DRAKKAR WORKSHOP 2017

SESSION 1
Benefits of high resolution to the science made with ocean/sea-ice models

1. **Yevgeny Aksenov (NOC - Southampton): Arctic Pacific water dynamics from model inter-comparison and observations.**

Abstract: Pacific Water imports heat and fresh water from the northern Pacific in the Arctic Ocean, impacting Upper Ocean mixing and dynamics, as well as Arctic sea ice. Pathways and the circulation of PW in the central Arctic Ocean are not well known due to the lack of observations. This study uses an ensemble of the sea ice-ocean models integrated with passive tracer released in the Bering Strait to simulate Pacific water spread. We investigate different branches and modes of Pacific water and analyse changes in the water mass distribution through the Arctic Ocean due to changes in the wind and ocean potential vorticity. We focus on seasonal cycle and inter-decadal variations. The first results have been published recently (Aksenov et al., 2015) as a part of Forum for Arctic Ocean Modeling and Observational Synthesis (FAMOS) project. In the present study we extend the examination further and discuss the role of the Pacific water variability in the recent changes in the Arctic heat and fresh water storage. We present insights in the projected future changes to Pacific water dynamics. (*yka@noc.ac.uk).*

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2. **Paul Myers (U Alberta - Edmonton) : Pan-Arctic Exchange, the Labrador Sea and the AMOC**

Abstract: We use several different regional configurations of the NEMO model (including AGRIF nests) to look at Arctic-Atlantic exchange. The role of river runoff, melt from the Greenland Ice sheet (as well as its iceberg discharge) and high-frequency atmospheric forcing is examined to evaluate the model in terms of exchanges at the Arctic Gateways, water formation in the Labrador Sea and the North Atlantic overturning. Water mass pathways are examined through the use of passive tracers. Additionally, a simplified biogeochemical model, BLING, is coupled to NEMO and used to look at questions of productivity. *(pmyers@ualberta.ca).*

Co-authors: the University of Alberta NEMO Modelling Group.

3. **Claudia Wekerle (AWI - Bremerhaven): Eddy-resolving simulation of the Atlantic Water recirculation in the Fram Strait.**

Abstract: The West Spitsbergen Current transports warm and saline Atlantic Water northwards through Fram Strait towards the Arctic Ocean. At Fram Strait, a fraction of the Atlantic Water recirculates and travels southward as part of the East Greenland Current. The mechanism of the recirculation is still not fully understood, and in particular the role of eddies. However, the pathways of Atlantic Water play an important role for the Arctic Ocean's heat budget. Experiments with three configurations of the global Finite Element Sea ice Ocean Model differing in mesh resolution in the Fram Strait area (4.5 km, 2 km and 1 km horizontal resolution) are used to investigate the mechanism of Atlantic Water recirculation. The Rossby radius of deformation, an indication for the size of eddies, is relatively small in high latitudes (around 2-6 km in the Fram Strait); and thus only the simulation with 1 km horizontal resolution can be considered as eddy-resolving. Our results show that this resolution is at least necessary to correctly represent the observed temperature structure and eddy kinetic energy in the Fram Strait. *(claudia.wekerle@awi.de).*

4. **Clark Pennelly (U. Alberta - Edmonton): Numerical modeling in the northern Atlantic: Labrador Sea freshwater and model sensitivity to atmospheric forcing.**

Abstract: The northern Atlantic contains regions of deep convection, areas where the surface water exposed to the atmosphere is sequestered to great depths due to winter-time buoyancy loss. The convection strength can be changed due to the stratification at convection locations. We used numerical simulations to understand the input of freshwater, which can strengthen the stratification in the Labrador Sea. Three configurations were used, ANHA4 (Arctic Northern Hemisphere Atlantic ¼ degree), ANHA12, and ANHA4 with an AGRIF nest in the sub-polar gyre to produce 1/12 degree resolution. We examined the freshwater transport, relative to 34.8 g/kg, across the 750m, 1000m, 1500m, and 2000m isobaths in the Labrador Sea. Freshwater transport was calculated using three velocities: the total ocean velocity, the mean velocity (averaged over 25 days), and the turbulent velocity. We also examine model sensitivity to four different atmospheric forcing datasets and their impacts on ocean processes in the northern Atlantic. We explore differences between the Canadian Meteorological Centre's Global Deterministic Prediction System (CMC-GDPS), ERA-Interim, DRAKKAR forcing set 5.2, and CORE2 atmospheric dataset in both their atmospheric state, as well as the ocean state when forced with identical conditions. *(pennelly@ualberta.ca). Co-Authors: Xianmin Hu, Paul G Myers.*

5. **Nicolas Jourdain (IGE – Grenoble): Impact of ice-shelf melt on the Amundsen Sea circulation and sea-ice.**

Abstract: This work is based on a regional 1/12° configuration of the Amundsen Sea, and makes use of the interactive ice shelf capability in NEMO-3.6. First, we quantify the impact of ice-shelf melt on the circulation inside and in front of the cavity (Antarctic Coastal current). Then, we show that more ice-shelf melt leads to less sea-ice in front of the cavities. We also discuss the influence of tides: how explicit tides influence ice-shelf melt, and how we can parameterize this effect in a simulation with no explicit tides. *(nicolas.jourdain@univ-grenoble-alpes.fr).*

Co-authors: Pierre Mathiot, Nacho Merino, Gaël Durand, Julien Le Sommer, Paul Spence, Pierre Dutrieux, Gurvan Madec.

6. **Lavinia Patara (GEOMAR – Kiel): Southern Ocean eddy activity and transient tracer uptake in the past 50 years in eddy-rich ocean simulations.**

Abstract: Ocean mesoscale eddies influence the way the Southern Ocean circulation adjusts to wind changes, and thus the degree of water mass ventilation and ocean CO_2 uptake. Eddy kinetic energy (EKE), a proxy of mesoscale eddy activity, is however also changing in response to climate change. In this presentation I will first discuss new findings regarding the variability and trends of Southern Ocean EKE in response to the strengthening of Southern Hemisphere winds occurring since the 1950s, and then show preliminary results regarding changes in Southern Ocean ventilation and CO_2 uptake in an eddying regime. The model configurations include ORCA025 (global 1/14° ocean model) and ORION12 (global 1/14° ocean model containing a 1/12° nest in the Antarctic Circumpolar Current domain). The model is coupled to a tracer model capable of simulating the uptake and spreading of the transient tracers CFC-12 and SF_6 as well as an 8-compartment biogeochemical model. Our findings include: 1) ORION12 captures the temporal variability of observed EKE over several regions of the Southern Ocean, 2) EKE increased by 17% since the 1950s, but spatial patterns are non-uniform, and 3) stochastic variability of EKE masks wind-driven changes in certain regions of the Southern Ocean. Ongoing work on the use of CFC-12 and SF_6 to estimate changes in ocean ventilation as well as on the variability of air-sea CO_2 fluxes will finally be presented. *(lpatara@geomar.de).*

Co-Authors: Claus Böning, Arne Biastoch, T. Tanhua, Aandreas Oschlis.

