PROJECT FINAL REPORT

MEDLEY

MixED LayEr heterogeneitY

FULL PROJECT TITLE: Mixed Layer Heterogeneity

Project acronym: MEDLEY

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Publishable summary

The future climate of our planet depends on the way heat and carbon dioxide (CO_2) are absorbed by the ocean. The top 50-200 metres, the ocean's surface layer, is well mixed by turbulence from wind, waves and convective circulations. This mixed layer mediates the transfers between the atmosphere and the deep ocean.

Transfers of heat, energy and gases through the mixed layer are extremely complex and spatially heterogeneous. The discontinuous and dynamic sea ice cover, and the occurrence of eddies, fronts and filaments at the kilometer-scale, are important heterogeneities which regulate the thickness and properties of the mixed layer. Large discrepancies in mixed layer depths are found among climate models used for IPCC scenarios, partly due to a misrepresentation of the integrated effect of these heterogeneities. This limits the usefulness of climate models in assessing the impacts of future climate change on European climate and marine ecosystems.

MEDLEY aims at furthering our understanding of mixed layer heterogeneity, focussing on the North Atlantic a hotspot of anthropogenic CO_2 storage, and in the rapidly warming Arctic Ocean. The core objectives of MEDLEY are:

- to evaluate the spatial heterogeneity of the fluxes and processes controlling the ocean mixed layer, its exchanges with the atmosphere, and with the deep ocean
- to improve the representation of the transfers through the mixed layer in climate models by taking this heterogeneity into account.

To fulfil these objectives, we make use of ocean and atmosphere observations, very high resolution numerical models (with a grid of a few kilometers) as well as lower resolution climate models. The global ocean models participating in OMIP (Ocean Model Intercomparison Project) are especially useful in the context of MEDLEY because the evaluation of simulations with observations is more straightforward than in fully coupled earth system models.

Taking advantage of OMIP models, we have evaluated the mixed layer variability at the global scale, focussing on the mixed layer heterogeneity created by mesoscale eddies, showing that the mixed layer tends to be shallower on average when these eddies are resolved explicitly by the models. We point out the importance of the representation of the Arctic halocline to simulate realistically the exchanges across the mixed layer. An analysis focussed on a key region for deep water formation, the Labrador Sea, reveals the role of eddies in shaping the deep mixed layers and the formation of deep water masses. Fine scale boundary currents have been shown to play an essential role in the interannual variability of deep water formation rates in the North Atlantic, providing a "fast escape" route for the newly formed waters.

A novel sea ice model, neXtSIM, has been analyzed to quantify the role of sea ice as a source of heterogeneity for mixed layer and sea-ice interactions. The neXtSIM model is unique in that it can reproduce the inherent heterogeneity of the ice cover without having to be run at extremely high resolution. This allows us to investigate the role of surface heterogeneity on the ice and upper ocean over long time-scales. In the model, openings in sea ice (leads) contribute to 25 to 40% of the total ice growth in the Arctic domain. The model also shows that this fraction increases by about 3% per decade in the first two decades of the 21st century. Ice formation in leads, as well as mechanical stirring when the ice breaks up, also influences the surface mixed layer. In MEDLEY, we have shown how a large breakup event, where the ice breaks up over a scale of thousands of kilometres, can cause a local deepening of the mixed layer. As the sea ice in the Arctic becomes

thinner and weaker in a warming climate, we can expect large breakup events to become more frequent. MEDLEY has shown that this thinning will impact ice formation and mixed-layer dynamics in the Arctic, but more work is needed for a detailed understanding of the processes, trends, and impacts involved.

Making use of recent observations, a new census of eddies has been performed in the Arctic Ocean, leading to a better quantification of the influence of subsurface eddies on the mixed layer and the sea ice. MEDLEY has collaborated with another European project to better estimate the mixed layer depth from observations using neural networks, with promising results in the Gulf Stream region.

The parameterized vertical mixing in the NEMO European Ocean-ice model has been revisited in the Arctic, in the presence of sea ice. Forced simulations with different mixing parameters have been performed with the 1° global NEMO configuration used for IPCC scenarios. The importance of a key parameter governing the penetration of turbulence below the mixed layer has been highlighted, and the interplay of this process with sea ice cover has been demonstrated. MEDLEY also contributes to the coupled model intercomparison project (CMIP) by providing updated guidelines for the computation of the mixed layer depth in models.

Two new datasets are a major outcome of MEDLEY. 1) a revised global climatology of the ocean mixed layer, tailored to the needs of climate modelers, that will be used in the next phase of IPCC, and 2) a climatology of the upper ocean pycnocline, the stratified layer at the bottom of the mixed layer, which will enable new assessment of the vertical stratification in coupled climate models.

Objective on sustainable development

MEDLEY contributes to the SDG 14, “Life below water”. The primary production in the ocean, the first step of the food chain, takes place in the surface mixed layer. Primary production depends on the spatial heterogeneity of mixed layer dynamics, the topic which is at the core of MEDLEY. Improving our capacity to understand and simulate the mixed layer will also contribute to better models of the spread of pollutants in the sea.

MEDLEY contributes to the SDG 13, “climate action”. The resilience and adaptation of societies that depend on the ocean ecosystems (living in arctic environments, harvesting fish, …) require better high resolution projections of climate change in the ocean. MEDLEY contributes to SDG13 by systematically evaluating the ocean components of climate models, contributing to the development of improved sea ice models, and understanding the role of the mixed layer as a conduit for heat and anthropogenic carbon uptake.

Work package 1: Heterogeneous mixed layer dynamics

1.1 Effect of heterogeneous ice cover on MLD in coupled neXtSIM-NEMO simulation

(NERSC, CNRS-LOPS, CNRS-IGE)

The characteristics and heterogeneity of the ocean mixed layer (OML) largely depend on interactions with the atmosphere and the conditions at the ocean surface. In the Arctic, these interactions are heavily modulated by the presence of sea ice, which itself has highly heterogeneous characteristics, such as concentration, thickness, and drift velocity. Today's commonly used sea-ice models cannot reproduce this heterogeneity, except when run at a prohibitively high resolution. In MEDLEY, NERSC and LOPS collaborated to couple the neXtSIM sea-ice model developed at NERSC with the widely used NEMO ocean model. The advantage of neXtSIM is that it can realistically reproduce sea-ice heterogeneity at medium or even low resolutions. This makes it feasible to study the impact of sea-ice heterogeneity over longer time scales than a year or two. Coupling neXtSIM with NEMO has allowed us to investigate the impact of sea-ice heterogeneity on the ocean and the OML in particular.

We have investigated sea-ice properties with the coupled NEMO-neXtSIM model, such as ice age, drift, and sea-ice mass balance (Boutin et al., 2023; Regan et al., 2023). We found that the ice in the coupled model is very well represented, the results are in close agreement with observations, and the model can give insights into the Arctic system beyond what observations alone can do. In the context of MEDLEY, a particularly important insight is the role of leads and polynyas in the sea-ice winter mass balance. Boutin et al. (2023) showed that leads contribute to between 25 and 35% of the total Arctic sea-ice production in the model (Figure 1). This aligns with previous observational estimates, but those were severely limited in time and space. The estimate of Boutin et al. (2023) is the first to be made on a pan-Arctic scale, and over several years, the study spanned 2000–2018. The model also shows that this contribution significantly increases over the modelling period at a rate of 3% per decade. Boutin et al. (2023) attribute this increase to the thinning of the ice cover and an associated mechanical weakening of the ice.

Ice formation in leads and mechanical stirring when the ice breaks up also influence the surface mixed layer, in addition to impacting the ice. To investigate this impact, the team at NERSC is working on a case study of a breakup event that occurred in the Beaufort Sea in late February 2013. In mid-February, an anticyclone moved from the Chukchi Sea towards the Beaufort Sea, causing strong along-shore winds along the Alaskan and Canadian coasts to the Beaufort Sea. This caused a series of fractures to form off the coast, stretching hundreds of kilometres into the central Beaufort Sea. As the anticyclone continued to move towards the Canadian coast, the ice cover in the Beaufort Sea became increasingly fractured until the wind caused it to detach from the coast of Banks Island, the easternmost limit of the Beaufort Sea. This spectacular event is well reproduced by neXtSIM (Rheinlænder et al., 2022), and fortuitously, three ice-tethered profiles (ITP) were also present in the ice during the breakup (Figure 2). Using the ITP observations and the coupled NEMO-neXtSIM model, the NERSC team can show that the breakup causes a significant deepening of the mixed layer, and the cause of this is the mechanical mixing that takes place at the surface, as the ice drifts much faster once fractured (Figure 3).

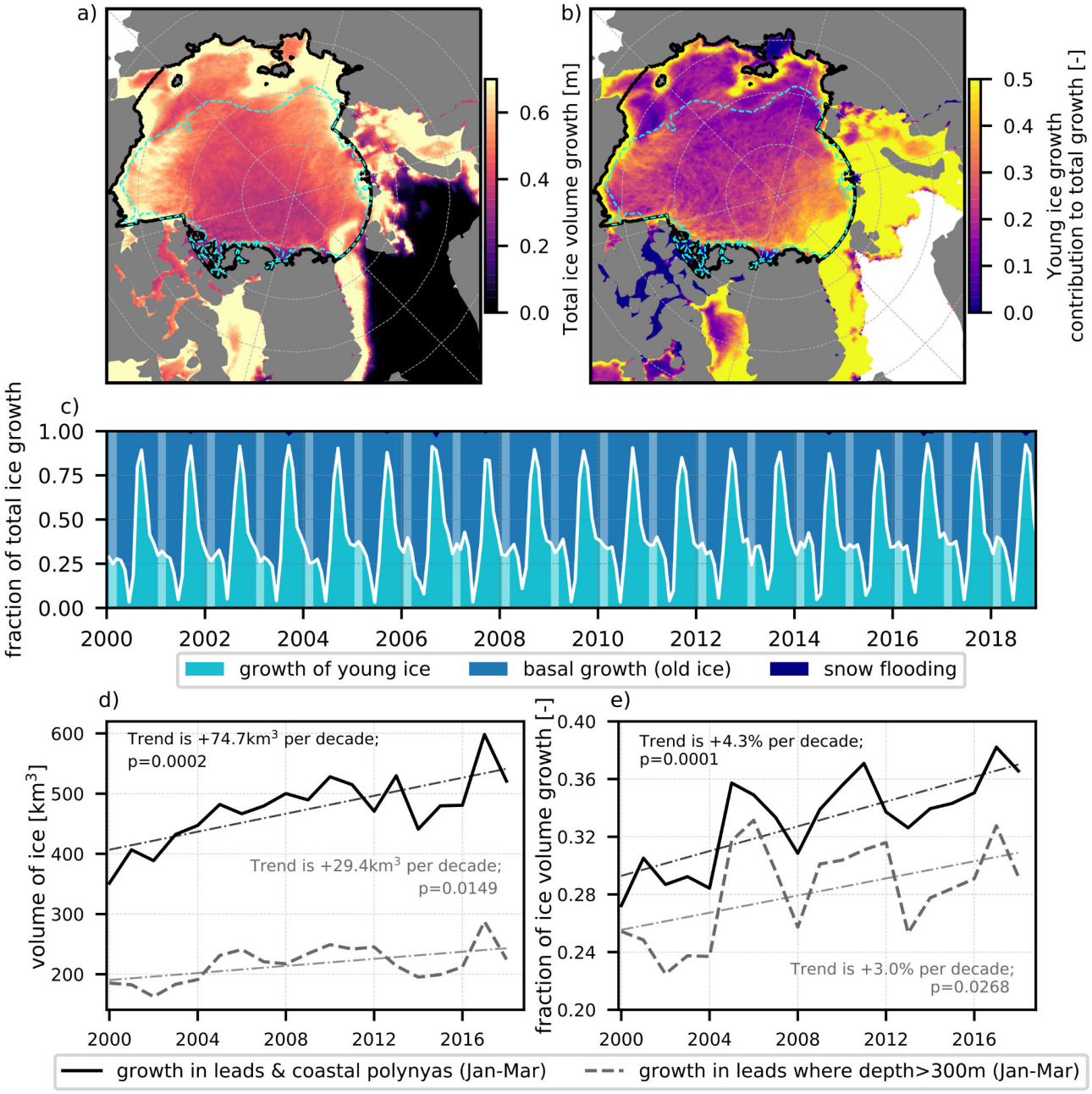

Figure 1: The 2000–2018 climatology of the spatial distribution of ice volume (per area) growth in leads and polynyas in winter (a) and its contribution (ratio) to the total ice growth in winter (b). Panel (c) shows the evolution of this contribution compared to other ice growth processes over the period 2000–2018 within the domain delimited by the thick solid black line in panels (a) and (b). The temporal evolution of the integrated winter young ice volume growth and its contribution to total ice growth integrated over the domain is shown in panels (d) and (e), respectively (solid black lines). The dashed grey lines represent the same quantities but for a sub-domain from which the regions shallower than 300 m are excluded (cyan contour in panels a and b). We also display the trends associated with each line and their associated p-value. From Boutin et al. (2023).

