

No emergence of deep convection in the Arctic Ocean across CMIP6 models

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Key Points:

- Oceanic deep convection does not emerge and persist in the Arctic in the majority of CMIP6 models, despite a cessation in the Nordic Seas.
- Arctic deep convection occurs only when both surface salinity and winds are increasing, year round, yet most models are freshening.
- The models with the strongest sensitivity, especially with an oceanic polar amplification, have the deepest Arctic mixed layers, most often.

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Abstract

As sea ice disappears, the emergence of open ocean deep convection in the Arctic has been suggested. Here, using 36 state-of-the-art climate models and up to 50 ensemble members per model, we show that Arctic deep convection is rare even under the strongest warming scenario. Only 5 models have somewhat permanent convection by 2100, while 11 have had convection by the middle of the run. For all, the deepest mixed layers are in the Eurasian basin, by St Anna Trough. When the models convect, that region undergoes a salinification and increasing wind speeds; it is freshening otherwise. We discuss the causality and potential reasons for the opposite trends. Given the model's different parameterisations, and given that the ensemble members that convect the deepest, most often, are those with the strongest sensitivity, we conclude that differences in deep convection are most likely linked to the model formulation.

Plain Language Summary

Both observations and modelling simulations suggest that deep vertical mixing (or deep convection) in winter may become the new normal in the Arctic as sea ice disappears. These simulations are often done using only one model, so here we used all models available that participated in the Climate Model Intercomparison Project phase 6, for the strongest warming scenario. We show that after removing those that are already inaccurate in the present, and even with a restrictive threshold, most models have no deep convection in the Arctic, or extremely rarely. Only 5 still had deep convection by the time the run finishes in 2100. We investigated the possible links between deep convection and surface salinity, surface temperature, sea ice concentration and surface wind speeds, and found that the salinity was most important. Deep convection regions and periods are associated with a saltier, windier surface, while the rest of the Arctic and/or rest of the run freshens. Causality is unclear; we need higher resolution than monthly output. Similar behaviours within model families, a strong link to the model sensitivity, and cited work make us conclude that ultimately, the differences are probably caused primarily by the different model designs.

1 Introduction

The Arctic Ocean is changing. The resulting reduction in Arctic sea ice extent and thickness (Mallett et al., 2021; Meier & Stroeve, 2022) could enhance vertical mixing: More brine may be rejected year-round as younger, saltier ice desalinates (Peterson, 2018) or as sea ice reforms in winter over the now seasonal-ice areas (Onarheim et al., 2018), while the ice-freed regions may become more susceptible to wind stirring (Timmermans & Marshall, 2020). In the Eurasian Arctic, the process known as Atlantification (Polyakov et al., 2017), whereby warm water of Atlantic origin penetrates further into the Arctic, may be further weakening the stratification and enhancing sea ice melt. These led Polyakov et al. (2017) to hypothesise that the Arctic may start exhibiting deep convection in winter, a result found by Lique et al. (2018) in the 4x CO₂ scenario using the model HiGEM.

However, this hypothesis is so far not confirmed. Peralta-Ferriz and Woodgate (2015) found that a deepening of mixed layers in the Arctic is unlikely, since stratification greatly dominates over the wind effect. The latest observations in the Eurasian Arctic (Schulz et al., under review) yielded mixed layers no deeper than 130 m, even in winter. Besides, in a recent Arctic study using models that participated in the Climate Model Intercomparison Project phase 6 or CMIP6 (Eyring et al., 2016), Muilwijk et al. (2023) showed that there was no agreement among models regarding future stratification and the effect of Atlantification under the strongest warming scenario (SSP5-8.5, O'Neill et al. (2016)). This suggests that HiGEM's deep convection in the Arctic may be a model artefact rather than the future of the Arctic.

We here determine whether deep convection emerges in the Arctic in the future scenario SSP5-8.5 using all CMIP6 models and all their ensemble members for which the mixed layer depth output was available, as described in section 2. In section 3, we detail the spatial and temporal patterns of future Arctic mixed layers and discuss possible reasons for these, focusing on the model biases and their trends in surface properties, sea ice and winds. We conclude in section 4.

2 Data and Methods

2.1 CMIP6 data

To investigate deep convection and its potential drivers in the future Arctic, we use all CMIP6 models and all their ensemble members that had monthly mixed layer depth (“mldst”), ocean surface salinity (“sos”) and temperature (“tos”), sea ice concentration (“siconc”) and surface wind speed (“sfcWind”) available on any of the Earth System Grid Federation (ESGF) nodes for the future scenario SSP5-8.5, for January 2015 to December 2100. The models and their ensemble members are listed in supp. Tables S1 and S2.

For AWI-CM-1-1-MR and GISS-E2-1-G, we used the sea ice thickness (“sivol”) because sea ice concentration was not available. For CAMS-CSM1-0, we generated the surface salinity from the full-depth salinity (“so”) as the former was not available; we used the salinity of the shallowest level, 5 m depth. Similarly, we used the models’ bathymetry (“deptho”) when it was available, but had to generate it from the full-depth salinity for 11 models, as the last level with salinity data. Finally, for CESM2-WACCM, GFDL-CM4 and MRI-ESM2-0, several grid types were available and we chose for simplicity the regularised grid (“gr”). For the other models, we took the one grid type available; see supp. Tables S1 and S2.

