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1 Marine heatwaves and global warming impacts on winter waters in
2 the Southern Indian Ocean

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28 Abstract

29

30 In the Southern Ocean, the term “winter waters” (WWs) refers to a water mass characterized by a
31 subsurface layer of minimum temperature that plays an important ecological role for marine
32 ecosystems, and in particular for top predators. Given that the Southern Ocean is experiencing warming
33 and intense marine heatwaves (MHWs), particularly at subantarctic latitudes, we investigate here how
34 different levels of warming might impact the presence, depth and minimum temperature of WWs in the
35 Indian sector of the Southern Ocean. In particular, we assess how WWs are impacted by surface MHWs
36 using *in situ* Argo hydrographic observations and biologging data. The results indicate that WWs are
37 substantially reduced, deeper and warmer during the presence of MHWs. Using the most recent climate
38 projections, we find a significant, but scenario-dependent, southward shift of WWs under global
39 warming. Potential impacts of such WW shifts on pelagic ecosystems, at different timescales (from daily to
40 decadal), are discussed.

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43 Keywords: Southern Indian Ocean ; winter waters ; marine heatwaves ; global warming

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47 1. Introduction

48

49 “Winter waters” (WWs) is a term used to qualify the subsurface minimum temperature layer present in
50 the Southern Ocean. The Polar Front, one of the most prominent hydrographic features in this basin, is
51 often defined as its northernmost extension (Gordon and Huber, 1984; Park et al., 1998; Pauthenet et al.,
52 2018). WWs are formed from the freezing cold surface waters of the winter mixed layer of the subpolar
53 Southern Ocean, and are then capped by a warmer and fresher surface layer in spring-summer as sea-ice
54 melts and air temperature warms. This seasonal cycle leaves behind a cold water mass in the subsurface
55 between about 100 and 400 m, which is stably stratified by the vertical salinity profile (Sharma and
56 Matthew, 1985; Park et al., 1993; Belkin and Gordon, 1996). WWs temperature typically ranges
57 between -2°C and 3°C (Gordon, 1975 ; Park et al., 1993 ; Sabu et al., 2020).

58 The distributions and characteristics of WWs depend on large-scale drivers such as wind stress or sea-
59 ice extent (Gordon and Huber, 1984), which are expected to change under global warming (Lee et al.,
60 2021). Water masses of the Southern Ocean are overall observed and projected to continue to warm in
61 the future (Sallée et al., 2013; Sallée et al., 2018; Auger et al., 2021). The observed temperature change
62 across the Southern Ocean is actually heterogenous. Cooling is observed in the southern end of the
63 Southern Ocean, while warming occurs at depth and also within and north of the Antarctic Circumpolar
64 Current (ACC; Armour et al., 2016; Llovel et al., 2016; Morrison et al., 2016; Sallée et al., 2018; Auger
65 et al., 2021; Fox-Kemper et al., 2021). No warming trends have yet been reported for the WWs and their
66 future evolution remains uncertain.

67 In this paper, we aim at shedding light on the impact of a warming climate on WWs. As WWs are
68 characterized by a minimum of temperature, their distribution and characteristics can be expected to be
69 affected by a warming climate. Our main motivation in this endeavor is underpinned by the
70 demonstrated importance of this water mass for Southern Ocean ecosystems. WWs have been shown to
71 play a structuring role for pelagic ecosystems and for the vertical distribution and relative abundance of
72 mesopelagic organisms (Béhagle et al., 2017; McMahon et al., 2019; Hunt et al., 2021). WWs in
73 particular are associated with mesopelagic organisms being more concentrated towards the surface and
74 thus easily accessible prey for top predators (e.g. king penguins, *Aptenodytes patagonicus*, Kooyman et
75 al., 1982; Kooyman et al., 1992).

76 There are two main ways climate change could impact WWs characteristics. First, changes in large-
77 scale circulation patterns may alter the distribution of WWs, and in particular the southward shift of the
78 Polar Front or the increase of eddy shedding southward from the Polar Front may push WWs southward
79 and change their distribution. Second, local surface warming occurring at the time of WWs formation in
80 winter, or penetrating downward in spring-summer by diffusion or vertical mixing, could warm WWs,
81 or eventually erode the temperature minimum entirely. Here, we first use observation-based datasets to
82 test the hypothesis that anomalously warm surface conditions affect WWs distribution and
83 characteristics through one or a combination of these two processes. Second, we use climate models to
84 investigate how these processes unfold into a net change in WWs distribution and characteristics under
85 a diverse range of global warming levels.

86 Anomalously warm surface conditions are commonly referred to as marine heatwaves (MHWs; Hobday
87 et al., 2016; Frölicher et al., 2018; Oliver et al., 2021). There is increasing evidence that MHWs detected
88 at the surface can penetrate to depth (Elzahaby and Schaeffer, 2019; Darmaraki et al., 2019; Hu et al.,
89 2021; Miyama et al., 2021; Großelindemann et al., 2022), with the potential to locally modify
90 subsurface water masses characteristics such as WWs. In addition, it was shown that MHWs in the
91 southern Indian basin can be associated with a southward shift of the Polar Front, which in 1997 led to a
92 mass mortality of Crozet king penguins as their foraging zones were shifted too far south from their
93 breeding island (Bost et al., 2015). We see here the importance of better understanding the impact of
94 warm surface conditions on WWs, which can have dramatic consequences for ecosystems. Such
95 extreme events can be seen as a snapshot into the future under a warmer climate. However, dominant
96 processes at short and long timescale can differ, so that a proper analysis of future projections must also
97 be carried out before any conclusions are drawn.

98 We focus our study on the Indian sector of the Southern Ocean because this is one of the regions of the
99 world that has experienced the largest increase in ocean heat content in recent decades (Roemmich et al.,
100 2015; Llovel et al., 2016; Sallée et al., 2018; Fox-Kemper et al., 2021). It has also been shown that the
101 position of the Polar Front can be highly variable west of the Kerguelen Plateau (Pauthenet et al., 2018).
102 Since this region also hosts a rich biodiversity and notably top predators whose behavior and foraging
103 success has been related to physical properties of water masses (McIntyre et al., 2011; Guinet et al.,
104 2014), the Southern Indian Ocean is of particular interest to study how warming can impact WWs and,
105 in turn, pelagic ecosystems.

