Large-scale ocean modeling on unstructured meshes

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1. Introduction

Ocean circulation modeling helps to gain understanding of ocean role in the changing climate. Most of modeling studies are performed with traditional ocean circulation models formulated on structured meshes, which warrants numerical efficiency. The complexity of basin geometry and the need to incorporate eddy motions on various scales, or the need to include physical processes that involve small scales (such as overflows or coastal upwelling zones) serve as motivation to studies at increasingly refined meshes. Such high-resolution simulations require immense computational resources and storage. Rather commonly the focus of simulations is on a particular area, and in such a case resolution in structured mesh models can be refined locally through nesting in order to spare resources (see, e. g. Debreu and Blayo, 2008). Nesting is available, for example, with NEMO and ROMS, and many models use it routinely in a build-in form.

A novel approach is offered by models formulated on unstructured meshes. While such models are common in coastal studies where geometrical complexity of coastlines and the need to resolve estuaries leave hardly any other choice, these models are only starting to be applied to simulate large-scale circulation. Unstructured meshes provide multi-resolution functionality and can accommodate multiple areas of arbitrary form with refined resolution, as dictated by practical tasks. Additionally, unstructured meshes can be aligned with coastlines or the continental break. This approach is offered by Finite-Element Sea-ice Ocean circulation Model (FESOM) (Wang et al. 2008, 2014) and MPAS-Ocean (Ringler 2013), and other developments, such ICON (see ICON website) or new core at AWI (Danilov 2012).

Compared to traditional nesting, the main advantage of using unstructured meshes is their unlimited refinement factor, lack of spurious reflections because of smooth transitions and consistent solution, and the ease of using: refinement is only the matter of mesh design. Their main drawback is their larger computational load per degree of freedom, and the fact that their time step is defined by the smallest element. Although unstructured-mesh models remain slower than their structured-mesh counterparts, at least one finite-volume implementation lags only by a factor about 3 (see Ringler et al. 2013), which is fully acceptable if one accounts for the relative immaturity of these models and the possibility to invest their degrees of freedom where needed. Time step limitation is not an issue in applications where the refined region contains the majority of the mesh nodes (see, e.g., Ringler et al. 2013).

It is therefore believed that models capable of working on unstructured meshes may be convenient and more optimal for certain tasks of large-scale ocean modeling. There is hope that they will contribute, for example, to reaching more realism with respect to simulation of overflows or dense water production in setups intended for climate studies. While unstructured grid models may not fully replace models formulated on structured meshes, the ability to invest the resources where necessary warrants their place in ocean modeling. It is also believed that with advancement of computer technology and further optimization the difference in computational efficiency between structured- and unstructured-mesh models will further decrease.

Finite-Element Sea-ice Ocean circulation Model (FESOM) is the first model designed to work on unstructured meshes on large-scales. MPAS-Ocean is more similar to traditional global ocean models with its finite-volume discretization and accompanying computational efficiency. The rest of this note deals with examples illustrating benefits of multi-resolution, preceded by a brief resort to mathematics.

2. Mathematical challenges

Development of models capable of working on unstructured meshes faces challenges on both numerical and computer science sides, which are subjects of ongoing research. While the latter are largely related to indirect memory addressing, the former have a geometrical origin and are explained below.

Unstructured meshes may be composed of various polygons. Most popular are triangular meshes which owes to their flexibility in varying resolution or fitting the mesh to the details of domain geometry (FESOM). By connecting circumcenters or centroids of triangles one can obtain dual quasi-hexagonal meshes (a special variant is used by MPAS-Ocean). Simplest co-located discretizations like that used in FESOM need to be stabilized against pressure modes. Staggered discretizations on triangular or dual meshes usually support families of spurious numerical modes. These modes arise because of disparity between the numbers of degrees of freedom used to represent velocity and pressure. They have geometrical origin: on triangular meshes the ratio of vertices to cells to edges is approximately 1:2:3. So if pressure is at vertices and velocity at cells, there are twice more velocities than needed (FV cell vertex discretization in Ringler and Randall (2002) and Danilov 2012). If pressure is at cells (triangles) and normal velocities at edges, there are too many pressure degrees of freedom (ICON). On dual quasi-hexagonal meshes (MPAS-Ocean) with pressure at centers and normal velocities at edges, there are 1.5 times more velocities than needed. For mathematical details see Danilov (2013) and references therein. It is important to note that the various spurious modes resulting from the mismatch in degrees of freedom are not equally problematic; some are challenging (e.g. ICON) while others are benign (e.g. MPAS-Ocean). This is the reason why the utility of particular discretization is determined not solely by the ability to accurately resolve physical perturbations (waves) but also severity of the spurious modes. Eliminating them can be more difficult than on regular quadrilateral meshes, and sometimes requires special algorithmic solutions.. Ongoing research seeks new discretizations with less numerical artifacts.

