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1 **Climate change impacts the vertical structure of marine ecosystem** 2 **thermal ranges**

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6 **Temperature drives global ocean patterns of biodiversity, shaping thermal niches**
7 **through thresholds of thermal tolerance. Global warming is predicted to change thermal**
8 **range bounds, yet research has primarily focused on temperature at the sea surface,**
9 **while knowledge of changes through the depths of the water column is lacking. Here**
10 **using daily observations from Ocean Sites and model simulations, we track shifts in**
11 **ocean temperatures, focusing on the emergence of thermal ranges whose future lower**
12 **bounds exceed current upper bounds. These emerge below 50 m depth as early as ~2040**
13 **with high anthropogenic emissions, yet are delayed several decades for reduced**
14 **emission scenarios. By 2100, concomitant changes in both lower and upper boundaries**
15 **can expose pelagic ecosystems to thermal environments never experienced before.**
16 **These results suggest the redistribution of marine species might differ across depth,**
17 **highlighting a much more complex picture of the impact of climate change on marine**
18 **ecosystems.**

19 Anthropogenic climate change impacts the world's oceans by warming significantly the upper
20 layers^{1,2}. This heat content increase is projected to alter long-term well defined thermal niches
21 driving species redistribution at a global scale^{3,4}. These changes are already affecting goods
22 and services provided by the oceans⁵, and are projected to be amplified with rising greenhouse
23 gas emissions. A close coupling between marine organisms' physiological thermal tolerances
24 and environmental temperature⁶⁻⁹ suggests that distributional shifts can be predicted by tracking
25 changes on the lower and upper bounds of the ecosystems' thermal ranges^{10,11}. Since the
26 vertical structure of temperature in the ocean is rarely considered, current understanding on
27 how and when climate change will drive changes in marine habitats is largely restricted to the
28 ocean surface (e.g., ref. ^{4,12,13}). However, considering only the ocean surface offers a limited
29 view of an ocean under anthropogenic pressure¹⁴, and broad scale studies on how species

30 distribution will be affected by changes in ecosystems' thermal ranges below the surface are
31 lacking. In this framework, we aim to track the emergence of future changes in marine
32 ecosystem thermal ranges across the water column by following the evolution of the vertical
33 structure of ocean temperature.

34 Predicting changes in marine ecosystems due to variations in environmental temperature relies
35 on the assumption that species' tolerance ranges reflect the magnitude of local temperature
36 variability^{8,15}. Marine organisms tend indeed to live in thermal environments tolerable within their
37 thermal tolerance limits^{7,16}. In an attempt to characterize organisms' thermal distribution, Stuart-
38 Smith et al.¹⁰ used the 5th and 95th percentiles range of sea surface temperature. We extend
39 this concept through the water column by considering the lower and upper limits of the thermal
40 range to be represented by the environmental temperature minimum (Tmin) and maximum
41 (Tmax). At each depth, Tmin and Tmax correspond to the annual 1st and 99th percentile as
42 computed using the statistical distribution of daily records, respectively. Since both boundaries
43 are warming or cooling differently across depth in response to climate change, marine
44 organisms will confront transformed thermal environments in the future. In this regard, the level
45 of dissimilarity with environmental conditions at which organisms are adapted to, or climate
46 novelty^{17,18}, may provide a measure of the range of temperatures never experienced before.
47 The ability of an organism to adapt to this novel thermal environment ultimately depends on the
48 speed at which significant changes emerge^{13,19,20}. Therefore, our overarching objective is to
49 understand where, when, and how global warming-induced changes over the water column in
50 the environmental thermal range bounds, i.e., Tmin and Tmax, will take place in the future
51 affecting current marine ecosystems.

52 We take advantage of comprehensive data sets of daily three-dimensional ocean temperatures
53 from both the long-term Ocean Sites (OS) network and state-of-the-art Earth System Models
54 (ESMs). We select six OS stations for which at least seven years of daily temperature
55 observations from the surface to ~1000 m are available (Supplementary Table 1). We map them
56 into polar, temperate, and tropical domains, and determine the surface area informed by each
57 station by computing the level of similarity in daily temperature profiles using a p-value analysis
58 (Fig. 1a, see Methods). A pattern of alternation of cooling and warming periods is seen over the
59 time of available observations (Fig. 1b). In the two southernmost stations, these episodes
60 predominantly consists on warming periods and last a few years. They last longer in the rest of
61 the stations, at which these episodes end towards general warming. The first 400 m of the water

62 column at station CIS-1 ends towards general cooling, though warming anomalies dominate
63 during most of the observational period. Though measurements' coverage is not complete along
64 depth and time for some stations, we consider they allow us to confidently compute annual Tmin
65 and Tmax, and extract trends to compare with ESM simulations.

66 Fifteen-member ensemble simulations were performed with CNRM-ESM2-1²¹ (see Methods)
67 encompassing the historical period (1850-2014) followed by three future projections (2015-
68 2100) that explore contrasted emission pathways²² developed for the sixth Coupled Model Inter-
69 comparison Project²³ (CMIP6); a low (SSP1-2.6), a moderate (SSP2-4.5), and a high (SSP5-
70 8.5) emission pathways. To test the robustness of our results, an ensemble of opportunity
71 consisting of two additional ESMs following a single member SSP5-8.5 simulation is used (see
72 Supplementary Table 2). At each OS location, we extract a subsample of the historical + SSP5-
73 8.5 simulation that matches the observational period. Comparison between both data sets
74 (Extended Data Fig. 1) show simulation deviates from observations at the northernmost
75 stations, especially at station FRAM at which observations show a warming period before 2010
76 that may originate from an anomaly advection of North Atlantic waters northwards²⁴. This
77 anomalous episode can also be behind the positive anomaly at station CIS-1.

78 Observations and model data are then used to compute profiles of Tmin and Tmax over the
79 observational period. We derive the anomalies of the lower and upper thermal range boundaries
80 by removing the mean temperature profile. These profiles are then employed to determine the
81 magnitude of the thermal range across depth (Fig. 2), informing the vertical structure of current
82 ecosystems' thermal environment. To assess that the vertical structure of the thermal
83 environment is not biased by the short time period of available observations, we additionally
84 compute these profiles for a 30 years subsample of model data at each station. A comparative
85 analysis (see Supplementary Fig. 1) shows that observational period profiles are consistent with
86 longer time span profiles. Thermal ranges decrease toward high and low latitudes⁸ being wider
87 at temperate domains, where they average $\sim 5^\circ$ C across the first 1000 m depth, and toward
88 deeper layers as the temperature interannual variability also declines. The largest amplitude of
89 the thermal range takes place in the first 200 m of the water column (5.8° C on average) where
90 most of the biota lives²⁵, while it narrows to below (1.4° C on average below 200 m).

91 Environmental thermal ranges can be represented by a combination of their breadth and their
92 midpoint (Fig. 2, middle panels). Thermal breadth corresponds to the difference between Tmin
93 and Tmax. Midpoint temperature (Tmidpoint) is computed as the arithmetic mean of Tmin and

94 Tmax. Thermal ranges show a wider breadth above 50 m that narrows rapidly with depth.
95 Modelled thermal ranges are in agreement with observed counterparts, except for an
96 underestimation at FRAM. Excluding FRAM, the agreement is further corroborated by Tmidpoint
97 profiles ($R^2 > 0.8$). At MBARI, simulated thermal ranges as well as the Tmidpoint profile are
98 warmer than derived from the observations, maybe due to the difficulties of ESMs to simulate
99 eastern boundary regions as the California upwelling (see ref. ^{21,26,27}).

100 **Concomitant changes in thermal range boundaries**

101 Concomitant changes in thermal range lower and upper boundaries can be seen as a
102 compound event²⁸ since they can result in several developments of the thermal range
103 (Extended Data Fig. 2). Profiles of the linear trends of change for Tmin and Tmax following
104 SSP5-8.5 (Fig. 2) show that the paces of change of current thermal ranges differ across depth.
105 In fact, significant trends in Tmin and Tmax over recent years (Extended Data Fig. 3 and 4) may
106 lead to various developments of the thermal ranges as depicted by the observations and as
107 simulated by CNRM-ESM2-1. In general, warming trends are stronger than cooling trends thus
108 resulting in warmer thermal ranges. Overlapping this warming, imbalanced warming of Tmax will
109 result in wider thermal ranges while excess warming of Tmin will shrink the thermal range. As
110 global warming trends are likely to increase²⁹⁻³¹, it is key to understand the time at which these
111 changes may occur, pending on the level of future greenhouse gases emission and associated
112 global warming levels.