106 The paper is organized as follows. First, we investigate the relationship between WWs and surface
107 extreme temperature anomalies, combining *in situ* data with multisatellite observations and a 1/12°
108 ocean reanalysis product. This is motivated by the findings that the pattern of intense MHWs at the
109 northern boundary of the ACC might be associated with mesoscale eddies (Su et al., 2021) and that,
110 consequently, advective processes could shift the position of WWs locally. This first part shows that
111 both advective and local diffusion processes related to surface warming can contribute to reducing WWs
112 extent or signal. We also highlight potential biases in the MHWs characteristics sampled by elephant
113 seals compared to random sampling by Argo floats. Second, we investigate how these impacts on WWs
114 are intensified under global warming, leading to a reduced extent of WWs, using CMIP6 models.
115 Finally, we discuss the potential mechanisms driving MHWs and global warming impacts on WWs
116 distribution, the contrast between observed trends, projections and paleoceanographic studies and the
117 potential ecological implications of a southward shift of the WWs.

118

119 2. Material and Methods

120

121 2.1. Observations and Mercator reanalysis

122

123 Temperature *in situ* profiles are collected from Argo float data between 2001 and 2019 over the area 20
124 -120°E 70-30°S (Argo, 2000). We download 170 352 profiles, among which 78 407 are complete
125 between 5 and 900 m. Temperature *in situ* profiles are also collected between 2004 and 2017 from
126 biologging in the Southern Indian Ocean and gathered by the Marine Mammals Exploring the Oceans
127 Pole to Pole or MEOP consortium (Treasure et al., 2017; Roquet et al., 2014). We download 140 436
128 profiles, among which 9 484 are complete between 5 and 900 m.

129 The GLORYS12V1 product is the Copernicus Marine Environment Monitoring Service (CMEMS)
130 global ocean eddy-resolving reanalysis delivered by Mercator Ocean. This product provides daily and
131 monthly mean temperature over 50 vertical levels and with $1/12^\circ$ horizontal resolution between 1993
132 and 2019. This product is used in this paper to provide a monthly climatology for the vertical
133 temperature profiles. The GLORYS12V1 product is also used to determine the probability of presence
134 of WWs between 1993 and 2019. This probability is estimated by detecting, for each day between 1993
135 and 2019 and for each grid cell, whether the minimum temperature between 100 and 400 m is found at a
136 depth less than 350 m, and then averaging the results (0 for absence of a temperature minimum in this
137 interval, 1 for presence) over time. WWs are also characterized by the temperature at the minimum (also
138 named WWs temperature) and the depth of this minimum (also named WWs depth), as in Sabu et al.
139 (2020).

140 The Operational Sea Surface Temperature and Ice Analysis (OSTIA) system run by the UK's Met
141 Office (Good et al., 2020) provides daily sea surface temperature free of diurnal variability, also called
142 the foundation sea surface temperature, at a $0.05^\circ \times 0.05^\circ$ horizontal grid resolution between 1982 and
143 2019. This product combines satellite measurements (L4 level) from both infrared and microwave
144 radiometers with in-situ measures from ships, drifting and moored buoys. This dataset was used for
145 surface MHW detection.

146

147 2.2. Marine heatwaves detection and characteristics

148

149 A MHW is identified as an event of at least 5 days for which the sea surface temperature (SST) is above
150 the 90th percentile of a data distribution using a seasonally-varying climatology for each grid point and
151 for each day of the year using an 11-day window (Hobday et al., 2016). The threshold is also smoothed
152 by applying a 30-day moving average. An average of 24 days/year under MHW is estimated between
153 1993 and 2019 over the area $20\text{-}120^\circ\text{E}$, $58\text{-}40^\circ\text{S}$.

154 The temperature anomaly depth, also called “MHW depth” in Elzahaby and Schaeffer (2019), is
155 calculated to investigate whether surface MHWs are associated with deeper temperature anomalies (see
156 Supplementary Methods). To do so, temperature anomaly profiles are obtained using the combination of
157 information from different datasets:

- 158 - OSTIA dataset: for the detection of surface MHW using Hobday et al. (2016) definition (90th
159 percentile)
- 160 - Argo float data: daily hydrographic profiles
- 161 - MERCATOR reanalysis: provide for each grid cell a monthly climatology profile

162 |

163 | From each Argo hydrographic profile, we compute the vertical cumulative temperature anomaly, and
164 the depth where 95% of the cumulative temperature anomaly is reached, also named “temperature
165 anomaly depth”. Temperature anomalies are defined as a departure from a seasonal climatological mean
166 produced from an ocean reanalysis (MERCATOR). Using satellite SST, we then group each of these
167 profiles as within a MHW or outside. The Argo profile is said to be in a MHW according to the surface
168 detection of a MHW using sea surface temperature observations (OSTIA). A bootstrap approach with
169 10000 iterations is used to obtain the mean values of the two metrics, as the sample sizes (in and out
170 MHW) differ.

171 |

172 | 2.3. Altimetry analysis

173

174 Altimetry-derived geostrophic velocities are computed by CLS/AVISO (Collecte Localization
175 Satellites/Archiving, Validation, and Interpretation of Satellite Oceanographic data) and distributed by
176 Copernicus Marine Environment Monitoring Service (CMEMS) as a gridded product on a $0.25^\circ \times 0.25^\circ$
177 horizontal grid resolution between 1993 and 2020 (<https://doi.org/10.48670/moi-00148>).

178 Using AVISO geostrophic velocities, the latitudinal advection of water parcels over 15 days backward
179 in time is estimated. The latitudinal displacement is positive when the water parcel has moved

180 southward over the last 15 days. The duration of 15 days for the advection is chosen as this is the typical
181 timescale for MHW durations (Oliver et al., 2018). A monthly climatology of latitudinal displacement is
182 determined over multiple years (1993-2020). Correlations between anomalies of latitudinal
183 displacement and the presence/absence of MHW are evaluated to investigate the co-occurrence between
184 MHW and an anomalous southward displacement of surface warmer water.