2.2 Methods

The thresholds and choices of this subsection are discussed in supplementary text S1. In agreement with Lique et al. (2018), we consider that there is deep convection in the Arctic if the mixed layer depth (MLD) exceeds 500 m. We here do not quantify overturned volumes. We only perform a binary detection of deep convection, so we select the overall maximum MLD, in space or time depending on the analysis. The ensemble members that exhibit deep convection in the Arctic over the observed part of SSP5-8.5 (2015-2023) are shown on the first figure and subsequently removed from the study, as they are already inaccurate at the beginning of the run. Consequently, of the originally 36 models, 27 remain for most of the analysis. We do not take biases in Nordic Seas MLD into account for model selection, as all CMIP6 models have spurious deep convection there (Heuzé, 2021).

The sea ice edge (supp. Fig S1) is detected as the contour of 15% concentration or 10 cm thickness, averaged over 2040-2060 and 2080-2100. We define the Eurasian basin as the region north of 80°N, longitudes 20°W - 140°E, deeper than 1000 m, and the Nordic Seas as the region of latitudes 66 - 80°N, longitudes 30°W - 20°, deeper than 1000 m - see contours on Fig 1. We perform cross-model correlations by comparing, for each model and each ensemble member, their maximum MLD and number of year where the MLD exceeds 500 m in the Eurasian basin, to:

1. Average surface temperature and salinity in the Eurasian basin over the first 20 years of SSP5-8.5;
2. Tropical and Mid-latitude (60°S - 60°N) and Arctic (north of 75°N) warming, as difference between the 2080-2100 and 2015-2035 average ocean surface temperature, which we use as a proxy for the model sensitivity. We also define the oceanic

109 polar amplification as the difference between the Arctic and tropical/mid-latitude
110 warming.

111 Besides, we compute correlations and trends for each grid cell, after interpolating
112 all the parameters onto each model's mlotst grid. The correlations and trends are com-
113 puted for each ensemble member separately, and averaged afterwards. We consider that
114 there is ensemble agreement if more than 50% of the ensemble members have a signif-
115 icant correlation/trend (determined using a t-test at 95% significance) of the same sign;
116 we then present the median value and its ensemble-spread. Finally, we present the com-
117 posite trends after grouping the models based on their Arctic deep convection behaviour,
118 as described in the result section.

119 3 Results and Discussion

120 3.1 Arctic deep convection is rare, restricted both in space and time

121 The maximum mixed layer depth reached in the Arctic over 2015-2100 varies strongly
122 across models (Fig. 1, note the logarithmic scale). The value does not exceed 100 m for
123 some, such as CAMS-CSM1-0, while others such as CMCC-CM2-SR5 exceed 2000 m in
124 the majority of the Eurasian basin. All models with deep MLD agree that the deepest
125 values are in the Eurasian basin, most commonly by St Anna Trough. Nine models have
126 MLD exceeding the 500 m threshold for deep convection already over 2015 to present
127 for all their ensemble members (red squares on Fig. 1). Interestingly, these are not only
128 by St Anna Trough but also north of Svalbard, suggesting that for these models the Nordic
129 Sea deep convection area extends too far north, most likely following the sea ice edge (shown
130 on supp. Fig. S1). All models presented on Fig. 1 have spuriously deep MLD in the Nordic
131 Seas.

132 After removing the models and ensemble members that are unrealistic in the present-
133 day regarding their Arctic MLD (asterisks in supp Tables S1 and S2), 27 models remain.
134 The temporal evolution of their MLD reveals four groups of models (Fig. 2 and supp Ta-
135 ble S3):

- 136 1. The first 11 models have no Arctic deep convection during the entire run. The Arc-
137 tic MLD time series (blue lines, Fig. 2) are mostly flat, with no year where the
138 MLD exceeds 500 m, regardless of the ensemble member. The maximum MLD across
139 these models and their ensemble members is often of the order of 100 m, i.e. like
140 currently observed in the Arctic (Schulz et al., under review).
- 141 2. Six models have deep convection in the Arctic on rare occasions, in the middle of
142 the run. The maximum number of years with deep convection for this group is 17
143 out of 86 (supp Table S3), but is most often 4 or fewer.
- 144 3. Five models also have deep convection in the Arctic in the middle of the run, more
145 often. It starts by 2030, peaks in the first half of the run, and then declines slowly,
146 with the ensemble average back under the 500 m threshold by the end of the run.
- 147 4. The last 5 models start convecting in the second half of the run, by 2070, and ap-
148 pear "stably" convecting at the end of the run. Unfortunately, only oneensem-
149 ble member of one of the models (ACCESS-CM2) is available beyond 2100, so we
150 cannot tell whether deep convection in these models would also decline later.

151 The Nordic Seas MLD (red lines, Fig. 2) falls below 1000 m for all models, and even be-
152 low 500 m for two thirds of them. The consistent cessation of Nordic Seas deep convec-
153 tion is not related to the models' behaviour in the Arctic. Therefore, unlike suggested
154 by Lique et al. (2018), deep convection does not migrate to the Arctic in response to its
155 cessation further south.