113 **Emergence of changes in current thermal ranges**

114 We estimate when and where substantial changes in the thermal ranges may emerge from
115 warming-induced changes in their bounds, by modifying the canonical approach of the Time of
116 Emergence³² (ToE). We track the evolution of Tmin across the water column under the three
117 contrasted scenarios with respect to the current (1990 to 2020) Tmidpoint and Tmax,
118 considered as key thresholds for marine ecosystems. We also built a 5th-95th confidence
119 interval for each ToE estimate accounting for internal climate variability, by using a distribution
120 of 100 randomly selected 30 yearslong subsamples of the piControl simulation. When Tmin
121 surpasses a first threshold (Tmidpoint), we consider that the shift of the thermal range may
122 represent a *warning* to current ecosystems since Tmidpoint has been observed to align well with
123 the temperature of maximum ecological success (see ref. ^{9,33}). Furthermore, when an
124 ecosystem will be exposed to a Tmin that is warmer than the current Tmax, we consider that

125 organisms should deal with a completely *new thermal range* (see Fig. 3a). Since marine
126 organisms are strongly sensitive to changes in their upper boundary (e.g., ref. ^{34,35}), we combine
127 this analysis with tracking the timing at which the accumulation of heat in the ocean due to
128 ocean warming causes T_{max} to exceed current natural variability, a threshold that can be up to
129 30% higher than current T_{max} . Altogether, these metrics provide a comprehensive view on how
130 climate change will transform marine thermal environments.

131 The earliest times of emergence of T_{max} from current natural variability appear before mid-
132 century (Fig. 3b). Consistently across scenarios, warmer T_{max} will affect the upper (0 – 50 m)
133 and lower (50 – 200 m) epipelagic waters in the next few decades (firstly appearing from 2022
134 to 2053, depending on the station), though this warming will occur sooner (as early as during the
135 present decade) in the mesopelagic waters (200 – 1000 m) of all stations. T_{max} -based times of
136 emergence delay up to several decades when moderate and low emission scenarios are
137 considered. However, this feature is less consistent at mesopelagic waters, where early
138 emergence times are relatively independent from the scenario considered, possibly arising from
139 warming commitment due to past emissions or to natural features of the ocean interior (see ref.
140 ^{36,37}).

141 For T_{min} -based times of emergence, we find a rather good agreement across all stations in the
142 first 200 m of the water column (Fig. 3b), with most T_{min} -driven changes in the thermal range
143 appearing within lower epipelagic waters (50 – 200 m). This feature, broadly simulated by the
144 three ESMs (see Supplementary Fig. 2), results from both the shape of current thermal ranges,
145 and the rather homogeneous pattern of higher warming of T_{max} over T_{min} in these layers (Fig.
146 2). In the four northernmost stations, the emergence of these warnings are delayed in the
147 deepest layers (> 700 m) as the rate of change of T_{min} decreases with depth, even though
148 current thermal ranges are the narrowest of the vertical profile (see Fig. 2). At BATS, at which
149 T_{min} and $T_{midpoint}$ are close across the mesopelagic layer, T_{min} crosses this threshold as
150 early as the present decade. Small rates of change in the thermal ranges preclude this warning
151 to emerge during this century at the mesopelagic layer of HOT-01 (see Extended Data Fig. 5),
152 though they appear by ~2040 below 700 m depth as T_{min} warms more rapidly (see Fig. 2).

153 The emergence of T_{min} crossing current T_{max} follows a similar profile of that for $T_{midpoint}$, but
154 with a delay of about two to four decades: all domains see emergence before 2080 for depths
155 above 200 m, and before 2070 for depths below 200 m. Appearance occurs sooner in the
156 tropics than in northern stations.

157 Consistently across all stations, Tmin-based emergence times are delayed by several years
158 when a moderate emission pathway is considered, and by up to decades when a low emission
159 pathway is accounted for. In general, the emergence of Tmin crossing current Tmidpoint occurs
160 earlier for the high emission scenario than the emergence of Tmin crossing current Tmax for the
161 moderate emission scenario, except at FRAM. However, taking into account the internal
162 variability confidence intervals considered here, it is difficult to distinguish between the
163 emergence times informed by different scenarios.

164 **End-of-the-century thermal ranges**

165 Under the high emission scenario, end-of-the-century (2080 to 2100) thermal ranges differ from
166 those estimated over the historical period (1990 to 2014) (Fig. 4 and Extended Data Fig. 6). In
167 general, both the lower and upper bounds will be warmer across the water column. Situations in
168 which end-of-the-century Tmin will be warmer than historical Tmax occur at all stations within
169 either the lower epipelagic or mesopelagic, or in both layers, in agreement with emergence
170 times shown in Fig. 3. The only exceptions are found in the deepest levels of FRAM, and in
171 most parts of the mesopelagic layer of HOT-01, where Tmax and Tmin are predicted to be
172 slightly cooler.

173 We track novel thermal space at the end of the century using *Climate Novelty* (C_N , see
174 Methods). This metric accounts for the difference between the historical and end-of-the-century
175 period's thermal ranges, and gives insights of the range of temperatures that has never been
176 experienced before for a particular environment. C_N profiles (Fig. 4) show most lower epipelagic
177 and mesopelagic waters' thermal ranges will be >50% novel, consistently with previous studies
178 (see ref. ³⁸ for climate velocity analysis). At HOT-01, C_N of mesopelagic waters indicates
179 relatively low levels of novelty. Nonetheless, this station presents novel thermal ranges at the
180 very deepest waters, in agreement with the emergence of Tmin crossing Tmax warnings (Fig.
181 3). At the upper epipelagic waters, the level of novelty is lower than 50% at all stations except
182 FRAM, at which C_N is closer to this value. However, while the overall level of novelty
183 experienced in the upper pelagic waters will be less than in the mesopelagic, organisms there
184 already have to deal with large interannual thermal variability, and may be near the upper limits
185 of their tolerance. As such, the emergence of warmer Tmax (Fig. 3) along with the occurrence of
186 short-term extreme events like marine heatwaves^{39,40} (MHW) will impact upper waters. In this
187 respect, an analysis on MHW duration and intensity (Extended Data Fig. 7; see Supplementary
188 Text) shows they will last longer (~2.6 days) and be more intense (>0.3°C) by 2100 at tropical

189 stations above 200 m considering SSP5-8.5.

190 Depending on the station and the layer considered, end-of-the-century thermal ranges will be
191 warmer/cooler as a result of comparable warming/cooling of T_{min} and T_{max} (Fig. 4). They can
192 also be warmer and narrower as a result of quicker warming of T_{min}, or warmer and wider by
193 T_{max} warming more rapidly than T_{min}. Wider thermal ranges will result above 200 m at all
194 stations under a high-emission scenario, with the only exception at CIS-1 due to an excess
195 warming of T_{min} below 50 m (Extended Data Fig. 6). Below 200 m, the pace of warming of both
196 bounds are comparable, generating both wide or narrow thermal ranges depending on the
197 station. Both T_{min} and T_{max} changes as long as C_N profiles remain similar when considering a
198 moderate emission scenario (SSP2-4.5) (Extended Data Fig. 8), but showing lower difference
199 values between end-of-the-century and historical thermal range bounds. Considering a high
200 mitigation scenario (SSP1-2.6), all stations show warming anomalies (Extended Data Fig. 9),
201 except at station CIS-1 where both bounds will generally be cooler than the historical mean.
202 Only developments at stations FRAM and K276 are consistent across all emission scenarios.

203 **Implications of the work**

204 Current research, mainly based on monthly surface data, suggest an expansion of marine
205 ectotherms toward their poleward range boundaries as a response to the warming of the
206 oceans^{41–43}. Our work reveals a much more complex picture, demonstrating the added-value of
207 scrutinizing climate change perturbations on ecosystem thermal ranges across the water
208 column with respect to surface data. We find that climate change will generate changes across
209 the water column in the upper and lower thermal range bounds on six OS stations. If
210 anthropogenic emissions continue to rise, we project that the upper bound of thermal ranges will
211 emerge from current natural variability within the present decade, while the lower bound may
212 cross the upper limit of current thermal ranges as early as ~2040 in pelagic waters. These
213 changes can be delayed several decades with immediate emission reduction consistent with a
214 high mitigation scenario, in line with results included in the last IPCC AR6 report⁴⁴, implying
215 marine habitats are committed to change even if reaching net zero emissions by mid-century. In
216 response to ocean warming, thermal ranges will mostly be warmer by 2100. Nonetheless,
217 excess warming of T_{min} with respect to T_{max} will result in narrower thermal ranges, while
218 excess warming of T_{max} with respect to T_{min} will result in wider thermal ranges (Extended
219 Data Fig. 10). In the former case, new conditions will defy local adaptation of inhabitant
220 organisms, possibly leading to the loss of ecosystems' habitability if species cannot adjust their

221 lifecycle to the contraction of their thermal environment. In the latter, possible spread of species
222 from neighbour habitats may generate additional stresses by changing species interaction^{4,45},
223 especially at high-latitude stations where the range of tolerable temperature for marine
224 ectotherms are narrow⁸, and the warming of temperate waters may increase the abundance of
225 species at their poleward range boundaries⁴⁶. Furthermore, wider thermal ranges may challenge
226 the capacity limits of species already exposed to large interannual thermal variability by the
227 excess warming of current T_{max}. In addition, C_N profiles indicate that the thermal environment
228 will be novel at several depth levels below upper layers, suggesting marine organisms living at
229 depth might be impacted before upper waters thermal ranges undergo substantial changes;
230 including the emergence of warmer T_{max} that appear sooner in mesopelagic waters.