7. **Nacho Merino (IGE – Grenoble): Impact of increasing Antarctic glacial freshwater release on regional sea-ice cover in the Southern Ocean**

Abstract: The sensitivity of Antarctic sea-ice to increasing glacial freshwater release from Antarctica into the Southern Ocean is studied in a series of 30-year ocean/sea-ice/iceberg model simulations. Glaciological estimates of ice-shelf melting and iceberg calving are used to constrain the spatial distribution and magnitude of freshwater forcing around the Southern Ocean. Two scenarios of glacial freshwater forcing are designed to account for a decadal perturbation in glacial freshwater release to the Southern Ocean. For the first time, this perturbation explicitly takes into consideration changes in the volume of Antarctic ice shelves, which is found to be a key component of changes in freshwater release to the Southern Ocean. In addition, glacial freshwater-induced changes in sea ice are compared to changes induced by the evolution of atmospheric states over the last decades. Our results show that, in general, the increase in glacial freshwater release increases Antarctic sea ice extent, but the opposite sensitivity is found in some regions. We also note that changes in freshwater forcing may induce large changes in sea-ice thickness, explaining about one half of the total change due to the combination of atmospheric and freshwater changes. Our results are a strong incentive for improving the representation of freshwater sources and their evolution in climate models. *(ignacio.merino@univ-grenoble-alpes.fr).*

Co-Authors: Julien Le Sommer Gael Durand Nicolas Jourdain Hugues Goosse, Pierre Mathiot

8. **Joël Hirshi (NOC – Southampton): On the persistence of mesoscale features in satellite altimetry and ORCA12.**

Abstract: The persistence times of ocean mesoscale features are computed from absolute surface velocities obtained from satellite altimetry and from an interannually forced ORCA12 simulation. The persistence times are calculated by using every timestep (5-day averages for ORCA12, weekly values for altimetry) in turn as point of reference from which the circulation then naturally diverges. The persistence time (or divergence time) is then defined as the average time needed for divergence to reach saturation. The fastest divergence times of 5 to 15 days are typically observed along the coasts or in regions such as the Caribbean basin. It is noteworthy that areas with known large eddy variability (e.g. Gulf Stream extension) do not stand out as regions of fast divergence but actually exhibit times (typically 15-30 days) that are not much different from those seen in the interior of the Subtropical Gyres (20-50) days. We also find good agreement between the divergence times found in ORCA12 and the altimetry derived velocities. Finally, we note that these divergence times are much shorter than those seen in perturbed ensembles - especially when the perturbation is non-optimal and where we find divergence times of up to 1000 days. *(joel.hirschi@noc.ac.uk).*

9. Clément Rousset (LOCEAN – Paris): LIM3 in NEMO.
(clement.rousset@locean-ipsl.upmc.fr)

10. René Schubert (GEOMAR – Kiel): Prevalence of Instability-Driven Benthic Storms in the Western North Atlantic.

Abstract: Mixed barotropic-baroclinic instability accompanied by deep cyclogenesis is a major driver for benthic storms below the Gulf Stream. To show this the output of the 1/20°-horizontal resolution ocean general circulation model VIKING20 was examined to investigate the relation between eddy-current energy transfer and benthic storms in the western North Atlantic. Benthic storms occurred most frequently below the Gulf Stream and the North Atlantic Current. Both currents were found to be associated with very strong eddy-current energy transfers.
Between Cape Hatteras and the New England Seamounts the Gulf Stream predominantly releases its energy to the eddy field. A part of this energy is provided to the development of benthic storms. The relevant physical process is identified to be cyclogenesis: developing meander troughs of the Gulf Stream are accompanied by cyclones that extent over the whole water column and occasionally are associated with large bottom velocities of up to more than 0.6 m/s. Regions of eddy kinetic energy source due to energy transfer were found to be located upstream of the center of the structure of highest benthic storm probabilities and upstream of the near-bottom eddy kinetic energy maxima. The upstream shift is characteristic for baroclinic instability, indicating that benthic storms in this region are mainly driven by instabilities of the Gulf Stream. *(rschubert@geomar.de).*

11. Eric Chassignet (FSU – Tallahasse): Impact of horizontal resolution (1/12 to 1/50 degree) on Gulf Stream separation and penetration in a series of North Atlantic numerical simulation

Abstract: The impact of horizontal resolution (1/12 to 1/50 degree) on Gulf Stream separation and penetration is analyzed in a series of identical North Atlantic HYCOM configurations. The specific questions that will be addressed are as follows: How well do the simulations compare to observations? When is a solution "good enough"? Are the mesoscale and sub-mesoscale eddy activity representative of interior quasigeostrophic (QG) or surface quasigeostrophic (SQG) turbulence? We will show that the increase in resolution (1/50 degree) does lead to a substantial improvement in the Gulf Stream representation (surface and interior) when compared to observations and the results will be discussed in terms of ageostrophic contributions and power spectra. *(echassignet@fsu.edu).*
Co-Autor: Xiaobiao Xu.

12. Julien Le Sommer (IGE- Grenoble): Sensitivity of resolved fine scales to model parameters in the submesoscale range: lessons from NATL60.

Anne Marie Treguier (LOPS - Brest): Lessons learned from global mesoscale-resolving modelling: a personal view.

Abstract: During the past 4 years, global ocean modelling with the NEMO configuration ORCA12 has been a major focus of DRAKKAR. Many multi-decadal simulations are now available. Results have been reported at annual Drakkar meetings and in more than 25 peer-reviewed publications. This talk presents a personal view of the main advances - and setbacks - resulting from the analysis of Drakkar ORCA12 simulations. The discussion with the audience will hopefully help identify the original and unique findings that Drakkar should advertize to the international community. *(anne.marie.treguier@ifremer.fr).*
This presentation will be given as an introduction of a Discussion Session.