185

186 2.4. CMIP6 models

187

188 Coupled models from the Coupled Model Intercomparison Project 6 (CMIP6) have been used to
189 conduct historical and projection simulations notably to investigate how the Earth system responds to
190 forcing (Eyring et al., 2016). The 12 models used here (described in Supplementary Material S1) are
191 selected among 26 CMIP6 models as they provide a realistic representation of the circumpolar mean
192 position of WWs between 1995-2014 using their historical simulations (Supplementary Methods and
193 Supplementary Material S2). Historical (1850-2014) and projection (2015-2100) simulations from
194 CMIP6 are used here. Three emission trajectories, also called Shared Socioeconomic Pathways (SSPs),
195 are considered: the SSPs 1-2.6, 2-4.5 and 5-8.5 (Lee et al., 2021). The variable considered here is
196 monthly *theta* (sea water potential temperature across different depth levels in °C). WWs are detected
197 through the presence of a temperature minimum between 100 and 400 m at a depth less than 350 m. The
198 outputs of the 12 models under the three SSPs are combined following the so-called ‘time-shift
199 approach’, which consists in averaging the models outputs over a period that, for each model,
200 corresponds to a given global warming level (GWL ; Herger et al., 2015; Chen et al., 2021; Lee et al.,
201 2021; see Supplementary Methods).

202

203 3. RESULTS

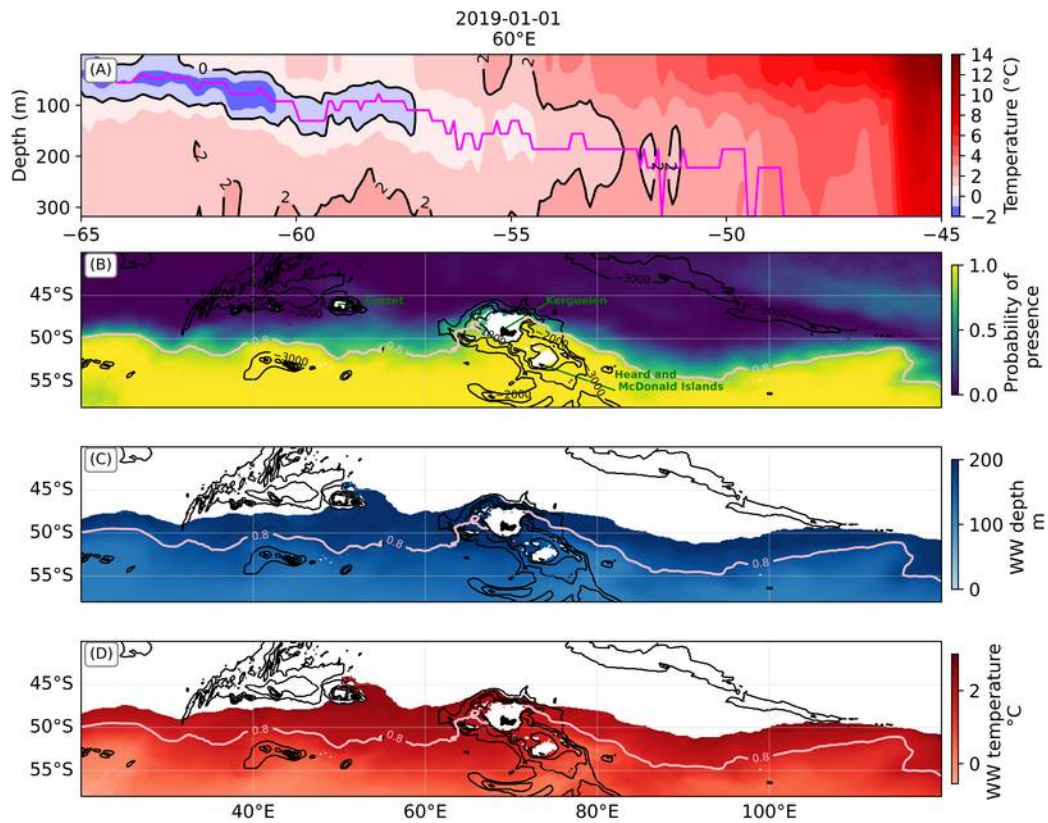
204

205 3.1. Winter waters distribution and modulation by marine heatwaves

206

207 Based on the MERCATOR reanalysis product presented above, we describe the typical characteristics
208 of WWs in the Southern Indian Ocean (20-120°E, 70-30°S). On average between 1993-2019, their
209 northernmost extension is estimated to be between 52°S and 46°S, and it can be noted that at their
210 northern edge, WWs presence is no longer continuous as illustrated on Figure 1A. WWs mean
211 temperature is 1.3°C but varies between -0.55°C and 3°C depending on the latitude/longitude (Figure
212 1D ; note that we use a maximum historical WWs temperature at 3°C; see Supplementary Methods) and
213 WWs mean depth is 155 m and varies between 110 and 280 m (Figure 1 C). By definition, the water
214 mass north of the WWs is not characterized by a minimum temperature between 100 and 400 m and is
215 warmer than the water masses south of the Polar Front throughout the upper 400 m (e.g. Figure 1A). We
216 now focus on the variability of presence, temperature, and depth of WWs and seek to determine what is
217 the influence on its variability of warm surface events, such as marine heatwaves.

218



219

220

221 Figure 1: Winter waters climatological description and characteristics using MERCATOR reanalysis

222 product between 1993 and 2019. (A) Example of the vertical signature of winter waters (minimum

223 temperature between 100 and 400 m) at 60°E on the 1st of January 2019. The position of the minimum

224 temperature along the cross section is indicated in magenta. The characteristics of the winter waters

225 studied here are the probability of presence of winter water (B, presence is 1, absence is 0), the depth of

226 the minimum temperature (C) and the temperature minimum value (D). A mask to only select grid cells

227 where on average the minimum temperature is below 3°C was used on C and D. The contour of the 80%

228 probability of presence of winter waters is shown in pink on B, C and D.

229

230 3.1.1. Southward shift of winter waters distribution under marine heatwaves

231 |

232 | We first seek to determine whether MHWs are deep reaching in the Indian sector of the Southern Ocean.

233 In MHWs, the temperature anomaly depth is 3 times deeper than outside MHWs (Figure 2B),

234 highlighting that MHWs are not limited to the surface layer but extend at depth. We note that outside

235 MHWs the mean temperature anomaly depth is by construction much shallower because many profiles

236 associated with null or negative vertical temperature anomalies would be associated with a depth of 0.

237 Consistent with the estimated difference in temperature anomaly depth, in MHWs, the typical

238 cumulative temperature anomaly is much larger than outside, almost 5 times larger, with a mean

239 cumulative temperature anomaly estimated at 549 °C.m (± 8 °C.m; Figure 2C).