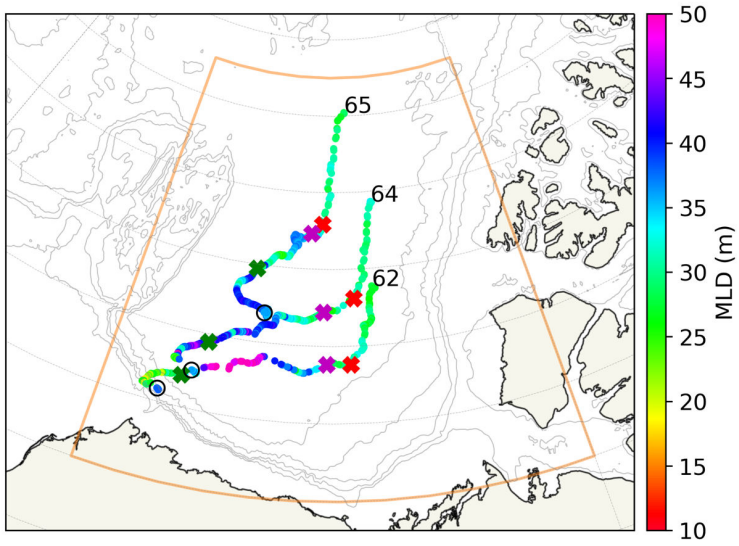

Figure 2: Mixed layer depth along the ITP trajectories between January and April 2013. Crosses mark the location on February 1st, March 1st and April 1st. The ice cover breaks up during late February and the ITPs drift into an area of broken-up ice during March and April.

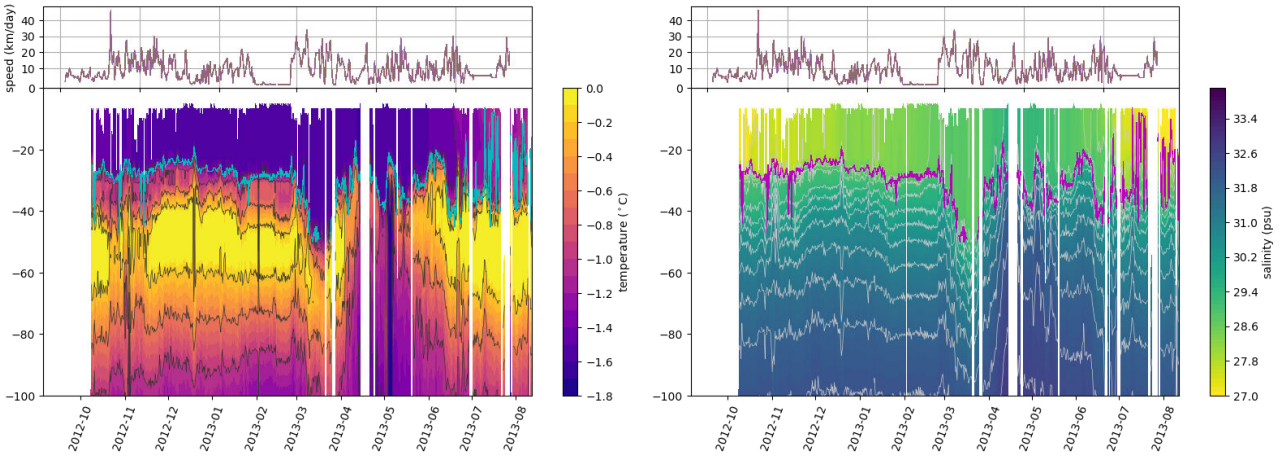

Figure 3: Temperature (left) and salinity (right) along the ITP64 trajectory during the 2013 breakup event. The ITP drift speed is plotted over the temperature and salinity profiles. Note the period of no drift in early February, which ends as the ice cover breaks up in mid-February. Following the breakup, the OML deepens substantially.

1.2 Heterogeneous mixed layer dynamics in the Arctic

(UCLouvain, CNRS-LOPS)

UCLouvain evaluated the ability of ocean–sea ice general circulation models participating in the CMIP6 Ocean Modelling Intercomparison Project (OMIP) to simulate the oceanic mixed layer (OML) depth and its seasonal cycle in the Arctic region. During summer months, all models systematically underestimate the depth of the OML compared to observational data from the Monthly Isopycnal Mixed layer Ocean Climatology (MIMOC; Toole et al., 2015) and Ice-Tethered Profilers (ITP; Holte and Talley, 2009). In autumn and winter, differences of several tens of meters were observed between the models themselves and between the models and observational data (Figure 4). We then analyzed the origin of the model biases in autumn and winter in ice-covered regions, where the sea surface salinity and OML depth are largely determined by the brine release

associated with sea ice growth. Focusing first on the central Arctic Ocean, defined here as the region north of 80° N, we found that all models simulate similarly the sea ice mass balance and hence salt flux to the ocean during sea ice formation. In addition, all models show a strong relationship between the vertical stratification profile of the ocean in September and the depth of the mixed layer at the end of winter. We concluded that the discrepancies between models are therefore not so much related to the surface salt balance, but rather to the accuracy with which these models reproduce the vertical salinity profile. In short, a weakly stratified ocean tends to create a deep OML, while strong stratification leads to a shallow mixed layer. To support this conclusion, we applied a simple conceptual model (Martinson, 1990), which computes the month-by-month evolution of the OML depth using vertical salinity gradients and surface salt fluxes from ocean–sea ice general circulation models as input data. Surprisingly, this simplified model captures the behavior of the more complex ocean general circulation models very well, highlighting the role of the vertical stratification in governing the depth of the mixed layer during the ice growth season (Figure 5). Moreover, this link can also explain the large OML biases noticed in other ice-covered regions of the pan-Arctic seas, even if sea ice–ocean interactions are not the only driver of the autumn and winter mixed layer variability in these regions. These results, which are detailed in Allende et al. (2023), underline the importance of an accurate representation of the Arctic halocline in global sea ice–ocean general circulation models used for climate studies. Future research efforts should focus on improving the fidelity of this representation, which would lead to more reliable climate projections in the Arctic.

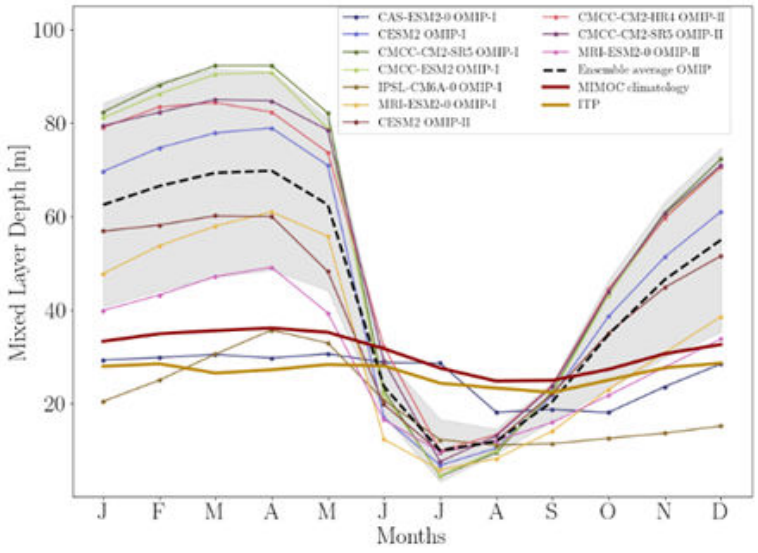

Figure 4. Seasonal cycle of the OML depth in the central Arctic Ocean. Data are averaged in time between 2007 and 2009 for OMIP1, and between 2007 and 2011 for OMIP2 and ITP. Data are averaged in space between 80° N and 90° N, and between 180° W and 180° E. Solid lines with points correspond to OMIP models. The black dashed line corresponds to the model ensemble mean, the black-shading range represents the ensemble standard deviation and the blue dashed line corresponds to the average of observational data. Red and yellow solid lines correspond to the MIMOC climatology and ITP profiles, respectively.

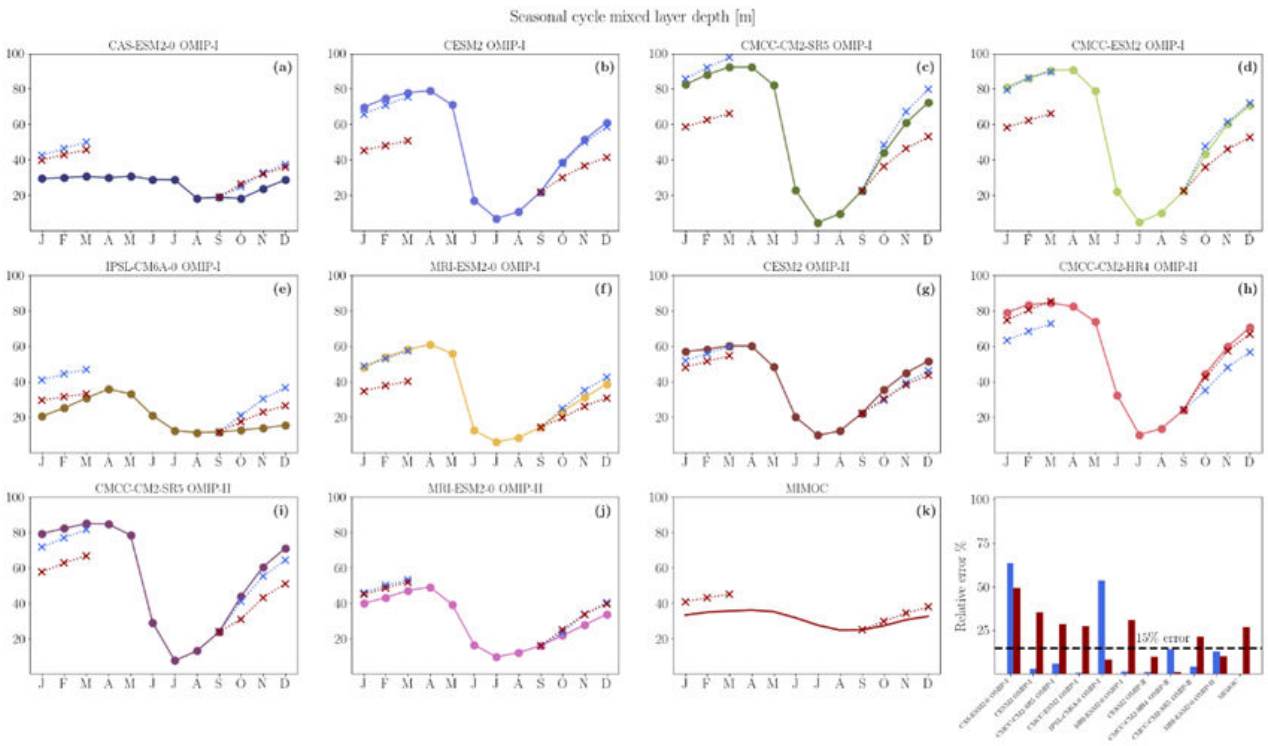

Figure 5. Reproduction of the seasonal cycle of the OML depth for each OMIP model and the MIMOC observational data in the central Arctic Ocean using Martinson's model. The blue dashed lines were obtained using the values in each grid cell. The red dashed lines were obtained using the averaged values of the salinity gradient and salinity flux. Please note that, while the seasonal cycle is here represented with months varying from January to December, our iteration procedure uses September as the initial time. The right bottom panel shows the relative March OML depth error for each OMIP model, with the corresponding methodologies in red and blue colour bars.

1.3 Spatio temporal variability of the mixed layer depth in the Ocean Model Intercomparison Project

(CNRS-LOPS, CNRS-IGE, UCLouvain, CMCC)

For reliable projections of the future climate, the mixed layer depth and its variability need to be well represented in numerical models, but it is not the case presently. Biases in coupled climate models are difficult to interpret, because they may be related to atmospheric as well as oceanic processes. The Ocean Model Intercomparison project (OMIP) is an opportunity to study the spatio-temporal variability of the mixed layer in different ocean climate models, at different resolutions, under a common atmospheric forcing (Tsujino et al., 2018). We analyzed OMIP simulation pairs run by 6 different groups internationally, with low (typically 1°) and high (1/10°) resolution, following Chassignet et al (2020).

We have found that large inter-model differences persist at high resolution. The mixed layer depth (MLD) is improved at high resolution in the Gulf Stream and Kuroshio region, but it is not the case in the Southern Ocean for all the models. Except in the Southern Ocean, the MLD tends to be shallower in high resolution models, suggesting that the dominant effect of mesoscale eddies on the MLD may be their tendency to restratify the upper layer of the ocean (Figure 6).

