Drakkar International Research Network

2014-2017 report

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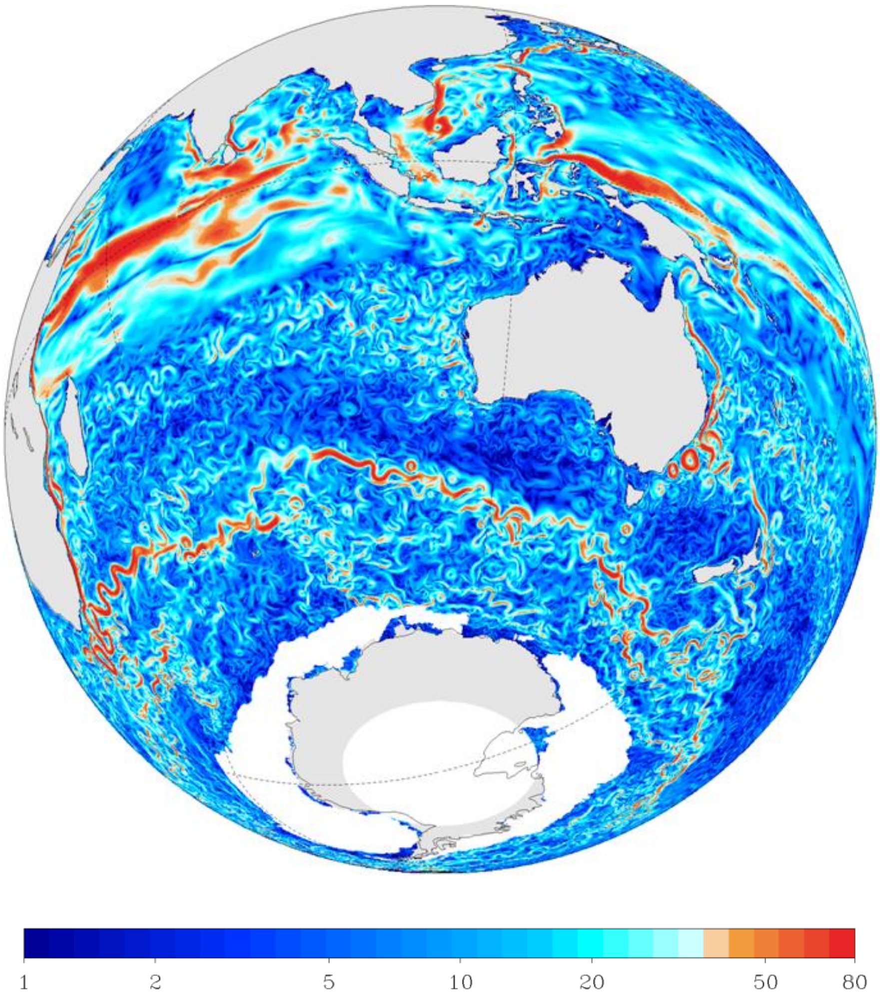

Figure 1: Instantaneous surface velocity in the ORCA12 model (cm/s). White areas represent the sea-ice cover. www.drakkar-ocean.eu

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1 Introduction

The ocean plays a major role in the regulation of the Earth's climate. The ocean circulation controls to a large extent the ocean biomass and biogeochemical cycles, the ocean acidification, its uptake and sequestration of CO_2, and the patterns of regional sea level. Ocean currents vary on spatial scales that are much smaller than the size of the ocean basins: mesoscale turbulence (meanders and eddies of 10 km to 100 km size) and boundary currents flowing along continental slopes and shelves contribute to a large part of the oceanic transports of heat and freshwater between the subtropics and the polar latitudes. These fine-scale eddies, narrow boundary currents, and their associated non-linear contributions to the global scales represent a huge challenge for numerical ocean models: resolving them globally requires model configurations with a large number of grid points. Their high computational cost makes it necessary to coordinate the efforts of different teams in order to perform and analyze multiple simulations relevant for climate (e.g., simulations over many decades).

A group of European modellers from France, Germany and the U.K. have been coordinating their efforts since the mid 2000s to develop and use high resolution global ocean-ice models based on the NEMO modelling platform. The Drakkar group (2007) reported the first multidecadal simulations performed with the global model ORCA025 at 1/4° resolution, developed jointly with Mercator-Ocean. A few years later, the development of ORCA12 started (at 1/12° resolution). The collaboration continued from 2014 to 2017 in the framework of an International Research Network (IRN, formerly GDRI) sponsored by CNRS and Ifremer (France), NOC (U.K.) and Geomar (Germany). This network acts, informally, as a central node for an international group of scientists that is wider than just its formal partner institutions. The annual Drakkar workshop gathers researchers from many institutes and universities in Europe and beyond, working on the same challenge (high resolution global ocean-ice modelling based on NEMO).