240

241

242 Figure 2: (A) Spatial distribution of 78407 Argo hydrographic profiles that are complete up to 900 m
243 between 2001 and 2019. Mean MHW depth (B) and mean cumulative temperature anomaly (C)
244 calculated from the anomaly profiles between Argo profiles and a monthly reference obtained with
245 MERCATOR reanalysis over the area 20-120°E, 70-30°S. The mean values of the two metrics, in and
246 out of a MHW, are shown (dashed vertical lines). Examples of Argo profiles in a MHW (red; 30.1°E/53.
247 2°S on 20/11/2019 (D); 37°E/51.8°S on 10/12/2015 (E)) and outside a MHW (blue; 30.1°E/54°S on
248 20/11/2013 (D); 37.9°E/52°S on 08/12/2014 (E)); together with associated monthly reference from
249 MERCATOR reanalysis (black solid for reference to Argo observation out a MHW; black dashed for
250 reference to Argo observation in a MHW). The temperature anomaly depths associated with these
251 profiles are shown directly on (D) and (E) and reported on (B) for the MHW cases (dotted lines).

252

253 As MHWs are associated with deeper and intense temperature anomalies (Figure 2), we investigate
254 whether this is due to a replacement of water masses through the southward advection of warmer waters.
255 Positive correlations are found across the Indian sector of the Southern Ocean between an anomalous
256 southward latitudinal displacement of water parcels over 15 days (typical MHW duration ; the
257 convention used here is that the latitudinal displacement is positive when the water parcel has moved
258 southward), and the presence of MHW, estimated using OSTIA dataset, between 1993 and 2020 (mean
259 correlation coefficient over the area of 0.2, Figure 3A). These correlations are higher in the area where
260 the most intense MHWs have previously been found (see Figure 3A in Azarian et al., 2023), north of the
261 Southern ACC Front between 20°E and 40°E and between the Subantarctic Front and the Northern
262 boundary between 40°E and 70°E (correlation coefficient of more than 0.3 and up to 0.87 ; Figure 3A).
263 MHWs are therefore associated with the southward advection of water. If this occurs across the Polar
264 Front, within mesoscale eddies or front meanders, it would imply that northern and warmer water mass
265 es are advected southward, effectively pushing WWs southward, and generating a deep positive
266 temperature anomaly (e.g. Figure 2B). Indeed, the water mass north of the northernmost extension of
267 WWs often have transitional properties between Antarctic Surface Waters and Subantarctic Surface
268 Waters (the latter dominates north of the Subantarctic Front), with temperatures typically ranging

269 between 3° and 8°C, though their properties mostly depend on mixing (Carter et al., 2008). Consistently,
270 we find that the presence of MHW significantly decreases the probability of presence of WWs, using
271 MERCATOR ocean reanalysis between 1993 and 2019 (Figure 4A). This southward shift of WWs in
272 presence of MHWs is also consistent with *in situ* observations analysis (Supplementary Materials S3).

273

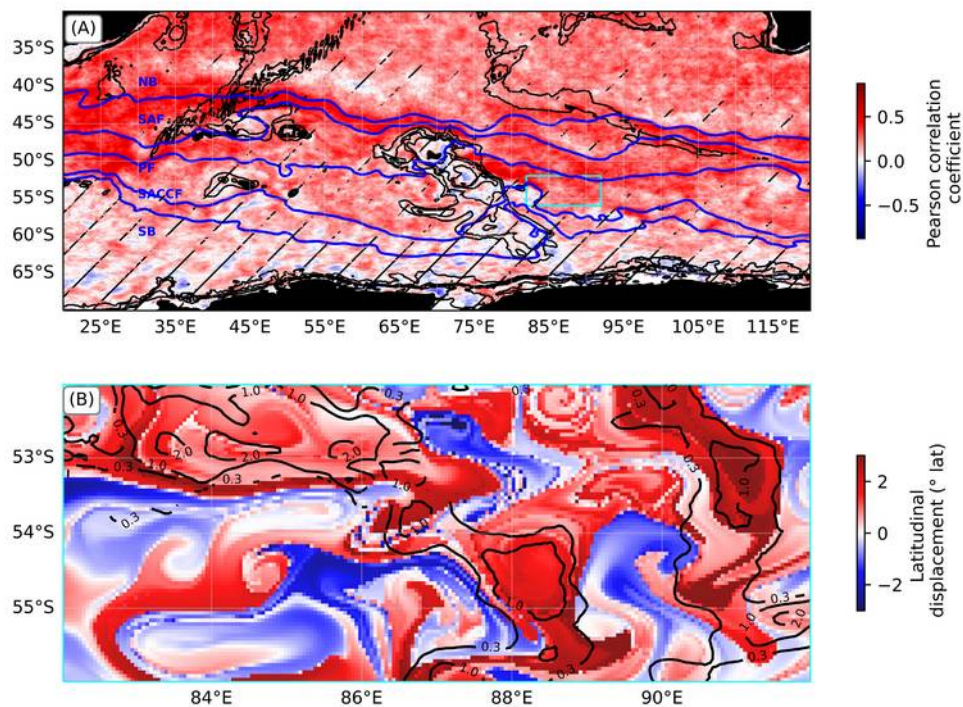
274 The impact of warm ocean surface conditions on WWs can therefore come from a southward water
275 transport that would cause both a local MHW and a displacement of WWs further southward. This is
276 illustrated by the example on Figure 2E: there is no longer a minimum temperature on the Argo profile
277 during the MHW and the profile is warmer than the MERCATOR reference at the same location
278 throughout the water column, suggesting the presence of a different water mass. However, remaining
279 WWs temperature and depth can also be directly affected: either because their distribution is shifted or
280 because of vertical heat diffusion. This is illustrated by the example on Figure 2D: the temperature
281 anomaly during the MHW is the most intense at the surface and there is still a minimum temperature,
282 although this minimum is deeper and slightly warmer than the MERCATOR reference at the same
283 location. Indeed, WWs in MHWs are deeper and warmer than WWs that are not in a MHW (Figure 4 B
284 and C). The mean difference between the mean WWs depth anomaly in and out MHWs is around 17 m
285 (± 25 m, spatial standard deviation). The mean difference between the mean WWs temperature anomaly
286 in and out MHW is around 0.33°C (± 0.45 °C, spatial standard deviation).