SESSION 2
Atmospheric driving of eddying OGCMs

13. Alex Megann (NOCS - Southampton): Evaluating Forcing Datasets for late 20th-Century NEMO integrations.

Abstract: The Atlantic Climate System Integrated Study (ACSIS) is a major new NERC-funded programme in the UK, whose main objective is to understand recent changes in the North Atlantic climate system. A suite of NEMO/CICE configurations is being set up under ACSIS, which will be integrated in forced mode at both 1/4° and 1/12° resolutions from 1959 to the present decade. The principal aim of the initial stage of the project is to select a forced ocean configuration that reproduces changes in the ocean over the last fifty years with an acceptable realism. An ensemble of trial integrations at 1° and 0.25° using CORE2, DFS5.2 and JRA55 forcing reveals a range of responses to the different forcing datasets. The models all drift, with some showing unrealistic trends in the surface temperature and others having an imbalance in surface heat flux of up to 1 W/m2, leading to excessive long-term tendencies in ocean heat content. The large-scale evolution of the upper ocean is found to be more sensitive to the choice of forcing than to the horizontal resolution. The downwelling longwave flux in both CORE2 and DFS5.2 datasets is known not to represent well the anthropogenic radiative forcing changes in recent decades. We will describe a modification to the applied longwave flux to make it more consistent with that simulated in the CMIP5 model ensemble, and the changes this brings to the model simulations. *(apm@noc.ac.uk).*
Co-authors: Bablu Sinha, Adam Blaker, Simon Josey.

14. Gilles Garric: (Mercator Océan – Toulouse): Evaluation of 7 atmospheric datasets in the Arctic Ocean over the period 2007-2014.

Abstract: The Mercator Océan R&D team is currently assessing (in partnership with Canada) a pan-Arctic (the CREG configuration) system (including NEMO-LIM model and assimilation components) at "eddy-resolving" resolution to take into account the specific monitoring of the Arctic Ocean. These developments, recently stabilized with the latest NEMO3.6 version and organized in order to calibrate and evaluate specifically the hindcasts, nowcasts and forecasts Arctic products, are designed to set up the next CMEMS (Copernicus Marine Environment Monitoring Service) real time global operational system version.
Global operational systems at Mercator Ocean are all driven at the surface by the atmospheric analysis and forecasts from the ECMWF (European Centre for Medium-Range Weather Forecasts) Integrated Forecasting System (IFS). For the sake of consistency, the various 2007-2014 experiments performed so far with the pan-Arctic configuration at "eddy-permitting" ¼° resolution all used the IFS datasets. A strong negative bias in the summer sea ice cover quickly installed. A sensitivity experiment performed with the atmospheric forcing from the NCEP-R2 reanalysis products showed a more realistic summer sea ice extent and raised this question: our Arctic sea ice biases can be related to the atmospheric forcing?
We propose to revisit the work of Lindsay et al. (2014) with the same methodology but over the period 2007-2014 and using the different following atmospheric datasets: IFS, ERA-Interim, NCEP-R2, MERRA, CFSR/CFSv2, JRA-55 and CGRF. Compared to other forcings, the atmospheric ECMWF-related forcings (IFS & ERA-Interim) show a similar mean singular state over the Arctic Ocean, a warmer surface conditions (up to 2°C), differences up to 30W/M^2 for downward surface radiative fluxes and higher wind speeds.
The modelled mean ensemble sea ice extent estimate shows a better interannual variability than single estimates; Mean and distribution of ice thicknesses are assessed with the ICESat-radar data, the Unified CDR in situ datasets and the CryoSat-2 freeboards measurements. Although all the experiments show a general overestimation of sea ice conditions in the Canadian Basin, only experiments using ECMWF-related forcing shows an underestimation in the Eurasian Basin. *(ggarric@mercator-ocean.fr).*
Co-Auteurs: Clément Bricaud[1], Frédéric. Dupont[2], Jérôme. Chanut[1], [1]Mercator-Ocean, [2]Environment Canada.

15. Rafael Abel (GEOMAR – Kiel): Feedback of mesoscale ocean currents on atmospheric winds in high-resolution coupled models and implications for the forcing of ocean-only models

Abstract: The repercussions of surface ocean currents for the near-surface wind speed and the air-sea momentum flux are investigated in two versions of a global climate model with eddying ocean. We find a clear signature of a mesoscale oceanic imprint in the wind fields over the energetic areas of the oceans, particularly along the extensions of the western boundary currents and the Antarctic Circumpolar Current. These areas are characterized by a positive correlation between mesoscale perturbations in the surface currents curl and the wind curl. The positive feedback of mesoscale current features on the near-surface wind acts in opposition to their damping effect on the wind stress. A tentative incorporation of this feedback in the surface stress formulation of an eddy-permitting global ocean-only model leads to a gain in the kinetic energy of up to 10%, suggesting a fundamental shortcoming of present ocean model *configurations. (rabel@geomar.de).*
Co-Authors: Claus W. Böning (GEOMAR), Richard J. Greatbatch (GEOMAR), Helene T. Hewitt (Met Office), Malcolm J. Roberts (Met Office).

16. Lionel Renault (UCLA): Surface current feedback: which strategy is the best to force a high-resolution ocean model?

Abstract: Several studies pointed out the need to take into account surface currents when computing the air-sea wind stress. Using relative wind stress instead of absolute wind stress slows down the large-scale circulation and acts as a strong "eddy killer" at mesoscale. If computing the relative wind in an ocean-atmosphere coupled model is quite straightforward, its implementation in bulks used to force an ocean model is like trying to square the circle. A larger relative stress will slow down surface (10m) winds that are therefore not independent from the surface currents. Wind products based on observations have "seen" real currents that will inevitably not correspond to model currents (at least at mesoscale), whereas reanalyzes products often neglect surface currents or use surface currents that, again, will differ from the surface currents of the model we want to force. As we will show, additional errors are made when using 10 winds derived from a pseudo stress (e.g. Quikscat) as, in this case, the impact of the surface current on the 10m winds has the wrong sign.
There is thus no perfect solution to take into account the surface currents when computing the wind stress in the bulks of a forced ocean model. The goal of our work is thus to quantify the error we do with the different existing strategies and propose the better (not to say less worse) method to minimize the error done in the evaluation of the wind stress. To do so, we will use a high-resolution (1/12°) ocean-atmosphere coupled simulations with relative or absolute stress that will be used as references and compared to the equivalent oceanic simulations forced with the 10m winds, the estimated 10m winds or the wind stress from the coupled simulations.
(lrenault@atmos.ucla.edu).
Co-Author: Sébastien Masson (main author, LOCEAN-UCLA).