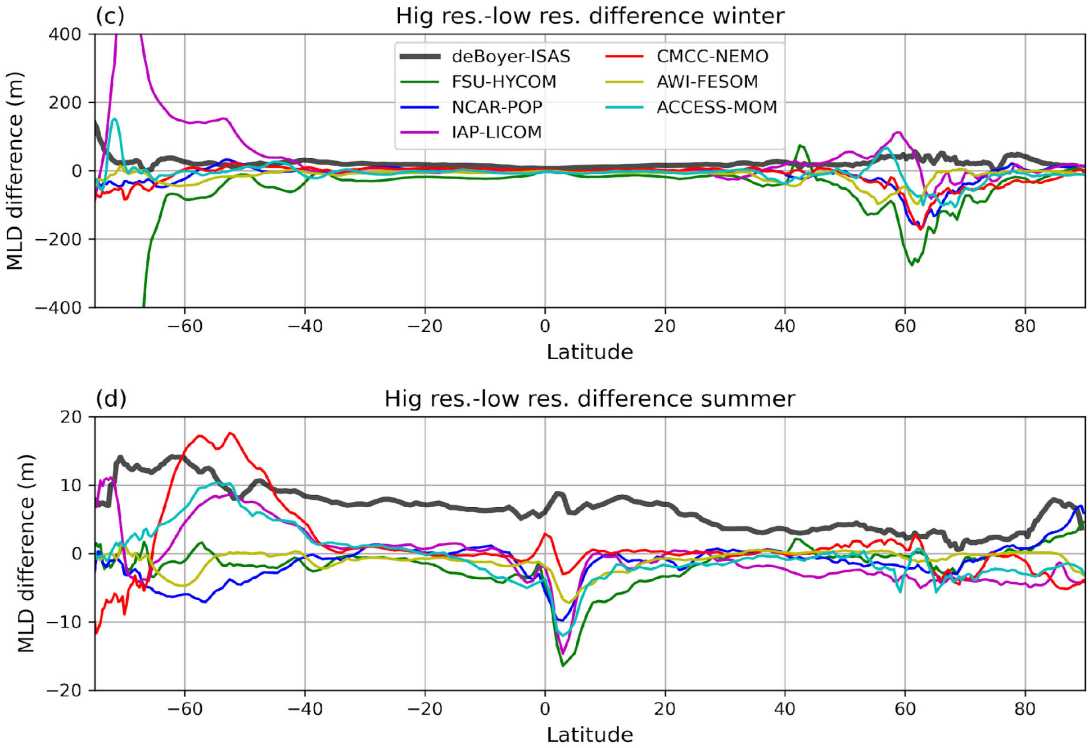

Figure 6: Zonal mean of the difference of the Mixed Layer Depth between the high resolution model and the low resolution model from each of the 6 participating groups. The black line is the difference between two observational products (MLD computed from individual ARGO profiles vs. MLD computed from a low resolution climatology). In mid latitude, the mixed layer is mostly shallower in high resolution models.

In this work (Treguier et al., 2023) we also present guidelines for the computation of the MLD in models, and a new evaluation of sampling errors when using high resolution simulations. This is a contribution to the next phase of the model intercomparison projects (CMIP and OMIP). An evaluation of MLD interannual variability and trends has been initiated, motivated by the hypothesis that the summer MLD has deepened in recent decades (Sallée et al., 2021). This finding, which relies on sparse observations does not seem to be supported by the OMIP simulations, except in the Southern Ocean. A publication is in preparation.

1.4 Heterogeneity of the Labrador Sea mixed layer in the High-Res OMIP-2 models

(CMCC, CNRS-LOPS)

CMCC assessed the ability of global ocean–sea ice models participating in the CMIP6 OMIP to simulate the mixed layer depth and its interannual and seasonal variability in the Labrador Sea (LS). This ocean basin plays a vital role in the climate system as the water formed in this basin is a key contributor to the lower limb of the Atlantic Meridional Overturning Circulation (AMOC). This region is characterized by intricate physical processes, including deep convection, interactions between sea ice and the ocean and numerous oceanic eddies. The latter are generated both from lateral density gradients that exist during the convection season, and from baroclinic and barotropic instabilities that occur within the boundary currents. From the above, it is clear that mesoscale eddies in this region significantly influence water mass formation and distribution.

First, CMCC uses OMIP-like simulations based on a hierarchy of CMCC global ocean-sea ice configurations (Table A, Iovino et al. 2023) to assess how climate-relevant changes in LS mean state and variability are associated with the grid enhancement from non-eddying (low-, nominally 1° horizontal grid spacing), eddy-permitting (medium-, nominally 0.25°) to eddy-rich (high-, 0.0625°) resolutions in our ocean components.

Table A. Outline of grid characteristics, and ocean timesteps used for the CMCC ocean models.

	NEMOv3.6 model	horizontal grid points	lateral spacing	vertical levels	H_{max}	Δz_{min}	Δz_{max}	ocean time step	# cores ocean/ice
LR	ORCA1	360×291	1°	50	5904	1.05	409.6	3600	128/96
MR	ORCA025	1440×1050	1/4°	50	5904	1.05	409.6	1200	1008/972
HR	GLOB16 *(simplified ice)*	5760×3962	1/16°	98	6182	0.8	161.7	200	2098

Eddy Kinetic Energy (EKE) is a measure of the energy contained in the turbulent motion of ocean currents, which is critical for understanding oceanic processes like heat transport, nutrient mixing, and overall ocean circulation. Comparing the spatial distribution of EKE in Figure 7, we show the role of the mesoscale eddy field in representing the complex ocean circulation in the region. Model data are compared to AVISO estimates. The general pattern is similar between simulations and compares with AVISO estimates (only geostrophic velocity).

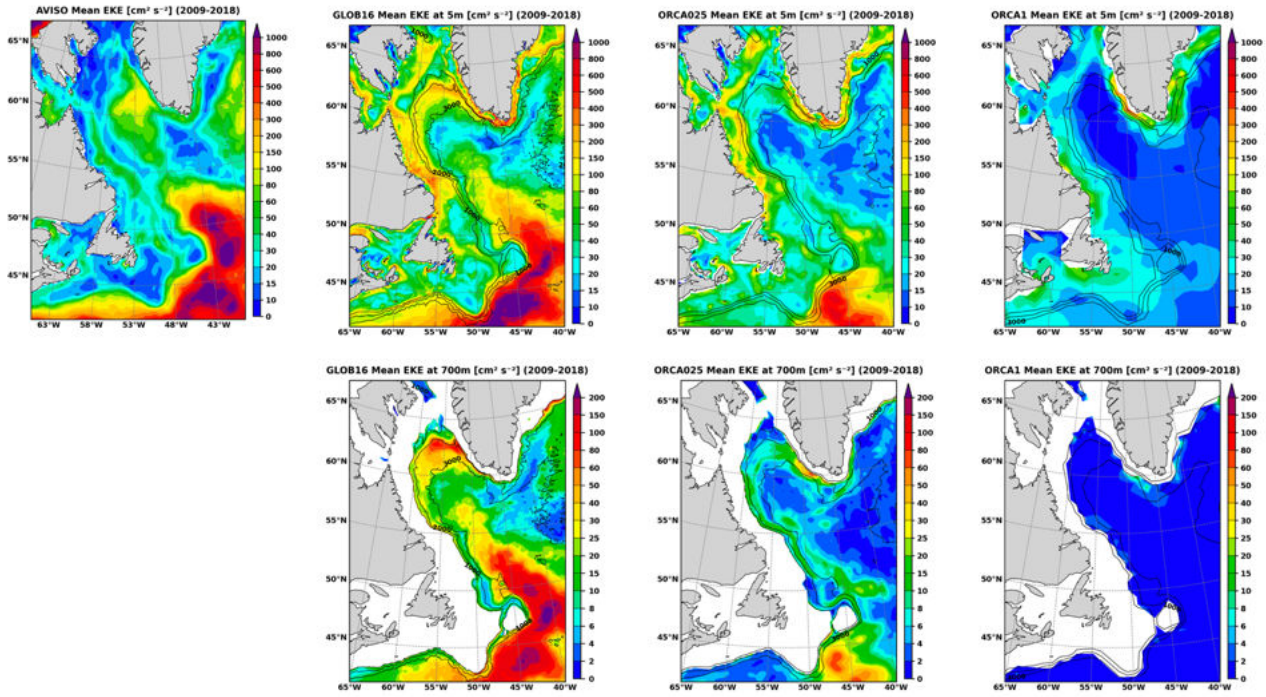

Figure 7. EKE at the surface and 700m, from the 2009-2018 mean state (computed using 1d velocity fields) for the three simulations and AVISO dataset.

At high resolution, the maximum EKE is collocated with the path of the boundary current from the west coast of Greenland, extending into the interior of the basin around 62 N, and along the coastal shelf break. The magnitude between models is highly different. There is a large difference also within the interior of the Labrador Sea. In ORCA025, the EKE remains low in a large portion of the interior region (the blue area) where GLOB16 EKE is doubled but still lower than fields from AVISO. In ORCA1, the EKE is largely underestimated in the entire basin. Only in GLOB16, the signal is still present at depth following the boundary current indicating that the current still exchanges heat via eddies in all its depth extension.

To evaluate the impact of resolving mesoscale on the stratification strength in the LS, Figure 8 shows the modelled convective energy computed as the amount of energy needed to produce a neutrally stratified

column extending down to 2000m reference depth. A weakly stratified water column corresponds to low convective energy values (Pennelly and Myers 2020). With more mesoscale features and stronger eddy fluxes from the Greenland coast, the GLOB16 convective energy is higher, and the spatial extent of the weakly stratified region (in blue) is spatially limited within the basin interior, as opposed to ORCA025 where it spills out of the basin. With fewer eddies resolved, the ORCA025 interior lacks the buoyancy flux and remains very weakly stratified across a wide region. In ORCA1, there is no clear distinction between the boundary current and the basin interior.

All our analyses were applied to a suite of OMIP2 runs at eddy-rich resolution (from 1/10° to 1/20°) made available through the Clivar Ocean Model Development Panel (OMDP). In Figure 8 (bottom row), we also show results from four high-res simulations. CMCC model results reveal as expected large differences in the representation of Labrador Sea dynamics for varying resolution, with a reduction of the area and volume of convected waters that feed the deep basin when mesoscale advection is included, but not all high-res models confirm this result. Large differences are surprisingly present also among eddy-rich oceans. Not all models achieve improvements when resolution is increased so it is crucial to recognize that model numerics and parameterizations play a key role in faithful simulations.

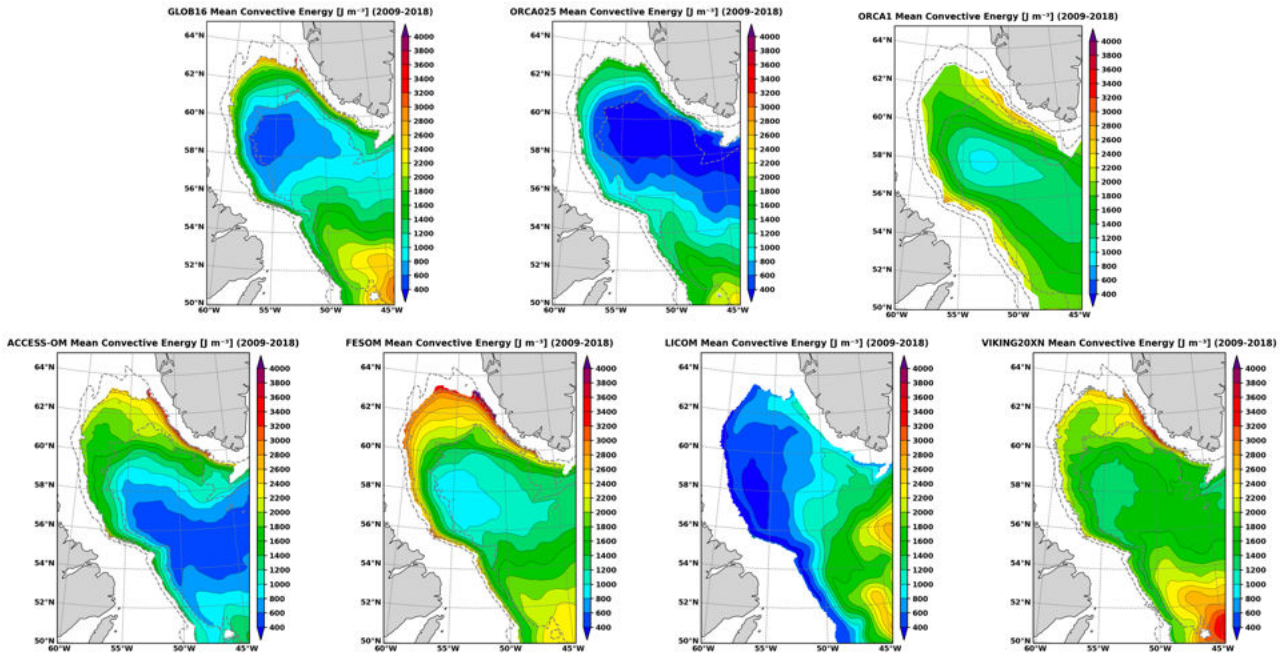

Figure 8. Convective energy (CE), the strength of stratification down to a reference depth of 2000 m, in the OMIP simulations. Top row: CMCC models. bottom row: Four high resolution OMIP models.

1.5 Mixed layer statistics in COPERNICUS data products.

CNRS-LOPS

This work is a collaboration between MEDLEY and the European ARGO EARISE project, aimed at reconstructing the heterogeneity of the mixed layer in an eddy-rich region (Gulf Stream) using a machine learning technique (Pauthenet et al., 2022). A bootstrapped multilayer perceptron has been trained to simultaneously predict temperature and salinity (T−S) profiles down to 1000 m and the mixed-layer depth (MLD) from surface data covering 1993 to 2019. OSnet (Ocean Stratification network) is trained to fit sea surface temperature and sea level anomalies onto all historical in situ profiles in the Gulf Stream region. To achieve vertical coherence of the profiles, the MLD prediction is used to adjust a posteriori the vertical gradients of predicted T−S profiles, thus increasing the accuracy of the solution and removing vertical density inversions. The prediction is generalized on a 1/4° daily grid, producing four-dimensional fields of

temperature and salinity, with their associated confidence interval issued from the bootstrap. OSnet profiles have root mean square error comparable with the observation-based Armor3D weekly product and the physics-based ocean reanalysis Glorys12. The OSnet reconstructed field is coherent even in the pre-Argo years, demonstrating the good generalization properties of the network in the study region (Pauthenet et al., 2022). After this first success, we have attempted to apply the network to the Nordic seas with mixed results. We conclude that generalization to any region of the ocean is not yet possible without further refinements of the network.