287

288 We note that the spatial patterns of warming and deepening during MHWs tend to follow mean dynamic
289 topography contours, which represent the general circulation (Figure 4). In particular, changes are
290 weaker in areas of northward cold water mass intrusion such as around Conrad Rise (20-26°E), the Fawn
291 Trough (74-83°E) or east of the Southeast Indian ridge (110-116°E). Hotspots of deepening and
292 warming of WWs under MHWs are found west of Crozet Plateau (25-34°E) and east of Kerguelen
293 Plateau (76-102°E), which are standing meanders and areas of high eddy kinetic energy (Figure 4 ;
294 Siegelman et al., 2019; Dove et al., 2022). The differences between WWs temperature anomalies (and
295 depth anomalies) in MHWs compared to outside MHWs are two to three times warmer (and deeper) in
296 these two locations compared to the regional mean of those differences. These two locations also

297 correspond to the areas where the difference between the probability of presence of WWs given a MHW
 298 and the probability of presence of WWs given no MHW is the strongest. The probabilities of WWs
 299 presence given a MHW are 71% lower (than those given no MHW) on average in these two locations
 300 and up to 100% lower. A 100% decrease means that no WW is detected during a MHW in a grid cell
 301 where WW can be detected when there is no MHW.

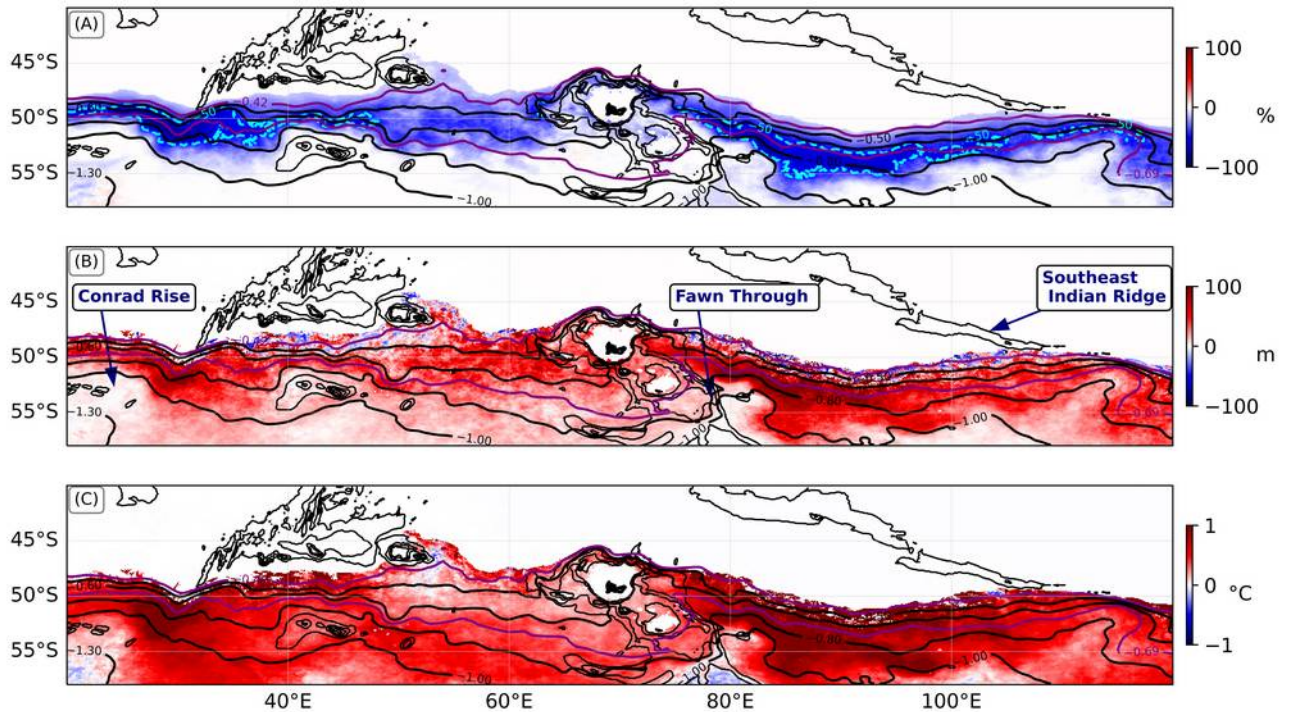
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303

304 Figure 3: (A) Correlation between the latitudinal displacement anomaly (using AVISO geostrophic
 305 velocities) and the presence/absence of marine heatwaves (MHWs, using OSTIA daily data and Hobday
 306 et al., 2016 definition, 90th percentile) using monthly averages over multiple years between 1993 and
 307 2020. The Antarctic Circumpolar Current (ACC) fronts such as the Subantarctic Front (SAF), the Polar
 308 Front (PF) and the Southern ACC front (SACCF), as well as the Northern (NB) and the Southern (SB)
 309 boundaries are shown in blue (from Park and Durand, 2019). Hatched areas indicate where the results
 310 are not significant ($p > 0.01$). (B) Example of the overlap between marine heatwaves intensity and the

311 latitudinal displacement over 15 days on the 27th of december 2017 over the area 82-92°E 56-52°S (area
 312 shown in cyan in A). The black contours correspond to MHW intensity of 0.3°C, 1°C and 2°C.
 313



314
 315
 316 Figure 4: Impacts of marine heatwaves (MHWs) on winter waters (WWs) using MERCATOR
 317 reanalysis product between 1993 and 2019, through (A) the difference between the probability of
 318 presence of WWs given that there is a MHW and the probability of presence of WWs given that there is
 319 not a MHW (contour of 50% difference in cyan); (B) the difference between the WW depth anomaly
 320 (relative to a monthly climatology, 1993-2019) in and out of a MHW; and (C) the difference between the
 321 WWs temperature anomaly (relative to a monthly climatology, 1993-2019) in and out of a MHW. A
 322 mask to only select grid cells where a minimum temperature between 100 and 400 m less than 3°C is
 323 observed on average over 1993-2019 is applied on these figures. Mean dynamic topography contours
 324 (mean between 1993 and 2012, HYBRID-CNES-CLS18-CMEMS2020, Mulet et al., 2021) are shown
 325 in black, with the -0.69 and -0.42 m contours, which have been respectively associated with the southern
 326 and northern branches of the Polar Front (Chapman et al., 2017), that are shown in purple on these
 327 figures.

