# DRAKKAR: developing high resolution ocean components for European Earth system models

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## 1. Introduction

DRAKKAR is a consortium of European ocean modelling teams. It was "created to take up the challenges of developing realistic global eddy-resolving/ permitting ocean/sea-ice models, and of building an ensemble of high resolution model hindcasts representing the ocean circulation from the 1960s to present" (quoting the DRAKKAR Group, 2007, in a CLIVAR Exchanges paper where the DRAKKAR strategy was presented for the first time). Now in the second decade of its existence, the DRAKKAR Group is active and thriving, and it is now timely to present recent developments and future plans in this special issue of CLIVAR Exchanges.

DRAKKAR was initiated when a group of leading ocean modelling teams in Europe decided to use common global ocean-ice model configurations based on the NEMO platform in order to explore the ocean variability forced by the atmosphere, at time scales from seasonal to multi-decadal, with the highest possible spatial resolution. High resolution is required to resolve narrow boundary currents and energetic mesoscale eddies, which are ubiquitous in the world ocean. High resolution global simulations have considerable added value compared to regional models, because eddies and unstable jets can transfer eddy energy across ocean basins and from one basin to the next. Such features are difficult to reproduce in limited-area models - unless high resolution (both temporal and spatial) boundary conditions are used at the open boundaries, which again requires high resolution global simulations. The DRAKKAR simulations are well-suited both for the analysis of the global ocean variability forced by the atmosphere, and as boundary conditions for regional models. Furthermore, the multi-decadal forced simulations carried out by DRAKKAR are necessary steps to assess ocean model configurations as trustworthy components of earth system models, in preparation for - or as companion to - the CORE multi-century forced ocean-ice simulations (Coordinated Ocean Reference Experiments, e.g., Danabasoglu et al., 2014).

## 2. Global ocean simulations: from 1/4° to 1/12°

The three key ingredients of DRAKKAR global configurations are
- the NEMO modelling platform (Madec, 2008), based on the OPA ocean code and the sea-ice model LIM;
- the ORCA tripolar global grid, which is almost isotropic (it is refined as the cosine of the latitude in the Southern hemisphere and also refined poleward in the Northern hemisphere). The ORCA grid allows a good representation of the Arctic Ocean and its exchanges with the Pacific and Atlantic oceans (e.g., Lique et al., 2009)
- the DRAKKAR forcing sets (DFS, Brodeau et al., 2010).

These atmospheric forcings follow the methodology of Large and Yeager (2010) but use ECMWF atmospheric variables instead of NCEP. Within DRAKKAR, simulations with DFS are compared with simulations using the Large and Yeager forcing, following the CORE protocol (Griffies et al., 2012).

The first DRAKKAR simulations were carried out in 2006 used ORCA025, a global configuration with resolution 1/4° at the equator (DRAKKAR Group, 2007; see also Barnier et al., 2006, and Penduff et al., 2007). The model configuration was shared with MERCATOR-Ocean, the French operational oceanography agency. MERCATOR-Ocean tested ORCA025 in operational mode; the DRAKKAR teams developed it further, regarding numerical schemes, parameterisations and bathymetry, which benefitted not only research projects but also the operational forecasts. Recognizing the need for increased vertical resolution in the surface layers (of order 1m to represent the diurnal cycle), the UK Met Office and MERCATOR-Ocean operational centres and the DRAKKAR Group jointly agreed on a new vertical grid with 75 levels. ORCA025 simulations carried out by DRAKKAR partners have made possible a large number of scientific studies about, for instance, the global and regional variability of the ocean circulation, heat and salt content; the oceanic response to atmospheric modes of variability; eddy dynamics and their impacts on biogeochemical cycles and biology. About 50 peer-reviewed articles per year based on DRAKKAR ORCA025 simulations or DFS forcings have been published between 2011 and 2013.

