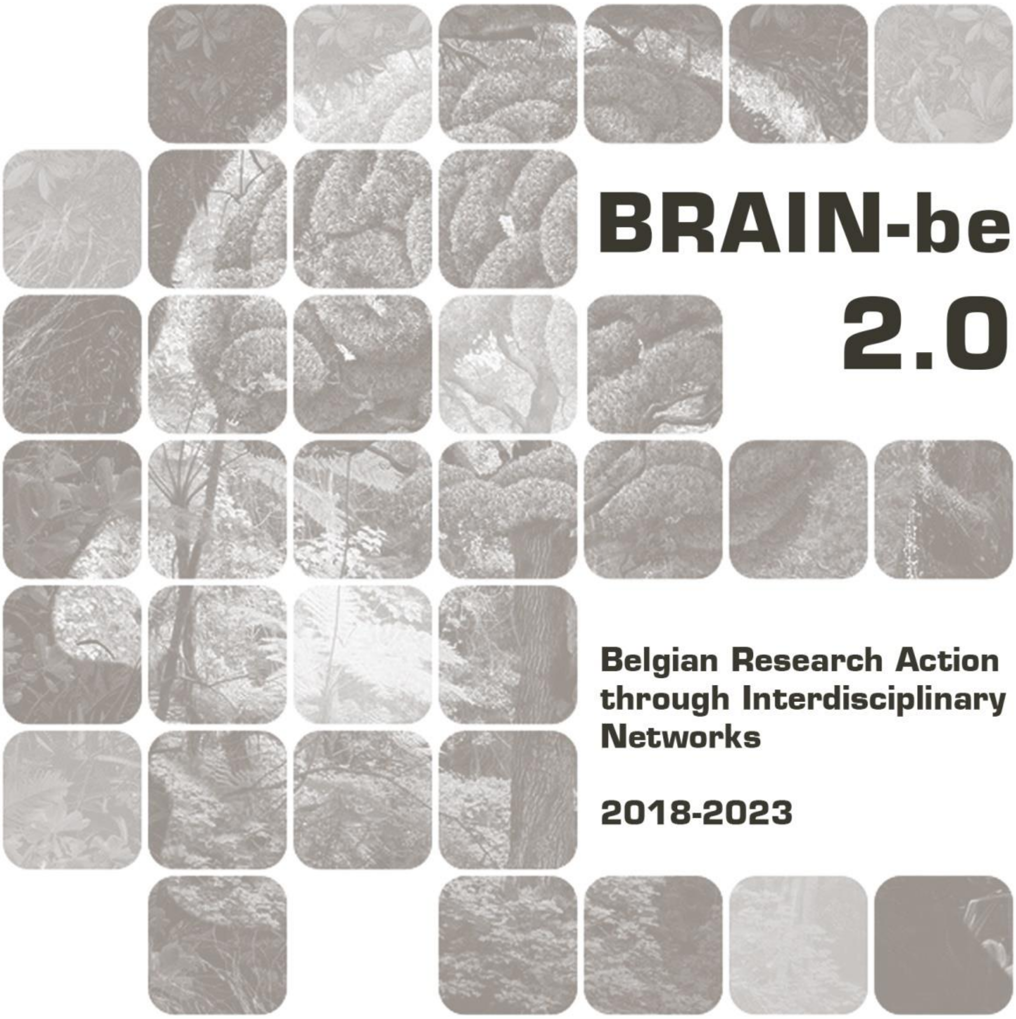

MEDLEY

Mixed layer heterogeneity

Sofia Allende Contador, Thierry Fichefet, François Massonnet and Hugues Goosse

Pillar 1: Challenges and knowledge of the living and non-living world

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Belgian Research Action through Interdisciplinary Networks

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NETWORK PROJECT

MEDLEY

Mixed layer heterogeneity

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FINAL REPORT

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ABSTRACT

Heat, energy and gas transfers through the oceanic mixed layer are extremely complex and spatially heterogeneous. The discontinuous, dynamic sea ice cover and the presence of oceanic eddies, fronts and filaments on a kilometer scale are major heterogeneities governing the thickness and properties of this layer. Current climate models used for IPCC's (Intergovernmental Panel on Climate Change) climate projections show major discrepancies in the simulation of the mixed layer depth, partly due to a poor representation of the integrated effect of these heterogeneities. This limits the usefulness of these models in assessing the impacts of future climate change in Europe and on marine ecosystems.

MEDLEY was a European project within the JPI Oceans & Climate that aimed to improve our understanding of the heterogeneity of the oceanic mixed layer in the northern North Atlantic Ocean, a hotspot for anthropogenic CO_2 storage, and in the rapidly warming Arctic Ocean. Its main objectives were (1) to assess the spatial heterogeneity of fluxes and processes controlling the oceanic mixed layer, and (2) to improve the representation of the transfers across this layer in global climate models by taking this heterogeneity into account.

The project integrated state-of-the-art observational datasets and basin-scale ocean models resolving the kilometer scale, innovative sea ice models and the latest generation of global climate models that account for the eddying nature of the ocean. Relying on interdisciplinary collaborations between its partners (six institutions, including UCLouvain), MEDLEY took advantage of the most advanced data analysis methods. More precisely, the project aimed to improve the tuning and consistency of the mixed layer representation in the ocean component of global climate models through multi-scale modelling and validation against recent high-resolution observations. As part of this project, UClouvain's attention was focused on the ice-covered regions of the Arctic Ocean and its peripheral seas. Our efforts culminated in the publication of two key results in major scientific journals.

In a first study, we 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 depth and its seasonal cycle in the Arctic region. During summer months, all models systematically underestimate the depth of the mixed layer compared to observational data from the Monthly Isopycnal Mixed layer Ocean Climatology and Ice-Tethered Profilers. In autumn and winter, differences of several tens of meters were observed between the models themselves and between the models and observational data. We then analyzed the origin of the model biases in autumn and winter in ice-covered regions, where the surface salinity and mixed layer 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 mixed layer, while strong stratification leads to a shallow mixed layer. To support this conclusion, we applied a simple conceptual model, which computes the month-by-month evolution of the mixed layer 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 behaviour 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. Moreover, this link can also explain the large mixed layer 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.