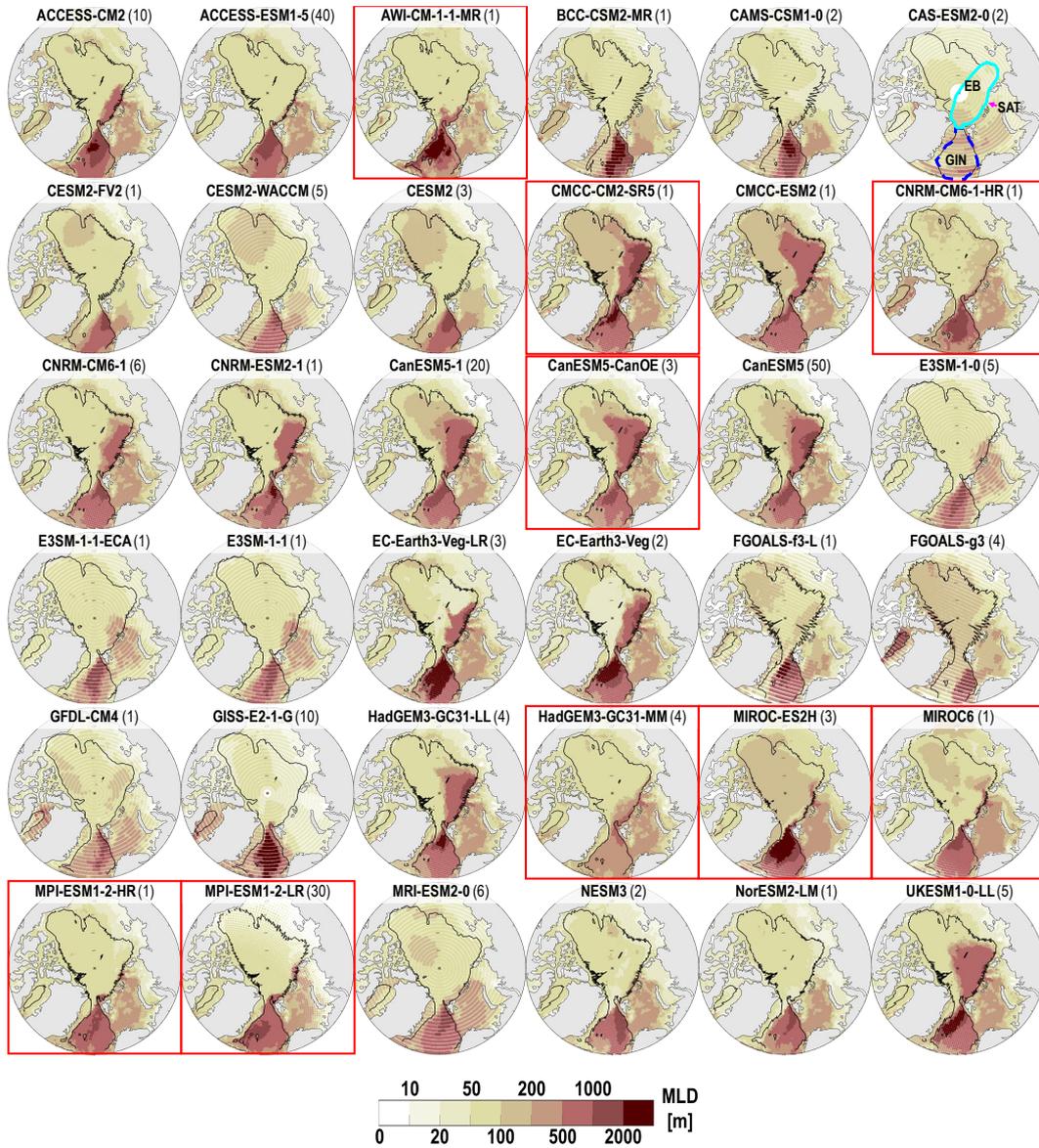


Figure 1. Maximum MLD over January 2015 - December 2100 (shading, logarithmic scale) for SSP5-8.5 at each grid cell. For each model, parentheses indicate the number of ensemble members available (see supp. Tables S1 and S2); when this number is larger than one, the figure shows the ensemble median. Black contours are the 1000 m isobath. Red squares indicate the models for which all ensemble members have deep convection in the Arctic already over 2015-2023, and which are therefore not considered for further analysis. Locations discussed in the manuscript are indicated on the top-right panel: Cyan contour “EB” is the Eurasian Basin, indigo dashed contour “GIN” is the Nordic Seas, and magenta arrow “SAT” is the St Anna Trough.