The present report summarizes the results of the Drakkar network for the 2014-2017 period. The report is organized in four sections summarizing the progress on the four objectives defined in 2014 :
- Maintain a coherent hierarchy of global model configurations based on the NEMO modelling framework, and in particular, lead the development and improvement of the global 1/4° ORCA025 model and the 1/12° ORCA12 model;
- Develop atmospheric forcing fields suited for multi-decadal global ocean model simulations, and the tools and expertise necessary to run, evaluate and analyze these simulations;
- Perform and analyse coordinated global ocean hindcasts at eddy-resolving resolution and make the results available to a wide community;
- Utilize realistic ocean simulations as a testbed for new parameterizations, and to systematically evaluate the benefits of higher spatial resolution for earth system models.

A final section summarizes the networking activities.

2 The DRAKKAR hierarchy of global models and tools

The 1/12° global model ORCA12 has been the focus of the Drakkar network over the 2014-2017 period. A short paper in Clivar Exchanges (the Drakkar group, 2014) documented the network strategy and the first scientific results obtained with ORCA12; an updated list of results is presented in section 4. Here we summarize the recent developments of ORCA025 and 0RCA12 that have been facilitated by the international partnership.

The global 1/4° model configuration ORCA025, co-developed by Drakkar and NEMO partners since the early 2000s, had a huge impact in the modelling community in Europe and beyond. The reference publication documenting ORCA025, Barnier et al (2006), has gathered 344 citations. From 2014 to 2017 there are between 32 and 44 citations each year, reflecting a sustained use of the model by a large community. ORCA025 has been used within the European MyOcean project to perform real time ocean analyses, forecasts and long term ocean reanalyses (GLORYS), and has now become the ocean component of many European earth system models to be used in CMIP6 (the next IPCC process): UKMO, Météo-France, CERFACS, CMCC, and EC-Earth. It has been included in the seasonal and decadal forecasting systems of the UK Met Office (UKMO), and "through an improved representation of North Atlantic sea-surface temperature biases, has led to a step-jump in the skill of the forecasts for winter conditions for the UK" (Scaife et al, 2014, the Drakkar group 2014). In Germany, ORCA025 is used as a support for regional high-resolution zooms using the AGRIF grid-refinement tool. In the UK and in France, ORCA025 is also used to evaluate the oceans' uptake of heat and carbon, including biogeochemical couplings.

Finally, a significant achievement of the last 4 years is the development of NEMO's probabilistic version (Bessières et al, 2017) to perform the first large ensemble (50 members) of multi-decadal forced ORCA025 simulations, as part of the French OCCIPUT project (Penduff et al, 2014; Serazin et al, 2017; Leroux et al, 2017). Probabilistic modelling/analysis tools are now being adapted for operational applications in the framework of the GLO-HR CMEMS project. The OCCIPUT dataset is made available to all Drakkar partners, and is currently being analyzed in collaboration with several of them to better assess the detection and attribution of climate change signals in the ocean (PIRATE OST/ST project, SMURPHS NERC project)

The evolution of ORCA025 reference configurations has been a topic of discussion at all Drakkar meetings, facilitating the coordination of the numerical choices made by different climate centers. ORCA025 is used as a testbed for new developments, before using them in more expensive configurations such as ORCA12. Examples of new developments presented and discussed at Drakkar meetings are:

- coupling with sea ice, with the new ice model LIM3 but also with other models (CICE and GELATO)
- coupling with surface waves (a special session on the subject, joint with the NEMO-WAVE group, was held in 2017)
- extending the domain in the Ross and Weddell Sea and parameterizations to represent better the under-ice shelf seas;
- introducing the new equation of state TEOS10, and consequences for model intialization;

- trade-offs regarding the choice of the different vertical mixing schemes in NEMO: TKE *vs* GLS;
- the importance of parameterizing mesoscale eddies in ORCA025, in polar regions where the grid does not resolve the Rossby radius of deformation.

At the beginning of 2014, three multidecadal experiments had been run using ORCA12, two by IGE using the GENCI computing centres in France, and one at NOC Southampton. Over the following years, other multidecadal simulations (starting in 1958) have been run and documented with the new Drakkar forcing set and continued into the most recent period (2015-2016). As part of a hierarchy of models, ORCA12 can be used to assess the robustness of ORCA025 results. This is an asset in the context of climate scenarios which may suffer from the insufficient resolution of ORCA025. It was noted that ORCA12 could be used more to assess the need for parameterizations in lower resolution configurations such as ORCA025: e.g. is an adapted version of the Gent-McWilliams parameterization of mesoscale eddies necessary at 1/4°?

The ORCA12 experiments require a significant amount of computer resources and are often selected as pilot projects for new supercomputing machines. As an example, the French group has obtained 43590000 CPU hours on the GENCI computing centres over 4 years for DRAKKAR simulations. 18500000 CPU hours have been allocated on the European infrastructure PRACE for the ensemble of ORCA025 simulations (ANR project OCCIPUT). Issues of parallelization, optimization, data storage and access have been discussed at each DRAKKAR workshop to ensure that each group using ORCA025 or ORCA12 obtains the best computing performance, making use of the experience gained by other groups.