In a second study, we assessed the performance of the vertical turbulent kinetic energy (TKE) mixing scheme of the NEMO4.2-SI^3 (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. Specifically, we tested the model sensitivity to parameters involved in an ad hoc parameterization (referred to as TKE mixed layer penetration (MLP) parameterization) recently added to the default TKE mixing scheme to take into consideration the effect of small-scale processes such as near-inertial oscillations and ocean swells and waves. We evaluated this parameterization for the first time in three regions of the Arctic Ocean: the Makarov, Eurasian and Canadian Basins. We demonstrated the strong effect of the scaling parameter that accounts for the presence of sea ice. Our results confirm that the TKE MLP parameterization must be scaled down below sea ice to avoid unrealistic deep mixed layers. The other parameters considered were the percentage of eddy kinetic energy penetrating below the mixed layer and the length scale of its decay with depth. All these parameters affect the simulation of the mixed layer 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 mixed layer and a reduction in sea ice thickness ranging between 5 and 30 cm, reflecting the impact of more mixing. In contrast, in the second case, we noticed that a lower mixed layer 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 mixed layer depth during periods of sea ice reduction, which is consistent with observed trends. These results 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.

Keywords: ocean mixed layer, spatial heterogeneity, climate models, North Atlantic, Arctic Ocean, sea ice, mesoscale eddies, sub-mesoscale fronts, observational datasets, high-resolution models.

1. INTRODUCTION

The oceanic mixed layer (OML) regulates the transfers between the atmosphere, sea ice and the deep ocean, which makes it a major player in the climate of our planet. This layer acts as a conduit, when surface cooling, evaporation, brine rejection associated with sea ice formation and/or wind stress create large volumes of well mixed water masses that may be exported into the deeper ocean and shielded from further interactions with the atmosphere for years or centuries. Conversely, the OML may act as a barrier, for instance, when surface warming, rainfall, runoff and/or sea ice melting make it very buoyant, overlying a strongly stratified layer nearly impermeable to atmospheric influences.

Understanding the OML dynamics is essential for deciphering the intricate mechanisms driving climate variability and change. Over the past decades, the ocean has played a pivotal role in absorbing excess heat generated by human activities, thus mitigating some of the impacts of global warming. However, this heat uptake is not uniform across the World Ocean, with regions like the northern North Atlantic and Arctic Oceans exhibiting distinct patterns of mixing and circulation due to factors such as sea ice cover and atmospheric dynamics.

The discontinuous, dynamic sea ice cover and the presence of oceanic eddies, fronts and filaments on a kilometer scale are important heterogeneities governing the thickness and other characteristics of the OML. Current global climate models used for IPCC's (Intergovernmental Panel on Climate Change) climate projections show major biases in the simulation of the OML depth, partly due to a poor representation of the integrated effect of these heterogeneities. Addressing this issue requires a comprehensive understanding of the processes controlling the OML dynamics and their interactions with the other components of the Earth's climate system.

The MEDLEY (Mixed layer heterogeneity) project aimed to fill this gap by assessing the spatial heterogeneity of fluxes and processes determining the OML depth, and incorporating this heterogeneity into climate models. More specifically, the project focused on the northern North Atlantic and Arctic Oceans, where OML dynamics are particularly complex due to the presence of sea ice. Drawing on recent observational datasets and a hierarchy of ocean–sea ice models, MEDLEY sought to advance our understanding of OML dynamics and improve their representation in global climate models.

2. STATE OF THE ART AND OBJECTIVES

The OML mediates the transfer of momentum, heat, freshwater and trace gases between the atmosphere, sea ice and the ocean. Hence, the mixed layer transfer function must be represented accurately in global climate models, especially in the northern North Atlantic and Arctic Oceans, which are hotspots of anthropogenic CO_2 storage and warming, respectively. Large discrepancies in OML depth were found in these areas in simulations performed with low-resolution global climate models that participated in the fifth and sixth phases of the Coupled Model Intercomparison Project (CMIP5 and CMIP6), in part because these models do not parameterize properly the spatial heterogeneities mentioned in Section 1.

In this context, MEDLEY addressed the crucial role of the OML as a transfer function between the atmosphere, sea ice and the ocean. The overall objectives were *(1) to evaluate the spatial heterogeneity of fluxes and processes controlling the OML*, *and (2) to account for this heterogeneity in order to improve the representation of the OML transfer function in global climate models*. The region of interest, which extends from the northern North Atlantic Ocean to the Arctic Ocean, is especially relevant to future changes of the European climate.

MEDLEY was a European project conducted within the JPI Oceans & Climate. This project integrated state-of-the-art observational datasets and basin-scale ocean models resolving the kilometer scale, innovative sea ice models and the latest generation of global climate models. Relying on interdisciplinary collaborations between its partners (six institutions, including UCLouvain), MEDLEY took advantage of the most advanced data analysis methods. More precisely, the project aimed to improve the tuning and consistency of the OML representation in the ocean component of global climate models through multi-scale modelling and validation against recent high-resolution observations.

MEDLEY was organized in three work packages:

- WP1. Heterogeneous OML;
- WP2. Sources of heterogeneities in the fluxes at the ocean surface;
- WP3. Heterogeneous transfers between the OML and the ocean interior.

Each of these work packages was divided into three different tasks. UCLouvain was involved in three of them:

- T1.1. Diagnosing the heterogeneity of OML dynamics in ice-covered regions;
- T2.1. Impact of fragmented sea ice on air-sea fluxes;
- T3.1. Heterogeneous water mass formation under sea ice.

UCLouvain contributed to these tasks by carrying out two studies on (1) the ability of ocean–sea ice general circulation models that participated in the CMIP6 Ocean Model Intercomparison Project (OMIP) to simulate the OML depth and its seasonal cycle in the Arctic Ocean (T1.1 & T3.1), and (2) the impact of ocean vertical mixing parameterization on the simulated Arctic sea ice and upper ocean characteristics using a low-resolution ocean–sea ice general circulation model (T2.1 & T3.1). In the following, we briefly report on the methodologies and main outcomes of these studies. For more details, we refer the reader to Allende et al. (2023, 2024).