SESSION 3

The eddy-permitting regime (e.g. ORCA025)

17. Graeme MacGilchrist (U. of Oxford): Characterising chaotic ventilation of the ocean.

Abstract: Through the process of ventilation, the upper ocean communicates with the atmosphere on interannual to decadal timescales, playing an important role in climate variability by exchanging heat and carbon dioxide. The turbulent nature of ocean circulation, manifest in a vigorous mesoscale eddy field, means that pathways of ventilation, once thought to be quasi-laminar, are in fact highly chaotic. We characterise the chaotic nature of ventilation pathways by defining a nondimensional 'filamentation number', which estimates the reduction in filament width of a ventilated fluid parcel due to mesoscale strain. In the subtropical North Atlantic of an eddy-permitting ocean model (ORCA025), the filamentation number is large everywhere across three upper ocean density surfaces, increasing with depth, implying highly chaotic ventilation pathways. Confirming this result, an advective mapping of surface properties onto the density surfaces reveals highly filamented structure. The spatial distribution of these filaments is shown to be well characterised by the filamentation number. The approach offers valuable insight into the ventilation process in eddy-permitting numerical simulations. *(graeme.macgilchrist@earth.ox.ac.uk).*

18. Stephan Juricke (U. of Oxford): The Random Ocean: Development, implementation, and investigation of stochastic ocean parametrizations.

Abstract: An adequate representation of oceanic variability is essential to accurately simulate the ocean and coupled ocean-atmosphere systems. Timescales and amplitude of oceanic variability impact the ocean's response to changes in external forcing. Both aspects are also highly relevant when it comes to providing skillful seasonal to decadal predictions. Due to the interactions of large and small scales, improving the simulation of small scale variability can influence the variability of the large scale circulation. In this study we introduce novel stochastic sub-grid scale perturbation schemes to the NEMO model at 1° resolution. These schemes enhance unresolved sub-grid scale variability both in uncoupled (decadal) and coupled (seasonal) ocean simulations. We will describe the implementation of these schemes in the NEMO framework as part of a stochastic module and investigate their impact on low frequency ocean variability and seasonal forecast skill.

1° resolution, ocean models are lacking high frequency eddy variability, largely underestimating low frequency variability in eddy active regions such as the Southern Ocean and along Western Boundary Currents. In a first set of forced climate simulations, we show that the stochastic schemes increase and consequently improve the simulation of low frequency variability for a variety of variables (e.g. sea surface height and sea surface temperature). Additionally, in seasonal ensemble forecasts, the stochastic schemes are used to incorporate model uncertainty estimates. They increase model spread of subsurface variables such as 300 m heat content in eddy active regions by 20% and more. As these regions are generally under-dispersive (i.e. the ensemble spread does not capture the forecast error), increased ensemble spread leads to better calibrated probabilistic forecasts. Probabilistic skill of near-surface atmospheric variables is also improved.

The novel stochastic schemes, which follow the same physical properties as the underlying deterministic parametrizations of oceanic mixing, successfully simulate the effects of increased resolution. This highlights the potential for stochastic schemes to be used as an alternative to computationally costly increases of model resolution. *(Stephan.Juricke@physics.ox.ac.uk).*

Co-Authors: Laure Zanna, Dave McLeod, Antje Weisheimer, and Tim Palmer

19. Guillaume Sérazin (LEGOS – Toulouse): A global probabilistic study of the Ocean Heat Content low-frequency variability: atmospheric forcing versus oceanic chaos.

Abstract: A global 1/4° ocean/sea-ice 50-member ensemble simulation is used to disentangle the low-frequency imprints of the atmospherically-forced oceanic variability and of the chaotic intrinsic oceanic variability (IOV) on the large-scale (10° x 10°) ocean heat content (OHC) between 1980 and 2010. The IOV explains most of the interannual-to-decadal large-scale OHC variance over substantial fractions of the global ocean area that increase with depth: 9%, 22%, and 31% in the 0-700m, 700-2000m and 2000m-bottom layers, respectively. Such areas concern principally eddy-active regions, mostly found in the Southern Ocean and in western boundary current extensions, but also concern the subtropical gyres at intermediate and deep levels. The oceanic chaos may also induce random multidecadal fluctuations so that large-scale regional OHC trends computed on the 1980-2010 period cannot be unambiguously attributed to the atmospheric forcing in several oceanic basins at various depths. These results are likely to raise detection and attribution issues from real observations. *(guillaume.serazin@legos.obs-mip.fr). Co-Authors: Thierry Penduff (IGE).*

20. Thierry Penduff (IGE – Grenoble): Atmospherically-modulated oceanic chaos; observational implications.

Abstract: One of the 3 NEMO-based 1/4° ensemble oceanic simulations performed during the OCCIPUT project is a North Atlantic (NATL025) hindcast, where the 50 ensemble members are slightly perturbed at the beginning and then driven by the same ensemble-mean DFS5.2-based air-sea fluxes from 1993 to 2012. These ensemble simulations are being analyzed to study the respective imprints of the intrinsic/chaotic oceanic variability (which feeds the ensemble spread) and of the atmospheric variability on the ocean state and multi-scale evolution. The analysis of the results in and around the Gulf of Mexico reveal a rich variety of instantaneous ensemble statistics, ranging from quasi-gaussian with a simple temporal modulation of its mean value by the atmospheric variability, to highly non-gaussian (e.g. bimodal) with a more complex atmospheric modulation. We propose an entropy-based metric to identify the regions (and periods) where the atmospheric forcing reduces the inherent ocean chaos (ensemble entropy or disorder). We conclude by a presentation of research projects which aim to valorize such ensemble simulations for observational oceanography in various regions of the Global Ocean. *(thierry.penduff@univ-grenoble-alpes.fr).*
Co-Authors: Pierre-Vincent Huot, Stéphanie Leroux, Ixetl Garcia-Gomez, Jean-Michel Brankart.