The ORCA025 global configuration is now the ocean component of high resolution coupled climate models (Scaife et a.l, 2014), and it is anticipated that a large number of European climate centres will use it for CMIP6, at least for short term scenarios (time scales of a few decades).

Although the ORCA025 grid allows for the development of baroclinic instability and large eddies, such as Agulhas rings, it has long been known that even higher resolution is required to represent faithfully the mid-latitude western boundary currents systems such as the Gulf Stream and Kuroshio and their recirculation gyres (Smith et al, 2000). This has been recognised by the operational centres, and in 2009 MERCATOR-Ocean brought the 1/12° ORCA12 configuration into pre-operational mode (Hulburt et al., 2009). The use of such a costly ocean model for multi-decadal simulations was a challenge that the DRAKKAR group decided to take up in a coordinated fashion. Long experiments (10 to 30 years) were carried out by three DRAKKAR teams in 2012, followed in 2013 and 2014 by a climatological simulation (84 years) and a long interannual simulation (from 1958 to 2012).

## 3. Recent results

The DRAKKAR ORCA12 simulations are a unique opportunity to investigate the variability of the Atlantic Meridional Overturning Circulation (AMOC), the eddy or small scale mechanisms that contribute to its variability, and its stability. Indeed, there was concern that coarse resolution climate models may be at odds with observations for the representation of a key property of the AMOC: its stability with respect to an increased freshwater input in the northern high latitudes (Hawkins et al., 2011). Following the introduction of the AMOC bistability concept by Ramstorf (1996), modellers have focussed on a specific indicator: FTov, the salinity anomaly transport (or conversely, freshwater anomaly) by the AMOC at the entrance of the South Atlantic along 30°S. When the AMOC imports fresh waters into the Atlantic, an increase in AMOC leads to a reduction in Atlantic Ocean salinity (negative feedback on the AMOC) while in the opposite case, a stronger AMOC imports more salt into the northern latitudes, inducing more dense water formation (a positive feedback and possible instability of the AMOC). Using four ORCA12 simulations and two ORCA025 simulations, Deshayes et al. (2013) showed that the ORCA12 simulations are in better agreement with observations than ORCA025 simulations or coarse resolution climate models in terms of the FTov indicator. This is because the AMOC maximum is located at a more realistic depth in relation to the water masses at 30°S. These results confirm that the present -day AMOC could be in the bi-stable regime. These results hint that future coupled scenarios with high resolution ocean components could predict more dramatic future changes of the AMOC, compared to the present coarse resolution scenarios.

Just like this stability issue, the AMOC variability requires more than a single simulation in order to understand which events are robust, and what is their significance. Blaker et al. (2014) use a total of seven simulations; six ORCA025 simulations with different forcings and one ORCA12 simulation, in order to investigate the dramatic minimum in AMOC observed during the winter 2009-2010 by the RAPID array (McCarthy et al., 2012), which was followed by a similar event the next winter. The two simulations covering the observational period (up to 2011) reproduce the weakening events, demonstrating that these events are directly forced by the atmosphere, as shown in Figure 1. The long time series provided by the DRAKKAR simulations allow Blaker et al. (2014) to look for historical analogues of these weakening events. At least two pairs of events have occurred in the past, and these events show substantial meridional coherence.

ORCA12 simulations give us a unique opportunity to investigate in detail the mechanisms of AMOC variability. Analysis of the RAPID array have shown that wind forcing is a driver at the seasonal scales, and the dynamics near the eastern boundary have a strong impact on the AMOC at 26°N. ORCA12 provides a four-dimensional context to these observations, and shows how the relationship between the wind stress curl and the density structure is influenced by small scale features such as the Canary Islands (Duchez et al., 2014). Other studies are targeted at the North Atlantic subpolar gyre, considering the circulation in the boundary currents (Marzocchi et al., 2014) or wind-forced variability in relation to atmospheric weather regimes (Barrier et al., 2014). Hughes et al. (2014) have recently investigated the "Southern mode" of variability of the Antarctic circumpolar transport in both ORCA025 and ORCA12. The availability of many simulations and also the contrast between the interannual simulations and those forced by a repeated