3. METHODOLOGY

In the first study, we assessed the capability of the sea ice–ocean general circulation models participating in OMIP to reproduce the observed seasonal cycle of the OML depth in the central Arctic Ocean (i.e., north of 80° N), which is an oceanic area almost completely covered by multiyear sea ice, and in seasonally ice-covered adjacent seas, namely the Beaufort, Chukchi, East Siberian, Laptev, Kara and Barents Seas. These models were chosen instead of the global climate models that contributed to the CMIP6 High-Resolution Model Intercomparison Project (HighResMIP) (as initially planned in the project) because they were forced by atmospheric reanalysis data (Tsujino et al., 2018; Tsujino et al., 2020) and were therefore expected to better simulate the dynamics of the OML in polar regions. OMIP consisted of two phases: OMIP1, in which the models were driven by the CORE-II dataset (Griffies et al., 2016), and OMIP2, in which the model forcing was the JRA55-do reanalysis (Tsujino et al., 2018; Tsujino et al., 2020). In OMIP2, some of the models were also run at a higher horizontal resolution. We built climatologies from each phase, spanning from 2007 to 2009 for OMIP1 and from 2007 to 2011 for OMIP2.

The model outputs were thoroughly compared to the MIMOC (Monthly Isopycnal & Mixed layer Ocean Climatology) observational data (Schmidtko et al., 2013), which have a 0.5° horizontal resolution and cover the period 2007–2011. In this climatology, the OML depth is calculated using the algorithm of Holte and Talley (2009), which performs a statistical optimization based on traditional threshold and gradient methods applied to temperature, salinity and density individual profiles, thereby improving the accuracy of the OML depth. As discussed by Schmidtko et al. (2013), this methodology provides good agreement with the common threshold density criteria $\Delta\rho = \rho(z) - \rho(z_{ref}) = 0.03$ kg m^{-3} utilized in the OMIP framework, also known as *sigma-t* criterion (Griffies et al., 2016). We also included in the analysis the Ice-Tethered Profilers (ITP) data of Toole et al. (2015) from 2004 to 2011 to substantiate the MIMOC ones. These observations allowed us to derive vertical potential density profiles using the TEOS-10/GSW Python library, thus facilitating a comparison with OMIP model outputs. Only the OMIP models that diagnose the OML depth consistently with the MIMOC data and that supply all the outputs required for our analysis were considered. Regarding sea ice data, we made use of the OSI-450 dataset, which covers the period January 1979 – December 2015 (Lavergne et al., 2019). This dataset, with a grid spacing of approximately 25 km, provided consistent records for our study.

Our analysis focused on key variables such as the OML depth, the seawater salinity and potential temperature, the sea ice concentration and the change in sea ice mass due to thermodynamics. We worked with a subset of 10 models featuring diverse ocean and sea ice components as well as various vertical resolutions, ensuring a robust comparison with observational data. All variables were interpolated to match the nominal spatial resolution of the MIMOC dataset before analysis.

In the second study, we evaluated the performance of the ocean vertical mixing scheme of the NEMO4.2-SI^3 (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 – for turbulent kinetic energy, is based on the turbulent closure model developed by Bougeault and Lacarrère (1989) for the atmosphere. It was adapted to the ocean by Gaspar et al. (1990) and 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 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 $e_{inertial}$, is parameterized as : $e_{inertial} = \chi\, f_r\, e_{surf} \exp(-z/h_\tau)$ if $z > 0$ and 0 if $z = 0$, where z is the depth, f_r is the fraction of the surface TKE (e_{surf}) that penetrates into the ocean, h_τ 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. f_r (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. h_τ 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, $\chi = 1$, which means no sea ice influence. When nn_eice = 1, $\chi = 1 - \tanh(10\, f_i)$, with f_i the sea ice concentration. When nn_eice = 2, $\chi = 1 - f_i$. Finally, when nn_eice = 3, $\chi = 1 - \min(1, 4f_i)$, which is equivalent to disabling the TKE MLP parametrization when sea ice concentration exceeds 25%.

A control run was first conducted with NEMO4.2-SI^3 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 assessed the model performance by comparing the model outputs to different sets of observational data and to a sea ice reanalysis product. Specifically, we employed the OML depth climatology of de Boyer montégut (2024; hereinafter referred to as IFREMER-LOPS climatology), the ITP data, the World Ocean Atlas (WOA) data (Reagan et al., 2024), the EUMETSAT OSI-SAF sea ice data (Lavergne et al., 2019) and the PIOMAS (Pan-Arctic Ice-Ocean Modelling and Assimilation System) reanalysis sea ice data (Zhang and Rothrock, 2003). With this comprehensive assessment, we sought to elucidate the effectiveness of the TKE MLP parameterization in improving the representation of ocean vertical mixing processes in NEMO4.2-SI^3 and its implications for the simulation of Arctic climate dynamics.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

Figure 1 shows the mean seasonal cycle of the OML depth in the central Arctic Ocean as simulated by the OMIP models and as observed. During summer months, all models underestimate the OML depth by about 20 m. The origin of this systematic bias is still unclear. In fall and winter, discrepancies reach up to several tens of meters, not only between the models and the observational data but also between the models themselves. Some models produce too deep OML, and others simulate too shallow OML, whatever the atmospheric forcing or horizontal resolution. Similar biases were noticed in the seasonally ice-covered Beaufort, Chukchi, East Siberian, Laptev, Kara and Barents Seas.