3. Practical examples

Multi-resolution (unstructured-mesh) models are gradually becoming reality. FESOM participates in CORE-II intercomparison project, demonstrating that on meshes typical for current climate models it manages to maintain the large-scale ocean circulation with degree of realism typical for structured-mesh models despite its very different numerical core (see Ocean Modelling, virtual special issue Core-II). MPAS explores the impact of refinement on eddy statistics, and demonstrates feasibility of global eddy-resolving simulations on unstructured meshes (Ringler et al. 2013). Particular examples below illustrate the potential of multi-resolution models.

3.1 Freshwater transport through the Canadian Arctic Archipelago

Figure 1 shows the mesh configured to study the Arctic Ocean freshwater circulation (Wekerle et al., 2013) with FESOM. Arctic Ocean presents a large freshwater reservoir owing to high net precipitation and runoff of numerous rivers. The freshwater exchange of the Arctic Ocean with the North Atlantic happens partly through the Fram Strait and partly through the straits of the Canadian Arctic Archipelago (CAA). The excessive freshwater storage in the Arctic is due to precipitation and runoff of numerous rivers, and the outflow is largely driven by the pressure difference between the Arctic and the North Atlantic. Since the path of freshwater lies in the vicinity of main convection sites, the redistribution of freshwater between Fram Strait and the CAA has global implications, in particular on the strength of the meridional overturning circulation (MOC).

The transport of freshwater through the CAA is mostly associated with volume transport. Most of the current climate models simulate it by artificially increasing the width of major channels (Parry Channel and Nares Strait). While this may be sufficient to simulate the mean transport, it is not necessarily so for the transport variability. The study by Wekerle et al. (2013) explores these issues with FESOM by comparing the performance of two global model versions, the control configuration with 24 km resolution in the CAA, which is common for climate models, and the other one with 5 km resolution in the CAA. Both resolve the Arctic Ocean with 24 km, getting coarser in the rest of the ocean except for the vicinity of coastlines. The fine resolution of the CAA (see Fig. 4) adds about 50% nodes to the surface mesh and limits the time step to be about 10 min, yet the model is still fast enough to allow for multidecadal simulations.

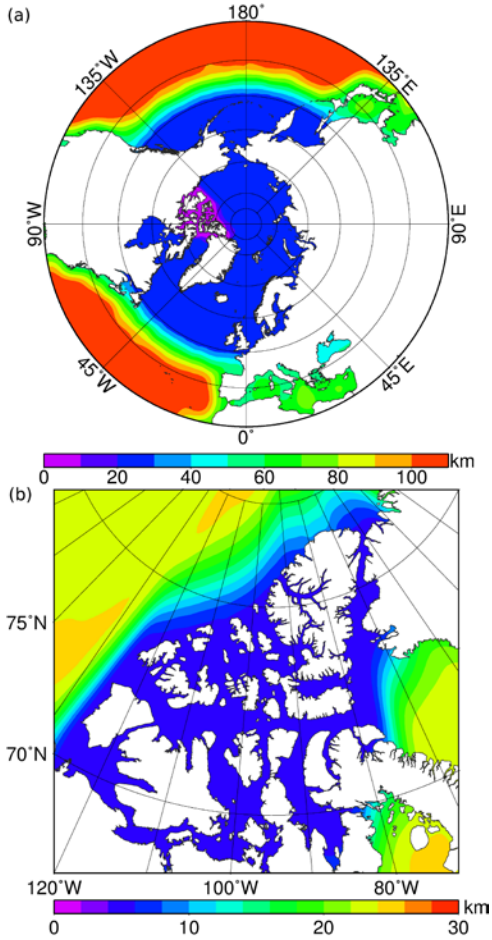

Figure 1: Horizontal resolution of the mesh with the CAA region refined used by Wekerle et al (2013): (a) view in the stereographic projection and (b) zoomed into the CAA region.

The comparison between the simulation results and available observational data by Wekerle et al. (2013) demonstrates that the fine resolution run is indeed able to simulate the transport variability in closer agreement with the observational data. Further analysis shows that the freshwater transported through the CAA stays confined to the coast in the Labrador Current, while the increased salinity in the Eastern and Western Greenland Currents in the fine-resolution run leads to an increased mixed layer depth in the Labrador Sea, which, in turn, increases the strength of the MOC. The analysis also shows that the variability in freshwater transport is driven by the large-scale atmospheric pressure system. The global impact of the regional improvement indicates the potential of unstructured meshes in climate simulations.

3.2. MPAS-Ocean

While mesoscale eddies play an important role in setting the climate of the ocean, globally resolving these eddies with climate system models is still a computationally demanding endeavor. Multi-resolution ocean models allow for the opportunity to resolve mesoscale eddies in regions of interest while parameterizing mesoscale eddies elsewhere. Figure MPAS-Ocean-1 shows fluid kinetic energy at a depth of 100 m from a global MPAS-O simulation. The grid resolution is 10 km within a portion of the North Atlantic and transitions to 80 km elsewhere. Mesoscale eddies are well-represented within the 10 km region.