231 Assuming organisms are adapted to current environmental conditions, such changes may lead
232 to important rearrangements of marine habitats across latitude and depth⁴⁷ in the decades to
233 come. Though the possibility of looking for refuge at depth may exist for some organisms (e.g.,
234 ^{41,48}), vertical rearrangements may be limited by the capacity of the organisms to acclimate to
235 higher hydrostatic pressure⁴⁹, by high light requirements (e.g., ⁵⁰), or by deeper thermal ranges
236 that are not suitable anymore. Our work indicates that the resilience of polar organisms, which
237 are very sensitive to elevated temperatures^{51,52}, will be profoundly affected by substantial
238 changes on current thermal ranges (C_N ~ 100% between 100 to 500 m depth) along with
239 variations in the sea ice coverage (e.g., ref. ⁵³). In tropical regions, where some species live
240 near their physiological limits⁵⁴, our results indicate marine organisms living at depth will be
241 challenged sooner, as rapid warming of T_{min} in the mesopelagic layer will reduce their thermal
242 environment. The reduced capacity of adaptation to warmer upper thermal boundaries of
243 organisms living at these aseasonal regions^{46,55-57} will reinforce their vulnerability in the next
244 decades by the emergence of T_{max} from current natural variability. In temperate areas,
245 ectotherms like the *Atlantic Cod* may be affected by a warmer thermal environment above 200
246 m, where spawning takes place⁵⁸ and by changes in the vertical structure of their thermal range
247 that may disrupt their daily vertical migration (e.g., ref. ⁵⁹). In addition, extreme events like
248 MHWs are expected to increase (ref. ⁶⁰ and Extended Data Fig. 7; see Supplementary Text)
249 with devastating effects on marine ecosystems (e.g., ref. ⁶¹⁻⁶³).

250 Anthropogenic climate change is pushing marine organisms to adapt to a less-oxygen acidified
251 warmer ocean^{64,65}. These climatic impact drivers, along with numbers of anthropogenic
252 stressors like fishing⁶⁶, acoustic pollution⁶⁷ or plastics⁶⁸, and extreme and compound events⁶⁹,

253 exacerbate marine ecosystems degradation. Our results add new insights on the timing of long-
254 term global warming impacts acting throughout the water column, and suggest that future
255 research should consider the three-dimensional extension of the thermal environment of marine
256 organisms in the assessments of climate change impacts.

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263 **Author Contributions** Y.S.F. and R.S. conceived the study, developed the data sets,
264 performed the computations and wrote the manuscript.

265 **Competing interests** The authors declare no competing interests.

266 **Figure captions**

267 **Figure 1: Overview of the Ocean Sites (OS) stations.** (a) Geographic location and period of
268 the six available long-term OS stations. Colour code indicates how the OS stations are grouped
269 into polar (blue), temperate (green) and tropical (orange) ocean domains. The shading indicates
270 the ocean domains that are informed by each OS station. (b) Depth-time variations of daily
271 ocean temperature anomalies over the observational period from the surface to 1000 m.
272 Anomalies are computed by removing the daily climatological temperature to daily temperature.
273 Red (blue) colours indicate warmer (cooler) daily temperature variations with respect to the daily
274 climatological temperature. Blank space indicates lack of observational data.

275 **Figure 2: Profiles of thermal ranges.** Profiles of the lower (bluish) and upper (reddish) thermal
276 range boundaries anomalies relative to temperature mean over the observational period, for
277 both observations (shading) and model (lines). Model profiles are represented with (bold) and
278 without (thin) applying the observational mask in space and time. Dashed lines demarcate the
279 upper epipelagic, lower epipelagic and mesopelagic layers. Middle panels show profiles of
280 thermal ranges' thermal midpoint (line) and breadth (shading) for observations (orange) and

281 model (grey). At right, profiles of the linear trends from 1990 to 2100 following SSP5-8.5 are
282 given for both thermal range boundaries.

283 **Figure 3: Emergence of climate change signals in thermal ranges.** (a) Schematic explaining
284 how the evolution of Tmin and Tmax may result in the emergence of substantial changes in
285 current thermal ranges. (b) Profiles of the timing of when future Tmin is warmer than current
286 Tmidpoint and Tmax. Confidence interval of the emergence of these thresholds is included by
287 accounting for climate variability. Profiles of the timing of when future Tmax exceeds the natural
288 variability of current Tmax are included. Dashed lines demarcate the upper epipelagic, lower
289 epipelagic and mesopelagic layers. Solid, dashed, dotted lines represent SSP5-8.5, SSP2-4.5,
290 SSP1-2.6.

291 **Figure 4: End-of-the-century thermal ranges.** Profiles illustrate anomalies for Tmin and Tmax
292 with respect to temperature mean over last years of the historical simulation (1990 to 2014) for
293 historical and end-of-the-century (2080 to 2100) periods, considering SSP5-8.5. Reddish
294 (bluish) shading areas indicate ocean layers where end-of-the-century Tmin and Tmax are
295 warmer (cooler) than the historical period. Dashed lines demarcate the water column into upper
296 epipelagic, lower epipelagic and mesopelagic. Middle panels *Climate Novelty* profiles represent
297 the novel environmental temperatures experienced with respect to the end-of-the-century
298 thermal range. Boxes indicate how changes in both boundaries have reshaped thermal ranges
299 under the three scenarios.

300 **References**

- 301 1. Barnett, T. P. *et al.* Penetration of human-induced warming into the World's Oceans.
302 *Science (80-.)*. **309**, 284–287 (2005).
- 303 2. Levitus, S. *et al.* Global ocean heat content 1955-2008 in light of recently revealed
304 instrumentation problems. *Geophys. Res. Lett.* **36**, n/a-n/a (2009).
- 305 3. Poloczanska, E. S. *et al.* Global imprint of climate change on marine life. *Nat. Clim.*
306 *Chang.* **3**, 919–925 (2013).
- 307 4. García Molinos, J. *et al.* Climate velocity and the future global redistribution of marine
308 biodiversity. *Nat. Clim. Chang.* **6**, 83–88 (2016).
- 309 5. Free, C. M. *et al.* Impacts of historical warming on marine fisheries production. *Science*
310 *(80-.)*. **363**, 979–983 (2019).

- 311 6. Hughes, N. F. & Grand, T. C. Physiological ecology meets the ideal-free distribution:
312 Predicting the distribution of size-structured fish populations across temperature
313 gradients. *Environ. Biol. Fishes* **59**, 285–298 (2000).
- 314 7. Tittensor, D. P. *et al.* Global patterns and predictors of marine biodiversity across taxa.
315 *Nature* **466**, 1098–1101 (2010).
- 316 8. Sunday, J. M., Bates, A. E. & Dulvy, N. K. Global analysis of thermal tolerance and
317 latitude in ectotherms. *Proc. R. Soc. B Biol. Sci.* **278**, 1823–1830 (2011).
- 318 9. Waldock, C., Stuart-Smith, R. D., Edgar, G. J., Bird, T. J. & Bates, A. E. The shape of
319 abundance distributions across temperature gradients in reef fishes. *Ecol. Lett.* **22**, 685–
320 696 (2019).
- 321 10. Stuart-Smith, R. D., Edgar, G. J. & Bates, A. E. Thermal limits to the geographic
322 distributions of shallow-water marine species. *Nat. Ecol. Evol.* **1**, 1846–1852 (2017).
- 323 11. Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L. & Levin, S. A. Marine taxa track
324 local climate velocities. *Science (80-.)*. **341**, 1239–1242 (2013).
- 325 12. Beaugrand, G., Edwards, M., Raybaud, V., Goberville, E. & Kirby, R. R. Future
326 vulnerability of marine biodiversity compared with contemporary and past changes. *Nat.*
327 *Clim. Chang.* **5**, 695–701 (2015).
- 328 13. Trisos, C. H., Merow, C. & Pigot, A. L. The projected timing of abrupt ecological
329 disruption from climate change. *Nature* **580**, 496–501 (2020).
- 330 14. Levin, L. A. & Le Bris, N. The deep ocean under climate change. *Science (80-.)*. **350**,
331 766–768 (2015).
- 332 15. Deutsch, C. A. *et al.* Impacts of climate warming on terrestrial ectotherms across latitude.
333 *Proc. Natl. Acad. Sci.* **105**, 6668–6672 (2008).
- 334 16. Sunday, J. M., Bates, A. E. & Dulvy, N. K. Thermal tolerance and the global redistribution
335 of animals. *Nat. Clim. Chang.* **2**, 686–690 (2012).
- 336 17. Radeloff, V. C. *et al.* The rise of novelty in ecosystems. *Ecol. Appl.* **25**, 2051–2068
337 (2015).
- 338 18. Lotterhos, K. E., Láruson, Á. J. & Jiang, L.-Q. Novel and disappearing climates in the
339 global surface ocean from 1800 to 2100. *Sci. Rep.* **11**, 15535 (2021).
- 340 19. Mora, C. *et al.* The projected timing of climate departure from recent variability. *Nature*
341 **502**, 183–187 (2013).
- 342 20. Henson, S. A. *et al.* Rapid emergence of climate change in environmental drivers of
343 marine ecosystems. *Nat. Commun.* **8**, 14682 (2017).
- 344 21. Séférian, R. *et al.* Evaluation of CNRM Earth System Model, CNRM-ESM2-1: Role of
345 Earth system processes in present-day and future climate. *J. Adv. Model. Earth Syst.*