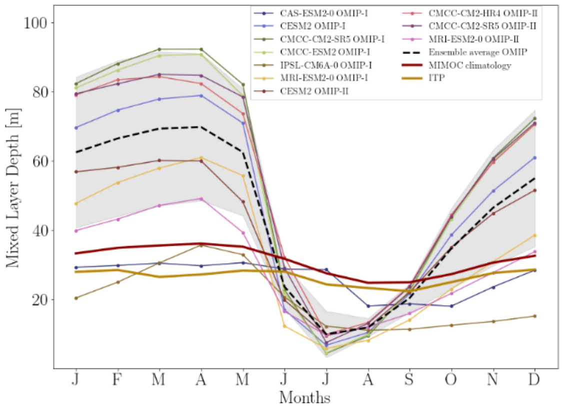

Figure 1. Seasonal cycle of the OML depth in the central Arctic Ocean. Data are averaged in time between 2007 and 2009 for OMIP1, and between 2007 and 2011 for OMIP2 and ITP. Data are averaged in space between 80° N and 90° N, and between 180° W and 180° E. Solid lines with points correspond to OMIP 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.

In fall and winter, the OML depth in ice-covered regions is mostly determined by brine rejection associated with sea ice growth. As such, one may naturally think that the differences between models and between models and observations relate to discrepancies in sea ice mass balance. However, Figure 2 reveals that this is not the case. All models simulate more or less the same sea ice mass balance, resulting in very similar salt fluxes into the ocean during sea ice formation.

As can be seen from Figure 3, large differences exist between models in the ocean stratification at the beginning of the sea ice growth season. In the central Arctic Ocean and in the Beaufort and Chukchi Seas, there is a clear relationship between the ocean stratification in September and the OML depth at the end of winter: a weakly (strongly) summer stratified water column is associated with a deep (shallow) mixed layer in late winter. Furthermore, one observes that OMIP models with ocean stratification closer to observational data perform better in simulating the OML depth evolution in late winter.

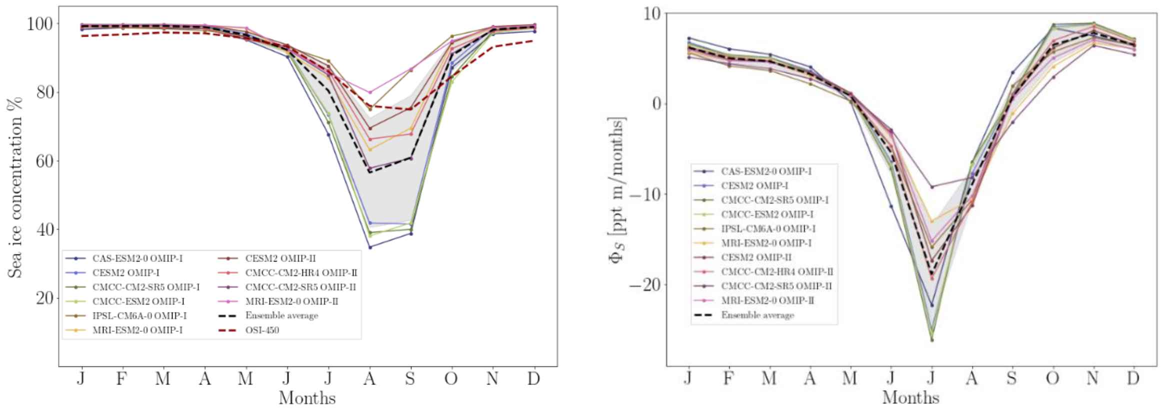

Figure 2. Left : Seasonal cycle of the mean sea ice concentration in the central Arctic Ocean. Colour lines correspond to OMIP models and the red dashed line to the observational data OSI-450. Right : Seasonal cycle of the mean salinity flux from sea ice in the central Arctic Ocean. Colour lines correspond to OMIP models.

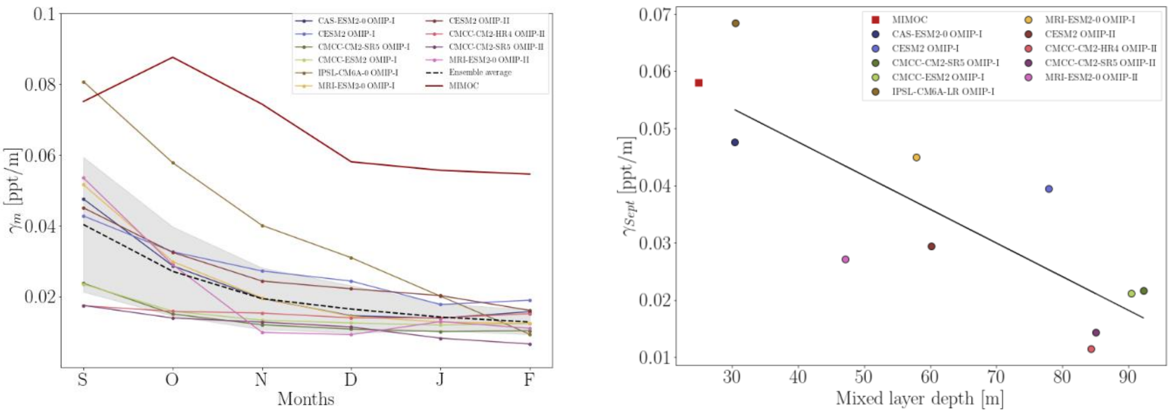

Figure 3. Left: Ocean stratification computed between the base of the OML and the depth corresponding to the OML of the following month for OMIP models and MIMOC observational data. Right: Relationship between the OML depth in March and the ocean stratification in September until the OML depth in March for all OMIP models and MIMOC observational data.

To consolidate these findings, we used the one-dimensional analytical model developed by Martinson (1990), which describes the nature of the fall and winter sea ice–ocean interactions and determines the main processes maintaining the vertical stability of the upper ocean in polar regions. By driving this model with salt fluxes resulting from sea ice growth and the strength of the salinity gradient in the Arctic halocline during September derived from OMIP models, we obtained fall and winter deepenings of the OML in the central Arctic Ocean and in the Beaufort and Chukchi Seas very close to the ones simulated by OMIP models (Figures 4 and 5), which emphasizes the important role of the vertical stratification in the control of the OML depth in these regions. In the East Siberian, Laptev, Kara and Barents Seas, the OML dynamics is different. The fall and winter deepening of this layer is no longer dominated by the salt flux related to sea ice formation. Other processes that are not accounted for in Martinson's model, such as surface cooling, wind-driven mixing or horizontal advection, play a role.