Work package 2: Sources of heterogeneity in the fluxes at the ocean surface

2.1 Impact of fragmented sea-ice on air-sea fluxes

(UCLouvain, CNRS-LOPS)

UCLouvain assessed the performance of the ocean vertical mixing scheme of the NEMO4.2-SI3 (Nucleus for European Modelling of the Ocean – Sea Ice Modelling Integrated Initiative) global ocean–sea ice model at a 1° resolution in ice-covered regions of the Arctic Ocean. This scheme, known as TKE (Turbulent Kinetic Energy) was implemented in the OPA (Océan Parallélisé) model, which is part of the NEMO platform, by Blanke and Delecluse (1993). Over time, significant updates, including those by Madec et al. (2016), have been made to improve the representation of turbulent mixing processes in the model. A key recent modification is the introduction of a mixed layer penetration (MLP) parameterization, which aims to address deficiencies in simulating the Ocean Mixed Layer (OML) depth, especially in scenarios with windy conditions during summer months, as observed in the Southern Ocean (Rodgers et al., 2014). This parameterization accounts for the effect of small-scale processes such as near-inertial oscillations and ocean swells and waves, which are not fully captured by the default TKE scheme. It is activated (switched off) when the model parameter nn_etau is set equal to 1 (0). The TKE MLP contribution, denoted einertial, is parameterized as : einertial = χ fr esurf exp(-z/hτ) if z > 0 and 0 if z = 0, where z is the depth, fr is the fraction of the surface TKE (esurf) that penetrates into the ocean, hτ is a vertical mixing length scale controlling the exponential shape of the penetration and χ is a scaling parameter that takes into account the presence of sea ice. fr (rn_efr in the model namelist) ranges between 0 and 0.1, with a standard value of 0.05, which means that 5% of the surface TKE is redistributed below the OML. hτ is taken equal to either 10 m if nn_htau = 0, to a latitude-dependent value that ranges from 0.5 m at the equator to 30 m poleward of 40° if nn_htau = 1 or to hemisphere-dependent values if nn_htau = 4. χ corresponds to nn_eice in the model namelist. When nn_eice = 0, χ = 1, which means no sea ice influence. When nn_eice = 1, χ = 1 – tanh(10 fi), with fi the sea ice concentration. When nn_eice = 2, χ = 1 – fi. Finally, when nn_eice = 3, χ = 1 – min(1, 4fi), which is equivalent to disabling the TKE MLP parametrization when sea ice concentration exceeds 25%.

A control run was first conducted with NEMO4.2-SI3 driven by the ERA-5 reanalysis atmospheric data (Hersbach et al. 2020) over the period 1960–2022. In this simulation, rn_efr = 0.08, nn_eice = 3 and nn_htau = 1. We then performed a series of sensitivity experiments under the same surface boundary conditions in which rn_efr was varied from 0 to 0.1. In addition, we ran the model with nn_htau = 0. In a last series of experiments, we set nn_eice equal to 0, 1 and 2. It should be noted that all these parameters were modified one at a time. For each simulation, we evaluated the model performance by comparing the model outputs to different sets of observational data and to a sea ice reanalysis product.

Figure 9 depicts the mean seasonal cycle of the OML depth from the control run, the sensitivity experiments and IFREMER-LOPS' climatology (de Boyer Montégut, 2024) in each of the Makarov, Eurasian and Canadian Basins of the Arctic Ocean. When the parameters of the TKE MLP parameterization vary, a similar behavior is noticed in all three regions. Three distinct settings with notable differences from the control simulation are

identified: deactivating the TKE MLP parameterization, maximizing the TKE MLP mixing without sea ice attenuation and scaling sea ice attenuation proportionally to sea ice concentration. Simulations using a scaling parameter as a function of the sea ice concentration (i.e., nn_eice = 1, nn_eice = 2 and nn_eice = 3) exhibit OML depths closer to IFREMER-LOPS' ones.

All parameters affect the simulation of the OML depth and its seasonal cycle, the sea surface temperature and salinity as well as the underlying ocean vertical stratification. In particular, we observed significant impacts on sea ice thickness in the Arctic Ocean in two scenarios: when the scaling parameter due to the presence of sea ice is absent and when the TKE MLP parameterization is disabled. In the first case, we found an increase of several meters in the depth of the OML and a reduction in sea ice thickness ranging between 5 and 30 cm compared to the control run, reflecting the impact of more mixing (Figure 10). In contrast, in the second case, we noticed that a lower OML depth is accompanied by an increase in sea ice thickness, ranging from 5 to 20 cm, as expected from a weaker mixing. Furthermore, analysis of the interannual variability of the upper ocean and sea ice characteristics simulated by the model showed that experiments including a scaling parameter based on sea ice concentration display an increased OML depth during periods of sea ice reduction, which is consistent with observed trends.

These results, which are discussed in detail in Allende et al. (2024), highlight the importance of taking into account properly the influence of small-scale processes on oceanic vertical mixing in ice-covered oceans through the use of appropriate physically-based parameterizations in models.

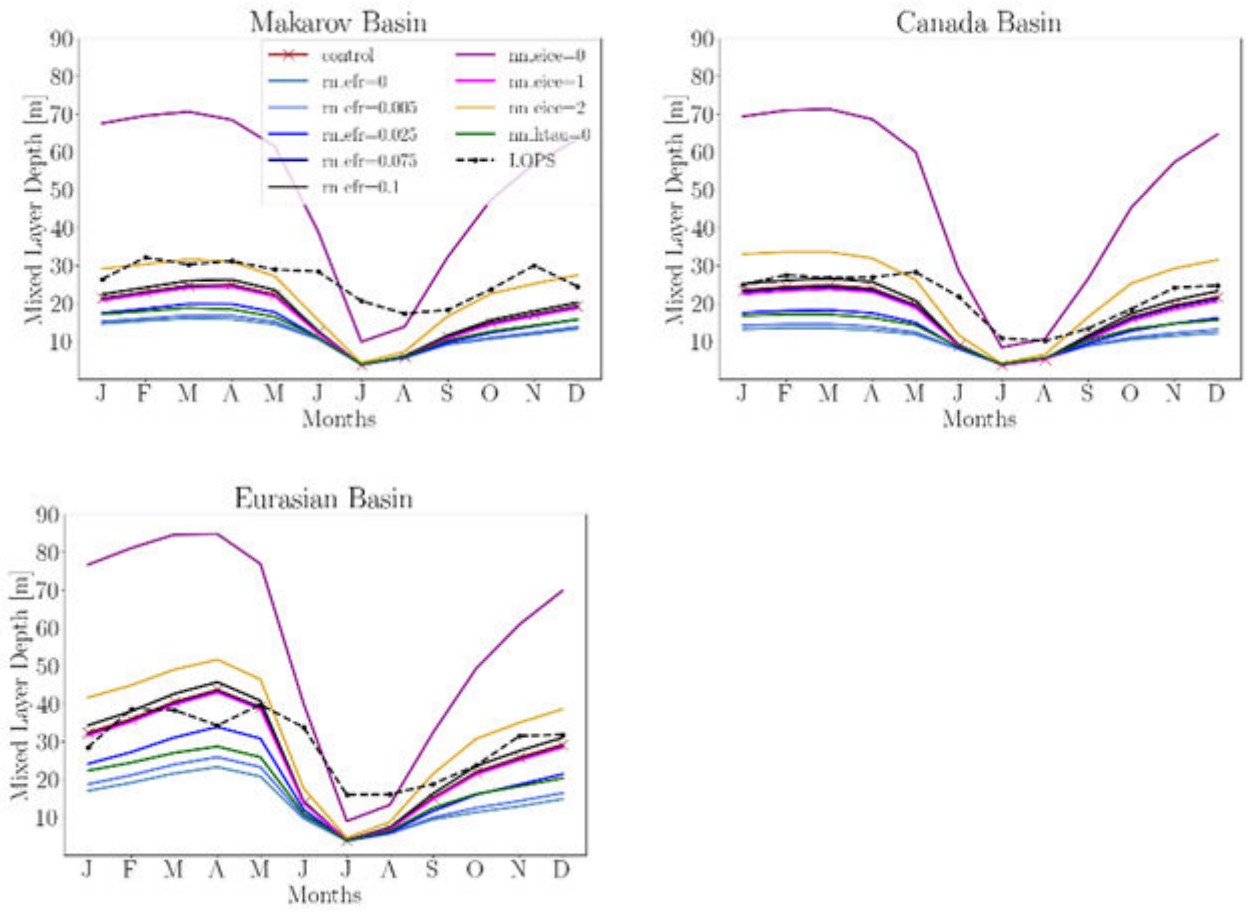

Figure 9. Mean seasonal cycle of the OML depth as simulated by NEMO-SI3 and from IFREMER-LOPS's climatology in the Makarov, Eurasian and Canadian Basins of the Arctic Ocean.

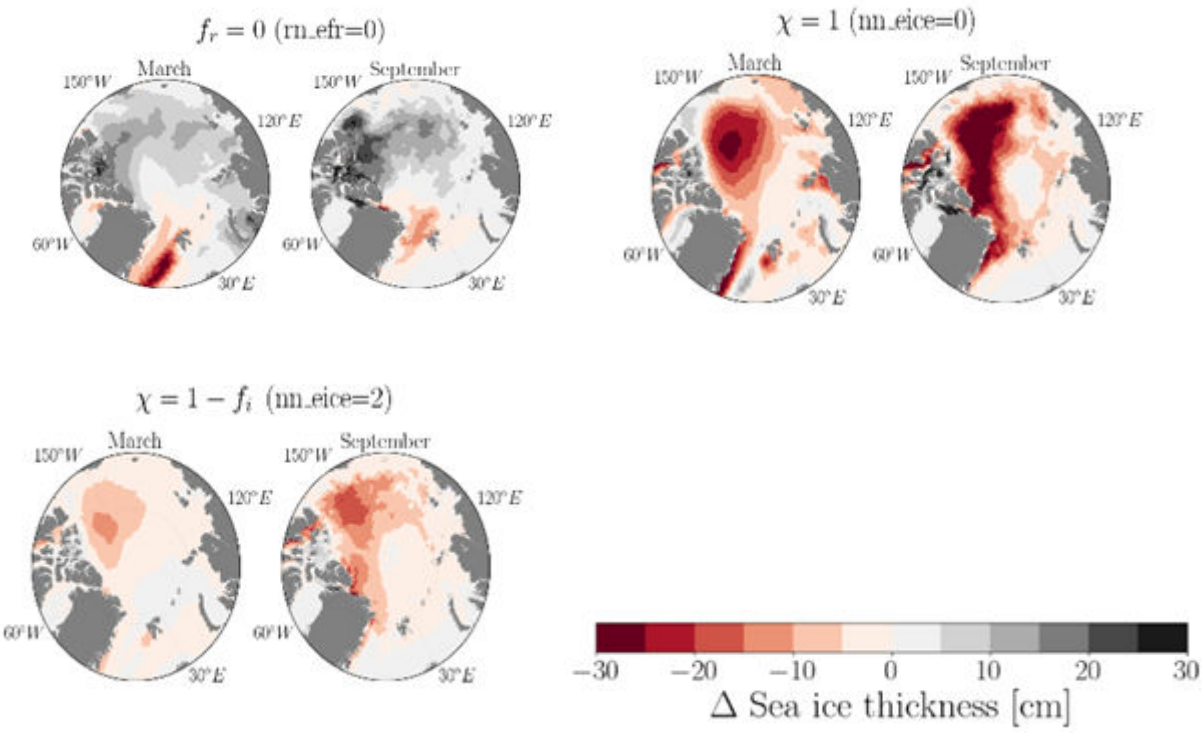

Figure 10. Differences in sea ice thickness between experiments rn_efr = 0, nn_eice = 0 and nn_eice = 2, and the control run in March and September. Model outputs are averaged in time between 1970 and 2021.

2.2 Air-sea fluxes and mixed layer depth evolution: a generic framework

(CNRS-IGE)

This work started using the coupled ENERGETICS simulation, but the insufficient quality of the simulation motivated a change in plans. We instead worked on a physics-based characterization of the ocean Mixed Layer Depth (MLD) evolution in the outputs of several ocean simulations. Simulated MLD evolutions often differ mutually and from their observed counterparts due to the inaccurate representation of the mesoscale (sometimes resolved) and smaller-scale (mostly parameterized) processes that control its dynamics. These processes are in mutual interaction and under the combined influence of buoyancy air-sea fluxes and wind stress.

We analyzed the MLD evolution in existing and new ocean simulations based on the NEMO ocean model at different resolutions and in various configurations: the eORCA1 and eORCA1GM global ocean 1° setups (without and with the Gent-McWilliams (GM) parameterization), and the eNATL60 North Atlantic 1-km resolution configuration.