- 346 11, 4182–4227 (2019).
- 347 22. Gidden, M. J. *et al.* Global emissions pathways under different socioeconomic scenarios
348 for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the
349 century. *Geosci. Model Dev.* **12**, 1443–1475 (2019).
- 350 23. Eyring, V. *et al.* Overview of the Coupled Model Intercomparison Project Phase 6
351 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**, 1937–1958
352 (2016).
- 353 24. Beszczynska-Möller, A., Fahrbach, E., Schauer, U. & Hansen, E. Variability in Atlantic
354 water temperature and transport at the entrance to the Arctic Ocean, 1997–2010. *ICES J.*
355 *Mar. Sci.* **69**, 852–863 (2012).
- 356 25. Sutton, T. T. Vertical ecology of the pelagic ocean: classical patterns and new
357 perspectives. *J. Fish Biol.* **83**, 1508–1527 (2013).
- 358 26. Richter, I. Climate model biases in the eastern tropical oceans: causes, impacts and
359 ways forward. *WIREs Clim. Chang.* **6**, 345–358 (2015).
- 360 27. Pozo Buil, M. *et al.* A Dynamically downscaled ensemble of future projections for the
361 California Current System. *Front. Mar. Sci.* **8**, (2021).
- 362 28. Leonard, M. *et al.* A compound event framework for understanding extreme impacts.
363 *WIREs Clim. Chang.* **5**, 113–128 (2014).
- 364 29. Kwiatkowski, L. *et al.* Twenty-first century ocean warming, acidification, deoxygenation,
365 and upper-ocean nutrient and primary production decline from CMIP6 model projections.
366 *Biogeosciences* **17**, 3439–3470 (2020).
- 367 30. Bopp, L. *et al.* Multiple stressors of ocean ecosystems in the 21st century: projections
368 with CMIP5 models. *Biogeosciences* **10**, 6225–6245 (2013).
- 369 31. Cheng, L., Abraham, J., Hausfather, Z. & Trenberth, K. E. How fast are the oceans
370 warming? *Science (80-)*. **363**, 128–129 (2019).
- 371 32. Hawkins, E. & Sutton, R. Time of emergence of climate signals. *Geophys. Res. Lett.* **39**,
372 n/a-n/a (2012).
- 373 33. Stuart-Smith, R. D., Edgar, G. J., Barrett, N. S., Kininmonth, S. J. & Bates, A. E. Thermal
374 biases and vulnerability to warming in the world's marine fauna. *Nature* **528**, 88–92
375 (2015).
- 376 34. Filbee-Dexter, K. *et al.* Marine heatwaves and the collapse of marginal North Atlantic kelp
377 forests. *Sci. Rep.* **10**, 13388 (2020).
- 378 35. Román-Palacios, C. & Wiens, J. J. Recent responses to climate change reveal the
379 drivers of species extinction and survival. *Proc. Natl. Acad. Sci.* **117**, 4211–4217 (2020).
- 380 36. Silvy, Y., Guilyardi, E., Sallée, J.-B. & Durack, P. J. Human-induced changes to the global

- 381 ocean water masses and their time of emergence. *Nat. Clim. Chang.* **10**, 1030–1036
382 (2020).
- 383 37. Cheng, L., Zheng, F. & Zhu, J. Distinctive ocean interior changes during the recent
384 warming slowdown. *Sci. Rep.* **5**, 14346 (2015).
- 385 38. Brito-Morales, I. *et al.* Climate velocity reveals increasing exposure of deep-ocean
386 biodiversity to future warming. *Nat. Clim. Chang.* **10**, 576–581 (2020).
- 387 39. Frölicher, T. L. & Laufkötter, C. Emerging risks from marine heat waves. *Nat. Commun.* **9**,
388 650 (2018).
- 389 40. Oliver, E. C. J. *et al.* Marine Heatwaves. *Ann. Rev. Mar. Sci.* **13**, 313–342 (2021).
- 390 41. Perry, A. L., Low, P. J., Ellis, J. R. & Reynolds, J. D. Climate change and distribution
391 shifts in marine fishes. *Science (80-.)*. **308**, 1912–1915 (2005).
- 392 42. Chaudhary, C., Richardson, A. J., Schoeman, D. S. & Costello, M. J. Global warming is
393 causing a more pronounced dip in marine species richness around the equator. *Proc.*
394 *Natl. Acad. Sci.* **118**, e2015094118 (2021).
- 395 43. Burrows, M. T. *et al.* Ocean community warming responses explained by thermal
396 affinities and temperature gradients. *Nat. Clim. Chang.* **9**, 959–963 (2019).
- 397 44. Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A.,
398 Craig, M., Langsdorf, S. & Löschke, S. Möller, V. Okem, A. Rama, B. (eds. . IPCC, 2022:
399 Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working
400 Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate
401 Change. (2022).
- 402 45. Cahill, A. E. *et al.* How does climate change cause extinction? *Proc. R. Soc. B Biol. Sci.*
403 **280**, 20121890 (2013).
- 404 46. Hastings, R. A. *et al.* Climate change drives poleward increases and equatorward
405 declines in marine species. *Curr. Biol.* **30**, 1572-1577.e2 (2020).
- 406 47. Jorda, G. *et al.* Ocean warming compresses the three-dimensional habitat of marine life.
407 *Nat. Ecol. Evol.* **4**, 109–114 (2020).
- 408 48. Dulvy, N. K. *et al.* Climate change and deepening of the North Sea fish assemblage: a
409 biotic indicator of warming seas. *J. Appl. Ecol.* **45**, 1029–1039 (2008).
- 410 49. Thatje, S. Climate warming affects the depth distribution of marine ectotherms. *Mar. Ecol.*
411 *Prog. Ser.* **660**, 233–240 (2021).
- 412 50. Manuel, S. A., Coates, K. A., Kenworthy, W. J. & Fourqurean, J. W. Tropical species at
413 the northern limit of their range: Composition and distribution in Bermuda’s benthic
414 habitats in relation to depth and light availability. *Mar. Environ. Res.* **89**, 63–75 (2013).
- 415 51. Peck, L. S., Webb, K. E. & Bailey, D. M. Extreme sensitivity of biological function to