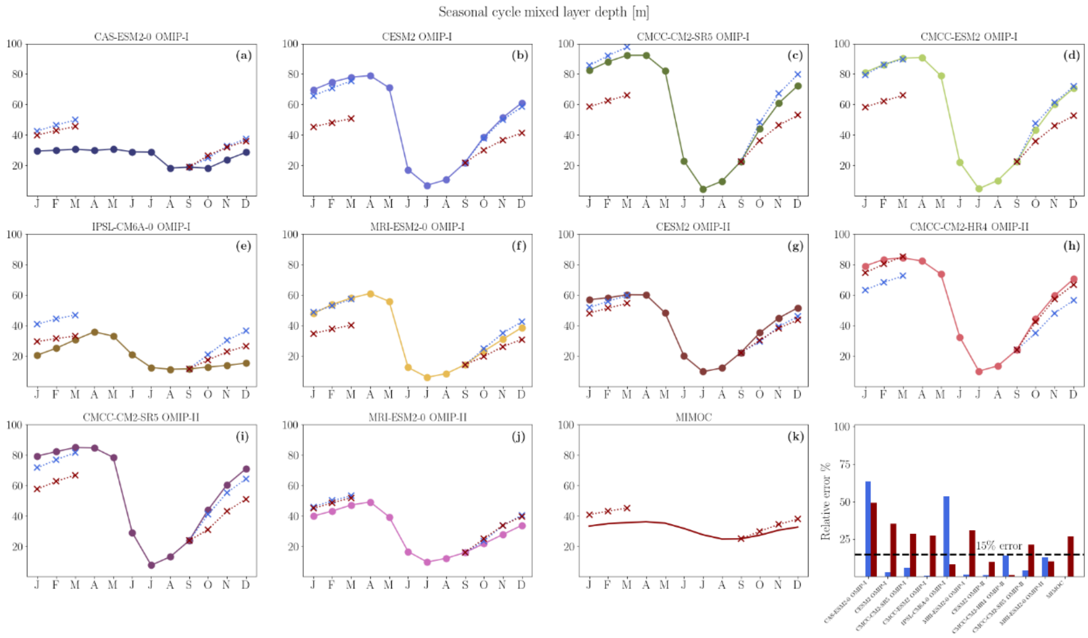

Figure 4. Reproduction of the seasonal cycle of the OML depth for each OMIP model and the MIMOC observational data in the central Arctic Ocean using Martinson's model. The blue dashed lines were obtained using the values in each grid cell. The red dashed lines were obtained using the averaged values 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.

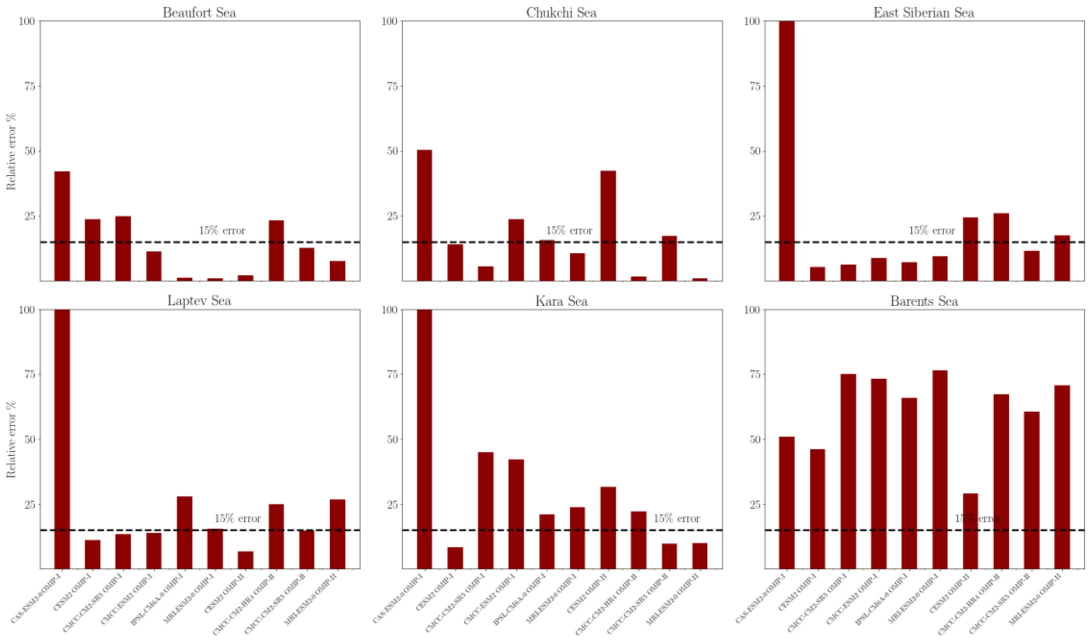

Figure 5. Relative error of the amplitude of the OML depth seasonal cycle between OMIP outcomes and the OML depth estimated using Martinson's model with the averaged values.

These results 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. In addition, the study of other drivers of the seasonal evolution of the OML depth, beyond interactions between sea ice and the ocean, in regions where model biases are large would provide a better understanding of the complex mechanisms governing the Arctic climate variability.

In our second study, as mentioned above, we evaluated by means of sensitivity experiments the performance the TKE MLP parameterization recently incorporated into NEMO4.2-SI^3 in the central Arctic Ocean, particularly, in the Makarov, Eurasian and Canadian Basins. Figure 6 depicts the mean seasonal cycle of the of OML depth from the control run, the sensitivity experiments and IFREMER-LOPS' climatology in each of these basins. When the parameters of the TKE MLP parameterization vary, a similar behaviour is noticed in all three regions. Three distinct settings with notable differences with 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.