The analysis of large model datasets required powerful tools. Jean-Marc Molines at IGE has developed CDFTOOLS, a library of Fortran routines, gathering contributions from researchers of different laboratories. In 2016-2017, a new version of the library adapted to the latest NEMO code (variable volumes) has been released on the github MEOM-group platform. IGE also maintains a svn server for DRAKKAR configurations that are not included in the standard NEMO release (ORCA12 for instance).

3 Forcing ocean models

DRAKKAR continued the development of a coherent atmospheric forcing based on ECMWF reanalyses, initiated in 2007 (Brodeau et al, 2010). These developments are consistent with the CMIP simulation protocol. A new version of the DFS forcing, DFS5.2 has been finalized and made available to the community (a report describing this dataset of surface weather data is posted on the DRAKKAR site). DFS5.2 combines ERA interim and ERA40 to give an atmospheric forcing set of resolution 0.7°, 3h over the period 1958-2014.

The evaluation of forcings is a continuous work, which is also based on the evaluation of the ECMWF reanalyses which are the basis of DFS forcing. This systematic evaluation within the Drakkar community led to the discovery of spurious features in the original reanalysis data, on the one hand in the equatorial Pacific (moisture flux errors related to the assimilation method, Josey et al, 2014), and on the other hand, in the properties of tropical cyclones whose intensity is largely underestimated and the localization biased (Jourdain et al, 2014). Drakkar configurations have been widely used to highlight these problems.

The DFS forcing has been developed along the same principle as the CORE forcing (Coordinated Ocean Reference Experiments, Large and Yeager, 2010). Both forcing sets are used for DRAKKAR configurations, CORE mainly at GEOMAR and DFS at IGE and NOC. CORE is based on the NCEP reanalysis which has a low spatial resolution. An international workshop initiated by the WCRP Ocean Model Development Panel was held in Grenoble in 2015, jointly with the DRAKKAR annual workshop. The aim was to discuss the choice of atmospheric forcing for the future Ocean Model Intercomparison Project (OMIP) within CMIP6. The Japanese reanalysis JRA has been chosen as a higher resolution substitute for NCEP. In 2016 and 2017, IGE and GEOMAR have started to test the JRA forcing using DRAKKAR configurations at varying resolutions.

The freshwater discharge from the Antarctic continent into the Southern Ocean is an important forcing. Until recently, it was represented by a freshwater source at the coast, neglecting the advection of icebergs by the ocean circulation. Merino et al (2017) have implemented a method which allows to take into account the drift of icebergs, resulting in a better mapping of the freshwater input, which occurs where the icebergs melt.

4 Scientific results from the DRAKKAR simulations: focus on 1/12° simulations

The 1/4° model configuration ORCA025 is now used by a large number of teams internationally. ORCA025 is often used to complement analysis of in situ data: recent examples at NOC and at Ifremer are the mapping of full-depth temperature trends in the North Atlantic (Desbruyères et al, 2014), the investigation of mechanisms of decadal heat content change in the subpolar gyre (Desbruyères et al, 2015) or more recently the composition of freshwater on the slope of the Labrador Sea (Benetti et al, 2017).

Scientific results obtained using ORCA025 are too numerous to synthetize in this short report. Rather, we choose to focus on the newest 1/12° model configurations. During the last four years, ORCA12 has become a mature ocean-ice model configuration, and the first scientific analyses have been published (40 papers over 4 years). These publications have all benefited from the Drakkar network through the regular meetings, allowing each group to be aware of the overall plan for the scientific exploitation of ORCA12 simulations. Preliminary results have been presented at Drakkar workshops, allowing collaboration on numerics and model result analysis tools as well as fruitful interactions on topics such as ocean variability and eddy dynamics. A few selected results are presented here; the complete list of ORCA12 publications is found in section 7.

4.1 Variability of the ocean circulation and ocean transports

The variability of the Atlantic Meridional Overturning Circulation (AMOC) impacts the global climate. Multidecadal simulations with a fine grid global model such as ORCA12 are well suited to study the mechanisms of variability at multiple time scales and the role of eddies. The Drakkar group (2014) pointed out new results made possible by the fine mesh of ORCA12, regarding the bi-stability of the AMOC (Deshayes et al 2014), the role of eastern boundary currents (Duchez et al, 2015), the origin of the 2009-2010 AMOC minimum observed by the RAPID array (Blaker et al, 2014), or the structure and strength of intrinsic AMOC variability in ORCA025 and ORCA12 (Grégorio et al, 2015; Leroux et al, 2017).