- 416 temperature in Antarctic marine species. *Funct. Ecol.* **18**, 625–630 (2004).
- 417 52. Peck, L. S., Morley, S. A., Richard, J. & Clark, M. S. Acclimation and thermal tolerance in
418 Antarctic marine ectotherms. *J. Exp. Biol.* **217**, 16–22 (2014).
- 419 53. Walsh, J. E. Climate of the arctic marine environment. *Ecol. Appl.* **18**, S3–S22 (2008).
- 420 54. Storch, D., Menzel, L., Frickenhaus, S. & Pörtner, H.-O. Climate sensitivity across marine
421 domains of life: limits to evolutionary adaptation shape species interactions. *Glob. Chang.*
422 *Biol.* **20**, 3059–3067 (2014).
- 423 55. Araújo, M. B. *et al.* Heat freezes niche evolution. *Ecol. Lett.* **16**, 1206–1219 (2013).
- 424 56. Pörtner, H. O., Peck, L. & Somero, G. Thermal limits and adaptation in marine Antarctic
425 ectotherms: an integrative view. *Philos. Trans. R. Soc. B Biol. Sci.* **362**, 2233–2258
426 (2007).
- 427 57. Qu, Y.-F. & Wiens, J. J. Higher temperatures lower rates of physiological and niche
428 evolution. *Proc. R. Soc. B Biol. Sci.* **287**, 20200823 (2020).
- 429 58. Cohen, D.M., Inada, T., Iwamoto, T., and Scialabba, N. *FAO species catalogue. Vol. 10.*
430 *Gadiform fishes of the world (Order Gadiformes). An annotated and illustrated catalogue*
431 *of cods, hakes, grenadiers and other gadiform fishes known to date. FAO Fish. Synop.*
432 (FAO, 1990).
- 433 59. Strand, E. & Huse, G. Vertical migration in adult Atlantic cod (*Gadus morhua*). *Can. J.*
434 *Fish. Aquat. Sci.* **64**, 1747–1760 (2007).
- 435 60. Frölicher, T. L., Fischer, E. M. & Gruber, N. Marine heatwaves under global warming.
436 *Nature* **560**, 360–364 (2018).
- 437 61. Wernberg, T. *et al.* Climate-driven regime shift of a temperate marine ecosystem.
438 *Science (80-.).* **353**, 169–172 (2016).
- 439 62. Smale, D. A. *et al.* Marine heatwaves threaten global biodiversity and the provision of
440 ecosystem services. *Nat. Clim. Chang.* **9**, 306–312 (2019).
- 441 63. Cheung, W. W. L. & Frölicher, T. L. Marine heatwaves exacerbate climate change
442 impacts for fisheries in the northeast Pacific. *Sci. Rep.* **10**, 6678 (2020).
- 443 64. Brierley, A. S. & Kingsford, M. J. Impacts of climate change on marine organisms and
444 ecosystems. *Curr. Biol.* **19**, R602–R614 (2009).
- 445 65. Bijma, J., Pörtner, H.-O., Yesson, C. & Rogers, A. D. Climate change and the oceans –
446 What does the future hold? *Mar. Pollut. Bull.* **74**, 495–505 (2013).
- 447 66. Jackson, J. B. C. *et al.* Historical overfishing and the recent collapse of coastal
448 ecosystems. *Science (80-.).* **293**, 629–637 (2001).
- 449 67. Duarte, C. M. *et al.* The soundscape of the Anthropocene ocean. *Science (80-.).* **371**,
450 eaba4658 (2021).

451 68. Rochman, C. M. & Hoellein, T. The global odyssey of plastic pollution. *Science* (80-.).
452 **368**, 1184–1185 (2020).

453 69. Gruber, N., Boyd, P. W., Frölicher, T. L. & Vogt, M. Biogeochemical extremes and
454 compound events in the ocean. *Nature* **600**, 395–407 (2021).

455

456 **Methods**

457 **Ocean Sites observations**

458 The *Ocean Sites* (OS) network constitutes a worldwide effort to monitor ocean parameters
459 through high-quality data extracted from long-term, high-frequency observations at several
460 locations of the World ocean. Six OS stations, listed in Supplementary Table 1, were selected
461 because of the availability of continuous daily measurements of ocean temperature and salinity
462 across the water column for more than seven years, allowing a robust computation of thermal
463 range boundaries (see below). All of the six stations provide data from the surface to about
464 1000 m depth, that have been resampled daily at each depth, and then interpolated into the
465 vertical grid of CNRM-ESM2-1 (see below).

466 Observational data is accessible through [http://tds0.ifremer.fr/thredds/catalog/CORIOLIS-](http://tds0.ifremer.fr/thredds/catalog/CORIOLIS-OCEANSITES-GDAC-OBS/DATA/)
467 [OCEANSITES-GDAC-OBS/DATA/](http://tds0.ifremer.fr/thredds/catalog/CORIOLIS-OCEANSITES-GDAC-OBS/DATA/). Last accessed was in October 2020.

468 **Simulations**

469 This work exploits simulations from a state-of-the-art Earth system model, CNRM-ESM2-1²¹,
470 that has been developed by the CNRM-CERFACS climate group for the sixth phase of the
471 Coupled Model Inter-comparison Project (CMIP6²³). The ocean component of CNRM-ESM2-1 is
472 NEMOv3.6⁷⁰, which resolves ocean dynamics on an eORCA1 grid⁷¹ with 75 vertical z-
473 coordinate levels. This grid offers a horizontal resolution of about 1° with a grid refinement up to
474 0.3° in the tropics.

475 In this study, we performed five simulations with CNRM-ESM2-1: a 250 year-long pre-industrial
476 control simulation (without anthropogenic forcing) to estimate the model's internal variability;
477 and a historical simulation from 1850 to 2014 followed by three future scenarios from 2015 to
478 2100, which are used to derive present and future variations in temperature minimum and

479 maximum. For each simulation, an ensemble of 15 members has been performed in order to
480 account for the influence of the internal variability in the computation of quantiles (see below).

481 These simulations were produced using the external forcing as recommended by CMIP6 for the
482 pre-industrial state and the historical period. For the future scenarios we used contrasting
483 pathways: a low (SSP1-2.6), moderate (SSP2-4.5), and high (SSP5-8.5) emission pathways as
484 described in ref. ²².

485 All simulations provide daily outputs from the ocean surface to 4000 m for ocean temperature
486 and salinity as well as oxygen, pH and net primary productivity. Here, we exploit only the first 47
487 vertical layers for ocean temperature and salinity in order to describe the first 1000 m depth of
488 the water column. Finally, to ensure both observations and model data (historical + SSP5-8.5
489 simulation) cover exactly the same period, model data was selected to begin and end at the
490 same date as observations.

491 Two additional ESMs (details on Supplementary Table 3) have been used in the study to assess
492 the robustness of our results. This robustness analysis is based on a simple intercomparison
493 where model properties (thermal range and ToE) are compared between each other using only
494 a single realization for each model.

495 **Model internal variability**

496 As a consequence of the chaotic nature of processes in the Earth systems being simulated
497 (ocean-atmosphere-land-biosphere-cryosphere), one of the main sources of uncertainties in
498 climatic future projections is their internal variability⁷². One way to isolate these uncertainties is
499 to generate an ensemble of model realizations⁷³. Here we make use of an ensemble of 15
500 members in order to minimise the influence of the internal variability in our computation. Each
501 realization sampling different states of the model climate.

502 **Ocean domains informed by Ocean Site stations**

503 Though OS networks are located throughout the World ocean, our selection of OS stations is
504 disproportionately located in the North Atlantic and North Pacific oceans (see Fig. 1 and
505 Supplementary Table 1). To assess how large is the surface area of ocean domains informed
506 by our six selected OS stations, we compute the level of similarity between daily profiles as

507 provided by observations and the model hindcast over the current period (1990 to 2020) using
508 the statistical approach presented in ref. ⁷⁴. This approach compares simultaneously the mean
509 and the daily variations of OS daily profiles with a neighbour grid-point model profile using a
510 Chi-squared-based test. The test consists in comparing the cumulative sum of the Welch's t_z^2 ⁷⁵
511 across depth levels to an empirical Chi-squared distribution with 47 degrees of freedom (i.e., the
512 number of depth levels). We use 10,000 random samples of this Chi-squared distribution to
513 estimate the empirical distribution of the Chi-squared law. The distribution is then used to
514 compute an empirical 'integrated' p-value that represents an objective metric to determine how
515 far the two profiles are consistent between each other within the depth interval.

516 The empirical 'integrated' p-value allows us to quantify the match between profiles. We establish
517 a threshold of 0.90 to consider a profile over a grid-cell consistent with the OS profile. For
518 further analysis, stations were grouped into three ocean domains: polar, temperate and tropical
519 waters.

520 **Estimation of the environmental temperature range boundaries**

521 The working definition of the ecosystem thermal range, or the environmental temperature range
522 that experiences an ecosystem, employed in this work assumes that organisms track changes
523 in environmental temperature^{7,11,76}, and that the magnitude of the local temperature variability
524 reflect their ranges of temperature tolerance^{8,77}. As a consequence, we infer the vertical
525 structure of ecosystem thermal ranges from their lower and upper limits, which are captured by
526 the minimal and maximal environmental temperature across the water column, respectively.

527 Thanks to high-frequency data, we provide a robust yearly estimate of these bounds using the
528 annual first (p01, Tmin) and last (p99, Tmax) percentiles of both model and observation
529 temperature time-series at each depth level. Though this approach encompasses most of the
530 range of temperature variability, it can yield more pessimistic projections as tolerance ranges
531 can be wider than environmental thermal ranges^{15,55}, and as ectotherms display some plasticity
532 to adapt to environmental temperatures that challenge their tolerance limits^{78,79}. Nonetheless,
533 there is limited capacity of acclimation when long-term heating occurs⁸⁰, especially for tropical
534 species⁸¹ and during reproductive stages⁸².

535 In order to minimize the influence of the internal climate variability when comparing model and
536 data results, we estimate model annual percentiles by grouping the 15 ensemble members.

537 Thus, model percentile for thermal range is derived from a $365 \times 15 = 5475$ sample of daily outputs
538 at each depth.

539 The breadth of thermal ranges are estimated as the difference between T_{max} and T_{min} at each
540 depth level. Midpoint temperatures ($T_{midpoint}$) correspond to the arithmetic mean of T_{min} and
541 T_{max} , thus assuming normality in the distribution of T_{min} and T_{max} .