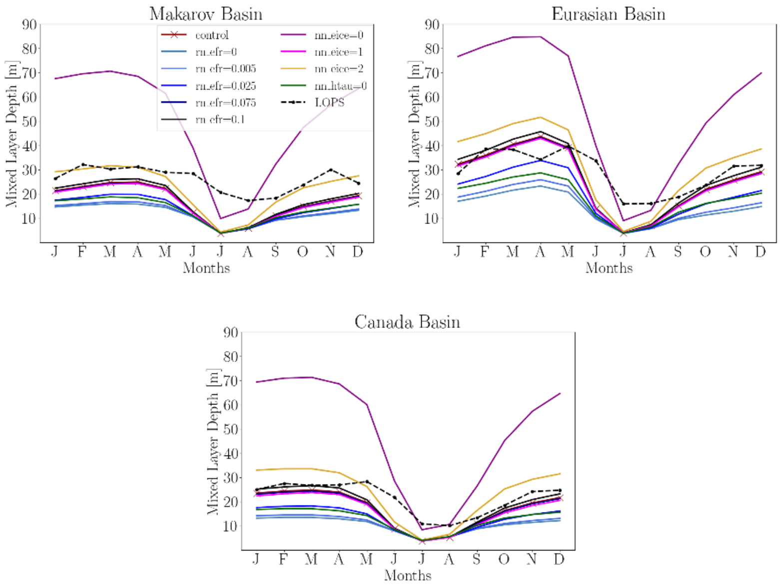

Figure 6. Mean seasonal cycle of the OML depth as simulated by NEMO-SI^3 and from the IFREMER-LOPS climatology in the Makarov, Eurasian and Canadian Basins of the Arctic Ocean.

Figure 7 illustrates the differences between experiments rn_efr = 0, nn_eice = 0 and nn_eice = 2, and the control run for March and September. The largest changes in OML depth are observed for nn_eice = 0 (no sea ice attenuation), with the OML being 20 m deeper compared to the control run in both months and all regions. Similarly, setting nn_eice = 2 (sea ice attenuation proportional to sea ice concentration) leads to a 10-to-20-m deeper OML in both months. On the other hand, the greatest thinning of the OML, of up to 20 m in the Canadian Basin, occurs for rn_efr = 0 (TKE MLP parameterization turned off). It is worth pointing out that decreasing the characteristic depth of TKE penetration from 30 to 10 m (nn_htau = 0) has an impact almost identical to that of decreasing the fraction of the surface TKE penetrating into the ocean (rn_efr).

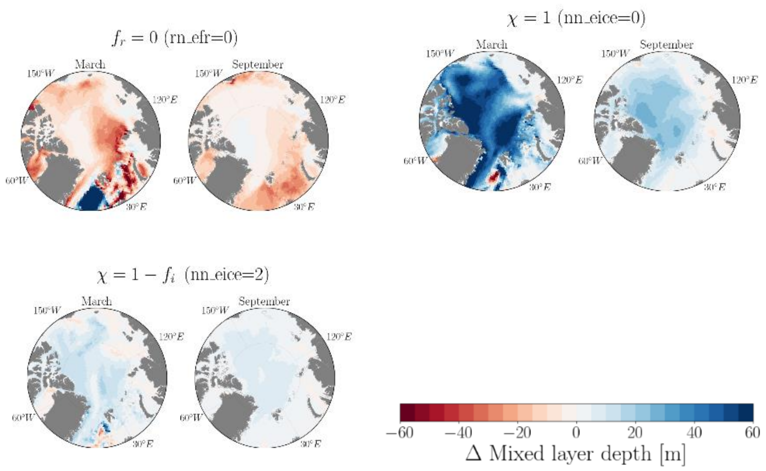

Figure 7. Differences in OML depth between experiments rn_efr = 0, nn_eice = 0 and nn_eice = 2, and the control run in March and September. Model outputs are averaged in time between 1970 and 2021.

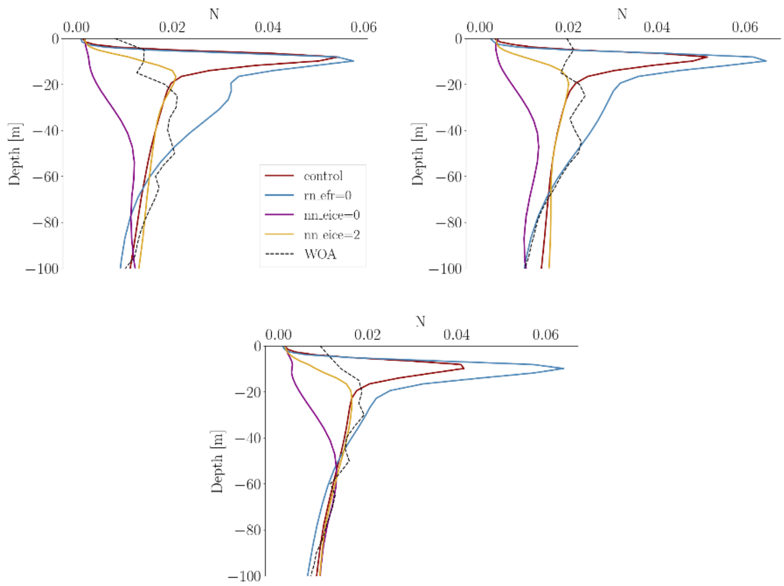

Figure 8. September Brunt-Väisälä frequency (*N*) in the Makarov (top, left), Eurasian (top, right) and Canadian (bottom) Basins from the control run, experiments rn_efr = 0, nn_eice = 0 and nn_eice = 2, and the WOA. Model outputs and observational data are averaged in time between 1970 and 2021.

The time-averaged vertical profile of the September Brunt-Väisälä frequency (*N*) in the upper 100 m of each basin is displayed in Figure 8 for the control run, experiments rn_efr = 0, nn_eice = 0 and nn_eice = 2, and the WOA. A large (small) value of *N* is indicative of a strong (weak) stratification. Compared to the WOA, the upper ocean appears too stratified in both the control simulation and experiment rn_efr = 0, and not enough stratified in experiment nn_eice = 0, which is consistent with the behaviour of the OML depth. One sees, that the model results are in better agreement with observations when nn_eice = 2.