Ringler et al. (2013) compares and contrasts global, quasi-uniform simulations to global, multi-resolution simulations with enhanced resolution in the North Atlantic. The simulations are evaluated based the mean and variance of sea-surface height as compared to observations. The primary finding is that mesoscale eddy dynamics are simulated as well in the North Atlantic with the multi-resolution mesh as with the globally uniform mesh. Furthermore, the computational burden of the multi-resolution simulation was only 15% that of the globally uniform simulation. This finding has been confirmed in more idealized simulations of mesoscale eddy dynamics. Looking forward, opportunities exist to further enhance resolution within the specific regions of North Atlantic to study the dynamics of Gulf Stream separation, controls on the Northwest Corner and, more broadly, the importance of sub-mesoscale dynamics.

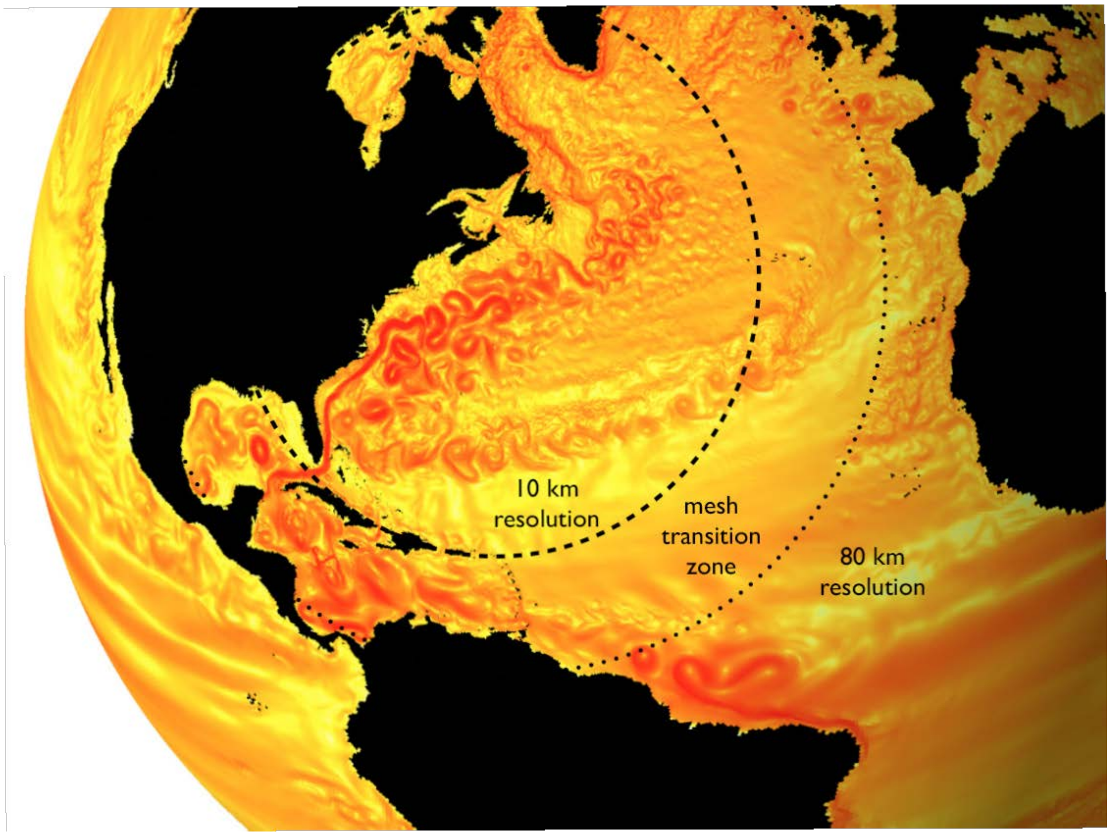

Figure 2. A snapshot of fluid kinetic energy at a depth of 100 m from a MPAS-Ocean, global, multi-resolution simulation. The mesh resolution is 10 km with the region of the North Atlantic containing the Gulf Stream, North Atlantic Current and Northwest Corner. Away from these currents of interest, the mesh transitions smoothly to 80 km.

4. Conclusions

Multi-resolution models formulated on unstructured meshes have matured over recent years. They promise a convenient and economical approach to research inquiring into regional dynamics in the context of large-scale global ocean circulation. We see their potential in facilitating downscaling or being used to learn about functioning of certain aspects of local dynamics. Ongoing research seeks the ways of further improving their computational efficiency which is, however, already sufficient for many practical applications. The accumulating practical experience makes data processing on unstructured meshes or setting up of the models proper easier, making these models even more appealing.

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