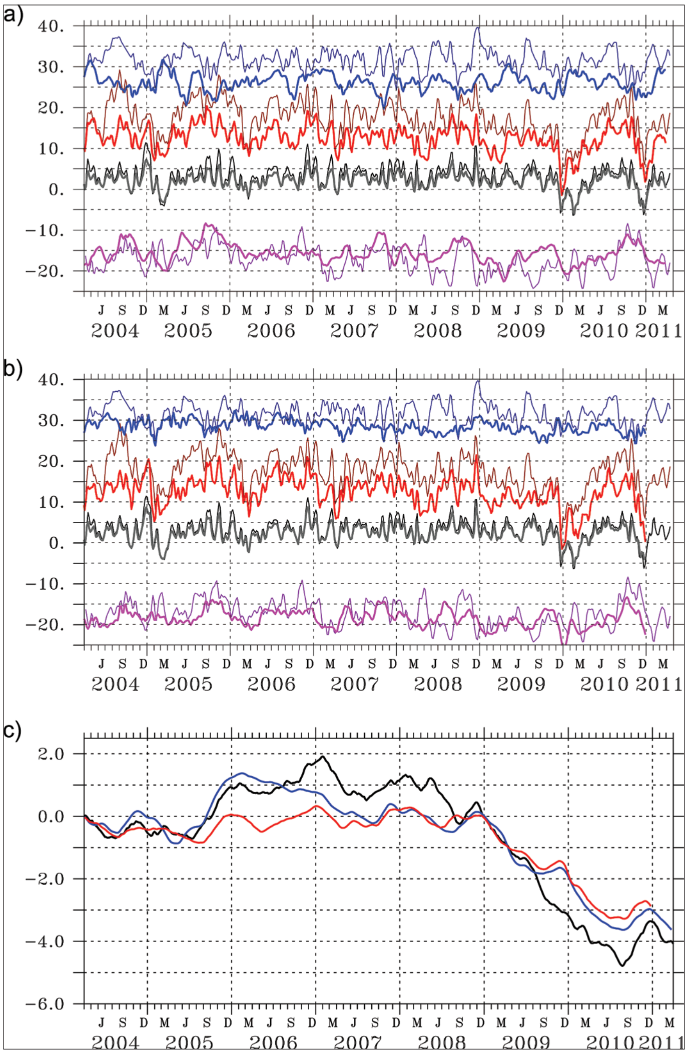


Figure 1: a, b) Comparison of RAPID observations of the AMOC (thin lines McCarthy et al., 2012) with an ORCA025 (a) and ORCA12 (b) simulation (Blaker et al., 2014). The time series of the total AMOC (red line) is the sum of three components: Gulf Stream transport (blue), Ekman transport (black) and the upper mid-ocean transport (pink). All time series are in units of Sv (Sverdrup). Note that the two events of weak AMOC at the end of years 2009 and 2010 are well simulated in ORCA12. c) Cumulative upper mid-ocean transport anomalies (following Bryden et al., 2014) for the RAPID observations (black), ORCA025 (blue) and ORCA12 (red). Units are Sv/year. The good agreement between ORCA025/ORCA12 and RAPID shows that the similar AMOC evolutions seen in model and observations in a) and b) are not just due to Ekman transports but also to the model's ability to capture a large fraction of the long-term evolution of the upper mid-ocean transport.

seasonal cycle (climatological runs) is the key to a quantification of the "intrinsic" ocean variability (Penduff et al., 2011, Hirschi et al., 2013). These studies initiated with ORCA025 are currently being pursued using ORCA12 and will also benefit from ensemble strategies at lower resolution (see Penduff et al., 2014, this issue).