The differences in mean sea surface salinity between experiments rn_efr = 0, nn_eice = 0 and nn_eice = 2, and the control run are plotted in Figure 9 for March and September. Overall, a decrease (increase) in OML depth compared to the control simulation is accompanied by a decrease (increase) in sea surface salinity. When ice melts in summer, if the OML is shallower, the freshwater flux associated with ice melting strongly reduces the sea surface salinity. This anomaly persists, to a lesser extent, in winter. Conversely, a deeper OML allows the freshwater input to mix deeper, resulting in a higher sea surface salinity.

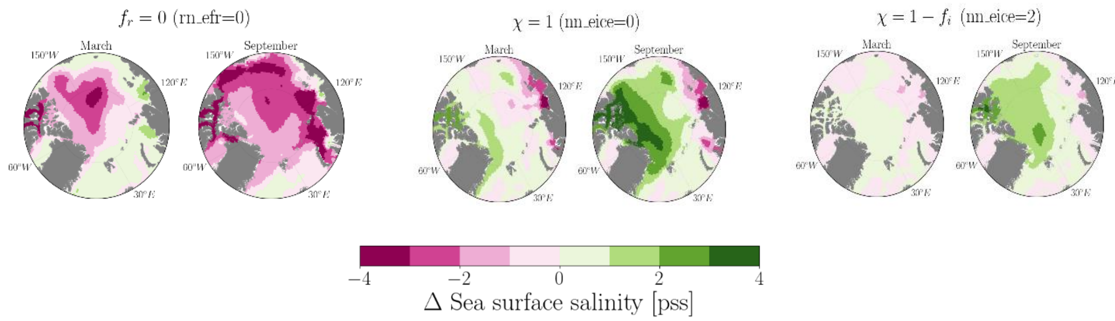

Figure 9. Differences in sea surface salinity between experiments rn_efr = 0, nn_eice = 0 and nn_eice = 2, and the control run in March and September. Model outputs are averaged in time between 1970 and 2021.

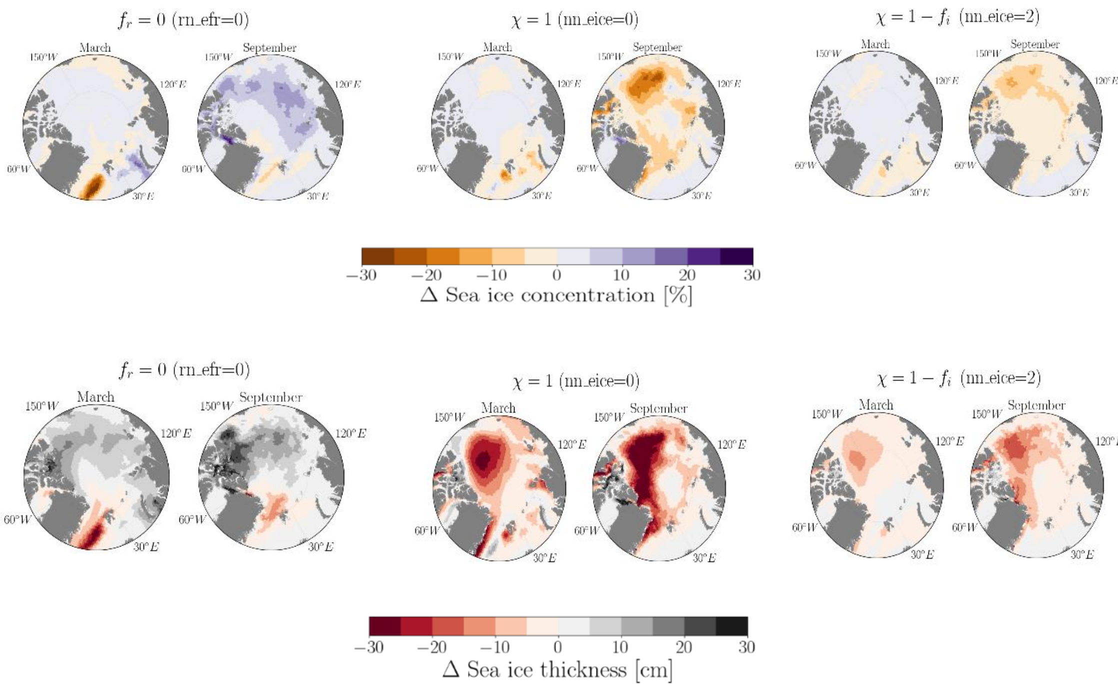

Figure 10. Differences in sea concentration (top) and thickness (bottom) between experiments rn_efr = 0, nn_eice = 0 and nn_eice = 2, and the control run in March and September. Model outputs are averaged in time between 1970 and 2021.

Figure 10 gives the corresponding changes in mean sea ice concentration and thickness. Compared to the control run, those two variables increase (decrease) nearly everywhere when rn_efr = 0 (nn_eice = 0 or 2). In experiment nn_eice = 0, the decrease in ice concentration (thickness) reaches 20–30% (more than 30 cm) in September in the region of the Beaufort Gyre, while in experiment nn_eice = 2, the decrease rarely exceeds 10% (15 cm). These differences between experiments may be explained by the changes in vertical ocean density profile (see Figure 8). A stronger (weaker) vertical stratification results in a larger (lower) Richardson number, which weakens (intensifies) the oceanic vertical mixing and its associated upward heat flux. Consequently, there is reduced (enhanced) exchange between the upper ocean and sea ice, leading to a decreased (increased) sea ice melt during summer months, as observed in experiment rn_efr = 0 (experiments nn_eice = 0 and nn_eice = 2).

Figure 11 illustrates the evolutions between 1970 and 2021 of the OML depth and sea ice characteristics during summer and winter in the Canadian Basin as observed and as simulated in the control run and experiments rn_efr = 0, nn_eice = 0 and nn_eice = 2. In this basin, since 2000, the ITP data exhibit an increasing trend in averaged OML depth of +0.19 m yr^{-1} in summer and +0.93 m yr^{-1} in winter. A similar behaviour is noticed in the Makarov Basin, with trends of +0.54 m yr^{-1} in summer and +0.88 m yr^{-1} in winter. In contrast, the Eurasian Basin experienced an increasing trend in averaged OML depth in summer (+0.37 m yr^{-1}) and a decreasing trend (–0.15 m yr^{-1}) in winter. It should however be noted that ITP data are relatively scarce in these last two basins. Interestingly, the simulation in which the TKE MLP parameterization is switched off (rn_efr = 0) fails in reproducing these trends. Therefore, not activating this parameterization could have negative consequences on the simulation of future trends in the Arctic Ocean.