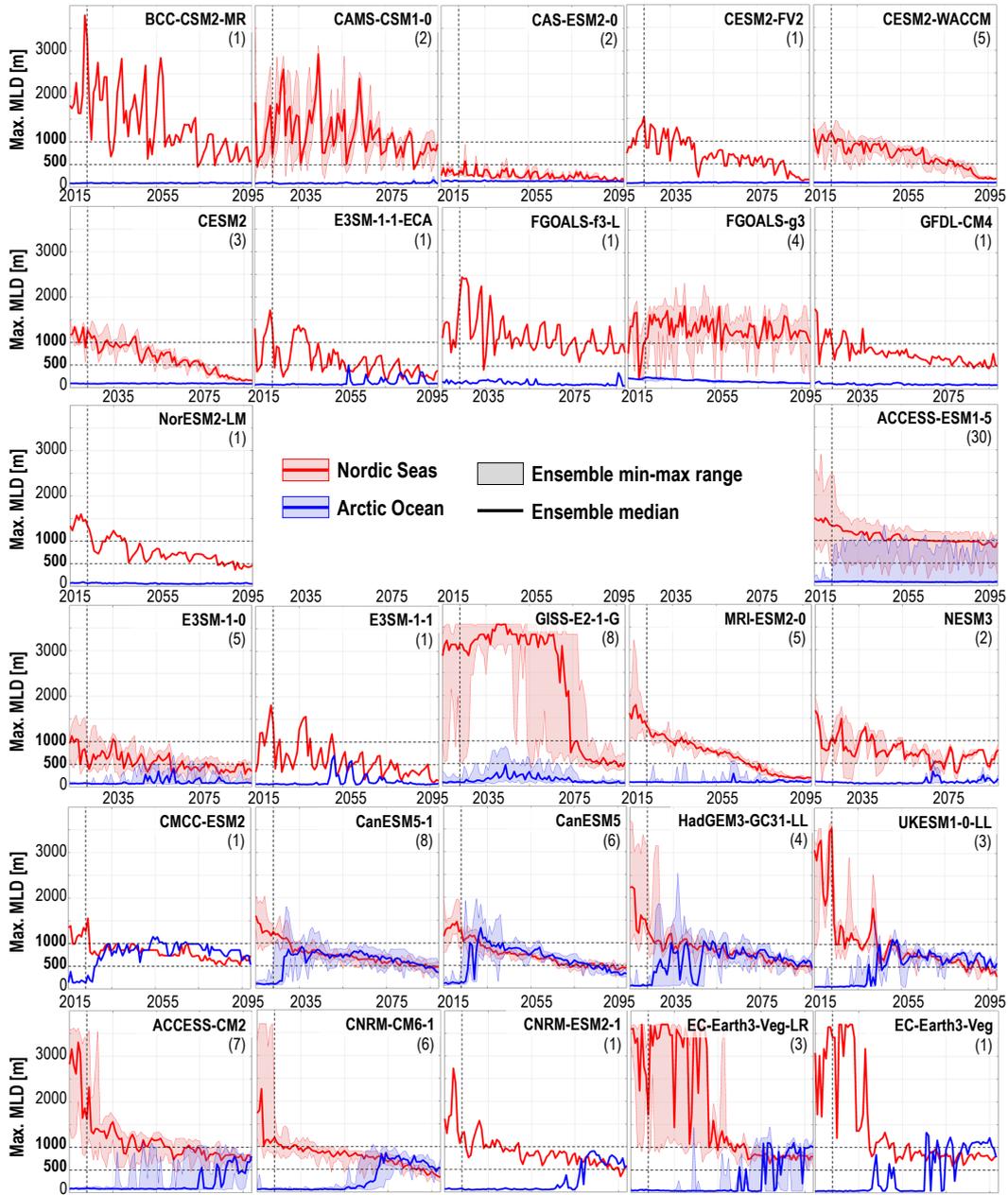


Figure 2. For the 27 models that do not have deep convection in the Arctic over 2015-2023, time series of their yearly maximum MLD in the Nordic Seas (red) and in the Arctic Ocean (blue). For each model, parentheses indicate the number of ensemble members remaining; when this number is larger than one, the figure shows the range across these ensemble members (shading) and the ensemble median (thick line). Horizontal black lines indicate the 500 and 1000 m MLD thresholds, indicative of deep convection. Vertical black line is the year 2023. Models are ordered based on their Arctic behaviour: First two rows and NorESM2-LM, no Arctic deep convection; ACCESS-ESM1-5 and fourth row, rare convection, by the middle of the run; fifth row, convection peaks by the middle of the run and then declines; bottom row, convection starts late in the run.

156 What causes these different behaviours then? Ensemble members usually have a
 157 consistent behaviour (the shading on Fig. 2 usually agrees with the thick line), and mod-
 158 els of the same family tend to belong to the same group. The only exception are the two
 159 ACCESS models (Fig. 2), but there are large differences in their designs and implemented
 160 schemes of relevance for polar regions and deep convection in particular, as discussed in
 161 Mohrmann et al. (2021). In the next section, we investigate in more details what could
 162 be causing the different Arctic deep convection behaviours, starting with model designs.

163 **3.2 Potential causes: High sensitivity, salinification, stronger winds**

164 The models that have deep convection in the Arctic usually have it at the same lo-
 165 cation (Fig. 1), but the temporal evolution of the mixed layer yields four groups of mod-
 166 els (Fig. 2). Models of the same family tend to belong to the same group; these usually
 167 have similar biases and sensitivities, so we first investigate these.

168 The mean temperature in the Eurasian Basin at the beginning of the SSP5-8.5 run
 169 and subsequent MLD are positively correlated across models (Fig. 3, left): the warmer
 170 at the beginning of the run, the deeper the mixed layers (correlation 0.40), the more of-
 171 ten (0.33). The same results are obtained when considering the ensemble members sep-
 172 arately, as on Fig. 3, and the ensemble mean (not shown). There is no such relationship
 173 with salinity. The relationship with temperature persists throughout the run, so that the
 174 models that warm the most (Fig. 3, centre), and quite strikingly, those for which the ocean
 175 surface warms more in the Arctic than in the midlatitudes (Fig. 3, right) are the ones
 176 with the deepest MLD, the most often. The models belonging to the E3SM project (cyan
 177 contour, Fig. 3) are the exception: They warm strongly but convect rarely or not at all,
 178 which could be because their design is very different from that of the other CMIP mod-
 179 els (Golaz et al., 2019).

