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Simulating the Agulhas system in global ocean models – nesting vs. multi-resolution unstructured meshes

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ABSTRACT

Many questions in ocean and climate modelling require the combined use of high resolution, global coverage and multi-decadal integration length. For this combination, even modern resources limit the use of traditional structured-mesh grids. Here we compare two approaches: A high-resolution grid nested into a global model at coarser resolution (NEMO with AGRIF) and an unstructured-mesh grid (FESOM) which allows to variably enhance resolution where desired. The Agulhas system around South Africa is used as a testcase, providing an energetic interplay of a strong western boundary current and mesoscale dynamics. Its open setting into the horizontal and global overturning circulations also requires global coverage.

Both model configurations simulate a reasonable large-scale circulation. Distribution and temporal variability of the wind-driven circulation are quite comparable due to the same atmospheric forcing. However, the overturning circulation differs, owing each model's ability to represent formation and spreading of deep water masses. In terms of regional, high-resolution dynamics, all elements of the Agulhas system are well represented. Owing to the strong nonlinearity in the system, Agulhas Current transports of both configurations and in comparison with observations differ in strength and temporal variability. Similar decadal trends in Agulhas Current transport and Agulhas leakage are linked to the trends in wind forcing.

Although the number of 3D wet grid points used in FESOM is similar to that in the nested NEMO, FESOM uses about two times the number of CPUs to obtain the same model throughput (in terms of simulated model years per day). This is feasible due to the high scalability of the FESOM code.

1. Introduction

Ocean general circulation models (OGCMs) in realistic configurations are powerful tools for ocean and climate research. They are not only utilized to study ocean dynamics and the role of the ocean in the climate system (e.g., Griffies and Treguier, 2013), but they also guide the establishment of ocean observing system and are used for analysis in conjunction with direct ocean observations (Fischer et al., 2014; Hirschi et al., 2003). In an interdisciplinary context, OGCMs play an important role by providing the physical circulation that determines the distribution of biogeochemical tracers or the spreading of marine organisms and particles (Duteil et al., 2014; Baltazar-Soares et al., 2014). Owing to the dominance of the mesoscale (Chelton et al., 2011), simulating ocean currents realistically necessitates the use of eddy-resolving horizontal grid sizes. Here, the baroclinic Rossby radius is a key quantity which varies with geographical latitude and vertical stratification. As a consequence, required grid sizes to resolve the mesoscale range from 1/2° at the equator to scales finer than 1/20° in coastal waters and (sub-)polar latitudes (Hallberg, 2013).

With every new computer generation and increasing storage capacity, OGCMs can be configured with finer grid sizes. At the same time, we have learned that many questions in ocean dynamics and climate variability require the use of global models. Even for regional, sometimes coastal applications, the global overturning and basin-scale gyre circulations provide important boundary conditions which one would like to explicitly include as part of the configuration. Even with modern computational resources applying traditional structured-mesh approaches at global 1/10° resolution is practically limited, allowing short integrations length and/or few experiments. To overcome this limitation, OGCMs with regional or basin-scale focus but global coverage use regionally enhanced grids, for example by stretching or rotating its coordinate systems (Roberts et al., 2006). An alternative, routinely available for ocean modelling for about a decade, is to nest a high-resolution domain into a global base model at coarser resolution

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(Debreu and Blayo, 2008). A wrapper interpolates and averages back and forth between both grids at the time step of the base model. Although being a relatively rigid approach, for example restricted to orthogonal regions, nesting effectively allows the simulation of regional dynamical systems together with their boundary conditions from the matching global simulations. If simulated with two-way interaction, nested models can also help to isolate the far-field response of mesoscale processes, e.g. by varying the nest sizes (Biastoch et al., 2008b) or by comparing the global base model with and without model nest (Biastoch et al., 2008a).

Another methodology, unstructured meshes, widely used in engineering (see, e.g., Chaskalovic, 2010) and regional modelling in complex geometry (Chen et al., 2006; Fringer et al., 2006; Swingedouw et al., 2012; Zhang et al., 2016) are new to global ocean general circulation modelling. Unstructured-mesh models use triangular or other polygonal surface meshes to span a flexible grid. By so-doing, they allow to specify resolution where required: around coastlines, within western boundary currents (WBC) or within frontal regions. To come up with significantly smaller numbers of grid points than on structured-meshes, the bulk of the open ocean, typically in the quieter centres of the large gyres, is then resolved at coarser non-eddying resolution. Although challenging given the vast range of oceanic processes that need to be represented, ocean modelling with unstructured-meshes has reached a state, where global configurations begin to be routinely used (Danilov, 2013; Ringler et al., 2013). We are, however, not aware of any systematic studies comparing structured- and unstructured-mesh approaches in global setups in which the mesoscale dominates regionally.