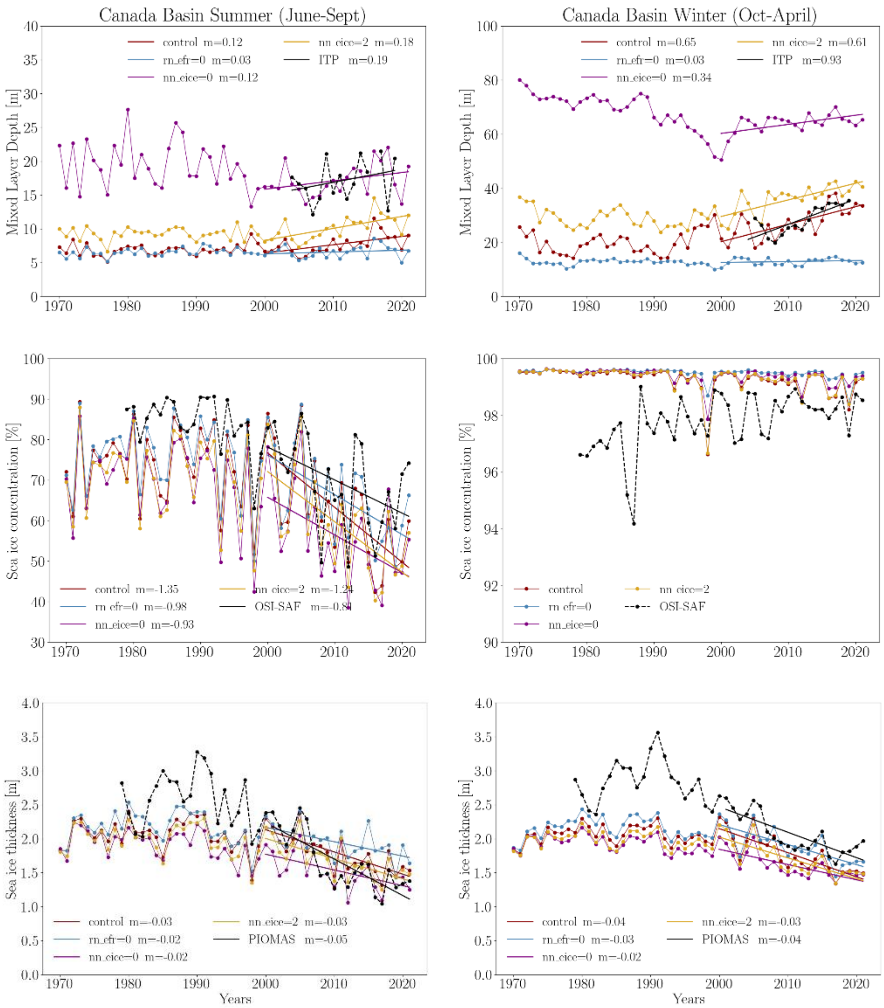

Figure 11. Evolutions during 1970–2021 of the OML depth, sea ice thickness and sea ice concentration averaged over the Canadian Basin in summer (June to September) and winter (October to April) as observed and from the control run and experiments rn_efr = 0, nn_eice = 0. Solid lines represent the linear regression, and *m* is the slope.

In summary, our results highlight the need to include in the TKE MLP parameterization a scaling parameter that takes into consideration the presence of sea ice, as its absence leads to excessively large OML depths in winter. The choice of the scaling parameter formulation significantly influences the simulation of the upper ocean stratification, with a stronger (weaker) stratification corresponding to a shallower (deeper) OML. Changes in this stratification notably impact the sea surface salinity, with a shallower (deeper) OML leading to a higher (lower) sea surface salinity, and the sea ice characteristics. We also found the activating the TKE MLP parameterization in NEMO-SI^3 is a prerequisite to realistically simulate the recent OML depth trends observed in the Arctic Ocean. However, the ad hoc nature of this parameterization raises concerns regarding its physical basis and time step dependency. Future research should focus on understanding the underlying mechanisms driving the TKE MLP and exploring alternative approaches to improve the robustness and accuracy of ocean vertical mixing parameterizations in NEMO-SI^3, especially in the presence of sea ice. Such efforts will be crucial for enhancing the fidelity of Arctic climate projections and advancing our understanding of polar climate dynamics.

5. DISSEMINATION AND VALORISATION

UCLouvain's contribution to MEDLEY will be very useful for the development of the next generation of global climate models that will participate in the seventh phase of CMIP in support of the IPCC's Seventh Assessment Report. 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-SI[3].

Our results are discussed in detail in two papers published in international refereed scientific journals (see Section 6). There were also presented orally or as posters by Sofia Allende at the different MEDLEY meetings, the 2022 GDR Meeting "Défis théoriques pour les sciences du climat" (Paris), the 2023 and 2024 General Assemblies of the European Geosciences Union (Vienna) and the 2024 DRAKKAR Ocean Modelling Worksop (Grenoble). In addition, Sofia Allende gave seminars on MEDLEY's outcomes at the Université d'Aix-Marseille (Marseille, 2022), IFREMER (Brest, 2023), the Université de Lille (Lille, 2024) and the Centro de Previsão de Tempo e Estudos Climáticos (São Paulo, 2024).

MEDLEY also took the initiative to organize two sessions on the surface layer of the ocean at the 2023 and 2024 General Assemblies of the European Geosciences Union, for which François Massonnet was co-convenor. Furthermore, Thierry Fichefet and François Massonnet gave a number of interviews on the importance of the World Ocean in the ongoing global warming to written, spoken and televised press. Finally, each year, their research team contributed to an activity on oceanography organized at UCLouvain for high-school students as part of the Spring of Sciences.

6. PUBLICATIONS

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