542 **Timing of crossing thermal range thresholds**

543 To track future changes in the thermal range boundaries, we employed a method inspired from
544 the well-established Time of Emergence (ToE) approach (see Supplementary Fig. 3 and 4). As
545 for the ToE approach, our method requires estimates of a climate change signal (S). We
546 estimate it using daily model outputs from 1990 to 2100 for an ensemble of 15 realizations from
547 CNRM-ESM2-1 that has been run following historical and low emission SSP1-2.6, moderate
548 emission SSP2-4.5, and high emission SSP5-8.5 pathways. For each pathway, we define S as
549 the smooth spline (four degrees of freedom) of the variation of T_{min} during the full simulation. In
550 general, the ToE approach is defined as the first year at which S surpasses twice the standard
551 deviation of the internal climate variability. Here, in contrast, we make use of different thresholds
552 that have a meaning for ecosystem functioning, which represent key characteristics of the
553 thermal range; $T_{midpoint}$ and T_{max} . These two thresholds are defined as the average of a
554 smooth spline (four degrees of freedom) of the variation of $T_{midpoint}$ and T_{max} during the past
555 30 years from today (1990 to 2020); a period considered to be representative of the current
556 period. We consider the emergence of substantial changes in the current range of temperatures
557 that defines the environmental conditions of a given habitat as the time at which the lower
558 boundary of this range (T_{min}) crosses in the future the current thresholds ($T_{midpoint}$ and
559 T_{max}).

560 We built a 5th-95th confidence interval for each ToE estimate accounting for the influence of the
561 internal climate variability. For that, we generate 100 30-yearslong samples selected randomly
562 from the piControl simulation. Then, we compute the annual T_{max} and $T_{midpoint}$ for these
563 samples, and remove the annual mean to them. Finally, we compute the 5th and 95th
564 percentiles of the statistical distribution of the 100 random T_{max} and $T_{midpoint}$ anomaly
565 samples.

566 We additionally compute the emergence of changes in the upper limit of the current thermal

567 range, i.e., T_{max} . Particularly, we estimate the time at which T_{max} crosses in the future a
568 threshold defined as the current (1990 to 2020) upper boundary plus twice the standard
569 deviation of the statistical distribution of the 100 random T_{max} anomaly samples from the
570 piControl simulation (see above).

571 In order to illustrate that emergence times are not an artifact of the current shape of thermal
572 ranges, we computed the trends of both boundaries during the 1990 to 2100 period following
573 the historical + SSP5-8.5 simulation (third subpanels at Fig. 2). We have chosen this period as it
574 represents the range of years for which we compute ToE. The shape of these profiles allow us
575 to confirm that ToEs are the results of both the vertical structure of the thermal ranges, and the
576 evolution of the lower and upper boundaries through time.

577 For illustration purposes, we illustrate how our approach works for four depth levels of HOT-01
578 station (Extended Data Fig. 5).

579 **End-of-the-century environmental temperature ranges**

580 End-of-the-century environmental temperature ranges provide a snapshot of the concomitant
581 changes in thermal range boundaries resulting from climate change. We compute the end-of-
582 the-century thermal ranges from daily data over the 2080 to 2100 period. Fig. 4 displays the
583 end-of-the-century thermal range anomalies of both T_{min} and T_{max} with respect to the mean
584 over 1990 to 2014, corresponding to the last years of the historical simulation. To compare with
585 the historical profiles, we also include their anomalies. At each depth level, we assess the
586 magnitude of the changes between the end-of-the-century and the historical profiles.

587 As changes in thermal range boundaries can evolve in both directions, and with a different
588 pace, they may result in a re-arrangement of the vertical shape of the thermal range. To track if
589 end-of-the-century thermal ranges are also wider or narrower, we compute the difference
590 between T_{max} and T_{min} anomalies at each depth level (Extended Data Fig. 6, 8, and 9). If the
591 difference is positive, thermal ranges will be wider, i.e., T_{max} warms more rapidly. If the
592 difference is negative, thermal ranges will be narrower, i.e., T_{min} warms more rapidly. If
593 differences are < 0.05 °C (i.e., level of uncertainty informed from the analysis of the internal
594 variability of thermal range profiles in Extended Data Fig. 4), we consider no changes in the
595 shape of thermal ranges will take place, i.e., only shifting toward warming or cooling is

596 projected. The three emission pathways are displayed in Extended Data Fig. 6, 8, and 9,
597 respectively.

598 In Fig. 4 we have assigned a colour code for each of these developments. A depiction of these
599 developments is provided in Extended Data Fig. 2.

600 We track novel thermal space resulting from changes in end-of-the-century thermal ranges that
601 differ from historical period counterparts using *Climate Novelty* (C_N). As in previous approaches
602 (e.g., ref. ^{17,18}), our metric approach accounts for the level of dissimilarity to baseline conditions.
603 This metric accounts for the difference between the last years of the historical period, i.e., 1990
604 to 2014, and end-of-the-century thermal ranges at each depth. It takes the space gained/lost by
605 the warming/cooling of T_{max} and T_{min} , and by the thermal space loss when future T_{min}
606 surpasses current T_{max} . This metric is expressed as follows:

$$607 \quad C_N = (\Delta_{max} + \Delta_{min} - \Delta_{mod})/ThBr ;$$

608 Where Δ_{max} corresponds to the difference between T_{max} at the end-of-the-century and at the
609 historical period. Δ_{min} corresponds to the difference between T_{min} at the end-of-the-century and
610 at the historical period. Δ_{mod} corresponds to the intersection of thermal space between future
611 and historical thermal ranges, i.e., when end-of-the-century $T_{min} >$ historical T_{max} . $ThBr$ is the
612 difference between T_{max} and T_{min} at the end of the century period. Thus, C_N informs of the
613 range of environmental temperatures that has never been experienced before with respect to
614 the thermal range at the end of the century. We express it in the manuscript as a percentage by
615 multiplying by 100.

616 **Data availability** Interpolated data presented in the paper can be accessed via Zenodo at
617 <https://doi.org/10.5281/zenodo.6940283>.

618 **Code availability** All code used in the current study is available from the corresponding author
619 upon reasonable request.

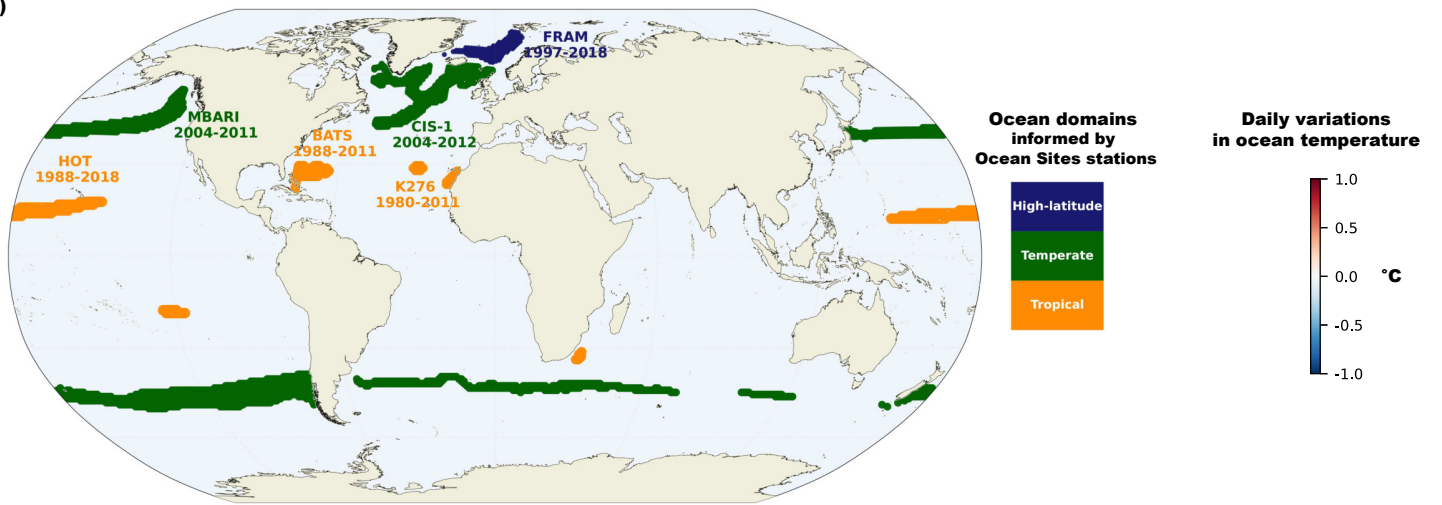
620 **Methods-only references**

621 70. Madec, G. *et al.* *NEMO ocean engine*. <https://www.earth-prints.org/handle/2122/13309>
622 (2017) doi:10.5281/zenodo.3248739.