21. Jan Klaus Rieck (GEOMAR – Kiel): Decadal Variability of Eddy Kinetic Energy in ORCA025 - Sensitivity Studies

Abstract: An ocean-sea ice model (NEMO 3.6, LIM2) at eddy-permitting resolution (1/4°, ORCA025) is used to study decadal variability of oceanic Eddy Kinetic Energy (EKE). In an exemplary region in the South Pacific (25-33°S, 153-180°W) decadal variability of EKE and its relative amplitude of ~100% of the mean EKE are consistently represented across various model resolutions and satellite observations. To investigate the causes for this decadal variability, two sensitivity model runs use either climatological (normal year) wind stress forcing and interannual buoyancy forcing or vice versa. Another experiment aims to show the influence of a reduced biharmonic viscosity operator on EKE. *(jrieck@geomar.de).*

22. Guillaume Maze (LOPS - Brest): Eddy-permitting ORCA025 representation of large-scale stratification features in the North-Atlantic.

Abstract: We will evaluate how the subtropical mode waters and pycnocline is represented in the ORCA025 GJM189 simulation with 75 vertical levels and present a major resisting flaw with regard to the representation of large-scale stratification features. The evaluation metrics will be computed from (i) the OACP algorithm (Feucher et al, 2016) that diagnoses objectively the properties of the subtropical permanent pycnocline and surface mode waters, (ii) the large-scale un-supervised classification of profiles (Maze et al, 2017) that diagnoses objectively interior ocean heat patterns and (iii) standard mode water diagnostics. These metrics will be assessed over time (from 1958 to 2015) and their climatology compared with Argo-based references. We will (1) show how subtropical surface mode waters and permanent pycnocline are biased toward warmer, shallower and more stratified states compared to observations, (2) document how the correct stratification features present in the initial conditions (1958) are destroyed and replaced by the biased model state, and (3) attempt to interpret these results in terms of wind-driven vs buoyancy-driven subtropical gyre circulations. *(Guillaume.Maze@ifremer.fr). Co-Authors: Charlène Feucher, Herlé Mercier.*

23. Jens Terhaar (LSCE-IPSL – Orsay): Simulated anthropogenic carbon in the Arctic Ocean in three DRAKKAR model configurations.

Abstract: The Arctic Ocean is projected to experience amplified ocean acidification, more than any other region in the world ocean. To simulate its future changes with ocean models, we must first be able to simulate baseline conditions and Arctic acidification over the industrial era, i.e., at least for the main driver, increasing CO2. Here we compare anthropogenic CO2 uptake in DFS-forced simulations of three global configurations of the NEMO-PISCES model (ORCA2, ORCA05, and ORCA025) and we evaluate results with available observations. The comparison revealed a notable dependence of the simulated anthropogenic carbon inventory (total mass stored in Arctic basin) on resolution. While the 2° configuration stored 1.6 Pg C between 1860 and 2005, the ½° and ¼° versions took up 1.9 and 2.2 Pg C, respectively. Those simulated results are lower than data-based estimates (3.0 Pg C), but the latter may over-predict anthropogenic carbon in the Arctic, as already shown in the Mediterranean Sea. Indeed, evaluation of the models with CFC-12 (another transient tracer) suggests that simulated ventilation of subsurface waters are roughly on target in the ORCA025 configuration, while data-based estimates overestimate deep-water concentrations. These simulations further indicate that about ¾ of the anthropogenic carbon in the Arctic Ocean enters that basin through lateral transport rather than by a flux across the air-sea interface (via gas exchange). In other ocean areas, transfer by gas exchange generally dominates. The simulated inventory increases with resolution as net lateral transport of anthropogenic carbon into the basin increases. Wider comparison to results from CMIP5 (typically coarse-resolution models) reveals larger diversity. Lateral transport is generally the dominant means by which anthropogenic carbon enters the Arctic, and that transport appears particularly sensitive to model resolution and bathymetry as well as an ocean model's forcing or coupling to an atmospheric model. *(terhaar.jc@gmail.com). Co-Authors: James Orr, Laurent Bopp*

24. Julie Deshayes (LOCEAN - Paris): Expected on the ORCA025 configuration at IPSL for use in ESM.

Abstract:

(jdlod@locean-ipsl.upmc.fr).

SESSION 4

OGCM evolution for basin-scale to global eddying simulations:
Future evolution of ocean/sea-ice models and of simulation practices.

25. Camille Lique (LOPS – Brest): On the importance of vertical mixing for simulating the Arctic Ocean and sea ice states.
(camille.lique@ifremer.fr).

26. Pierre Rampal (NERSC – Bergen): On simulating sea ice with the new fully Lagrangian model neXtSIM.
(pierre.rampal@nersc.no).

27. Qiang Wang (AWI - Bremerhaven): Arctic-Subarctic Ocean fluxes: mechanisms and oceanic linkage.
Abstract: The CORE-II (Coordinated Ocean-ice Reference Experiments Phase II) project provides a framework to evaluate ocean models and to study mechanisms of ocean phenomena and their variability. Although the performance and common issues in these ocean climate models were studied in a series of joint papers, the simulated oceanic linkage between the Arctic Ocean and North Atlantic has not been discussed. We use one of the CORE-II models (a FESOM configuration) to carry out sensitivity experiments to allow us (1) to better understand the driving mechanism of the variability of the Arctic-Subarctic Ocean fluxes and (2) to illustrate the oceanic linkage between the Arctic Ocean and North Atlantic. Besides the control simulation with CORE interannually variable forcing (IAVF), we did another two simulations. In one simulation we used the IAVF in the Arctic region while the normal year forcing (NYF) outside the Arctic Ocean, and in the other simulation we used the IAVF outside the Arctic Ocean while the NYF in the Arctic region. Using these simulations we identified different atmospheric modes controlling the interannual variability of Arctic-Subarctic ocean fluxes, and elucidated whether the variabilities of the Arctic Ocean and North Atlantic major circulations are linked through the oceanic pathways in the particular ocean model. *(qiang.wang@awi.de).*