Numerical models help to interpret the observations and also to pinpoint the best locations for AMOC measurements (Sinha et al. 2018). The North Brazil Current (NBC), being a "bottleneck" for the northward flowing branch of the AMOC, has been suggested as a suitable location for AMOC monitoring. Rühs et al (2015) have examined the NBC variability simulated by a hierarchy of DRAKKAR model simulations from 1/2° to 1/12° and concluded that the NBC transport is indeed related to the AMOC changes but that the relation is indirect, due to the wind-driven gyre variability.

The variability of the subpolar gyre, especially the strong event of the mid-nineties, has been examined using ORCA12 simulations (Marzocchi et al, 2015 and Barrier et al, 2015). Further north, the entrance of the warm water branch of the AMOC into the Arctic has been described by Koenig et al (2017), using an ORCA12 analysis produced by Mercator-Ocean to complement sparse observations north of Svalbard. In an interdisciplinary context to explore the impact of ocean currents on methanotrophic bacteria off Svalbard, Steinle et al. (2015) explored the distribution and variability near-bottom currents in ORCA12.

1/12° simulations have also been used to understand the variability of the Southern Ocean. The variability has been considered globally (e.g., the "southern mode" of variability, Hughes et al, 2014) or locally (e.g, the variability of the transport through Fawn Trough, Vivier et al 2015). Heuze et al (2015) used the model to assess the performance of the existing observing system to map the Southern Ocean variability.

The ocean regulates the earth climate through the meridional transports of heat and salt. ORCA12 simulations resolve mesoscale eddies well enough to compute the eddy contributions to large scale transports: such a calculation has been carried out for the global transport of salt, for the first time at such a high resolution (Treguier et al, 2014). Cross-Atlantic heat transports vary considerably on short time scales, as shown by the RAPID array and ORCA12 (Moat et al, 2016). The model shows that fluctuations of the Ekman transport explain the extreme heat transport extrema observed over periods of a few days.

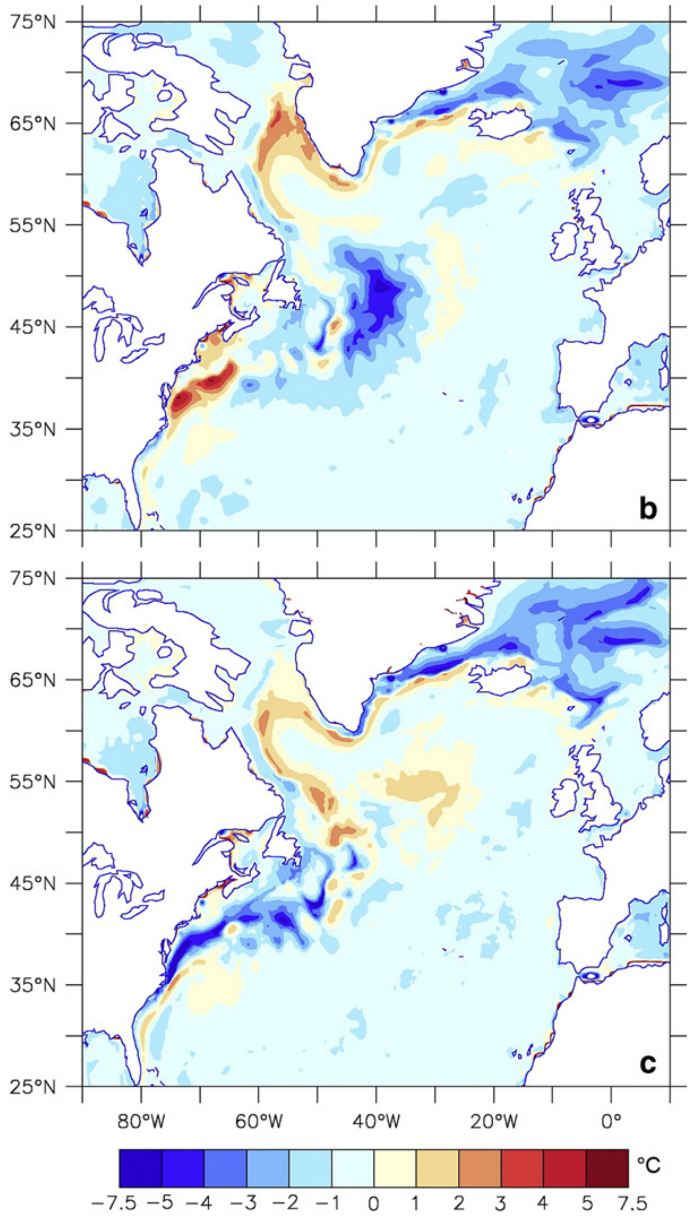

Figure 2 (reproduced from Marzocchi et al, 2015): Differences between the modelled Sea Surface Temperature and the Reynolds observational dataset in 2007 (annual mean). Top panel: 1/4° ORCA025 simulation. Bottom panel: 1/12° ORCA12 simulation. The path of the North Atlantic Current is improved in ORCA12, removing the extended region of cold bias east of the Grand Banks. The improvement of SST is key to a better ocean-atmosphere coupling and more reliable climate scenarios.