Long ORCA12 simulations (especially the unique, 84-years long climatological simulation) are well suited for an evaluation of the impact of transient ("eddy") correlations on the global meridional transports of heat and salt. Regarding the global salt balance, until last year the only estimate of the eddy contribution dated from the nineties and relied on a 0.5° numerical model. The new calculation carried out with ORCA12 by Treguier et al. (2014) demonstrates that eddy velocity-salinity correlations are responsible, on average, for about half the flux of salt out of the subtropical gyres that is required to balance the excess evaporation in these regions, as shown in Figure 2.

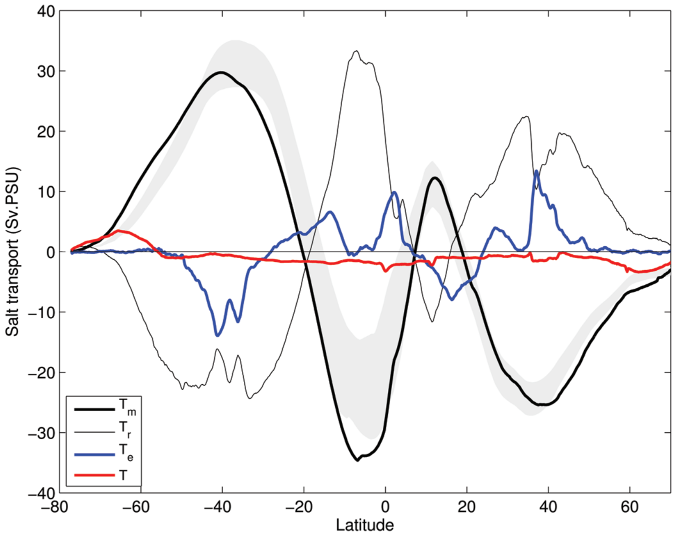


Figure 2: Decomposition of the meridional transport of salt in the climatological ORCA12 simulation, averaged zonally over the global ocean (Treguier et al., 2014). The total transport (T, red line) is close to zero, reflecting the equilibrium of the salinity distribution in this long experiment. The non-zero transport north and south of 60° is due to ice-ocean fluxes. This total transport results from the near-cancellation of three contributions: 1) the salt transport by the net ocean mass flux (Tm, thick black line) which is directly forced by the evaporation/precipitation balance and which compares well with the observations (Large and Yeager, grey shading), 2) the compensating transport by time-mean recirculations, overturning and gyres (Tr, thin black line), and 3) the salt transport by transient "eddy" velocity-salinity correlations (Te, blue line), which is as important as the mean in the mid latitudes (40°N and 40°S).

## 4. Conclusions and future plans

While global simulations at 1/10° to 1/12° resolution have been around for more than a decade, the possibility to run multiple multi-decadal experiments with such models is recent. In the past four years the DRAKKAR Group has run such simulations with the global 1/12° ORCA12 model based on the NEMO European modelling platform. The dramatic improvement of the western boundary current systems will certainly lead to great advances when these models are coupled to the atmosphere and to biogeochemical cycles.

However, we have also found new biases and drifts that arise at high resolution. For example, although the Gulf Stream separation is generally improved, the path of the North Atlantic current is not yet robust between the different ORCA12 simulations and in some cases appears less realistic than in the lower resolution configurations. Extensive tests carried out by the DRAKKAR Group suggest that despite its fine grid, ORCA12 is still very sensitive to the sub-grid scale parameterisations and numerics. Further work is needed to improve the representation of bathymetry, and to choose the optimal vertical resolution for ORCA12. The improvement of the global ORCA12 model will benefit from the exploration of even higher resolution regimes in key regions, using the AGRIF refinement package (e.g., Talandier et al., 2014; Biastoch et al., 2014, this issue).

It is the genuine collaboration across all the DRAKKAR modelling groups, and the planning and execution of coordinated sets of model integrations, that greatly enhances our ability to achieve rapid scientific advances with such high-resolution models. ORCA12 simulations are documented on the web site www.drakkar-ocean.eu and the results are available upon request.

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