28. Torge Martin (GEOMAR – Kiel): What to consider for a high-resolution Enhanced-Greenland-Runoff simulation with NEMO.
Abstract: The question of how enhanced melting of the Greenland ice sheet impacts the ocean seems to be answered. And yet, most of the studies implying that enhanced freshwater input to the subpolar North Atlantic yields a slowdown or even shutdown of the Atlantic Meridional Overturning Circulation (AMOC) are based on models of intermediate complexity or have insufficient spatial resolution to simulate mesoscale ocean activity. Böning et al. [2016] demonstrated that eddies spawned off the West Greenland Current play an important role in transporting freshwater into the subpolar gyre, where it affects deep convection. As part of the recently started PALMOD project the ocean and climate modeling group at GEOMAR currently sets up a new 1/10° ocean nest for the North Atlantic embedded in the new global Kiel Climate Model System (ECHAM6.3 T63L47, NEMO3.6-LIM2 0.5°L46) to better understand the role of mesoscale processes in translating Greenland meltwater into AMOC variability and quantify potential freshwater thresholds.
In preparation for Enhanced-Greenland_Runoff (EGR) experiments with this new model setup, a few matters that likely influence the impact of Greenland runoff on the model ocean need to be considered, such as the distribution of the runoff itself, the split between liquid and solid runoff (icebergs), remapping of the runoff to the ocean nest, and surface salinity restoring in the ocean-only reference case. We will discuss the spatial and seasonal inhomogeneity of Greenland runoff, a potential mask for iceberg meltwater input, runoff that gets lost on land, and questionable freshwater export from Arctic under-ice restoring as well as surface salinification of the East Greenland Current due to restoring. *(torge.martin@gmail.com).*
Co-Authors: Christina Roth, Arne Biastoch.

29. Marion Donat-Magnin (IGE - Grenoble): Impact of interactive ice-shelves on the ocean response to the SAM trend, and possible feedbacks with the ice-dynamics.
Abstract: The observed positive trend in the Southern Annular Mode (SAM) may warm the Southern Ocean sub-surface through decreased Ekman downward pumping. Here we use interactive ice-shelves in a 1/12° regional NEMO-3.6 configuration of the Amundsen Sea. Our results show that the inclusion of ice-shelves changes the ocean response to the projected SAM trend, i.e. it inhibits a part of the SAM-induced subsurface warming. Sub ice-shelf melt increases above 400m and decreases below in response to ocean warming. The melt sensitivity to poleward shifting winds is nonetheless small compared to the sensitivity to an ice-sheet instability, i.e. to a projected change in the shape of ice-shelf cavities. Our work suggests the need for including ice shelves into ocean models, and to couple ocean models to ice-sheet models in climate projections. *(marion.donat-magnin@univ-grenoble-alpes.fr).*
Co-Authors: Nicolas Jourdain, Hubert Gallée, Paul Spence, Stephen Cornford, Julien Le Sommer, Gaël Durand.

30. Pierre Mathiot (UKMO – Exeter): Attempt to separate effects of horizontal resolution and bathymetry resolution using eORCA12 and eORCA025.
(pierre.mathiot@metoffice.gov.uk)

31. Pedro Colombo (IGE - Grenoble): Denmark Strait overflow in NEMO: does the type of vertical coordinate matters?
Abstract: This paper compares the DSOW in realistic settings of NEMO using the different vertical coordinates available in NEMO: Z full cell, Z partial cell and the combination of Sigma-Z. *(pedro.colombo@univ-grenoble-alpes.fr). Co-Authors: Bernard Barnier, Thierry-Penduff, Jean-Marc Molines, Julien Le Sommer, Jérôme Chanut.*

32. Rémi Tailleux (U. of Reading): Conceptual issues and pitfalls associated with the use of neutral rotated diffusion tensors.
Abstract: The impossibility to construct an exactly neutral density variable in the ocean implies that the effective diffusivity of all physically well- defined density variables subjected to neutral rotated diffusion is necessarily controlled --- at least partly --- by isoneutral diffusion. This problem complicates the inference of actual diapycnal mixing from Walin-type water masses analysis, as well as of the spurious diapycnal mixing from numerical advection schemes based on diagnosing the evolution of Lorenz reference state. This talk will report on efforts to quantify the problem by the NERC-funded INSPECT project. *(r.g.j.tailleux@reading.ac.uk).*
Co-Authors: Antoine Hochet (main author), Till Kuhlbrodt and David Ferreira.

33. Mike Bell (UKMO – Exeter): Spurious baroclinic instabilities on the Lorenz grid
Abstract: NEMO uses the Lorenz grid for its vertical discretisation. Spurious short-wave baroclinic instabilities were found to occur on the Lorenz grid by Arakawa and Moorthi (1988). As the vertical resolution of the grid improves, the most active of these instabilities become more and more trapped near one of the boundaries but they continue to grow at almost the same rate as the main, physically realistic, instabilities. We have reproduced these spurious instabilities in an analytical calculation which reduces the stability problem to a quadratic equation for their phase speeds. We outline this calculation and discuss the interpretation of the instabilities and whether they account for noise seen near the surface in equatorial regions of ORCA025. *(mike.bell@metoffice.gov.uk).*
Co-Authors: Andy White, Dave Storkey

34. George Nurser (NOC – Southampton): Upper-ocean mixing by Langmuir circulations: implementing the OSMOSIS Ocean Boundary Layer Model into NEMO.
Abstract: As part of the OSMOSIS project in the UK, a new 1D ocean boundary layer (OBL) model has been developed that takes account of the qualitatively different mixing mechanisms inherent in Langmuir turbulence (large coherent vortices) rather than in normal shear turbulence (smaller, chaotic vortices). The development of the 1D OBL model has been informed by results from LES simulations and observations from the year-long OSMOSIS dataset. We describe the basic ideas behind the model and show results of NEMO simulations of the classic 1D datasets such as at OWS PAPA. Results look very promising, given the lack of model tuning so far. *(g.nurser@noc.ac.uk).*
Co-Authors: Alan Grant (Reading/UKMO), Stephen Belcher (UKMO), George Nurser (NOC, Southampton)

