Energising transport and diffusion of particles in ocean models

Joakim Kjellsson[1], Laure Zanna[2], Scott Bachman[3], James Anstey[4]

[1]GEOMAR, Kiel. [2]University of Oxford, UK. [3]NCAR, USA. [4]CCCma, Canada

Contact: Joakim Kjellsson, jkjellsson@geomar.de, http://joakimkjellsson.github.io

Find poster at:
http://joakimkjellsson.github.io

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Summary

- Kinetic energy and effective diffusivity is underestimated in eddy-permitting ocean models.
- This results in errors in particle-tracking models.
- Use eddy parameterisation based on non-Newtonian stress tensor.
- Parameterisation increases KE and effective diffusivity while decreasing velocity autocorrelation and leads to more realistic particle behaviour.

Introduction

Kinetic energy and intrinsic variability is underestimated in eddy-permitting ocean models. This leads to an underestimation of the transport and diffusion of particles and thus errors when modelling e.g. oil spills or the movement of biological materials. As an example, Fig. 1 shows particles passively advected by the flow in an eddy-permitting ocean model (ORCA025, dx ~ 25 km) and an eddy-resolving model (ORCA0083, dx ~ 8 km), and it is clear that particles in ORCA0083 experience a higher diffusivity. Here we will explore a method to parameterise the unresolved eddy momentum fluxes in eddy-permitting models to improve the simulated particles in ORCA025.

Rivlin-Ericksen parameterisation

We first define the velocity gradient tensor as

$$\nabla \mathbf{u} = \begin{bmatrix} u_x & u_y \\ v_x & v_y \end{bmatrix}$$

We then split the tensor into a symmetric and anti-symmetric parts, **S** and **W**, which represent strain and vorticity respectively. Following the notation by Anstey & Zanna (2017), the Rivlin-Ericksen (Rivlin & Ericksen, 1955) stress tensor for non-Newtonian fluids can be written as

$$\begin{aligned} \mathbf{A}_1 &= 2\mathbf{S} \\ \mathbf{A}_2 &= \frac{d\mathbf{A}_1}{dt} + \nabla \mathbf{u}^T \mathbf{A}_1 + \mathbf{A}_1 \nabla \mathbf{u} \\ & \ldots \\ \mathbf{A}_m &= \frac{d\mathbf{A}_{m-1}}{dt} + \nabla \mathbf{u}^T \mathbf{A}_{m-1} + \mathbf{A}_{m-1} \nabla \mathbf{u} \end{aligned}$$

and the momentum forcing is found by taking the divergence of the tensor. It can be shown that the first tensor, $\mathbf{A}_1$, is equal to Laplacian viscosity if the flow is non-divergent. We focus on the second tensor, $\mathbf{A}_2$, for which only the first term adds KE to the system (Anstey & Zanna, 2017). Retaining only this term and assuming non-divergence yields

$$\frac{\partial \mathbf{u}}{\partial t} = 2\kappa \frac{d\nabla^2 \mathbf{u}}{dt} + 2\kappa (\nabla^2 \mathbf{u} \cdot \nabla)\mathbf{u}$$

It can be shown that $\kappa > 0$ results in KE dissipation while $\kappa < 0$ increases KE.

Data

We simulate Lagrangian particles in the South Pacific sector of the ACC using the TRACMASS Lagrangian trajectory code (Döös et al., 2017), with velocity data from an eddy-permitting simulation, ORCA025, and an eddy-resolving simulation, ORCA0083. Roughly 40000 particles are started on 1 Jan 2000 and traced for up to one year.

The ORCA025 and ORCA0083 simulations were run using ERA-Interim forcing for the period 1979-2010. Both use the z* vertical coordinate, which is taken into account in TRACMASS. Velocity fields were saved each 5 days.