We built a collection of 1D water column simulations (model developed by Fearon et al., 2020) where the MLD evolution is controlled by a TKE mixing scheme and an Enhanced Vertical Diffusivity (EVD) scheme in case of static instability, and taking the Earth rotation into account. This collection contains dozens of yearly MLD 1D simulations over hundreds of locations disseminated in the global ocean; temperature and salinity profiles were initialized to their eORCA1 values at the beginning of each year, and their evolution is driven by the time-varying air-sea fluxes used in the eORCA1 simulation.

Four MLD evolution regimes were identified in the 3D and 1D simulations at all selected locations based on the relative rate of change of MLD (h), as follows:

- ∂_t h/h ≥ 10 %/day: Strong Deepening
- 1 %/day ≤ ∂_t h/h < 10 %/day: Deepening
- −1 %/day ≤ ∂_t h/h < 1 %/day: Stable
- ∂_t h/h < −1 %/day: Restratification

We introduce a new parameter space to facilitate the comparison of the regimes of MLD evolution across these simulations, and possibly in comparison with observations. This parameter space is defined using three dimensionless numbers which characterize the dominant controlling processes of MLD evolution:

- Rh (Richardson number) quantifies the balance between the stabilizing effect of stratification and the destabilizing effect of the wind-driven shear.
- λs assesses the relative influence of buoyancy and wind air-sea forcing on the turbulent kinetic energy (TKE) in the surface layer.
- f/Nh quantifies the relative importance of the Coriolis force, stratification, and the depth of the mixed layer.

Figure 11 presents one example of this classification of MLD evolution in many locations of the global ocean, highlighting quite consistent behaviors for various values of the three parameters. More generally, our analyses yield the following main results about model intercomparison, about the ability of this approach to predict the actual evolution of MLD in various models, and about the impact of lateral versus vertical processes on MLD evolutions:

- The three-dimensional parameter space (Rh, λs, f/Nh) allows for effective comparison and characterization of MLD evolution across different models.
- The predictive skill of the parameter space decreases with increasing model resolution due to the growing importance of lateral processes. Cases of poor skill increase from 1° (3%) to 1/60° resolution (22%).
- Additional dimensionless numbers (for example Sh, a dimensionless number related to horizontal density gradients) may improve predictability when Rh and λs alone are insufficient.
- The use of the GM parameterization (eORCA1GM) shows notable impacts, especially in regions with high values of Sh.
- In unstable water columns (Rh < 400), lateral restratification processes play a secondary role. The "strong deepening" regime of the MLD is maintained across different models.
- In zones dominated by surface buoyancy fluxes (λs < -3), the restratification or stable regimes are preserved in both 1D and 3D models, suggesting lateral processes are less significant compared to vertical processes.

This parameter space thus offers a useful and quite robust framework for comparing and understanding MLD dynamics across different numerical models. We highlight that while vertical processes are crucial in certain regimes, lateral processes become significant with higher model resolutions. This work (Legay et al.) is currently in revision for the Journal of Advances in Modeling Earth Systems (JAMES)

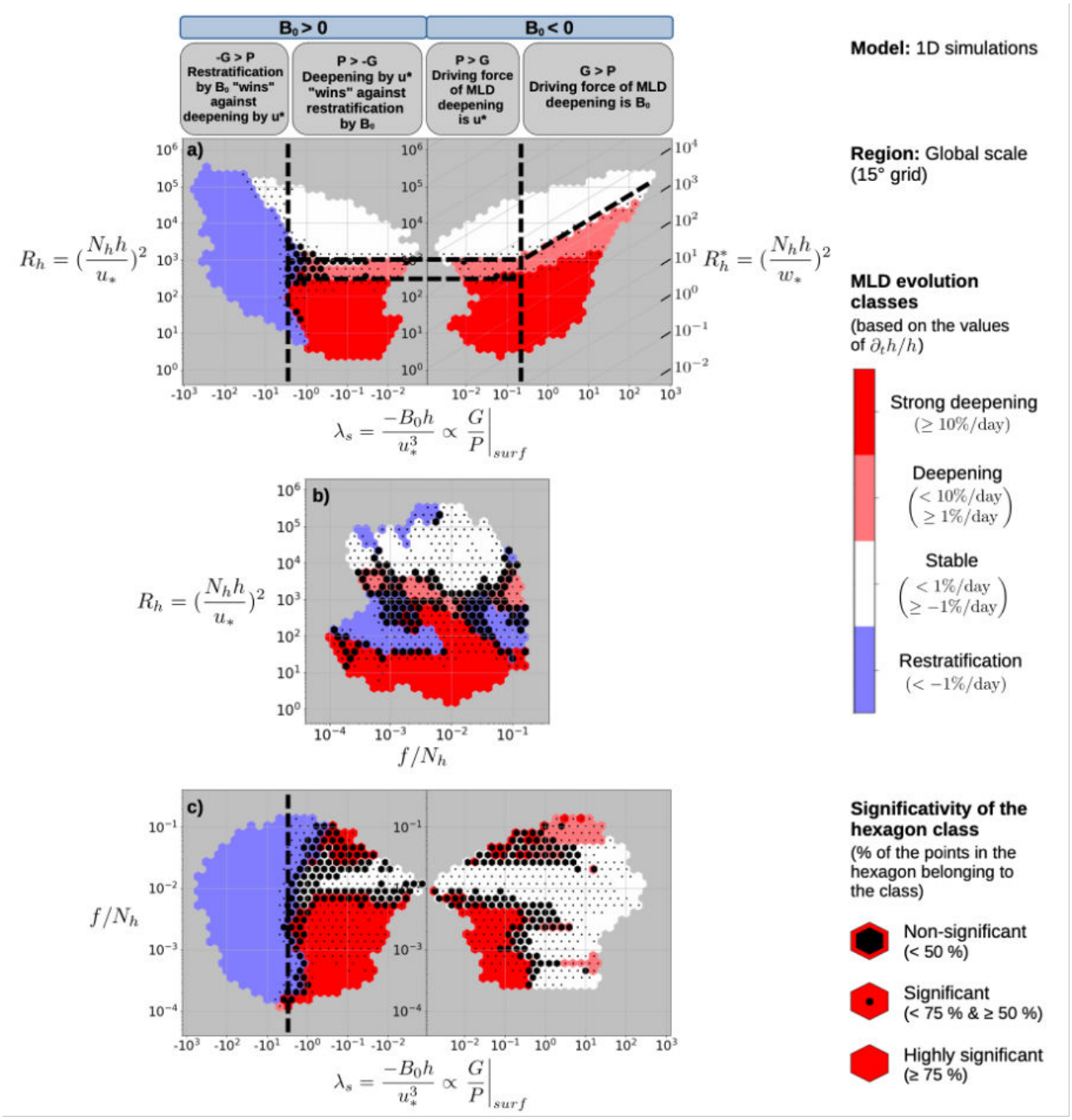

Figure 11. Results of the 1D simulations performed at all locations across the global ocean, plotted in the three different 2D projections of the 3D parameter space: (a) λs - Rh, (b) f/Nh - Rh and (c) λs - f/Nh. The MLD evolution classes are defined based on the values of $\partial_t h/h$ (see text). The class of a hexagon is the majority class of its constituent points. If this majority class represents less than 50% of the constituent points, the hexagon is tagged "non-significant" (superimposed black hexagon), if it is between 50 % and 75 % it is "significant" (superimposed black dot) and if it is higher than 75 % it is "highly significant" (nothing superimposed). A grid representing the slope 2/3 isolines of $Rh*$ is added in the λs > 0 panel of the λs - Rh parameter space. Dashed lines highlight demarcations between MLD evolution regimes discussed in the text.

2.3 Development and evaluation of the probability density function for MLD

(IORAS, CNRS-LOPS, CNRS-IGE)

Development of the theoretical probability density function (PDF) for MLD under the MEDLEY project is important, as such a function provides a novel avenue for diagnostics of the numerical experiments with

ocean GCMs and for comparison of the model results with observational data. We designed PDF based upon the Censored Modified Fisher-Tippet distribution CMFT PDF:

$$C^{-1} \times p(x;\alpha,\beta,\gamma) = \begin{pmatrix} 0, x \le \gamma \\ \alpha\beta \exp(-\beta x) \exp\left[-\alpha \exp(-\beta x)\right], x > \gamma \end{pmatrix} \quad (1)$$

where α is non-dimensional parameter and β holds the dimension of the inversed units of a variable (m^{-1}), $C = 1 - \exp[-\alpha \exp(-\beta\gamma)]$ is a normalized factor, γ is estimated as a minimum of sample. Conceptually this distribution is close to that used by Gulev and Belyaev (2012) for approximation of surface turbulent fluxes. Distribution (1) provides explicit equations for the mean and variance and also allows for estimating extreme values of MLD corresponding to high percentiles, like e.g. 99th or 99.9th.

To test this approach, we approximated MLD revealed by GLORYS12 data set using CMFT PDF. We analysed all daily profiles available from GLORYS12 at 1/12° resolution within 1-degree cells over a calendar month. Thus we formed quite a rich sample which was further used for building CMFT PDF, computation of the parameters and higher order percentiles. Then we derived long-term multiannual dataset of the PDF parameters and associated statistics for the global ocean. Figure 12a shows examples of March CMFT PDF derived for the three regions in the North Atlantic and Figure 12b demonstrates 99.9th percentiles of the MLD revealed by PDFs for March over the period from 2002 to 2012.

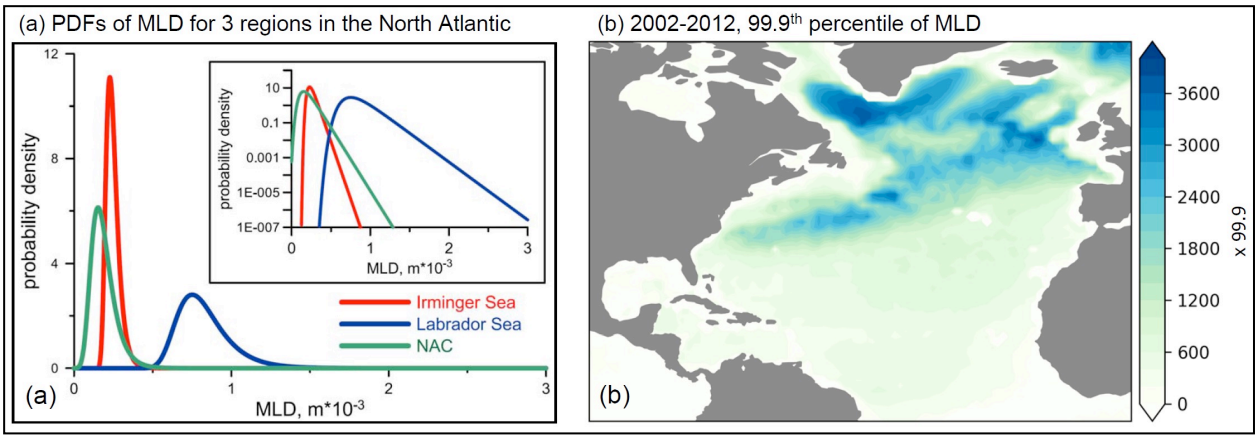

Figure 12. (a) Examples of March CMFT PDF derived for the three regions in the North Atlantic. Inlay shows PDFs in log-scale, demonstrating the behaviour of the heavy tails. (b) 99.9th percentiles of the MLD revealed by PDFs for March over the period from 2002 to 2012.

This analysis shows that characteristics of probability density distributions are quite different for different regions with e.g. Labrador Sea demonstrating much heavier tails compared to the Irminger Sea and the NAC. Extreme values of MLD for March can amount to more than 3000 meters in the Labrador Sea. This provides and effective diagnostic approach for intercomparison of different model experiments and also for validation of the model results against observational data, such as e.g. Argo buoys for which simplified characteristics of probability distributions were analysed by Johnson and Lyman (2022). An important issue still to be covered explicitly is the analysis of goodness of fit of CMFT PDF. Our pilot analysis shows that at least in the mid and subpolar latitudes the Kolmogorov–Smirnov (K–S) test returns the probability that the goodness of fit of distribution (1) is higher than 95% for most cases considered. In this respect additional analysis is needed to also prove that the selected CMFT PDF is most appropriate compared to the other alternative distributions.

2.4 Improving the representation of air-sea interactions in the subpolar gyre in NEMO

(IORAS, CNRS-IGE)

We used recently developed regional model configuration NNATL12 (Verezemskaya et al. 2024) based on NEMO 4.0, for analyzing the impacts of different aspects on the dynamics of the North Atlantic subpolar gyre and specifically MLD. We performed several integrations with different configurations of NNATL12. All experiments were forced with high-resolution output from the North Atlantic Atmospheric Downscaling (RAS-NAAD) model is a 40-yr dynamic hindcast based on the continuous integration of the WRF-ARW model for the North Atlantic (10°N to 80°N) with a spatial resolution of 14 km (Gavrikov et al. 2020).

Compared to the reference experiment MP415, experiment MP420 included also cool-skin effect in surface flux parameterization and the impact of surface current feedback (CFB) parameterization on kinetic energy fluxes. Experiment M421 additionally implemented the local-sigma coordinates on overflow dynamics (Colombo et al. 2022).