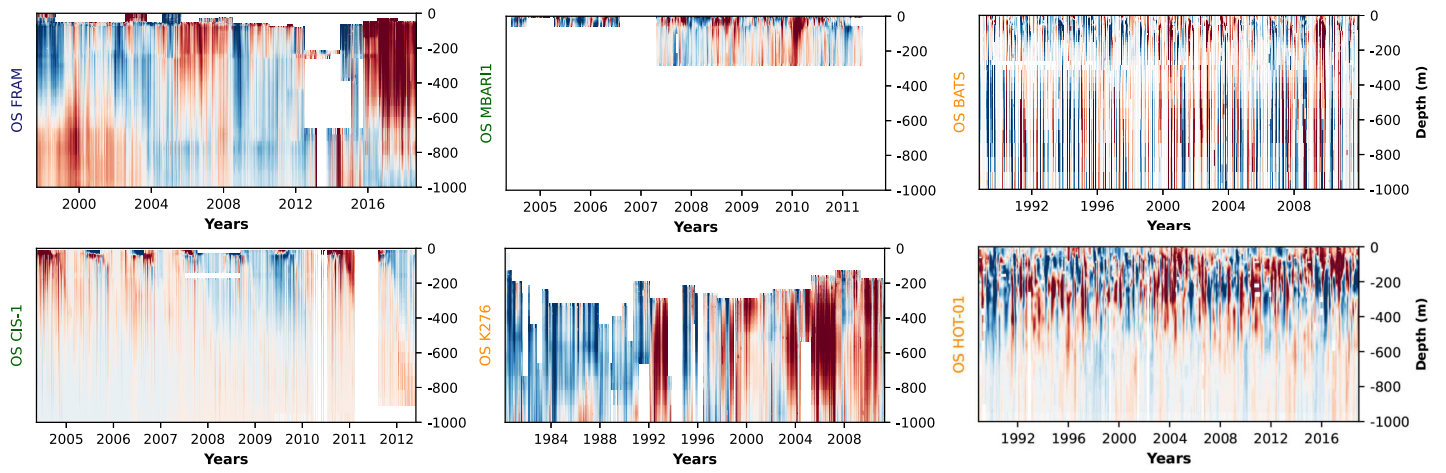
623 71. Mathiot, P., Jenkins, A., Harris, C. & Madec, G. Explicit representation and parametrised

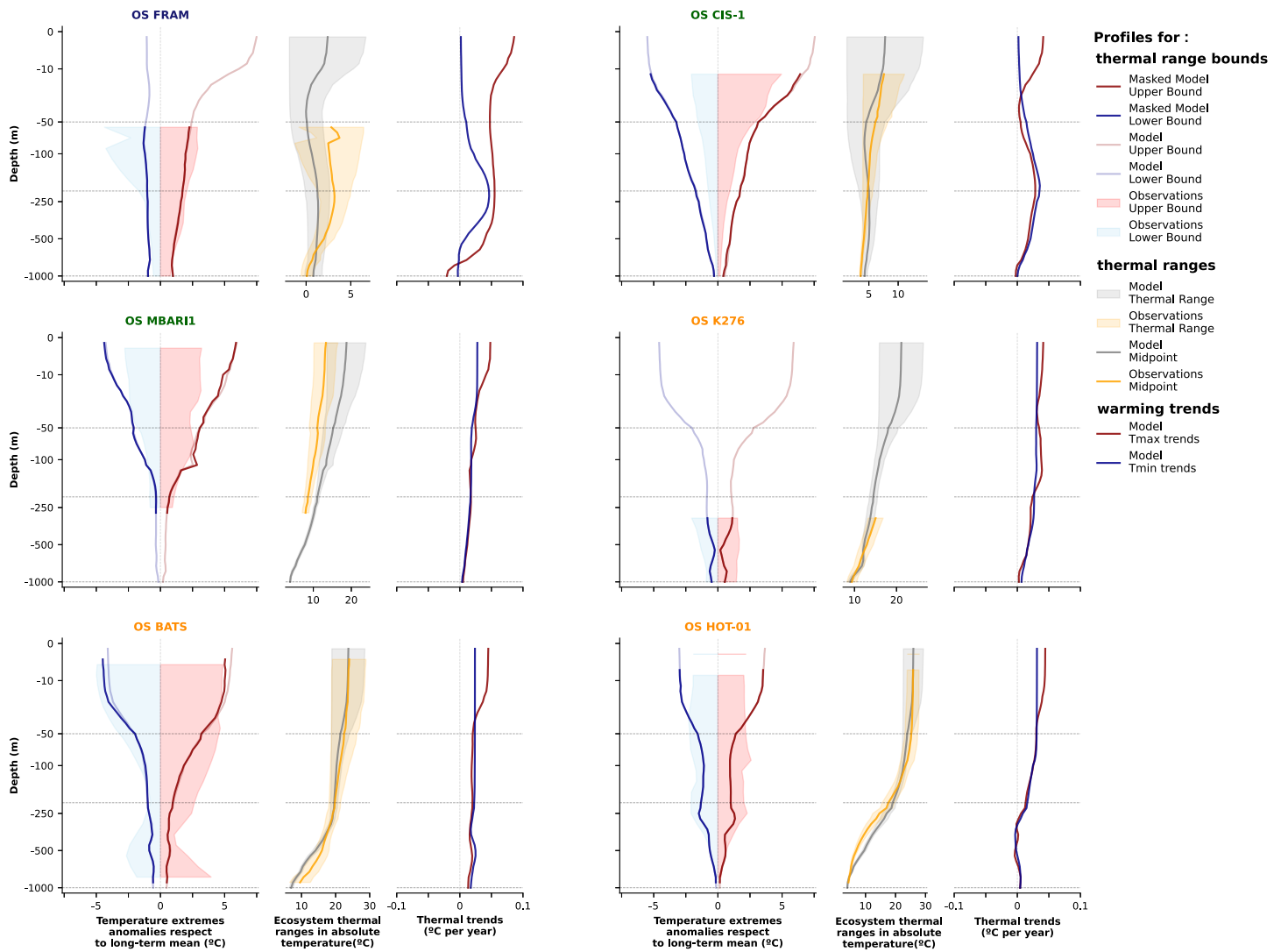
- 624 impacts of under ice shelf seas in the z -coordinate ocean model NEMO 3.6. *Geosci.*
625 *Model Dev.* **10**, 2849–2874 (2017).
- 626 72. Dai, A. & Bloecker, C. E. Impacts of internal variability on temperature and precipitation
627 trends in large ensemble simulations by two climate models. *Clim. Dyn.* **52**, 289–306
628 (2019).
- 629 73. Deser, C., Phillips, A., Bourdette, V. & Teng, H. Uncertainty in climate change
630 projections: the role of internal variability. *Clim. Dyn.* **38**, 527–546 (2012).
- 631 74. Middag, R. *et al.* Intercomparison of dissolved trace elements at the Bermuda Atlantic
632 Time Series station. *Mar. Chem.* **177**, 476–489 (2015).
- 633 75. Welch, B. L. The generalization of Student's' problem when several different population
634 variances are involved. *Biometrika* **34**, 28 (1947).
- 635 76. Lenoir, J. *et al.* Species better track climate warming in the oceans than on land. *Nat.*
636 *Ecol. Evol.* **4**, 1044–1059 (2020).
- 637 77. Janzen, D. H. Why mountain passes are higher in the Tropics. *Am. Nat.* **101**, 233–249
638 (1967).
- 639 78. Seebacher, F., White, C. R. & Franklin, C. E. Physiological plasticity increases resilience
640 of ectothermic animals to climate change. *Nat. Clim. Chang.* **5**, 61–66 (2015).
- 641 79. Hoffmann, A. A. & Sgrò, C. M. Climate change and evolutionary adaptation. *Nature* **470**,
642 479–485 (2011).
- 643 80. Sandblom, E. *et al.* Physiological constraints to climate warming in fish follow principles of
644 plastic floors and concrete ceilings. *Nat. Commun.* **7**, 11447 (2016).
- 645 81. Tewksbury, J. J., Huey, R. B. & Deutsch, C. A. Putting the heat on tropical animals.
646 *Science (80-.)*. **320**, 1296–1297 (2008).
- 647 82. Dahlke, F. T., Wohlrab, S., Butzin, M. & Pörtner, H.-O. Thermal bottlenecks in the life
648 cycle define climate vulnerability of fish. *Science (80-.)*. 369, 65–70 (2020).