328

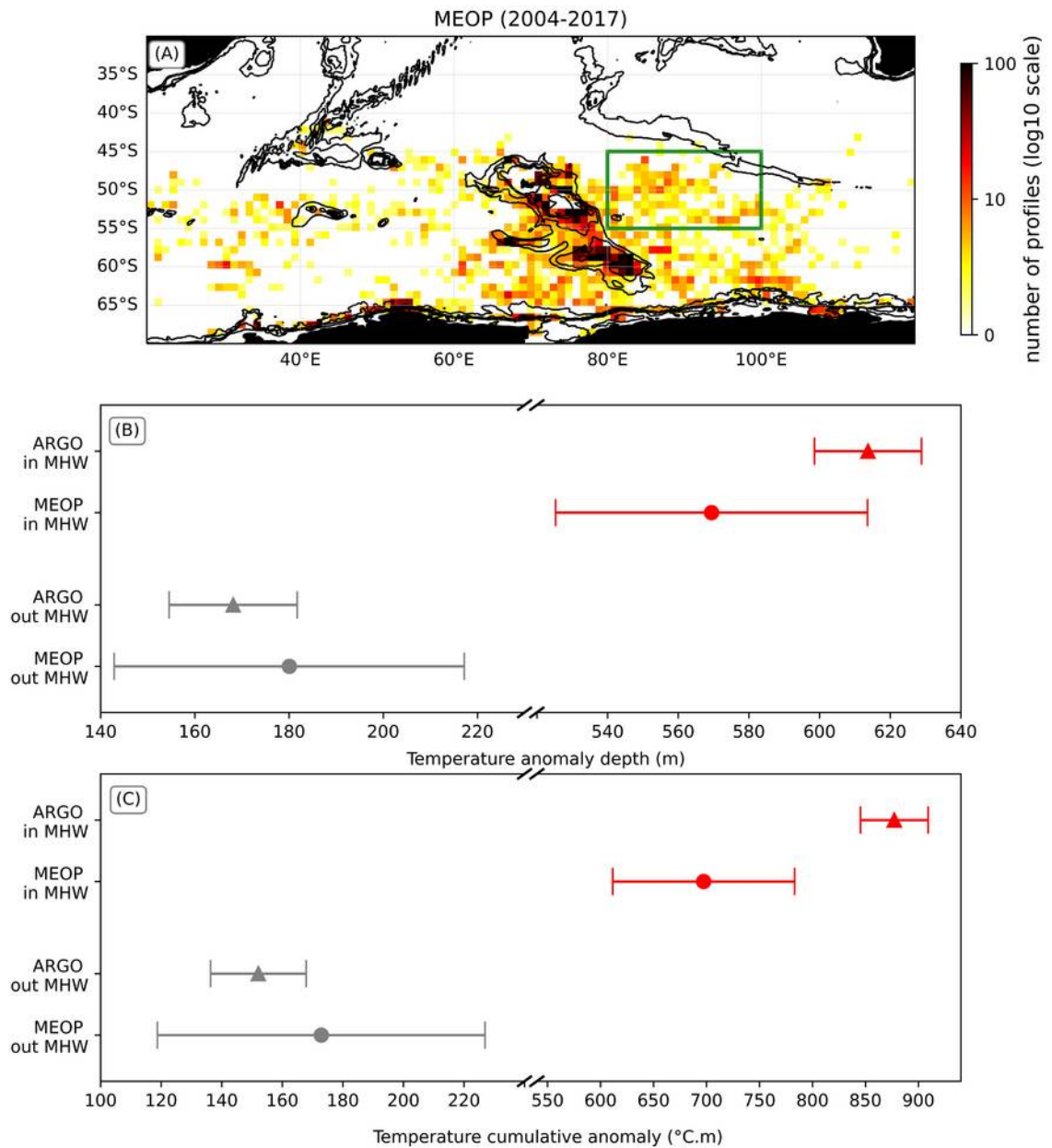
329 | 3.1.2. Shallow and cold bias in marine heatwaves sampled by elephant seals

330

331 Elephant seals often forage near the Polar Front and can rely on oceanographic conditions to adapt their
332 foraging strategy (McIntyre et al., 2011; Guinet et al., 2014). MEOP-CTD dataset (see section 2.1)
333 provides elephant seals hydrographic profiles that can be used to evaluate the temperature anomaly
334 depth during extreme events, as previously done with Argo float data. The aim here is to identify
335 possible biases in the water masses properties sampled by elephant seals in respect to Argo estimates.

336 We investigate in particular the depth of temperature anomalies during MHWs sampled by elephant
337 seals near the Polar Front east of the Kerguelen Plateau (80-100°E; 55-45°S), which is an important
338 foraging area (Bost et al., 2009; Dragon et al., 2010; Cotté et al., 2015; Allegue et al., 2022), and as such
339 represents a region where both elephant seal and Argo data are available (Figure 2A and 5A). We use
340 467 MEOP-CTD profiles available between 2004-2017 (Figure 5A) and 4101 Argo profiles between
341 2001 and 2019. The mean temperature anomaly depth is 7% shallower and the mean cumulative
342 temperature anomaly is 21% less intense using elephant seals data compared to Argo data, although
343 those same metrics outside a MHW are similar for both datasets (Figure 5B,C). These results suggest
344 that elephant seals do not sample (i.e., avoid) deeper and more intense marine heatwaves. While MEOP-
345 CTD dataset is complementary to Argo data, using elephant seal data to study MHWs can therefore
346 introduce a bias towards shallower and less intense MHWs possibly due to animal preference to avoid
347 higher-than-normal temperatures.

348



349

350 Figure 5: Spatial distribution of 9484 hydrographic profiles that are complete up to 900 m, from MEOP-
 351 CTD dataset between 2004 and 2017 (A). Mean temperature anomaly depth (in m, B) and mean
 352 cumulative temperature anomaly ($^{\circ}\text{C}\cdot\text{m}$, C) calculated from the anomaly profiles between elephant seals
 353 profiles (round marker) or Argo profiles (triangles) and a monthly reference obtained with
 354 MERCATOR reanalysis. These calculations are done both for profiles found in (red) and out (gray) a

355 MHW respectively over the area 80-100°E 55-45°S (green rectangle on A). The mean values and
356 errorbars are estimated using a bootstrap approach, as presented in section 2.2.