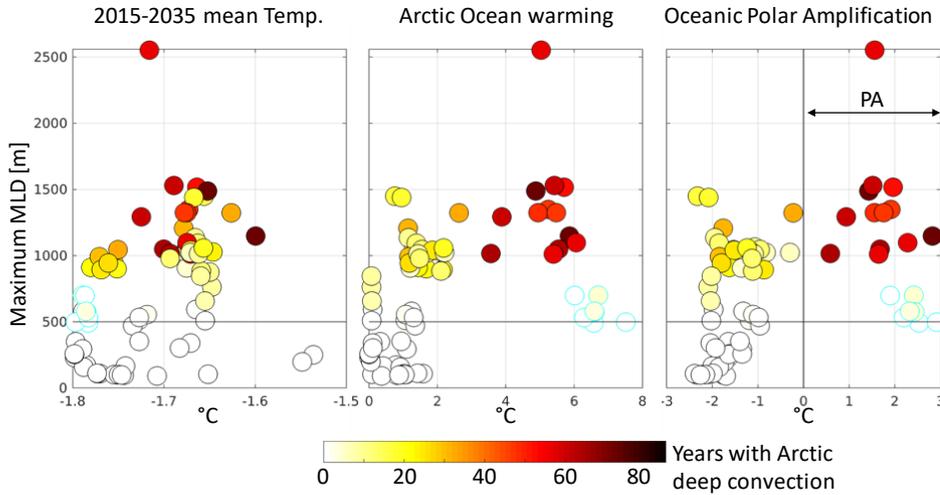


Figure 3. For each model and each ensemble member that were not removed from the study, scatter plot between the maximum MLD over 2015-2100, over the Eurasian Basin, and: Left, the mean ocean surface temperature over the Eurasian basin, over the first 20 years of the run; Centre, the Arctic warming, i.e. the mean ocean surface over the last 20 years of the run minus that of the first 20 years; Right, that Arctic warming minus that of the tropical to mid-latitudes, which we call "Oceanic Polar Amplification". See Methods for latitude definitions. Colors indicate the number of years where the Arctic MLD exceeds the 500 m threshold, as per supp. Table S3. Cyan contours highlight the E3SM project models (see text).

180 Although the salinity at the beginning of the run has no relationship with the max-
 181 imum MLD reached, salinity variations are strongly correlated to MLD variations (Ta-
 182 ble 1) and the correlation differs depending on the Arctic deep convection behaviour of
 183 the models. Most models that have no deep convection in the Arctic or rarely (first two
 184 blocks) have a positive correlation between their March MLD and the surface salinity
 185 one month before, and a negative correlation with the ocean surface temperature: These
 186 models have shallower MLD when they are fresher and warmer (as expected in a chang-
 187 ing Arctic, e.g. Peralta-Ferriz and Woodgate (2015)). In the two groups of convecting
 188 models, especially so in the convective region (lines “DC”, Table 1), the correlation is
 189 positive with salinity and temperature: deeper MLD are associated with saltier and warmer
 190 surface waters the month prior. Of the four drivers investigated, the MLD is most strongly
 191 correlated with salinity or temperature for the vast majority of models (bold fonts on
 192 Table 1); usually it is strongest with the salinity for the non or rarely convecting mod-
 193 els, and with the temperature for the convecting ones (as expected from the previous para-
 194 graph). Correlations are similar when considering possible drivers the summer before (not
 195 shown, see also supp. Text S1). Unsurprisingly, the possible drivers are not independent
 196 (supp. Table S4). The correlations between temperature and salinity, and between salin-
 197 ity and either sea ice concentration or wind speed are of different signs depending on the
 198 convecting behaviour, suggesting that different processes and/or water masses are involved
 199 (see next subsection).

200 From the correlation analysis, we suspect that the models with no or rare deep con-
 201 vection may be freshening, while those with convection may become saltier. A trend anal-
 202 ysis confirms this hypothesis:

- 203 1. The models with no deep convection in the Arctic become fresher throughout the
 204 Arctic, throughout the run (Fig. 4, first two lines). Their trends are rather weak
 205 compared to the other model groups. Their winter sea ice does not retreat far into
 206 the Arctic, even by the end of the run (supp. Fig. S1).
- 207 2. The models with deep convection at the middle of the run, be it rarely (Fig. 4,
 208 lines 3 and 4) or peaking and declining (lines 5 and 6) exhibit similar trends. Their
 209 ocean surface becomes saltier and winds stronger at the location where mixed lay-
 210 ers deepen in the first half of the run; they freshen in the rest of the Arctic. In the
 211 second half, when mixed layers are shallow again, the ocean surface freshens ev-
 212 erywhere. The main difference between these two groups is in their sea ice trends,
 213 with the models whose convection peaks and slowly declines having no winter sea
 214 ice by the end of the run (supp. Fig. S1).
- 215 3. The models that convect at the end of the run (Fig. 4, last two lines) have the op-
 216 posite salinity trends: first a freshening, then a salinification in the region where
 217 mixed layers deepen, along with stronger winds.

218 Note that the trend patterns are similar in summer (supp. Figure S2), indicating that
 219 the changes occur year round. The conclusion is that Arctic deep convection is associ-
 220 ated with both a saltier ocean surface and stronger winds. Stronger winds alone are not
 221 enough (see e.g. the no deep convection group, second half of the run).

222 3.3 On causality

223 Deep convection in the Nordic Seas ceases for all CMIP6 models, but rarely emerges
 224 as a stable feature in the Arctic. In the Arctic, we find that deep convection is associ-
 225 ated with a saltier ocean surface and stronger wind speeds, and is most intense and durable
 226 in the models with the strongest sensitivity, especially so if the Arctic warms more than
 227 the mid-latitudes. But are the trends we observe the causes or consequences of deep con-
 228 vection?