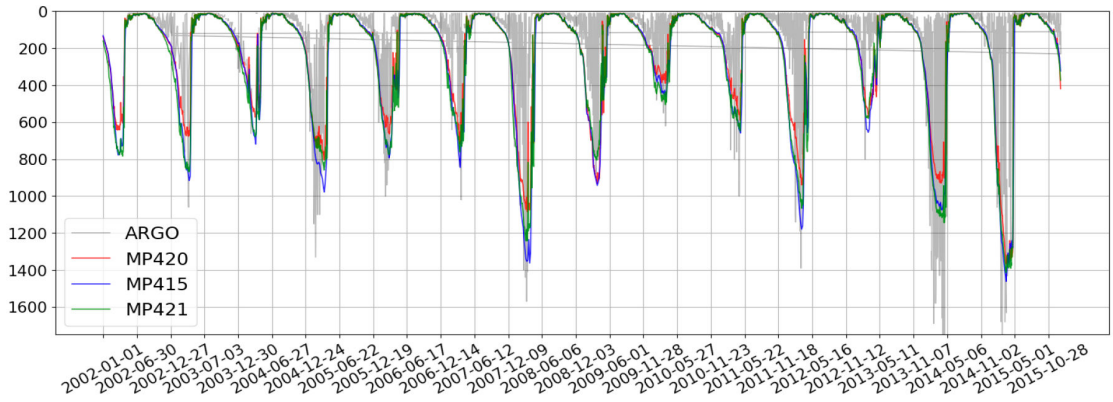

Figure 13. The means over the central Labrador Sea (56°–60°N, 56°–50°W) mixed layer depth given by (gray lines) Argo floats, (blue line) reference (MP415) experiment, (red line) CFB+CSWL (MP420) experiment and (green line) local-sigma coordinate experiment (MP421).

To assess the ability of the model to reproduce the Labrador Sea convection and to quantify the role of restratification in forming the MLD, we used Argo float data. To perform the diagnostic each Argo profile after initial quality control and elimination of the dummy profiles was interpolated onto 10-meter vertical steps and then, the mixed layer depth was estimated by applying the 0.01 density gradient criterion. Figure 2 shows the results of the comparison of different experiments with the results revealed by Argo floats.

The model reproduces the almost instantaneous re-stratification revealed by the Argo data and effectively captures the September-to-April deepening of the mixed layer with intensification in late January (Figure 13). The model reproduces the 2002–2007 continuous warming trend in the 600–1200 m layer, which was interrupted in 2008 by a deep convection event that mixed the ocean down to 1200 m. In comparison to the MP420 experiment, the MP415 model, which does not account for the cool skin effect, generally shows a deeper and more realistic MLD (by up to 350 m) for both extremely deep and shallow convection. In terms of the spatial distribution of vertical mixing, the mean absolute error between the mean March MLD in the base experiment MP415 and the observations decreased by 14 meters in MP421. This finding clearly hints at the complex dependence of convection depth on surface heat flux and ocean preconditioning (Pennelly and Myers, 2021).

Work package 3: Heterogeneous transfers between the mixed layer and the ocean interior

3.1 Heterogeneous water mass properties under sea ice

(CNRS-LOPS)

3.1.1. Observed Spatio-Temporal Variability of the Eddy-Sea Ice Interactions in the Arctic Basin

In the Arctic Basin, the ocean dynamics at mesoscale and submesoscale under sea ice are poorly quantified and understood. In a study led by A. Cassianides (Cassianides et al., 2023) we have analyzed comprehensive data sets from Ice Tethered Profilers and moorings from the Beaufort Gyre Observing System spanning the period 2004–2019 in order to characterize the space and time variations of the (sub)mesoscale flow. In seasonally ice-covered regions, the dynamics in the surface layer is largely determined by the presence of sea ice, with an increased eddy kinetic energy and numerous eddies in summer. Beyond these regions, the influence of the sea ice conditions on the first order dynamics is less clear. A wavenumber spectra analysis of observations at the surface and at depth under the sea ice pack reveals that a large variety of regimes can be found, independently of the time and space variations of the sea ice conditions. Focusing on a census of individual eddies, and their potential signature in sea ice, we found that around 500 eddies can be detected in the subsurface layer over 2004–2019, including both submesoscale (radius between 3 and 10 km) and mesoscale (up to 80 km) structures. Based on simple scaling calculations, we have quantified the dynamical or thermodynamical signature that these eddies may imprint at the surface. While they do not induce any significant heat flux and subsequent sea ice melt, subsurface eddies can induce a dynamic height anomaly of the order of a few centimetres, resulting into a surface vorticity anomaly strong enough to impact sea ice locally.

3.1.2 The role of sea ice leads in water mass formation in the Arctic

The Arctic sea ice, in particular the ice pack, acts as an insulator between the atmosphere and the ocean below. Leads and Linear Kinematic features are commonly found in the Arctic, and act as open windows between the ocean and the atmosphere facilitating the exchanges of heat, salt, moisture, and gases. Local observations have captured large heat fluxes through some leads (up to a few hundreds of W/m^2), that are at least an order of magnitude larger than those outside of the leads, leading to the speculation that air-sea exchanges through leads may contribute significantly to the Arctic Ocean surface buoyancy forcing. However, due to the lack of direct observations and high-resolution models capable of resolving leads, an estimate of the impact of leads on the ocean buoyancy forcing and water mass transformation has been elusive thus far.

Here we are making use of the newly developed pan-Arctic configuration SEDNA, which is based on NEMO/SI3 and has a sub-kilometer resolution everywhere in the Arctic Basin. A simulation covering the period 2009-2015 has been produced using the ERA5 reanalysis (Talandier & Lique, 2023). Sea ice leads are detected in the simulation based on a classical detection method (Hutter et al. 2019). On average, modelled leads represent around 22% of surface covered by sea-ice (Figure 14 a), which is consistent with previous estimate based on satellite observations. Although the surface buoyancy flux can be locally large within the leads, their integrated contribution to the total surface buoyancy flux is roughly proportional to the surface they cover (Figure 14 b).

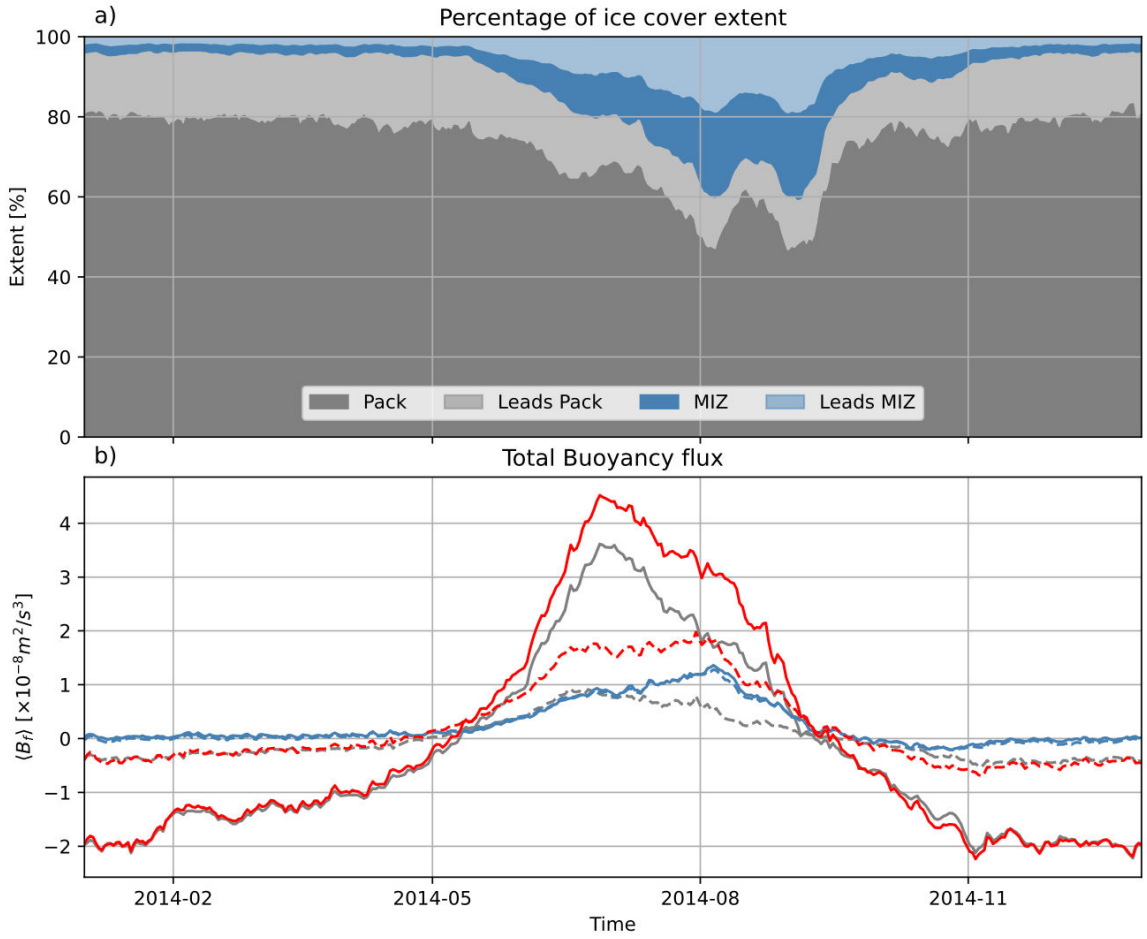

Figure 14: Time series during 2014 of a) the percentage of ice cover extent and b) the total buoyancy fluxes for the total ice covered (red), the ice pack (blue), the MIZ (grey), and the leads in the ice pack and the MIZ (dash lines). The MIZ is defined between ice concentration of 15-80%, the ice pack is defined where ice concentration > 80%, and the total ice covered is defined as the sum of the MIZ and ice pack.

Using a Walin (1982) watermass transformation framework, we further estimate the contribution of the watermass transformations occurring withing the leads. Again we find that around 20% of the transformation are done as a response of the flux within the leads, but there is no density classes that are formed preferentially within the leads. Thus, our results suggest that leads have a small contribution to Arctic Ocean dynamics, contrary to previous hypotheses.

These results are presented extensively in a paper submitted to Nature Geosciences (Martinez-Moreno et al., under review)

3.2 Heterogeneous characteristics of the transition layer

(CNRS-LOPS, CNRS-IGE)

The upper ocean pycnocline (UOP) that sits below the mixed layer base, sometimes referred to as the transition layer or as the seasonal pycnocline, remains poorly characterised though it is a ubiquitous feature of the ocean surface layer. The UOP often consists in a rapid change in density with depth and enhanced vertical shear that connects the well-mixed surface layer to the stratified ocean interior. The UOP is important

for the ventilation of the ocean as it represents a barrier to mixing between the upper ocean and the ocean interior.

We have produced the first climatology of the UOP (Serazin et al., 2023) based on in situ observations (from the ARGO network). We document the seasonal cycle of UOP properties – intensity, depth, thickness – to characterize the spatial and seasonal variations of upper ocean stratification. The largest stratification values $O(10^{-3}s^{-2})$ are found in the intertropical band, where seasonal variations of the UOP are also very small. The deepest (> 200 m) and least stratified $O(10^{-6}s^{-2})$ UOPs are found in winter along the Antarctic Circumpolar Current (ACC) and at high latitudes of the North Atlantic. The UOP thickness has a median value of 23 m with limited seasonal and spatial variations; only a few regions have UOP thicknesses exceeding 35 m (Figure 15).

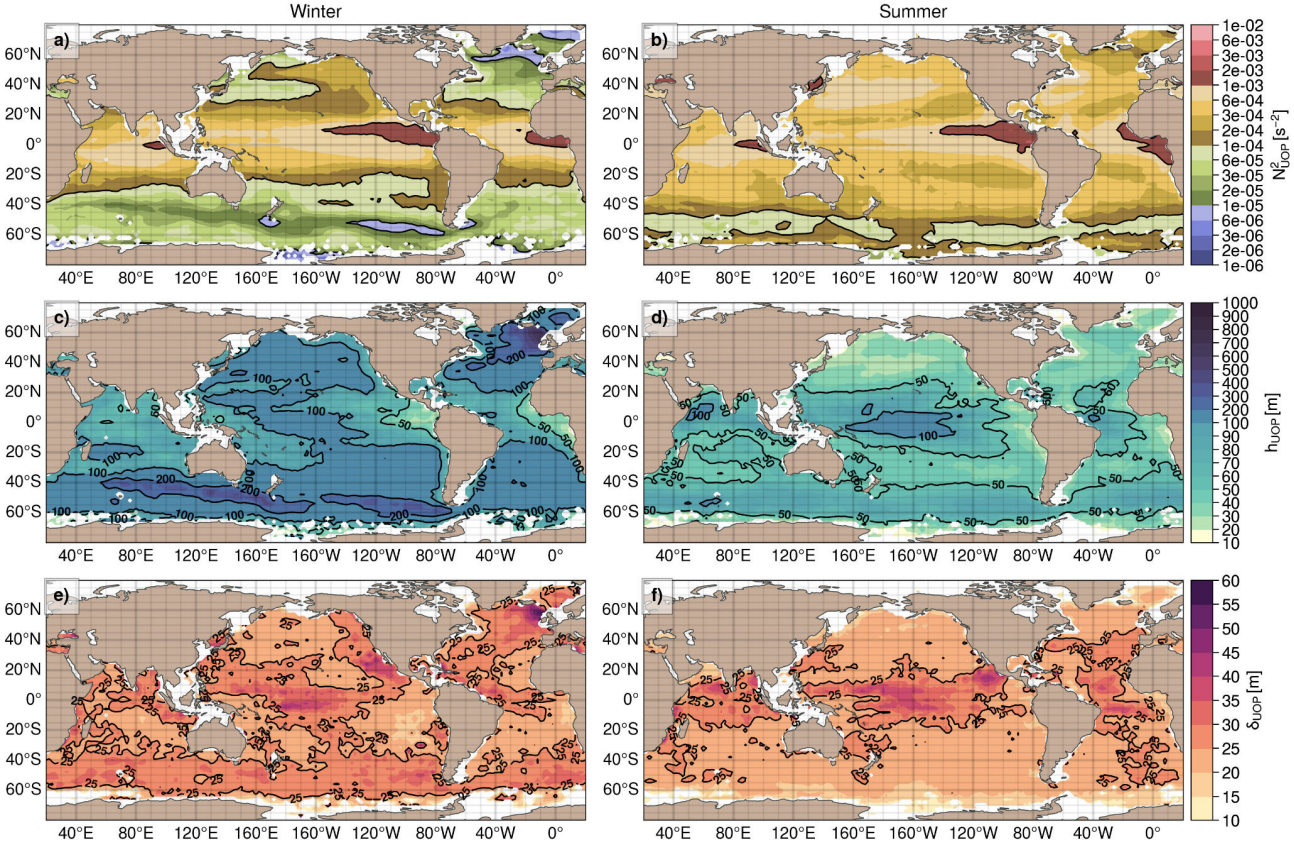

Figure 15 : Winter (left, A, C, E) and summer (right, B, D, F) climatologies of UOP characteristics for intensity (top, A, B), depth (middle, C, D), and thickness (bottom, E, F).

