolution. These studies have typically found that decreasing the temporal resolution had only a small effect on the Lagrangian trajectories. van Sebille et al. (2009) found that advecting particles using one- or five-day velocity fields in a 0.1° ocean model did not significantly alter the magnitude of the Agulhas leakage transport by the mesoscale eddies. Lique et al. (2010) used an ocean circulation model at an eddy-permitting resolution of 0.25° to study transport in the Arctic Ocean. There was little difference in the results between the five-day and the monthly temporal resolution fields in that the transport from the Bering Strait to the Fram Strait was negligible (0.02 vs 0.01 Sv) and the transport to the Davis Strait was similar (1.07 vs 1.11 Sv). Blanke et al. (2012) found that averaging the daily 1/12° resolution velocity fields in time from the factors of 3–12 led to a decrease of 28% for the fastest transfer times from the Sargasso Sea to the 15°W location in the North Atlantic. Finally, Griffa et al. (2004) employed a reduced gravity, quasi-geostrophic model with many turbulent features and found that the time averaging of the velocity fields affected the scatter of the Lagrangian particles but not the center of mass. In summary, most of these previous sensitivity tests have been performed on reduced domains and occasionally in 2D because of computational limitations (Goodman et al., 2005). Furthermore, none of the studies described above conducted a systematic examination of the relationship between the temporal resolution of the velocity fields and nor have the results of the Lagrangian experiment spanned multiple diverse regions.

The goal of this study is to quantify the differences in the Lagrangian trajectories in the global ocean and the energetic currents by integrating the particles in velocity fields of varying temporal resolutions, ranging from three days (the highest available global resolution) to 30 days. This study is performed using a high-resolution ocean general circulation model. Sensitivity experiments are also undertaken with isotropic lateral diffusion to determine whether the addition of diffusion to the particles can help compensate for the low temporal resolution. To quantify the uncertainty of the Lagrangian evolution, we study the position errors associated with the horizontal circulation and the connectivity transport and transit times in regions associated with large errors. Particular emphasis is placed on the 30-day averaging because many modeling centers only archive data as the monthly-mean model output.

The Lagrangian particles used in this study are driven by advection. Although we discuss the effect of adding random-walk-type diffusion to the particles, it is primarily the advective transports that are of interest. At the 1/10° horizontal scale used in this study, most of the mixing occurs by advection and explicitly resolved eddy stirring.

2. Model and methods

For the experiments, 3D velocity fields from the Oceanic General Circulation Model for the Earth Simulator (OFES, Masumoto et al., 2004) are used. OFES is a global ocean model with a 1/10° horizontal resolution and 54 vertical levels with a vertical resolution ranging from 5 m to 330 m. For the model evaluation, refer to Masumoto et al. (2004) and Masumoto (2010). The OFES data have been saved as three-day velocity fields for the period of 1980–2006. A temporal resolution of three days is the highest temporal resolution that is available for the OFES. The velocity fields used in this study are from 2001–2006. This period does not include any major El Niño–Southern Oscillation events and may be considered representative of typical ocean circulation conditions.

These velocity fields are subsequently degraded by temporally averaging them from the 9-day to the 30-day resolution, as summarized in Table 1. We use averaged fields rather than snapshots obtained at different sampling frequencies because global climate simulations will often archive monthly averaged outputs. Additionally, the effects of the sampling frequency on the Lagrangian mixing and dispersion have been previously investigated (e.g., Keating et al., 2011).

Six experiments are performed on a global domain within the velocity fields from a reference 3-day series and averaged series up to 30 days. We place particular emphasis on the 30-day averages because many models archive their data at this resolution. We also include a 30-day temporally averaged experiment with an additional horizontal isotropic diffusivity. This experiment is used to determine whether diffusivity can compensate for the reduced eddy kinetic energy (EKE) that results from the temporal averaging. A number of previous studies (Thorpe et al., 2004; Dawson et al., 2005) have included an additional lateral diffusion through the addition of a random Brownian motion component to the velocities to mitigate the effect of temporal averaging. We add lateral diffusion to the particles by providing a 'random kick' at every time step as $R\sqrt{\frac{2D_h}{t}}$, where R is a Gaussian random number between 0 and 1, D_h is the horizontal diffusivity, 1000 $cm^2\,s^{-1}$ in this study and t is the magnitude of the time step. The magnitude of this kick mimics a specified diffusivity (see also Paris et al., 2013).

The Lagrangian particles are advected forward in time using the Connectivity Modelling System (CMS, Paris et al., 2013). The 3D model velocity is integrated using a fourth-order Runge–Kutta scheme in which the local velocity is obtained through the tri-cubic spatial interpolation of the velocity fields with a six-hour time

Table 1
The Lagrangian experiments for the global ocean. *Global_3 is the reference experiment.

Exp	Time resolution (day)	Lateral diffusion
Global_3*	3	None
Global_9	9	None
Global_15	15	None
Global_24	24	None
Global_30	30	None
Global_30_d	30	1000 $cm^2\,s^{-1}$
Global_year	3	None
Global_pair	3	None