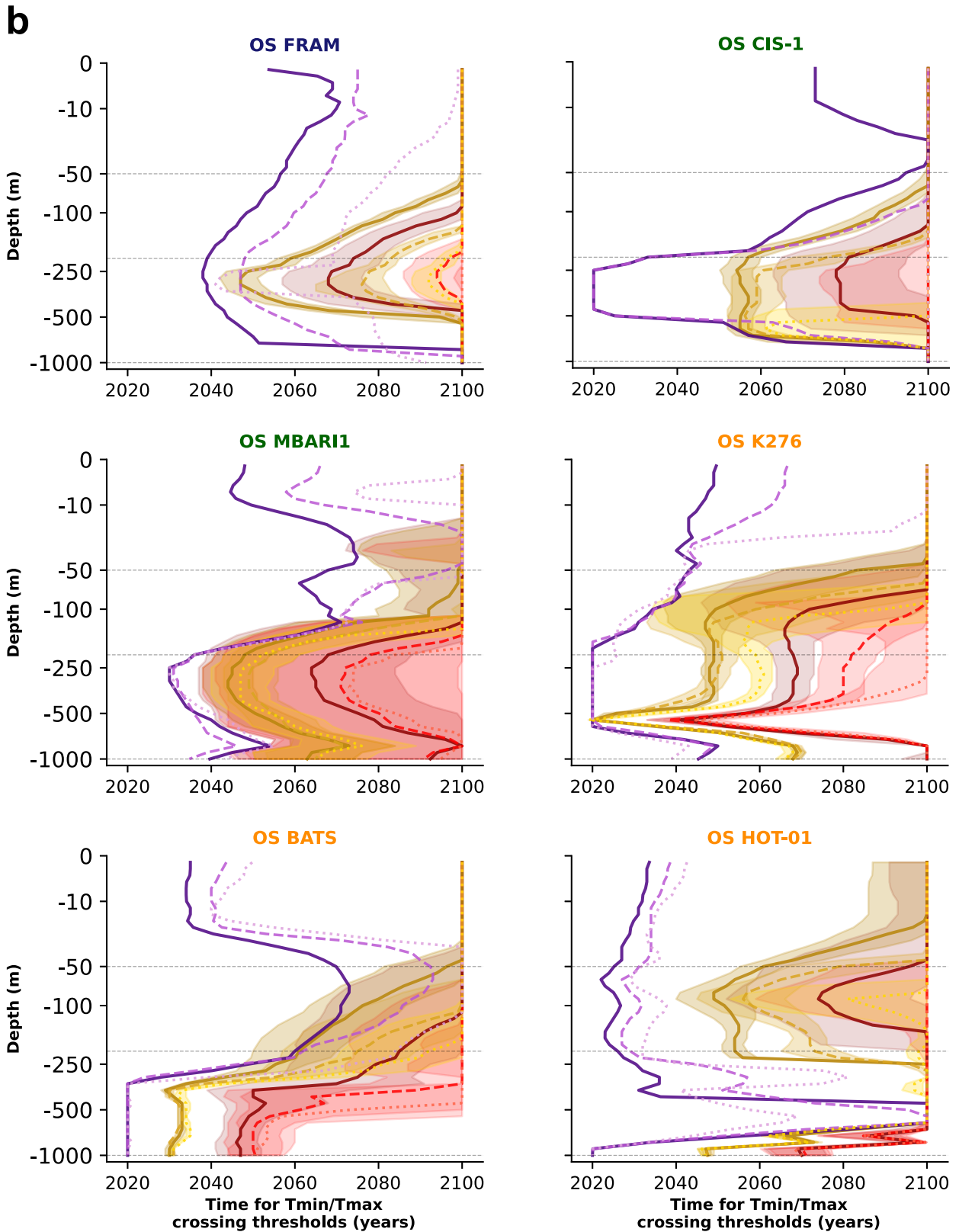
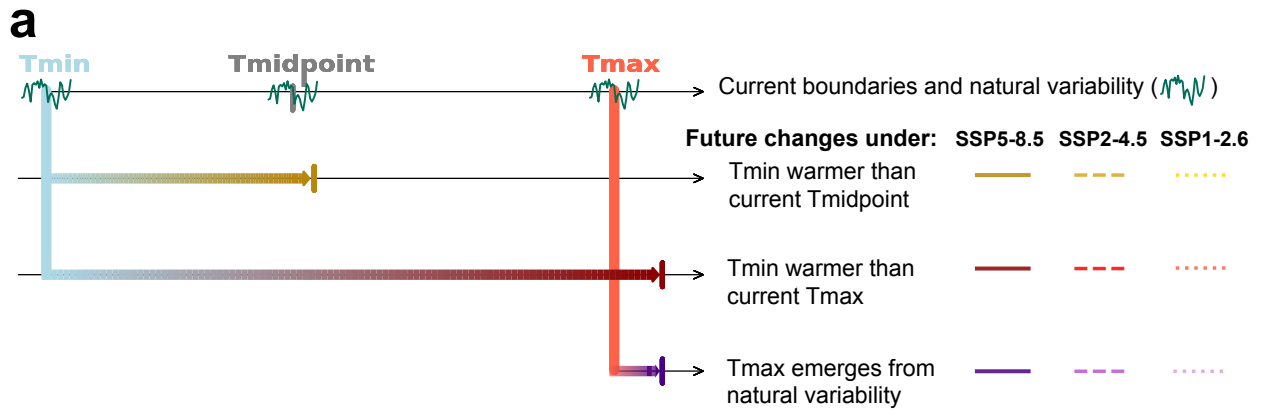
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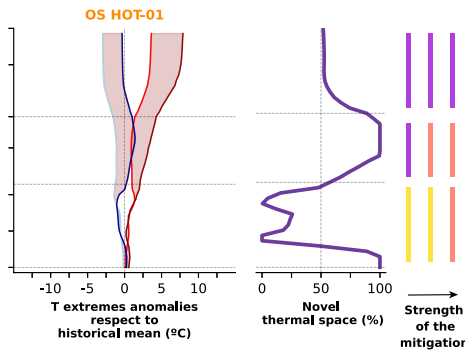
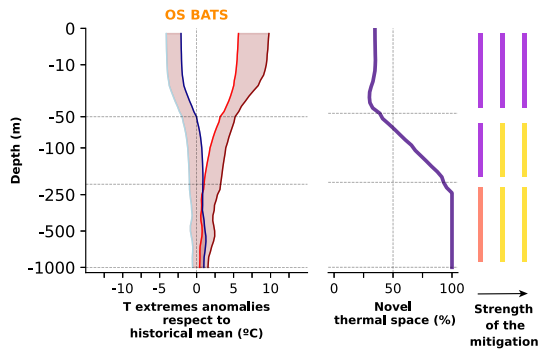
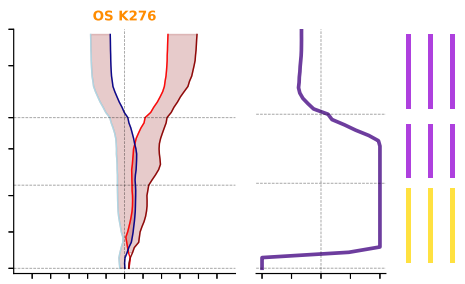
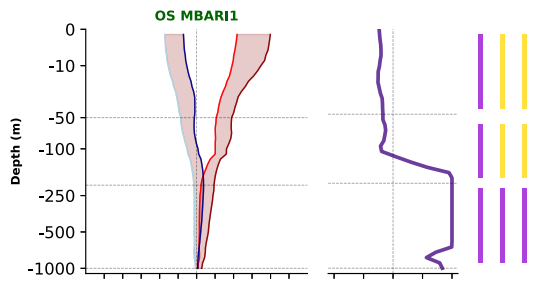
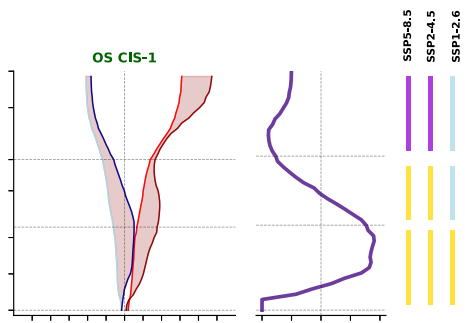
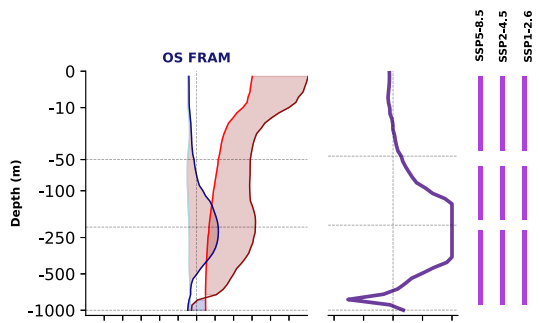


b)









Anomaly respect to historical (1990-2014) mean

- Historical Lower Bound
- Historical Upper Bound
- End-of-the-century (2080-2100) Lower Bound
- End-of-the-century (2080-2100) Upper Bound

Changes in thermal range

- End-of-the-century T extremes warmer than historical T extremes
- End-of-the-century T extremes cooler than historical T extremes
- Climate Novelty

Future changes in thermal range resulting from concomitant changes in both boundaries

- Cooler
- Warmer
- Warmer & Shrunk
- Warmer & Expanded