In mid-latitudes, both the UOP and the overlying mixed layer have a strong seasonal cycle, and the mesoscale and submesoscale turbulence generated by baroclinic instability also vary seasonally. We investigated the link between the seasonality of the stratification and baroclinic instability using a 1/60° simulation of the North Atlantic Ocean. We use a coarse-graining technique to investigate the spatial scales of the Vertical Buoyancy Flux (VBF) which represents the exchange between potential and eddy kinetic energy (Serazin et al., 2024, in preparation). In the Gulf Stream extension, vertical buoyancy fluxes (VBFs) are found to be maximum in winter in the ocean mixed layer and maximum in summer in the ocean interior. Mesoscale interior baroclinic instability is found to occur at around 1 to 1.5 times the first deformation radius. VBFs are generated in the mixed layer at a scale larger than predicted by the mixed layer instability theory.

3.3 Heterogeneous water mass formation and ventilation pathways at fine scales

CNRS-LOPS

In this task, we have investigated how the heterogeneity of the deep mixed layers at the mesoscale, and the presence of boundary currents, mediate the translation of atmospheric forcing variability into the ocean interior. MacGilgrist et al (2021) used offline trajectories in a model to track backward the North Atlantic Deep Water (NADW), to its origin in the surface mixed layer. In the North Atlantic subpolar gyre, the location of subduction is found to be a key factor of ventilation, in addition to the timing. Most of the variability of the subducted NADW is traced back to the Labrador Sea and the narrow boundary current. A key result is that the interannual variability of NADW does not depend only on the mixed layer depth but also on the speed at which water parcels escape the atmospheric influence, the boundary current being a region of "fast escape".

We have also studied the heterogeneity of the opposite process, by which waters are upwelled into the surface mixed layer. This process is at the origin of the high nutrient content and productivity of the Eastern Boundary Upwelling Systems (EBUS). The Atlantic EBUS has been evaluated in coupled ocean-atmosphere models at resolutions of 1°, 1/4° and 1/12°. Each EBUS is spatially heterogeneous, with marked differences in strength and seasonality at different latitudes. The CMIP and HighREsMIP scenario simulations show that this spatial heterogeneity persists in the future (Flugel et al., 2024).

References

Allende S. et al., 2023 : On the ability of OMIP models to simulate the ocean mixed layer depth and its seasonal cycle in the Arctic Ocean. *Ocean Modelling*, **184**, 10226, doi : 10.1016/j.ocemod.2023.10226.

Allende S. et al., 2024 : Impact of ocean vertical mixing parameterization on Arctic sea ice and upper ocean properties using the NEMO-SI3 model. Geoscientific Model Development Discussion, doi : 10.5194/gmd-2024-49.

Blanke B. and P. Delecluse, 1993 : Variability of the tropical Atlantic Ocean simulated by a general circulation model with two different mixed-layer physics. Journal of Physical Oceanography, 23, 1363–1388, doi : 10.1175/1520-0485.

Boutin, G., Ólason, E., Rampal, P., Regan, H., Lique, C., Talandier, C., Brodeau, L., and Ricker, R.: Arctic sea ice mass balance in a new coupled ice–ocean model using a brittle rheology framework, The Cryosphere, 17, 617–638, https://doi.org/10.5194/tc-17-617-2023, 2023.

Cassianides, A., Lique, C., Tréguier, A.-M., Meneghello, G., & De Marez, C. (2023). Observed spatio-temporal variability of the eddy-sea ice interactions in the Arctic Basin. Journal of Geophysical Research: Oceans, 128, e2022JC019469

Chassignet, E. P., Yeager, S. G., Fox-Kemper, B., Bozec, A., Castruccio, F., Danabasoglu, G., Horvat, C., Kim, W. M., Koldunov, N., Li, Y., Lin, P., Liu, H., Sein, D. V., Sidorenko, D., Wang, Q., and Xu, X.: Impact of horizontal resolution on global ocean–sea ice model simulations based on the experimental protocols of the Ocean Model Intercomparison Project phase 2 (OMIP-2), Geosci. Model Dev., 13, 4595–4637, https://doi.org/10.5194/gmd-13-4595-2020, 2020.

Colombo, P., B. Barnier, T. Penduff, J. Chanut, J. Deshayes, J.-M. Molines, J. Le Sommer, P. Verezemskaya, S. Gulev, A.-M. Treguier, 2020: Representation of the Denmark Strait overflow in a z-coordinate eddying configuration of the NEMO (v3.6) ocean model: resolution and parameter impacts. Geosci. Model Dev., 13, 1–25, https://doi.org/10.5194/gmd-13-1-2020

de Boyer Montégut C., 2024 : Mixed layer depth over the global ocean : A climatology computed with a density threshold criterion of 0,03 kg m-3 from the value at the reference depth of 5 m. SEANOE, doi : 10.17882/98226.

Fearon, G., Herbette, S., Veitch, J., Cambon, G., Lucas, A. J., Lemarí e, F., & Vichi, M. (2020). Enhanced vertical mixing in coastal upwelling systems driven by diurnal-inertial resonance: Numerical experiments. Journal of Geophysical Research: Oceans, 125(9), e2020JC016208. doi: 10.1029/2020JC016208

Flügel R., S. Herbette, A.M. Treguier, R. Waldman, M. Roberts, 2024: Spatial variation of future trends in Atlantic upwelling cells from CMIP6 models, in revision in Deep Sea Research.

Gavrikov, A., S. K. Gulev, M. Markina, N. Tilinina, P. Verezemskaya, B. Barnier, A. Dufour, O. Zolina, Y. Zyulyaeva, M. Krinitsky, I. Okhlopkov, and A. Sokov, 2020: RAS-NAAD: 40-year high resolution North Atlantic atmospheric hindcast for multipurpose applications (New dataset for the regional meso-scale studies in the atmosphere and the ocean). J. Appl. Meteor. Climatol., 59, https://doi.org/10.1175/JAMC-D-19-0190.1

Gulev, S.K., and K.P. Belyaev, 2012: Probability distribution characteristics for surface air-sea turbulent heat fluxes over the global ocean. J. Climate, 25, 184-206, doi: 10.1175/2011JCLI4211.1

Hutter N, Zampieri L, Losch M (2019) Leads and ridges in Arctic sea ice from RGPS data and a new tracking algorithm. The Cryosphere 13(2):627–645. https://doi.org/ 10.5194/tc-13-627-2019

Iovino, D., Fogli, P. G., and Masina, S.: Evaluation of the CMCC global eddying ocean model for the Ocean Model Intercomparison Project (OMIP2), Geosci. Model Dev., 16, 6127–6159, https://doi.org/10.5194/gmd-16-6127-2023, 2023

Johnson, G. C., & Lyman, J. M. (2022). GOSML: A global ocean surface mixed layer statistical monthly climatology: Means, percentiles, skewness, and kurtosis. Journal of Geophysical Research: Oceans, 127, e2021JC018219. https://doi.org/10.1029/2021JC018219

Legay, A., B. Deremble, T. Penduff, and P. Brasseur : A generic framework for evaluating oceanic mixed layer dynamics. Journal of Advances in Modeling Earth Systems, in revision.

Madec G. et al., 2016 : NEMO ocean engine. Note du Pôle de modélisation de l'Institut Pierre-Simon Laplace N°27, ISSN N° 1288-1619.

Martinez-Moreno J., C Lique and C. Talandier, 2024: Is the surface forcing through sea ice leads transferred to the Arctic Ocean interior? Submitted to Nature Geosciences.

Martinson D.G., 1990 : Evolution of the Southern Ocean winter mixed layer and sea ice : Open ocean deepwater formation and ventilation. *Journal of Geophysical Research*, **95**, 11641–11654.

Pennelly, C. and Myers, P. G.: Introducing LAB60: A 1⁄60° NEMO 3.6 numerical simulation of the Labrador Sea, Geosci. Model Dev., 13, 4959–4975, https://doi.org/10.5194/gmd-13-4959-2020, 2020.

Rheinlænder, J. W., Davy, R., Ólason, E., Rampal, P., Spensberger, C., Williams, T. D., et al. (2022). Driving mechanisms of an extreme winter sea ice breakup event in the Beaufort Sea. *Geophysical Research Letters*, 49, e2022GL099024. https://doi.org/10.1029/2022GL099024

Rodgers K.B. et al., 2014 : Strong sensitivity of Southern Ocean carbon uptake and nutrient cycling to wind stirring. Biogeosciences, 11, 4077–4098, doi : 10.5194/bg-11-4077-2014.

Sallée, J.-B., Pellichero, V., Akhoudas, C., Pauthenet, E., Vignes, L., Schmidtko, S., Garabato, A. N., Sutherland, P., and Kuusela, M.: Summertime increases in upper-ocean stratification and mixed-layer depth, Nature, 591, 592–598, https://doi.org/10.1038/s41586-021-03303-x, 2021.

Schmidtko S. et al., 2013 : MIMOC : A global monthly isopycnal upper-ocean climatology with mixed layers. *Journal of Geophysical Research*, **118**, 1658–1672, doi : 10.1002/jgrc.20122.

Talandier C, Lique C (2023) Sedna-delta. https://doi.org/10.5281/zenodo.7656924

Toole J.M. et al., 2015 : The Ice-Tethered Profiler : Argo of the Arctic. *Oceanography*, **24**, 126–135, doi:10.5670/oceanog.2011.64.

Tsujino, H., et al.: JRA-55 based surface dataset for driving ocean–sea-ice models (JRA55-do), Ocean Model., 130, 79–139, https://doi.org/10.1016/j.ocemod.2018.07.002, 2018.

Verezemskaya, P., S. K. Gulev, B. Barnier, J.-M. Molines, P. Colombo, and A. Gavrikov (2024) A regional NEMO 4.0 configuration of the Subpolar North Atlantic. Ocean Modelling (in review after revision).

Walin G (1982) On the relation between sea-surface heat flow and thermal circula- tion in the ocean. Tellus 34(2):187–195. https://doi.org/10.1111/j.2153-3490.1982. tb01806.x

Deliverables and Milestones

Deliverables

Deliverable Nr.	Deliverable Title	due	Actual planning	Deliverable achieved	Comments on deviation
1	Mid term report	18		yes	Delivered on time.
2	Recommendations for parameterizing mixed layers processes in NEMO	48		yes	Publication revised in Geophysical Model Development (Allende et al.)
3	Fully validated fine scale Arctic ocean-ice model suitable to study the regional impacts of climate change (report and numerical code)	48		yes	Boutin et al. (2023)
4	Guidelines for the use of the ENERGETICS dataset for model validation (report)	48		No	Analysis of the ENERGETICS dataset has revealed problems related to the representation of land surfaces.
5	New diagnostics of mixed layer dynamics, based on observations and novel statistical methods, adapted to climate models.	48		Yes	Treguier et al, 2023, published. De Boyer Montegut, 2023, dataset (SEANOE open repository)
6	New knowledge on mixed layer heterogeneity and its consequences for air-sea ice exchanges and water mass formation	48		Yes	Scientific publications
7	Final report	48		Yes	The present report

Financial Status

Give an indicative account of the grant budgets spent by the partners. Indicate how this complies with the forecasts and explain any significant divergences.