Table 1. Correlation coefficient and its standard deviation for each model between the March MLD and the previous February ocean surface salinity (S), ocean surface temperature (T), sea ice concentration (SIC) and surface wind speed (Wind), for the Eurasian basin (EB) and, for the models with Arctic deep convection, where the maximum MLD of Fig. 1 exceeds 500 m (DC). Models are ordered based on their Arctic deep convection behaviour, as per Fig. 2. Only correlations significant at 95% are shown; for models with more than one ensemble member, median of the correlations of the dominating sign. For models with more than one ensemble member, standard deviation is the across-ensemble spread; spatial spread otherwise. Bold fonts highlight the maximum correlation for each model. Correlation between parameters is shown in supp. Table S4.

Model	Region	MLD vs S	MLD vs T	MLD vs SIC	MLD vs Wind
BCC-CSM2-MR	EB	0.47 \pm 0.15	-0.41 \pm 0.17	-0.28 \pm 0.35	0.23 \pm 0.24
CAMS-CSM1-0	EB	0.54 \pm 0.02	-0.49 \pm 0.00	-0.35 \pm 0.03	0.29 \pm 0.04
CAS-ESM2-0	EB	0.59 \pm 0.04	-0.49 \pm 0.06	0.51 \pm 0.06	-0.24 \pm 0.01
CESM2-FV2	EB	-0.29 \pm 0.37	0.22 \pm 0.37	-0.23 \pm 0.16	0.31 \pm 0.08
CESM2-WACCM	EB	0.34 \pm 0.06	-0.31 \pm 0.05	0.25 \pm 0.06	0.30 \pm 0.02
CESM2	EB	0.32 \pm 0.08	-0.30 \pm 0.04	0.30 \pm 0.05	0.32 \pm 0.02
E3SM-1-1-ECA	EB	0.43 \pm 0.14	-0.45 \pm 0.47	0.60 \pm 0.41	-0.31 \pm 0.31
FGOALS-f3-L	EB	0.51 \pm 0.21	-0.51 \pm 0.10	0.59 \pm 0.13	-0.26 \pm 0.16
FGOALS-g3	EB	0.89 \pm 0.01	-0.28 \pm 0.02	0.46 \pm 0.04	0.28 \pm 0.04
GFDL-CM4	EB	0.39 \pm 0.31	-0.25 \pm 0.39	-0.31 \pm 0.29	-0.27 \pm 0.19
NorESM2-LM	EB	-0.28 \pm 0.36	0.36 \pm 0.31	-0.26 \pm 0.22	0.26 \pm 0.16
ACCESS-ESM1-5	EB	-	-	-	-
	DC	-	-	-	-
E3SM-1-0	EB	0.38 \pm 0.01	-0.50 \pm 0.12	0.51 \pm 0.05	-0.26 \pm 0.04
	DC	-	-	-	-
E3SM-1-1	EB	0.39 \pm 0.14	-0.41 \pm 0.27	0.55 \pm 0.28	-0.28 \pm 0.27
	DC	0.51 \pm 0.01	0.34 \pm 0.02	-0.29 \pm 0.01	0.43 \pm 0.01
GISS-E2-1-G	EB	0.61 \pm 0.03	-0.59 \pm 0.04	0.35 \pm 0.08	0.27 \pm 0.04
	DC	0.48 \pm 0.14	0.67 \pm 0.10	-0.37 \pm 0.08	0.32 \pm 0.09
MRI-ESM2-0	EB	0.62 \pm 0.03	-0.40 \pm 0.04	0.29 \pm 0.05	0.31 \pm 0.04
	DC	-	-	-	-
NESM3	EB	-0.31 \pm 0.01	-0.24 \pm 0.01	-0.24 \pm 0.01	-0.23 \pm 0.02
	DC	-	-	-	-
CMCC-ESM2	EB	0.59 \pm 0.45	0.45 \pm 0.37	-0.31 \pm 0.43	0.28 \pm 0.25
	DC	0.65 \pm 0.11	0.49 \pm 0.14	-0.40 \pm 0.12	0.29 \pm 0.08
CanESM5-1	EB	0.50 \pm 0.03	0.39 \pm 0.11	-0.46 \pm 0.08	0.36 \pm 0.05
	DC	0.52 \pm 0.04	0.39 \pm 0.12	-0.48 \pm 0.08	0.36 \pm 0.05
CanESM5	EB	-	-	-	-
	DC	-	-	-	-
HadGEM3-GC31-LL	EB	-	-	-	-
	DC	-	-	-	-
UKESM1-0-LL	EB	0.56 \pm 0.02	0.64 \pm 0.01	-0.51 \pm 0.02	0.43 \pm 0.05
	DC	0.57 \pm 0.02	0.65 \pm 0.02	-0.54 \pm 0.02	0.43 \pm 0.06
ACCESS-CM2	EB	0.40 \pm 0.05	0.45 \pm 0.19	-0.28 \pm 0.08	0.28 \pm 0.03
	DC	0.44 \pm 0.05	0.76 \pm 0.11	-0.51 \pm 0.08	0.34 \pm 0.04
CNRM-CM6-1	EB	0.40 \pm 0.07	0.73 \pm 0.05	-0.62 \pm 0.05	0.38 \pm 0.05
	DC	0.46 \pm 0.05	0.77 \pm 0.08	-0.68 \pm 0.05	0.47 \pm 0.04
CNRM-ESM2-1	EB	0.44 \pm 0.15	0.77 \pm 0.48	-0.53 \pm 0.31	0.43 \pm 0.13
	DC	0.46 \pm 0.09	0.86 \pm 0.10	-0.57 \pm 0.16	0.47 \pm 0.12
EC-Earth3-Veg-LR	EB	0.44 \pm 0.04	0.85 \pm 0.05	-0.55 \pm 0.12	0.35 \pm 0.05
	DC	0.45 \pm 0.03	0.90 \pm 0.05	-0.66 \pm 0.04	0.39 \pm 0.03
EC-Earth3-Veg	EB	0.47 \pm 0.13	0.85 \pm 0.43	-0.49 \pm 0.17	0.32 \pm 0.09
	DC	0.52 \pm 0.10	0.89 \pm 0.07	-0.53 \pm 0.12	0.34 \pm 0.10