357

358 3.2. Winter waters in the future for different warming levels

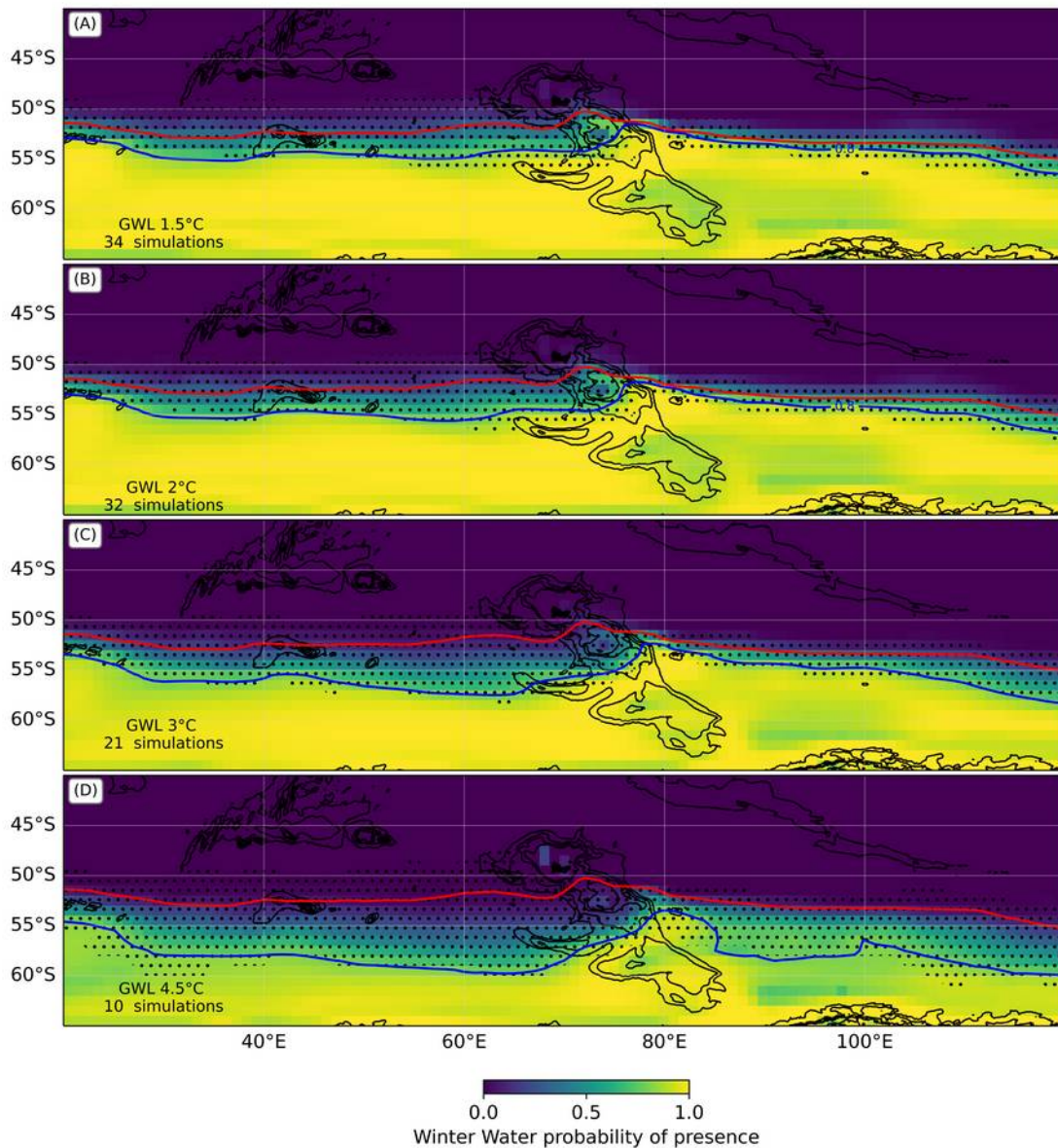
359

360 In the previous section, we show that in the past decades transient warm ocean surface events are
361 associated with anomalies in WWs characteristics, as WWs can shift southward or be warmed and
362 deepened, due to advective processes or local diffusion. In this section, we now seek to determine if in a
363 globally warmer climate, WWs would be affected durably in similar ways.

364

365 Consistently with a southward water mass displacement, as global warming levels increase, the
366 northernmost position of WWs (defined as the 80% probability of presence; referred to as Polar Front)
367 shifts southward in CMIP6 models. The mean southward shift is 1.6° ($\pm 0.9^\circ$, along longitudes standard
368 deviation), 2.1° ($\pm 1.3^\circ$), 3.1° ($\pm 1.4^\circ$) and 5.2° latitude ($\pm 1.5^\circ$ latitude) when averaged from 20°E to
369 120°E, for GWL 1.5°C, 2°C, 3°C and 4.5°C respectively (Figure 6).

370 There is an important asymmetry in the WWs southward shift between east and west of the Kerguelen
371 Plateau. West of the Kerguelen Plateau (20-70°E), WWs shift southward by around 2.2°, 2.8°, 3.9° and
372 5.9° latitude for GWLs 1.5°C, 2°C, 3°C and 4.5°C, respectively. East of the Kerguelen Plateau (70-
373 120°E), the WWs shift southward by around 1°, 1.4°, 2.3° and 4.6° latitude for GWLs 1.5°C, 2°C, 3°C
374 and 4.5°C, respectively (Figure 6). Compared to the western side of the plateau (65-70°E), on the eastern
375 side of the Kerguelen Plateau (75-80°E), the Polar Front is relatively stable for low warming levels
376 before shifting southward (Figure 7). This relative stability of the Polar Front east of the Kerguelen
377 Plateau is however very dependent on the chosen models. For each model and each scenario, we
378 determine the global warming level for which the Polar Front position anomaly in absolute starts to be
379 permanently greater than 0.4° latitude (that is twice the mean natural variability of the Polar Front
380 position between 75-80°E across models and scenarios). East of the Kerguelen Plateau, this mean
381 threshold is 2.6 °C ($\pm 0.6^\circ\text{C}$, intermodel and inter scenarios standard deviation; Figure 7C).



383

384

385 Figure 6: Winter waters probability of presence for a global warming level of 1.5°C (A), 2°C (B), 3°C

386 (C) and 4.5°C (D) relative to 1850-1900 using 12 CMIP6 models and SSP1-2.6, SSP2-4.5 and SSP5-8.5.