Name of partner	Grant budgets spent (in EUR and %)	Comments (if necessary) planning
NERSC	457000€ (100%)	
CNRS-LOPS	220838.41€ (98.2%)	Total grant 224863€ after transfer from CNRS-IGE
CNRS-IGE	102600€ (100%)	Total 102600€ after transfer of 21600 to CNRS-LOPS
CMCC	149940 € (100%)	
UCLouvain	173909 € (96%)	

Dissemination activities in the period in question

Publications:

Type (Peer-reviewed journals, Books, book chapters)	Partners involved	Title and authors	doi (if available) or link
Peer-reviewed journal	LOPS CNRS	MacGilchrist, G. A., Johnson, H. L., Lique, C., & Marshall, D. P. (2021). Demons in the North Atlantic: Variability of deep ocean ventilation. *Geophysical Research Letters*, 48, e2020GL092340	https://doi.org/10.1029/2020GL092340
Peer-reviewed journal	LOPS CNRS	Pauthenet, E., Bachelot, L., Balem, K., Maze, G., Tréguier, A.-M., Roquet, F., Fablet, R., and Tandeo, P.: Four-dimensional temperature, salinity and mixed-layer depth in the Gulf Stream, reconstructed from remote-sensing and in situ observations with neural networks, Ocean Sci., 18, 1221–1244, 2022	https://doi.org/10.5194/os-18-1221-2022
Peer-reviewed journal	NERSC IGE CNRS	Rheinlænder, J. W., Davy, R., Ólason, E., Rampal, P., Spensberger, C., Williams, T. D., et al. (2022). Driving mechanisms of an extreme winter sea ice breakup event in the Beaufort Sea. *Geophysical Research Letters*, 49, e2022GL099024.	https://doi.org/10.1029/2022GL099024
Peer-reviewed journal	LOPS, IGE CNRS	Serazin, G., Treguier, A.M., de Boyer Montégut, C., 2023: A seasonal climatology of the upper ocean pycnocline. Front. Mar. Sci., Volume 10 - 2023	doi: 10.3389/fmars.2023.1120112
Peer-reviewed journal	NERSC IGE CNRS	Regan, H., Rampal, P., Ólason, E., Boutin, G., and Korosov, A.: Modelling the evolution of Arctic multiyear sea ice over 2000–2018, The Cryosphere, 17,	https://doi.org/10.5194/tc-17-1873-2023
Peer-reviewed journal	LOPS CNRS	Cassianides, A., Lique, C., Tréguier, A.-M., Meneghello, G., & De Marez, C. (2023). Observed spatio-temporal variability of the eddy-sea ice interactions in the Arctic Basin. Journal of Geophysical Research: Oceans, 128, e2022JC019469	https://doi.org/10.1029/2022JC019469
Peer-reviewed journal	UCLouvain, LOPS CNRS	Allende, S., Fichefet, T., Goosse, H., and Treguier, A.: On the ability of OMIP models to simulate the ocean mixed layer depth and its seasonal cycle in the Arctic Ocean, Ocean Modelling, 184, 102 226, 2023.	https://doi.org/10.1016/j.ocemod.2023.102226
Peer-reviewed journal	LOPS, IGE, (CNRS), CMCC	Treguier, A. M., de Boyer Montégut, C., Bozec, A., Chassignet, E. P., Fox-Kemper, B., McC. Hogg, A., Iovino, D., Kiss, A. E., Le Sommer, J., Li, Y., Lin, P., Lique, C., Liu, H., Serazin, G., Sidorenko, D., Wang, Q., Xu, X., and Yeager, S.: The mixed-layer depth in the Ocean Model Intercomparison Project (OMIP): impact of resolving mesoscale eddies, Geosci. Model Dev., 16, 3849–3872,	https://doi.org/10.5194/gmd-16-3849-2023
Peer-reviewed journal in press	LOPS CNRS	Martínez-Moreno Josué, Lique Camille, Talandier Claude: Eddy-driven heterogeneity in sea ice during the ice-growth season. Geophysical Research letters, 2024	
peer-reviewed popular science	NERSC	Ólason, E, and Wilborn, H. (2021). Når sjøis sprekker. *Naturen*, 145, 112–118	10.18261/issn.1504-3118-2021-02-03-06
Peer-reviewed journal	NERSC, LOPS, IGE (CNRS)	Boutin, G., Ólason, E., Rampal, P., Regan, H., Lique, C., Talandier, C., Brodeau, L., and Ricker, R. (2023). Arctic sea ice mass balance in a new coupled ice–ocean model using a brittle rheology framework. The Cryosphere, 17(2), 617–638.	10.5194/tc-17-617-2023

In revision			
Peer reviewed journal, revised	UCLouvain, CNRS	Allende, S., Treguier, A. M., Lique, C., de Boyer Montégut, C., Massonnet, F., Fichefet, T., and Barthélemy, A.: Impact of ocean vertical mixing parameterization on Arctic sea ice and upper ocean properties using the NEMO-SI3 model, Geosci. Model Dev. Discuss. [preprint],	https://doi.org/10.5194/gmd-2024-49
Peer reviewed journal, revised	IGE	Legay A., B. Deremble, T. Penduff, P. Brasseur, J.M. Molines, 2024: A framework for evaluating ocean mixed layer depth evolution. In revision for JAMES.	
Peer reviewed journal, revised	LOPS CNRS	Flügel R., S. Herbette, A.M. Treguier, R. Waldman, M. Roberts, 2024: Spatial variation of future trends in Atlantic upwelling cells from CMIP6 models, submitted to Deep Sea Research.	
Peer reviewed journal, revised	LOPS CNRS	Martinez-Moreno J., C Lique and C. Talandier, Is the surface forcing through sea ice leads transferred to the Arctic Ocean interior? Submitted to Nature Geosciences	

Valorization:

MEDLEY has taken the initiative of a special session at the EGU conference in Vienna, focussed on the mixed layer. In 2022 and 2023 sessions titled "The ocean surface mixed layer: multi-scale dynamics and ecosystems in a changing climate" were convened by A.M. Treguier, F Massonet, B. Fox Kemper, R. Somavilla and S. Lennartz. In 2024, the title was slightly modified to "The ocean surface layer: multi-scale dynamics, atmosphere-ocean interactions and impacts on biogeochemistry", convened by A. M. Treguier, M. Kanakidou, Y. Dong, L. Umlauf, J. Carpenter, P. Tedesco, and L. Tinel. This session has been highly successful and will be carried on in the coming years by a renewed team of co-conveners.

In addition to a strong presence at EGU meetings, MEDLEY has been well represented at DRAKKAR workshops, and several other conferences and workshops. MEDLEY work has been presented in a total of 33 oral presentations and 22 poster presentations at various national and international conferences and workshops.

A web site has been published by CNRS to present the project and results at https://medley.cnrs.fr. This web site has been used to advertise the post-doc opportunities, as well as for press releases for specific publications and outreach opportunities. In addition, institutes participating in MEDLEY have published their own press releases for specific scientific publications, e.g. https://www.insu.cnrs.fr/fr/cnrsinfo/nouvelle-base-de-donnee-pour-la-couche-de-transition-oceanique and https://nersc.no/nyheter/a-third-of-the-new-winter-sea-ice-in-the-arctic-forms-within-cracks-in-the-sea-ice-cover.

As part of MEDLEY, NERSC researcher Einar Ólason and NERSC communications officer Henrike Willborn published a peer reviewed popular science article in Norwegian, titled "When sea ice cracks" ("Når sjøis sprekker"). The article explains the basic ideas and assumptions behind the inner workings of the neXtSIM model, used in the MEDLEY work conducted at NERSC (Boutin et al., 2022 and Regan et al., 2022).

An important part of the valorization of MEDLEY results is the project's participation in the CMIP process and the NEMO model development. The NEMO model is one of the most widely used ocean models in the world, and MEDLEY researchers are in close contact with the NEMO developers. UCLouvain's contribution to MEDLEY will be very useful for the development of NEMO. In this respect, Thierry Fichefet has attended in 2023 a discussion meeting at the Laboratoire d'Océanographie et de Climatologie of the Institut Pierre-Simon Laplace (Paris) on the future of NEMO4.2-SI3.

Medley is also participating in the CMIP process through the Ocean Model Development Panel (OMDP). Under the auspices of the World Climate Research Project (WCRP) and the Climate and Ocean - Variability, Predictability, and Change (CLIVAR) project, the OMDP provides guidance and a collaboration platform for ocean modelling for climate, and provides input on the Ocean Model Intercomparison Project (OMIP), a core component of the CMIP protocol. The participation of MEDLEY in the OMDP ensures that MEDLEY results shape the way run and evaluate ocean climate models in the future. An important aim for MEDLEY is that the guidelines for diagnosing the mixed layer in CMIP (two authors from MEDLEY participate in the publication in preparation regarding ocean variables for CMIP7).

Impact

Examples may include:

- Contributions to regulations, policies and management practices
- Training (post-graduate courses organized; PhD students and postdocs funded; PhD, MSc and BSc theses defended)
- Innovation (Intellectual property rights, prototypes, testing activities resulting from the project)
- Interlinkages with other JPI Oceans and/or JPI Climate projects

MEDLEY has contributed to the training of 3 master students on issues of mixed layer heterogeneity: Lilian Garcia (2020) worked on the statistical distribution of mixed layer depth in the North Atlantic; Baptiste le Masson initiated the study of the stratification below the mixed layer from observations; Raquel Fluguel (2022) studied the stratification in the upwelling regions, and continued this work as part of her Ph.D.

Three Ph.D. students worked in relation with MEDLEY: Alexandre Legay at CNRS-IGE, Angelina Cassianides and Raquel Flugel at LOPS. Each has submitted a publication as lead author (one paper is published, the other two are in revision).

Four post-doctoral researchers have been recruited for MEDLEY and have benefited from the international networking offered by MEDLEY. Sofia Allende, post doc at UCLouvain, has been awarded a Marie Curie fellowship in 2024, building on the skills in ocean dynamics that she learned in MEDLEY.

A fruitful collaboration has been initiated with the European project ARGO EARISE :
https://www.euro-argo.eu/EU-Projects/Euro-Argo-RISE-2019-2022
The joint work has led to better taking into account the mixed layer in the innovative product OSnet, an observation-based analysis of in situ and satellite data, based on a neural network, produced weekly on a 1/4° grid and over a depth of 1000m.

CNRS and UCLouvain participate in the project EERIE (Eddy Rich Earth system models, https://eerie-project.eu/). EERIE will make use of the knowledge gained in MEDLEY to improve the representation of upper ocean physics and promote a better use of observations to evaluate the eddy rich climate models.

MEDLEY has motivated the update of the definition of the mixed layer depth used in CMIP models that support the IPCC assessments. A.M. Treguier and C. de Boyer de Montegut (LOPS) participate in an international joint paper that will define ocean diagnostics for the next phase of CMIP (CMIP7).

Two new datasets are a major outcome of MEDLEY. 1) a revised global climatology of the ocean mixed layer, tailored to the needs of climate modelers, to be used in the next phase of IPCC, and 2) a climatology of the upper ocean pycnocline, the stratified layer at the bottom of the mixed layer, which will enable new assessment of the vertical stratification in coupled climate models.

Results

Please describe 3 major results that we could include in a valorization brochure

In MEDLEY, we have explored the role of small-scale sea-ice heterogeneity in the upper ocean and atmosphere-ocean-ice interactions in the Arctic. Our work takes advantage of a newly developed sea-ice model, which can capture the small-scale heterogeneity of sea-ice at moderate model resolutions. This has allowed us to demonstrate the role of small openings in the ice, or leads, on ice growth and the upper ocean for the first time. We found that ice formation in leads in winter contributes to 25 to 35% of the total ice growth and that this fraction is increasing. When leads open in the ice, the increased heat, moisture, and momentum exchange between the atmosphere and ocean impact the oceanic mixed layer and the atmospheric boundary layer. In MEDLEY, we have demonstrated, for the first time, how a sea-ice breakup event causes the oceanic mixed layer to deepen locally and increase its heterogeneity. These results demonstrate the importance of sea-ice processes in shaping the mixed layer heterogeneity in the Arctic and indicate that these processes will become more important as the ice becomes thinner and breaks up more easily.

The key role of mesoscale eddies in restratifying the upper ocean, and thus limiting the depth of the mixed layer, has been confirmed by two analyses of eddy-rich forced ocean models. These models participate in the international Ocean Model Intercomparison Project (OMIP). One study focused on the Labrador Sea, which is a major region of deep water formation in the world. The other study, at the global scale, pointed out the complexity of this restratifying effect of the mesoscale dynamics. The shallowing of the mixed layer in high resolution models compared with their low resolution counterparts dominates in the zonal average, but the spatial patterns are model-dependent.

The thin barrier between the ocean mixed layer and the ocean interior, the upper ocean pycnocline, has been mapped globally for the first time from observations. The UOP thickness has a median value of 23 m with limited seasonal and spatial variations; only a few regions have UOP thicknesses exceeding 35 m. The new dataset will be used to evaluate numerical models, especially the coupled climate models which contribute to the IPCC scenarios. It is important that the models represent the UOP accurately because it is expected to become stronger in the future, inhibiting the transfers of heat and carbon between the upper mixed layer and the deep ocean.

Annex I: Identification of project participants/beneficiaries

(1) Anne Marie Treguier, CNRS-LOPS, France

(2) Julien le Sommer, CNRS-IGE, France

(3) Einar Olason, NERSC, Norway

(4) Thierry Fichefet, UCLouvain, Belgium

(5) Doroteaciro Iovino, CMCC, Italy

Associated partner (non beneficiary): Sergey Gulev (IORAS, Russia)