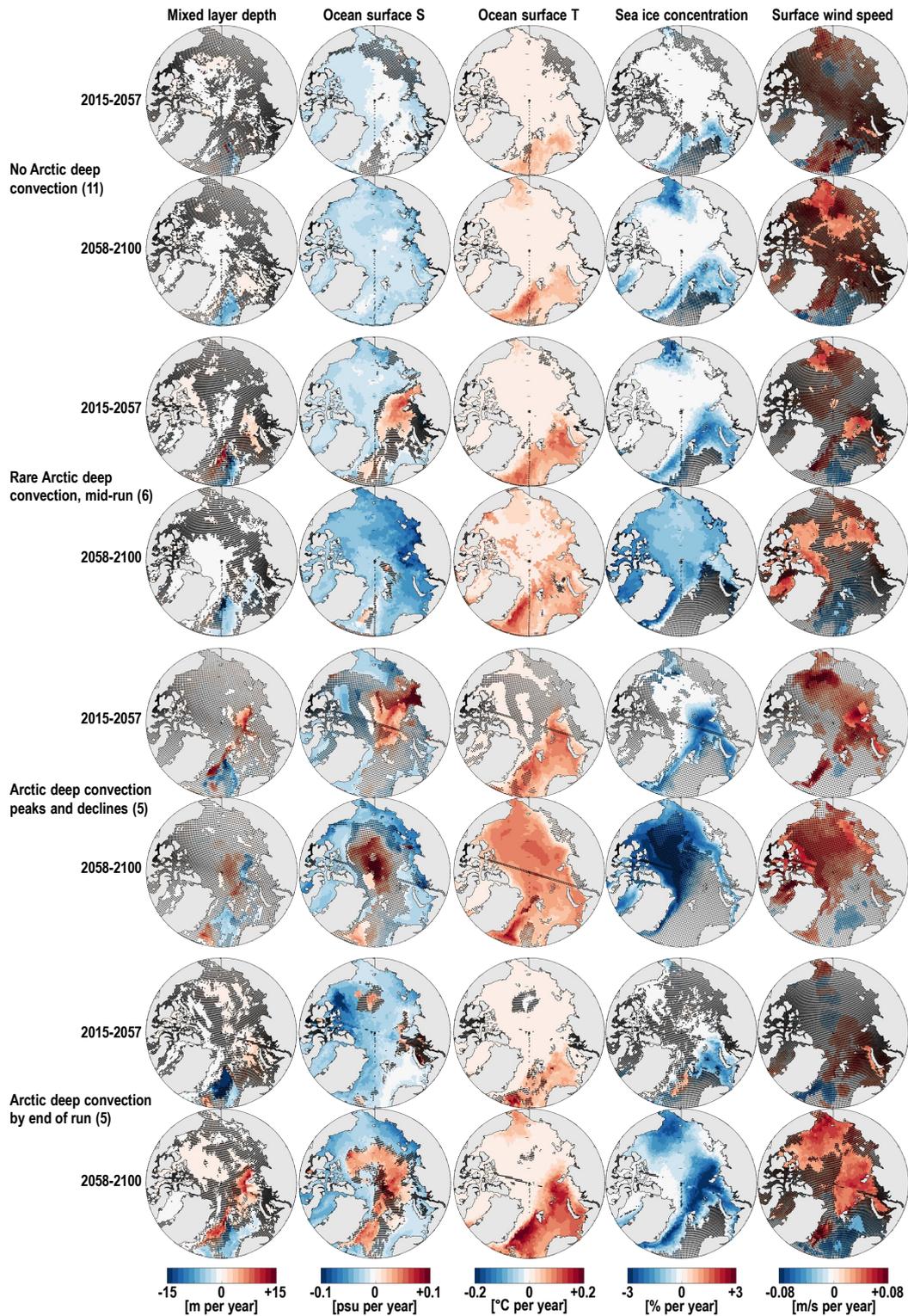


Figure 4. Composite trends based on the models’ Arctic deep convection behaviours of Fig. 2, for the first half of the 21st century run (top rows) and the second half (bottom rows), in March MLD (first column), and February ocean surface salinity (S, second), ocean surface temperature (T, third), sea ice concentration (fourth) and surface wind speed (last). Behaviours are described to the left of the figure, and number of models for each behaviour is given in parentheses. For each panel, stippling indicates non-significant trends and/or model disagreement regarding the trend’s sign. Straight stippled lines across the North Pole are an artefact of the necessary interpolation.