4.2 Characterizing the intrinsic variability of the global ocean circulation

In high-resolution ocean general circulation models (OGCMs), as in process-oriented models, a substantial amount of interannual to decadal variability is generated spontaneously by oceanic nonlinearities: that is, without any variability in the atmospheric forcing at these time scales. Serazin et al (2015) investigated the temporal and spatial scales at which this intrinsic oceanic variability has the strongest imprints on sea level anomalies (SLAs) using a 1/12° global OGCM ORCA12, by comparing a ‘‘hindcast’’ driven by the full range of atmospheric timescales with its counterpart forced by a repeated climatological atmospheric seasonal cycle. Outputs from both simulations are compared within distinct frequency–wavenumber bins. The fully forced hindcast is shown to reproduce the observed distribution and magnitude of low-frequency SLA variability very accurately (Figure 3).

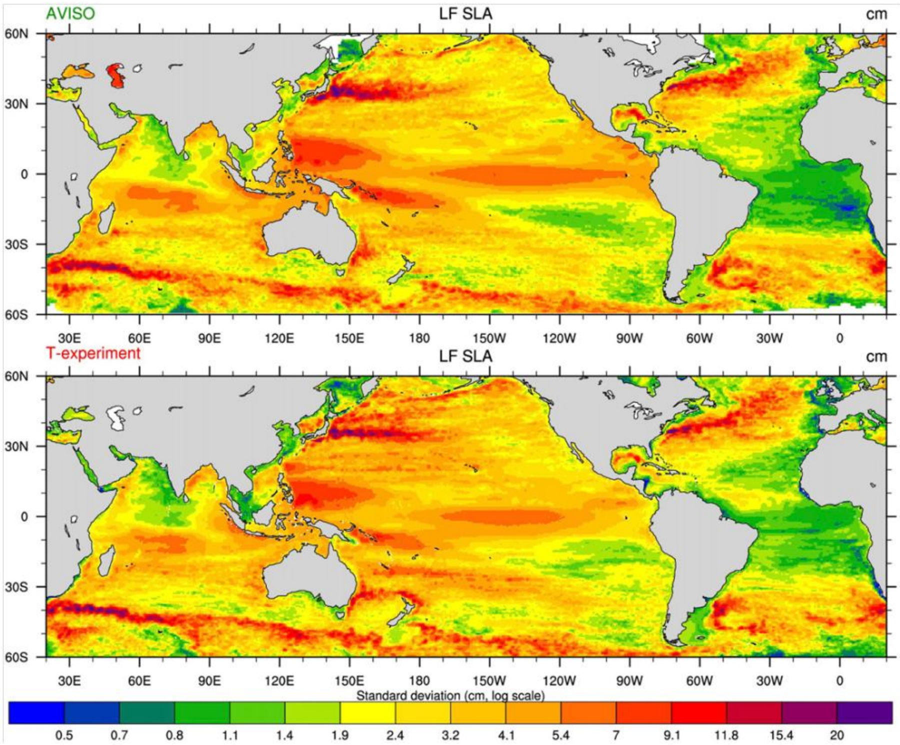

Figure 3: Low-frequency (T > 18 months) Sea Level Anomaly standard deviations computed over the period July 1994 – July 2011 from (top) the 1/ 4° AVISO dataset and (bottom) the 1/ 12° "hindcast" experiment driven by the full range of atmospheric timescales. From Sérazin et al (2015).

The small-scale (L < 6°) SLA variance is, at all time scales, barely sensitive to atmospheric variability and is almost entirely of intrinsic origin. The high-frequency (mesoscale) part and the low-frequency part of this small-scale variability have almost identical geographical distributions, supporting the hypothesis of a nonlinear temporal inverse cascade spontaneously transferring kinetic energy from high to low frequencies (confirmed in Sérazin et al, in revision). The large-scale (L > 12°) low-frequency variability is mostly related to the atmospheric variability over most of the global ocean, but it is shown to remain largely intrinsic in three eddy-active regions: the Gulf Stream, Kuroshio, and Antarctic Circumpolar Current (ACC) (Figure 4). Compared to its 1/4°

predecessor ORCA025, the 1/12° ORCA12 is shown to yield a stronger intrinsic SLA variability, at both mesoscale and low frequencies. Intrinsic variability studies are now extended using ensemble simulations in the framework of the OCCIPUT and PIRATE projects.