35. Klaus Getzlaff (GEOMAR – Kiel): A series of AGRIF configurations based on NEMO 3.6 using LIM2
Abstract: A family of AGRIF configurations based on NEMO3.6 using LIM2 with high-resolution focus onto the Agulhas region have been established. The focus is to investigate the role of meso- and sub-mesoscale variability in the Agulhas region around South Africa as well as the interplay between Agulhas and the Antarctic Circumpolar Current. Furthermore, the role of higher resolution for the basin wide circulation system and AMOC variability will be addressed. Our series ranges from 1/10° of a degree resolution nest (INALT10), hosted in ORCA05, via 1/20° nests (INALT20), hosted in ORCA025 spanning the entire South Atlantic and parts of the Indian Ocean up to a double nest with 1/60° resolution around South Africa (INALT60). The complement to this will be the new established successor of VIKING20 called VIKING20X which now covers the Atlantic with a 1/20° nest from 34S to 70N. It aims to reveal insights into the North Atlantic but also complement INALT20 to disentangle the influences resulting from an improved representation either of the North Atlantic with its deep water formation contributing to the lower limb of the AMOC or the South Atlantic with its impact by the Agulhas system to the upper limb.
In addition two AGRIF configurations coupled to an atmospheric model (ECHAM6.3) will be setup to investigate air-sea interactions and their regional as well as remote impact. One is the coupled INALT10 configuration complementing the series of nested configurations in the Agulhas region. The other one is PALMOD10, a 1/10° nest configuration in the North Atlantic hosted in ORCA05, which will be used to study the impact of Greenland meltwater on the ocean circulation and climate system on a mutli-decadal timescale with a focus on the role of mesoscale dynamics in redistributing the additional freshwater. *(kgetzlaff@geomar.de).*
Co-Authors: Franziska Schwarzkopf, Jan Harlaß, Torge Martin, Arne Biastoch, Claus Böning.

36. Helene Hewitt (UKMO – Exeter): Global ocean configurations for 'seamless' prediction

Abstract: As we move towards using coupled models for short-range forecasting as well as seasonal prediction and climate projections, there is a requirement for global ocean configurations at a range of resolutions to support these applications. Maintaining traceability across the resolutions is a key concern and we discuss the lessons learnt from this during the development of the GO6 configuration at ORCA1, ORCA025 and ORCA12 resolution. Our development process has been focussed on long timescale OMIP style runs which have a relatively slow turnaround so in future we intend to explore complimenting these with case study ensembles to look at initial error growth. Finally we discuss our vision for future configurations including prioritising process improvements. *(helene.hewitt@metoffice.gov.uk)*

Co-Authors: Bablu Sinha, Dave Storkey, Pierre Mathiot, Richard Wood, Adrian New.

37. Laurent Brodeau (BSC-Earth Science – Barcelona): NEMO optimization at BSC.

Abstract: The BSC-Earth Sciences department actively works on improving the NEMO model computational performance. Using cutting-edge performance analysis tools such as Extrae and Paraver, we are able to identify computational bottlenecks and hotspots. According to our study, inter-process communication has been identified as the main bottleneck constraining scalability and therefore the proposed optimizations pursued the reduction of messages to decrease the associated overhead. Additionally, a tool to find optimal domain decompositions and exclude land-only processes has been developed, this tool will allow to reduce the number of processes needed and the overhead. Future work includes the exploration of mixed precision approaches, reducing from double to single precision when possible. This work will improve the performance of the model while and demonstrate that single precision is enough to represent most of the variables. *(brodeau@gmail.com).*

Co-Authors: M. Castrillo, O. Tinto and M. Acosta.

38. Clément Bricaud (Mercator Océan – Toulouse): Coarsening in NEMO: state of the art.

SESSION 5

Ocean and wave model coupling

39. Fabrice Ardhuin (LOPS – Brest): Wave interactions with ocean circulation and sea ice, from a wave perspective

Abstract: Ocean waves transport energy and momentum across the air-sea boundary, in particular in the presence of ice. The momentum that is taken up by the ice layer and surface currents is, in a way a non-local redistribution of the wind stress. The magnitude and relevance of that effect is closely connected with the spatial variations of wave properties. In deep water, the gradients in the wave field are expected to be dominated by surface current (refraction, wave breaking ...) for scales shorter than 150 km, with a spectrum of the wave height field that is proportional to the surface current spectrum. These results based on forced wave model simulations are consistent with altimeter data (which are reliable for scales larger than 50 km). Also, waves are known to modify the wind stress, with a variation that is expected to depend on wave age, at should introduce large scale gradients in the ocean forcing, but the magnitude of that effect is still widely debated (e.g. the variability of ECMWF drag coefficients due to the coupled wave-atmosphere system appear to be exaggerated). All in all, there are wave-induced spatial modulations of the wind stress at short and large scales with unknown consequences for the ocean circulation (upwellings ...). In the presence of ice, the distribution of momentum losses are concentrated near the ice edge, and, in the Southern Ocean, are of the order of the wind effect acting on the first 100 km of the sea ice, which is probably an important source of compaction at the ice edge.
Wave energy dissipation amounts to about 70 TW at global scale. In the open ocean this is mostly going into very near-surface turbulence due to wave breaking, with about 10% of that energy flux expected to maintain Langmuir Circulations (LCs). The energetics of LCs is still poorly known, and their influence on entrainment at the base of the mixed layer is very poorly constrained. A wide range of parameterizations (some of which are energetically or conceptually inconsistent) have been proposed. I'll try to review a few (Axell 2012, Qiao et al. 2004, Harcourt et al., Rodgers et al. 2014). Why some of these parameterizations produce better mixed layers is not understood in terms of basic principles.
The wave energy balance in the presence of ice is another with a strong recent activity. *(ardhuin@ifremer.fr).*

40. Xavier Couvelard (LOPS – Brest): Toward improving oceanic forecasts through ocean and waves coupling.

Abstract: The objective of ALBATROS project is to improve the representation of the interactions between ocean, waves, and atmosphere in a global forecasting model at high resolution in the framework of CMEMS (Copernicus Marine Environment Monitoring Service). Part of this project is to couple the waves model WW3 with the ocean model NEMO through OASIS3-MCT. The coupling is set up through the Stand Alone Surface module (SAS) of NEMO. This approach has been chosen by the mid-term possibility of coupling it with the simplified Atmospheric boundary layer model SIMBAD (SIMplified Boundary Atmospheric layer moDel for ocean modeling purposes). As a first step toward the global simulations, it has been chosen to implement the coupling on the regional configuration IBI12 (North East Atlantic at 1/12 degree).The setup of the coupling between the hydrodynamic code (OPA) and the surface module (SAS) will be described. It will be shown that the constraints of the coupling only slightly change the surface forcing, while the differences on the surface velocities can be locally important. The coupling strategy between OPA-SAS and WW3 will be also presented. It will be shown that taking in account only the surface rugosity induced by the waves and the wind stress absorbed by the developing waves, has very little impact on simulated seasonal fields. Taking in account the TKE injection by wave breaking is expected to lead to more significant differences. *(Xavier.Couvelard@ifremer.fr).*
Co-Authors: Jean-Luc Redelsperger, F.abrice Ardhuin, Florian Lemarié, Claude Talandier, Guillaume Samson.