229 The Arctic Ocean surface warming and sea ice loss trends, year-round, are to be
 230 expected in a warming world (IPCC, 2019). Besides, they are consistent across-models,
 231 regardless of their convecting behaviour in the Arctic. Similarly, the models' sensitiv-
 232 ities have been attributed to their representation of cloud cover and cloud albedo (Zelinka
 233 et al., 2020), which locally can be affected by the heat and moisture fluxes from deep con-
 234 vection (Monroe et al., 2021), but in coarse models is more likely due to each model's
 235 cloud parameterisation (Zelinka et al., 2020). Finally, changes in both "normal" winds
 236 (Screen et al., 2018) and cyclones (Rinke et al., 2017) are most commonly attributed to
 237 the large scale atmospheric circulation, although local changes at the boundary layer be-
 238 cause of sea ice loss may accelerate winds (DuVivier et al., accepted).

239 As for the salinity, Lique et al. (2018) attributed the freshening - salinification dipoles
 240 to changes in the large scale oceanic circulation, whereas Davis et al. (2016) attributed
 241 the increased salinity to increased vertical mixing. That is, for the former it drives Arc-
 242 tic deep convection; for the latter, it is a consequence of it. A local change in salinity can
 243 be also caused by enhanced sea ice formation, but we find a negative correlation between
 244 winter salinity and sea ice concentration among the convecting models (supp. Table S4),
 245 which makes this causality unlikely given that the sea ice maps do not seem to exhibit
 246 polynyas (supp. Fig. S1). Salinification taking place year-round, at the same location
 247 as winds are increasing, would instead suggest an enhanced sea ice drift, but the detailed
 248 sea ice mass budget of Keen et al. (2021) shows the opposite.

249 Alternatively, the impact of deeper MLD on the Arctic surface salinity will depend
 250 on each model's Atlantic layer. Heuzé et al. (2023) showed strong biases in that layer,
 251 with most models having it too deep. Khosravi et al. (2022) further showed that there
 252 is no consistency across CMIP6 models regarding the changes of that Atlantic layer dur-
 253 ing SSP5-8.5, which Mulwijk et al. (2023) linked to the models' lack of consensus re-
 254 garding future changes in stratification in the Eurasian basin and in Atlantification. As
 255 stratification and deep convection are intimately linked, this is another feedback that makes
 256 the causality uncertain. One can unfortunately not study the onset of deep convection
 257 in more details without higher temporal resolution output. Most likely, the causality will
 258 be different for each model, based on their choices of parameterisation in the atmosphere
 259 (Zelinka et al., 2020), sea ice (Keen et al., 2021) and ocean (Heuzé et al., 2023), and even
 260 their definition of the mixed layer (Griffies et al., 2016). But individual model studies
 261 require access to each model's code, and are way beyond the scope of this paper.

262 4 Conclusions

263 We used all CMIP6 models and all their ensemble members for which the mixed
 264 layer depth and its potential drivers the surface salinity, temperature, sea ice concentra-
 265 tion, and wind speed, were available for the strongest warming scenario SSP5-8.5. Af-
 266 ter removing the ensemble members that had spurious Arctic deep convection (defined,
 267 as in Lique et al. (2018), as MLD deeper than 500 m) over 2015-2023, we were left with
 268 27 models, of which 11 had no deep convection in the Arctic over 2015 - 2100; 6 that had
 269 it extremely rarely (usually 4 years or fewer), by the middle of the run; 5 for which deep
 270 convection peaked in the first half of the run and then declined and disappeared; and
 271 5 in which deep convection emerged in the Arctic in the second half of the run and still
 272 convected in 2100. All models exhibit a cessation of deep convection in the Nordic Seas,
 273 showing that deep convection in the Arctic is not simply a northward migration of the
 274 Nordic Seas ventilation. The Arctic MLD was most strongly correlated with the surface
 275 salinity, and the sign of this correlation depended on whether the model convected or
 276 not. Similarly, when and where the models are not convecting, their surface salinity fresh-
 277 ens; at the location where they do, when they do, it becomes saltier and surface winds
 278 are increasing. Neither the exact mechanism triggering deep convection nor the direc-
 279 tion of the causality between deep convection and that compound salinification and wind
 280 event can be investigated in more details with CMIP6 monthly output. The fact that

281 models of the same family have the same convection behaviour; that the depth and fre-
 282 quency of the maximum MLD is strongly correlated to early-run biases and sensitivity;
 283 and that the other processes involved have been linked to individual model parameter-
 284 isations (Zelinka et al., 2020; Keen et al., 2021; Mulwijk et al., 2023) suggest that the
 285 trigger for Arctic deep convection is model-specific, and its determination requires in-
 286 depth sensitivity studies for each model. Such in-depth investigation could also lead to
 287 model improvement. CMIP6 models consistently exaggerate deep convection both in the
 288 North Atlantic and in the Southern Ocean (Heuzé, 2021). Understanding why they have
 289 no such consensus in the Arctic could hold the key to a more realistic representation of
 290 mixing, globally.

291 5 Open Research

292 All CMIP6 data are freely available via the Earth Grid System Federation. For this
 293 paper, we primarily used the German Climate Computing Centre (DKRZ) node [https://
 294 esgf-data.dkrz.de/search/cmip6-dkrz/](https://esgf-data.dkrz.de/search/cmip6-dkrz/).

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