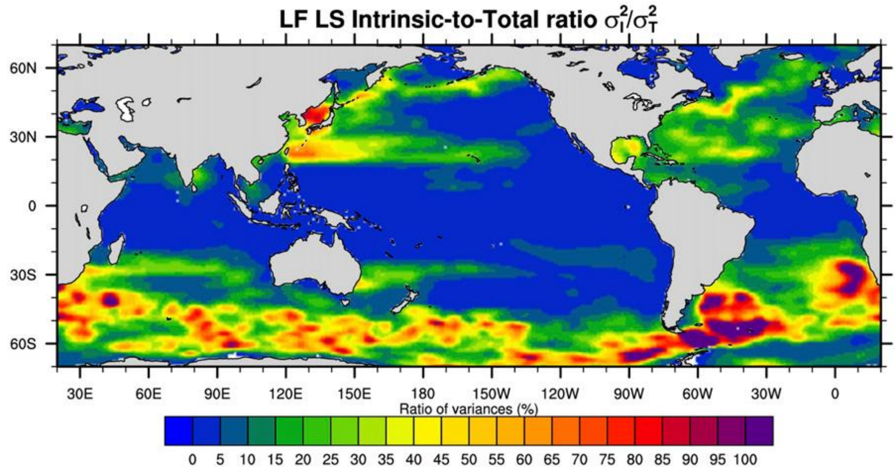

Figure 4: Intrinsic to total variance ratio (%) in the low-frequency large-scale range of scales. From Sérazin et al (2015).

4.3 Mesoscale eddy characteristics

Eddy characteristics are observed at the surface by satellite, but observations at depths are sparse. ORCA12 is an ideal tool to fill this gap. Stewart et al (2015) examined one eddy characteristic that had not been mapped globally and over the water column: the anisotropy of eddies. Anisotropic velocities are important because they force the eddy-mean flow interactions. At the surface, ORCA12 reproduces the observed anisotropy. Anisotropy increases at depth with a tendency of motions to be aligned with isobaths.

Eddy kinetic energy (EKE) at the ocean surface is modulated seasonally. Rieck et al (2015) have analyzed the vertical structure of the seasonal cycle in ORCA12. The model provides a framework to quantify the relationship between the seasonal cycle of EKE, large scale ocean properties, and surface fluxes. It shows that the summer maximum of EKE in the subtropics, down to a depth of 350m, is mainly driven by thermal fluxes. Patara et al (2016) used two nested 1/12° simulations with climatological vs. interannually varying winds to determine the origin of the interannual variability of EKE in the Southern Ocean. They found that the EKE variability is intrinsic in several regions, but mostly wind-driven in the Pacific and Indian sectors.

5 Evaluating the benefits of higher spatial resolution

Global model configurations with nested zooms using the AGRIF grid refinement technique clearly demonstrate the benefits of higher resolution. Such configurations are used at Ifremer (e.g., Talandier et al., 2014) and in Kiel where a large number of zoomed configurations based on NEMO have been developed. The most ambitious example is VIKING20, which is a 1/20° zoom covering the whole North Atlantic Ocean in the global ORCA025 model. Böning et al. (2016) use the VIKING20 model to demonstrate the effect of fine scale dynamics on the spreading of freshwater melt from Greenland. As the Greenland ice sheet loses mass at an accelerating rate due to climate warming, the question is whether the excess freshwater could reduce winter convection in the Labrador Sea and weaken the AMOC. Eddies are better represented in VIKING20, especially in the Labrador Sea. The consequence on the distribution of freshwater is shown in Figure 5: a tracer representing the melt water covers the Labrador Sea in VIKING20, carried into the interior by the West Greenland Current eddies. On the contrary, the tracer is confined to the boundary current in ORCA025, because the current around the Labrador Sea is much less turbulent at a 1/4° resolution.