41. Øyvind Breivik (NMI - Bergen): WAVE2NEMO: forcing a regional high resolution NEMO model with WAM fluxes and fields.

Abstract: The WAVE2NEMO project, funded by Mercator through the Copernicus Marine Environment Monitoring Service (CMEMS), aims to implement a number of wave-related effects in the latest version (3.6) of NEMO for regional applications. We have implemented the Coriolis-Stokes force in the momentum equation (see Breivik et al, 2014, 2015, 2016) as well as modifying the flux of turbulent kinetic energy from breaking waves (following the Craig and Banner, 1994, approach). The water-side momentum flux is also modified to account for the growth and decay of waves. We are also investigating an alternative implementation of the Langmuir production term in the turbulence kinetic energy equation. The project will deliver a version of NEMO which ingests relevant wave parameters from a version of WAM set up on the same grid. The model has been implemented and tested on 4 km resolution for a domain covering the North Sea and the Baltic Sea. The model shows promising results for storm surge applications (Staneva et al, 2016) and sea surface temperature in the Baltic Sea (Alari et al, 2016). *(oyvindb@met.no).*
Co-Authors: Joanna Staneva (HZG), Victor Alari (Tallinn University of Technology), Paolo Pezzutto(ISMAR).

42. **Stéphane Law-Chune: (Mercator Océan – Toulouse): NEMO forced with MFWAM wave model at Mercator Océan.**

Abstract: Météo France was chosen by the Copernicus Marine Environment Monitoring Service to ensure the provision of wave forecasts on a global scale. The consideration of waves in ocean circulation and its feedback on sea states are therefore important topics for the next phases of systems development. In order to answer to this demand, some classical wave-current interaction processes are studied at Mercator-Ocean. These include the taking into account of the wave roughness and their growth in the calculation of surface fluxes, the mixing associated with their dissipation and the introduction of new terms related to the Stokes velocities in the momentum equation. The impact of these coupling terms on waves will be illustrated in oceanic configurations similar to those used in Mercator's systems, in particular in a one-dimensional (vertical) configuration, which makes it possible to estimate their contribution to the reproduction of the seasonal cycle of the mixing layer. Some illustrations at the global scale will also be discussed. *(Stephane.lawchune@mercator-ocean.fr).*

43. **Emanuela Clementi (INGV – Bologna): NEMO-Wave coupling Working Group: overview and last achievements.**

Abstract: The NEMO consortium dedicates specific efforts in understanding the relevance of Atmosphere-Wave-Ocean exchanges processes and their roles in driving the ocean circulation at both coastal and global scales. To this end a Working Group on NEMO-Wave coupling has been created with the specific goal to identify required actions and code developments.

In particular the working group is exploring the way in which surface gravity waves can influence the ocean circulation. This presentation is meant to give an overview of the actual NEMO-Wave coupling implementation, in particular focusing on the last improvements achieved: new 3D Stokes Drift formulation, Stokes-Drift term, modified tracer advection, generalization of the surface boundary condition for momentum accounting for the wave effects, vertical enhanced mixing due to waves.

Co-Authors: J. Castillo[3], G. Madec[2], R. Benshila[2], Y. Aksenov[5], L. Aouf[4], L. Bricheno[5], A. Coward[5], D. Delrosso[1], M. Drudi[1], T. Graham[3], C. Guivarch[5], C. Harris[3], J. Hirschi[5], L. Hosekova[5], S. Law Chune[4], G.Mattia[1], A. New[5], G. Nurser[5], N. Pinardi[1], J. Wolf[5], M. Yelland[5] ([1]INGV, [2]LOCEAN, [3]UKMO, [4]MERCATOR-Ocean, [5]NOCS).

44. **Yevgeny Aksenov (NOC - Southampton): Modelling the waves, ocean and ice - A golden key to the future Arctic projections?**

Abstract: We present a development to couple the NEMO-CICE OGCM with ocean waves information and analyse the impact of the waves on sea ice and upper ocean. The motivation for the study stems from the recent changes in the Arctic sea ice: not only sea ice extent has been significantly lower in the recent decade than the climatology in summer and winter, but also it is much more broken and mobile, allowing the ocean surface waves propagate in the central Arctic. This mobile sea ice moderates momentum transfer from the atmosphere to the ocean and affects the heat storage in the upper mixed layer. We present the simulations with the newly implemented sea ice rheology, combined with floe size distribution analysis. We discuss the implications of the observed wave increase and sea ice fragmentation for the future state of the Arctic. The study is a part of the EU FP7 Project 'Ships and waves reaching Polar Regions (SWARP)', contributes to the Copernicus system and is linked to several ongoing UK national research initiatives. *(yka@noc.ac.uk).*

Co-authors: Stefanie Rynders, Lucia Hosekova, Tim Williams, Danny Feltham, George Nurser, Gurvan Madec, and Andrew Coward.

Waiting list

45. **Bernard Barnier (IGE - Grenoble): Low latitude western boundary current dynamics in the Indian Ocean.**

Abstract: Three hindcast simulations of the global ocean circulation differing by resolution (ORCA025 or ORCA12) or parameterization (free slip or partial slip) or atmospheric forcing (DFS or ERAi) are used to describe the interactions between the large anticyclonic eddies generated by the Somali Current system during the Southwest Monsoon. All three simulations bring to light that during the period when the Southwest Monsoon is well established, the Southern Gyre (SG) moves northward along the Somali coast and encounters the Great Whirl (GW). The interaction between the SG and the GW is a collision without merging, in a way that has not been described in observations up to now. This process is robust throughout the three simulations. The presentation will show that this process of interaction is not inconsistent with the satellite altimetry observations. The presentation will question the impact of model numerics on the representation of this dynamical process. *(bernard.barnier@univ-grenoble-alpes.fr).*

Co-Authors: Quam Akuetevi, Jean-Marc Molines, Jacques Verron, Albanne Lecointre.

46. Xiaobiao Xu (FSU – Tallahassee): Global 1/12 degree HYCOM internannual simulation with Drakkar atmospheric forcing. (Will be combined with Eric Chassignet's presentation in a 30 mn).

Abstract: Preliminary results of an interannual 1/12 degree HYCOM global simulation forced by the DRAKKAR atmospheric forcing data set will be presented. *(xxu3@fsu.edu).*

Co-Author: Eric Chassignet.