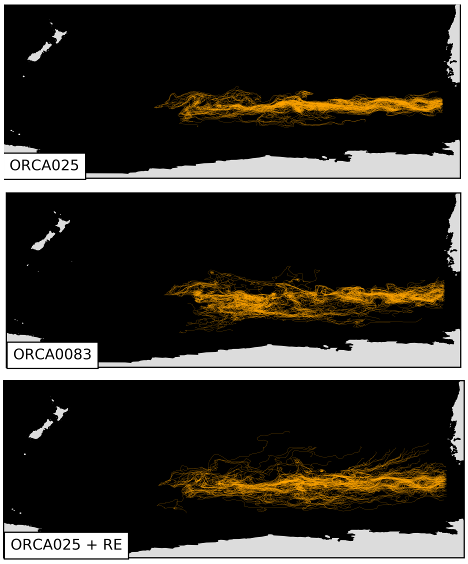

Fig 1. A subset of the simulated particles in the South Pacific from ORCA025 (top), ORCA0083 (middle) and ORCA025 with added parameterisation (lower).

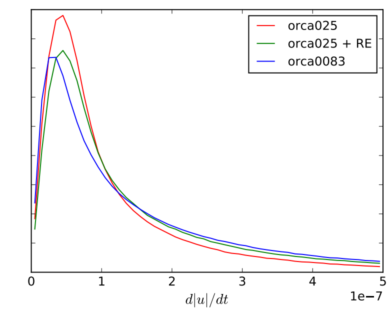

Fig 2. PDF of Lagrangian total 5-daily acceleration events for ORCA025 and ORCA0083 particles. Green line shows ORCA025 with the RE parameterisation added "offline".

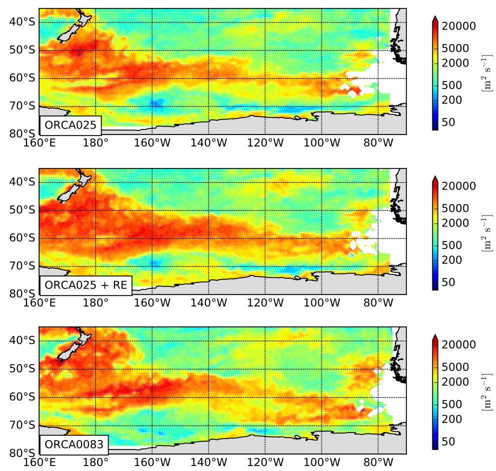

Fig 3. Absolute diffusivity of particles in ORCA025, ORCA0083 and ORCA025 with added parameterisation. Particles seeded each ~1/4 degrees. Diffusivity is averaged over 100-200 days since release and gridded on a 1x1 degree grid.

Results

We find that ORCA025 particles lack high acceleration events (Fig. 2), has lower diffusivity (Fig. 3), overestimates velocity autocorrelation (not shown) and underestimates KE (Fig. 4) compared to ORCA0083. We evaluate the RE parameterisation from the ORCA025 data and add it to the particle data after the particles have been run. The result is a distribution of acceleration events much more similar to those in ORCA0083.

We therefore implement the RE parameterisation into the TRACMASS trajectory code. Implementing the RE parameterisation to the ORCA025 particles increases the KE at all frequencies (Fig. 5) and increases absolute diffusivity (Fig. 3), resulting in better agreement with ORCA0083. We also note that adding the RE parameterisation does not change the overall pattern of diffusivity. This is due to the fact that the RE parameterisation is dependent on the velocity gradient and thus has a stronger effect in strongly eddying regions such as the ACC than in quiet regions.

We note that the parameterisation is unable to increase the mixing suppression in the ACC (not shown), likely because the parameterisation is added to the already stored ocean-model velocity fields and there is no feedback between energising the particles and the velocity field.

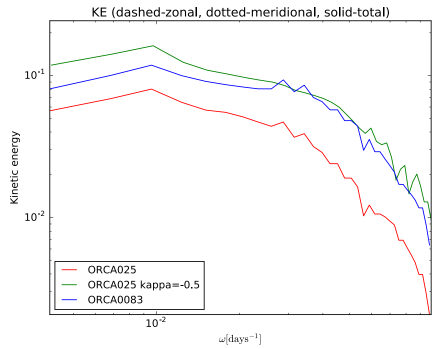

Fig 4. KE of simulated particles in the South Pacific from ORCA025, ORCA0083 and ORCA025 with added parameterisation.

Conclusions

We show that a parameterisation based on the Rivlin-Ericksen stress tensors reduces biases often found in eddy-permitting trajectory models. Hence, the parameterisation is a good candidate for improving current particle-tracking models. Furthermore, the parameterisation may also be a good candidate for representing unresolved momentum fluxes in Eulerian ocean models.

References

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