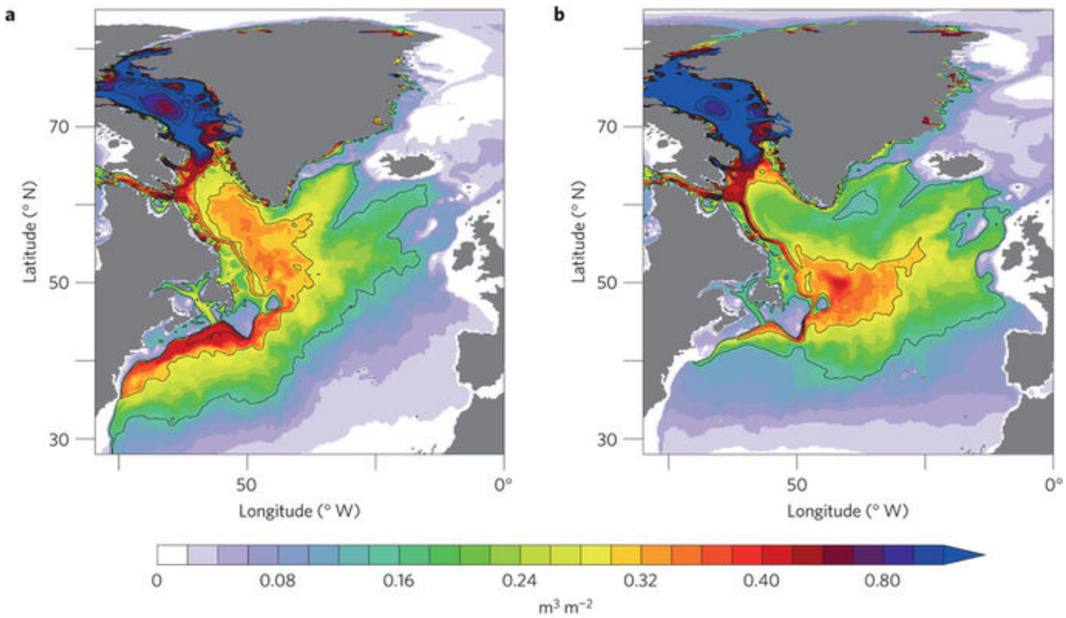

Figure 5 (reproduced from Böning et al, 2016): Distribution of vertically integrated tracer content, for a passive tracer mimicking the behaviour of the freshwater from Greenland melt. Left: in the high resolution VIKING model; right: in the ORCA025 model.

VIKING20 results are analyzed in two more recent studies. Breckenfelder et al. (2017) compare the modelled North Atlantic Current with observations from Ifremer (OVIDE project). Behrens et al (2017) investigate the origin and variability of the Denmark Strait overflow waters. Fischer et al. (2015) explored the intra-seasonal variability of the deep western boundary current in the subpolar North Atlantic.

Through simulated velocities VIKING20 served as an input to interdisciplinary Lagrangian applications such as the migration of the European eel (Baltazar-Soares et al., 2014) which directly benefited from the realistic representation of eddies and currents such as the Azores Current. In the deep ocean, Breusing et al. (2016) explored the connectivity of mussel larvae between hydrothermal vents and concluded that more vents are required in form of stepping stones to explain the observed genetic connectivity.

The results presented so far have been obtained by forcing the ocean models with a prescribed atmospheric state. However, the DRAKKAR group has also the objective to develop higher resolution ocean-ice models to be used as components of coupled earth system models. In the past four years, ORCA12 has been successfully integrated into the UK Met Office coupled system, in collaboration with NOC. The first results are presented by Hewitt et al (2016). ORCA12 is coupled with a high resolution atmospheric model (25 km grid) at an hourly frequency. The benefit of resolving the ocean eddy scale, the Rossby radius of deformation, in the mid-latitude ocean is clear: SST biases are reduced, heat transports compare better with the observations, and both the AMOC and Antarctic circumpolar current are stronger and more realistic. Comparing simulations with the same atmosphere and a lower resolution ocean demonstrates that the 1/12° ocean resolution is the key driver of these improvements. Roberts et al (2016) examine the relationship between air-sea fluxes, sea surface temperature and wind stress variability in coupled models at different resolutions, including the coupled 1/12° ocean.

6 Networking

Every year a DRAKKAR workshop is held in Grenoble in January, organized by IGE. A committee composed of representatives of the Drakkar network partners designs the workshop topics and drafts the program, after a call for abstracts has been issued. Statistics for the 4 years are shown in the table below.

Workshop	**2014**	**2015**	**2016**	**2017**
Participants	81	84	81	85
Laboratories/institutes	22	31	31	27
Countries	9	11	13	12
Submitted abstracts	43	35	40	44

7 Publications

7.1 List of peer-reviewed publications using 1/12° global simulations

2014 (11)

Benshila R., Durand F., Masson S., Bourdallé-Badie R., de Boyer Montégut C., Papa F., Madec G., 2014: The upper Bay of Bengal salinity structure in a high-resolution model. Ocean Modelling, 74, 36–52. http://dx.doi.org/10.1016/j.ocemod.2013.12.001.

Deshayes, J., A.M. Treguier, B. Barnier, A. Lecointre, J. Le Sommer, J.M. Molines, T. Penduff, R. Bourdalle-Badie, Y. Drillet, G. Garric, R. Benshila, G. Madec, A. Biastoch, C. Böning, M. Scheinert, A.C. Coward, J.J.M. Hirschi: Oceanic hindcast simulations at high resolution suggest that the Atlantic MOC is bistable. Geophysical Research Letters. vol 40, issue 12 3069–3073, DOI: 10.1002/grl.50534

Djath B., Melet A., Verron J., Molines J.-M., Barnier B., Gourdeau L., and Debreu L., 2014: A 1/36 degrees model of the Solomon Sea embedded into a global ocean model: on the setting up of an interactive open boundary nested model system, Journal of Operational Oceanography, 7(1), 34-46.

Djath B., J. Verron, L. Gourdeau, A. Melet, B. Barnier, J.-M. Molines, 2014: Multiscale analysis of dynamics from high resolution realistic model of the Solomon Sea. Journal of Geophysical Research, doi: 10.1002/2013JC009695.