In this study, we compare the two approaches in global configurations with focus on the Agulhas system around South Africa (Lutjeharms, 2006). This highly energetic region provides a unique testcase because of the required mesoscale resolution and the embedment into the global circulation. The Agulhas Current flows southward as a WBC along the Indian Ocean coast off South Africa. With current speeds exceeding 2 m s^{-1} and transports of 84 Sv (1 Sv = 10^6 m^3 s^{-1}) (Beal et al., 2015), it brings enormous amounts of heat and salt from the equatorial Indian Ocean towards subtropical latitudes. Controlled by topography and vorticity dynamics, the Agulhas Current overshoots the African continent and abruptly turns eastwards (Beal et al., 2011). While ~3/4 of its original transport flow eastward as Agulhas Return Current, the remaining ~1/4 leak into the South Atlantic. This 'Agulhas leakage', about 15 Sv as estimated from limited Lagrangian observations (Richardson, 2007), happens in form of direct inflow and mesoscale eddies, 'Agulhas rings'. Owing to the dominance of mesoscale processes, model resolution plays an important role in numerical simulations of the Agulhas system. Coarse-resolution ocean models have difficulties in representing Agulhas leakage: Biastoch et al. (2008b) and Durgadoo et al. (2013) reported an overestimation of Agulhas leakage by a factor of two, resulting in a too strong inflow of heat and salt from the Agulhas Current into the Atlantic, and in consequence into the Atlantic meridional overturning circulation (AMOC). Holton et al. (2017), in this case in a 2° climate model, instead described a strong underestimation of the spatio-temporal variability of Agulhas leakage. Mesoscale eddies, generated in the Mozambique Channel and southeast of Madagascar, may be influential for the triggering of Agulhas rings. Formed upstream of the actual Agulhas Current, they drift southward and through eddy-mean flow interactions can promote offshore displacements of the WBC, 'Natal Pulses', that rapidly travel downstream (De Ruijter et al., 1999). However, it is also clear that not all Natal Pulses travel down to the Agulhas retroflection region (Rouault and Penven, 2011).

Though the regional current system around South Africa is openly situated in the Atlantic, Indian and Southern oceans, it can be simulated by regional models. A sufficient grid resolution, advanced numerics and a proper atmospheric forcing are the main ingredients for realistic and correct simulations (Backeberg et al., 2009; Loveday et al., 2014; Speich et al., 2006). In addition to the regional character, the Agulhas system is an important link in the global circulation. Owing to the termination of the African continent at 35°S, the subtropical gyres in the Indian Ocean and the South Atlantic are connected, forming a 'supergyre' (Speich et al., 2002). The amounts of heat and salt, brought from the equatorial Indian Ocean into the colder/fresher South Atlantic eventually find its way into the North Atlantic. Since OGCMs have estimated an increase of Agulhas leakage by about 1/3 to 1/4 of its original value (Biastoch et al., 2009b), probably as part of a multi-decadal variability plus anthropogenic trend (Biastoch et al., 2015), the hypothesis has been raised if the additional amounts of salt could help to stabilize the AMOC in the North Atlantic which is currently at risk through freshening effects in the subarctic and subpolar North Atlantic (Beal et al., 2011; Stocker et al., 2013).

Any evaluation of the large-scale impact of the Agulhas system must consider high resolution in combination with a global coverage and a multi-decadal simulation length. These requirements make the Agulhas system a prime candidate to test the quality of an unstructured-mesh model. Here, we use the 'Finite Element Sea-ice Ocean Model' (FESOM; Wang et al., 2014) and compare its results with an established structured-mesh nested model based on the 'Nucleus for European Modelling of the Ocean' (NEMO; Madec, 2008).

After describing the two model configurations, in particular challenges for the individual settings, we will compare the two integrations in respect to their main characteristics, both for the global and regional circulations. We will explore the following questions:

- How well is the global circulation represented? Does the embedment of the Agulhas system into the global circulation work?
- How well do the configurations represent the circulation characteristics, spatio-temporal scales and integral transports in the Agulhas system?
- What are the computational costs for both approaches?

2. Model configurations

For the comparison, we utilize output from an existing well established OGCM which was specifically set up for the Agulhas system: The NEMO configuration used here is based on version 3.1.1 (Madec, 2008). Introduced as INALT01, it has been demonstrated to simulate the mesoscale details of the Agulhas system in great detail (Biastoch et al., 2015; Durgadoo et al., 2013; Loveday et al., 2014). Utilizing the 'Adaptive Grid Refine in Fortran' (AGRIF; Debreu et al., 2008) methodology, the configuration combines a nest covering the South Atlantic and the western Indian Ocean (70°W-70°E, 50°S-8°N) at 1/10° resolution and a global base model simulating the global ocean and a dynamic-thermodynamic sea-ice (Fichefet and Morales Maqueda, 1999) at coarser resolution (Fig. 1). The tripolar base model ORCA05 has a nominal 1/2° grid (ORCA05), starts with 55.6 km at the equator and varies southward as a Mercator grid and northward towards two northern poles over Canada and Russia (Fig. 1b). The minimum grid size (in the ocean) is 12.6 km. The resolution in the nest is increased by a factor 5 and hence varies between 7.2 and 11.1 km. Both grids have 46 vertical levels, with thicknesses ranging from 6 m at the surface to 250 m in the deep ocean. The bottom cell is allowed to be partially filled (Barnier et al., 2006). The bottom topography is interpolated from the 2 min Gridded Global Relief Data ETOPO2v2.

AGRIF is a wrapper providing the infrastructure for interpolating and averaging between both grids. Technically, after every base model time step (2160 s) it provides lateral boundary conditions (linearly interpolated between time steps n and $n + 1$) for the nest which is then integrated for 4 time steps (each 540 s). The lateral boundary conditions of the nest then updates the base model which is integrated for another time step until the procedure of the nest integrations start again. Every 3 nesting time steps, all nest grid points are averaged onto their corresponding base model grid points ('baroclinic update'). With