Drillet, Y., Lellouche, J. M., Levier, B., Drévillon, M., Le Galloudec, O., Reffray, G., Regnier, C., Greiner, E., and Clavier, M., 2014: Forecasting the mixed layer depth in the north east Atlantic: an ensemble approach, with uncertainties based on data from operational oceanic systems, Ocean Sci. 10, 1013-1029, doi:10.5194/os-10-1013-2014,

Duchez, A., E. Frajka-Williams, N. Castro, J. Hirschi, and A. Coward, 2014: Seasonal to interannual variability in density around the Canary Islands and their influence on the Atlantic meridional overturning circulation at 26N, J. Geophys. Res. Oceans, 119, 1843–1860, doi:10.1002/ 2013JC009416.

Ferrari, R., Provost, C., Park, Y.-H., Sennéchael, N., Koenig, Z., Sekma, H., Garric, G., Bourdallé-Badie, R., 2014: Heat fluxes across the Antarctic Circumpolar Current in Drake Passage: Mean flow and eddy contributions. J. Geophys. Res., 119, 6381-6402.

Harris, P. T., 2014: Shelf and deep-sea sedimentary environments and physical benthic disturbance regimes: A review and synthesis. Marine Geology 353 (2014) 169–184. http://dx.doi.org/10.1016/j.margeo.2014.03.023.

Hughes, C.W., J. Williams, A.C. Coward, and B.A. de Cuevas, 2014: Antarctic circumpolar transport and the southern mode: a model investigation of interannual to decadal timescales. Ocean Science, 10, 215–225.

Josey S. A., L. Yu, S. Gulev, X. Jin, N. Tilinina, B. Barnier, L. Brodeau, 2014: Unexpected impacts of the Tropical Pacific array on reanalysis surface meteorology and heat fluxes. Geophys. Res. Letters, Vol: 41, DOI: 10.1002/2014GL061302

Treguier, A.M., J. Deshayes, J. Le Sommer, C. Lique, G. Madec, T. Penduff, J.-M. Molines, B. Barnier, R. Bourdalle-Badie, and C. Talandier, 2014: Meridional transport of salt in the global ocean from an eddy-resolving model. Ocean Sci., 10, 243-255, 2014

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Bacon, S., Y. Aksenov, S. Fawcett, G. Madec, 2015: Arctic mass, freshwater and heat fluxes: methods, and modelled seasonal variability. Phil. Trans. R. Soc. A 373, 20140169. doi:10.1098/rsta.2014.0169.

Barrier, N., J. Deshayes, A.M. Treguier and C. Cassou, 2015: Heat budget in the North Atlantic subpolar gyre: impacts of atmospheric weather regimes on the 1995 warming event. Progress in Oceanography, 130, 75-90.

Blaker, A., J. Hirschi ,_ G. McCarthy, B. Sinha, S. Taws , R. Marsh, A. Coward, B. de Cuevas, 2015: Historical analogues of the recent extreme minima observed in the Atlantic meridional overturning circulation at 26N. Climate Dynamics, 44, 457-473.

Grégorio, S., T. Penduff, G. Sérazin, J.-M. Molines, B. Barnier, and J. Hirschi : Intrinsic variability of the Atlantic Meridional Overturning Circulation at interannual-to-multidecadal timescales. J. Phys. Oceanogr., 45, 7, pp. 1929-1946.

Heuzé C., Vivier F., Le Sommer J., Molines J.-M., and Penduff T., 2015: Can we map the interannual variability of the whole upper Southern Ocean with the current database of hydrographic observations? Journal of Geophysical Research-Oceans, 120 (12), 7960-7978, 2015.
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Rieck, Jan Klaus, Böning, Claus W., Greatbatch, Richard John and Scheinert, Markus (2015) Seasonal variability of eddy kinetic energy in a global high-resolution ocean model Geophysical Research Letters, 42 (21). pp. 9379-9386. DOI 10.1002/2015GL066152.
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Steinle, L., C. Graves, T. Treude, B. Ferré, A. Biastoch, I. Bussmann, C. Berndt, S. Krastel, R. H. James, E. Behrens, C. W. Böning, J. Greinert, M. Scheinert, C.-J. Sapart, S. Sommer, M. F. Lehmann, and H. Niemann, 2015: Water column methanotrophy controlled by a rapid oceanographic switch, Nature Geoscience, 8, 378-382, doi: 10.1038/NGEO2420.
Stewart K.D., Spence P., Waterman S., Le Sommer J., Molines J.M., Lilly J.M., and England M.H., 2015: Anisotropy of eddy variability in the global ocean. Ocean Modelling, 95, 53-65, 2015.
Vivier F., Park Y.-H., Sekma H. and Le Sommer J., 2015: Variability of the Antarctic Circumpolar Current transport through the Fawn Trough, Kerguelen Plateau. [doi] Deep Sea Research II, 114, 12-26.

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