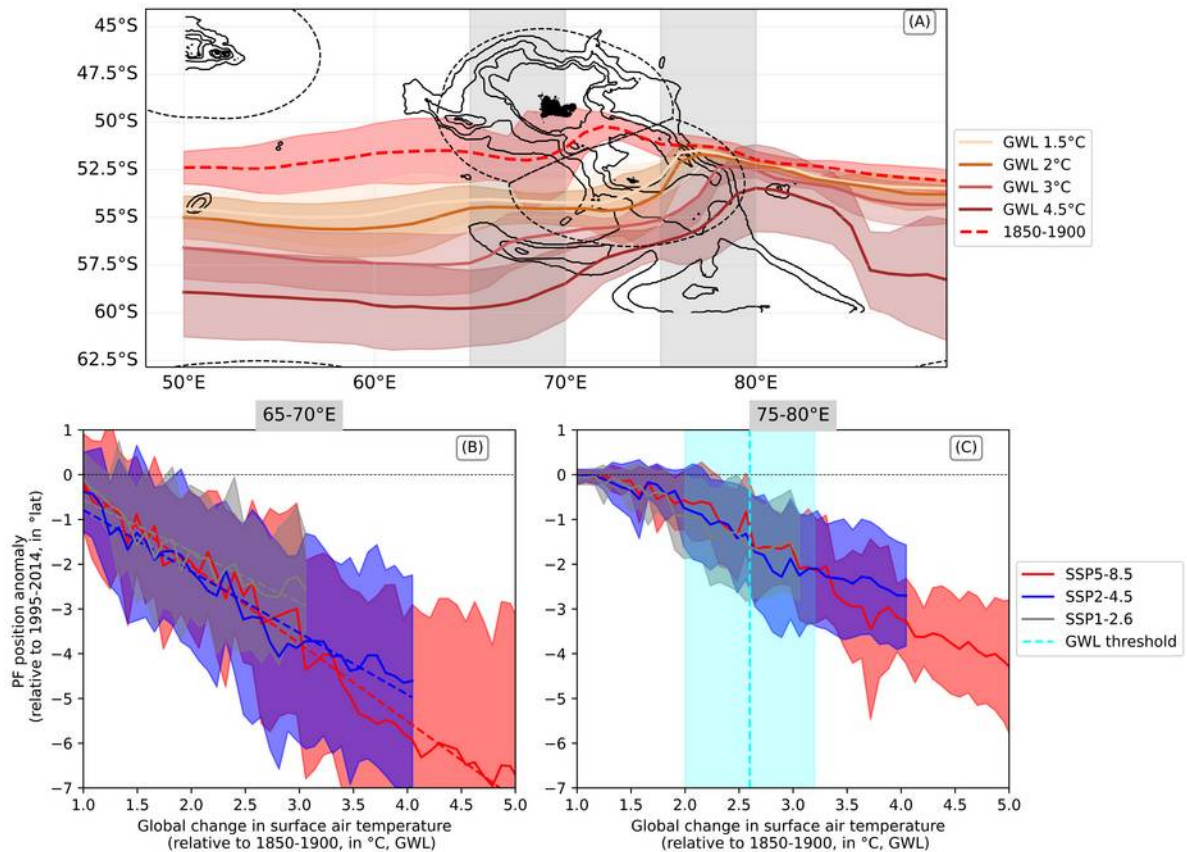
387 The blue contours indicate the northernmost limit of 80% probability of presence of winter waters for

388 each global warming level. The red contours indicate the northernmost limit of 80% probability of

389 presence of winter waters for the preindustrial period (1850-1900) for the same number of simulations in

390 each case. Dotted areas indicate where at least 80% of the simulations agree with the sign of the change

391 of presence/absence of winter waters relative to 1850-1900.



393

394

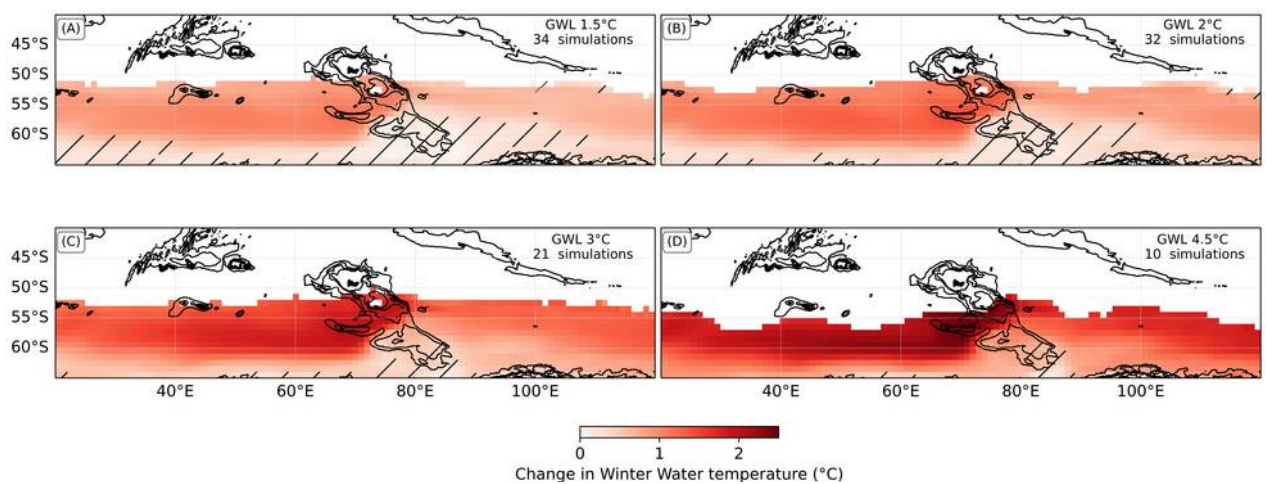
395 Figure 7: Northernmost limit of 80% probability of presence of winter waters (similar to Figure 6) for
 396 global warming levels (GWLs, global change in surface air temperature) 1.5°C, 2°C, 3°C and 4.5°C, as
 397 well as for the preindustrial period (1850-1900, dashed red line) between 50° and 90°E (A). The colored
 398 areas on (A) correspond to the intermodel standard deviation. Polar Front (PF) position anomaly
 399 (relative to 1995-2014) for the average of 12 CMIP6 models under SSP1-2.6 (gray), SSP2-4.5 (blue)
 400 and SSP5-8.5 (red), averaged over 65-70°E (B) and 75-80°E (C) for different GWLs (relative to 1850-
 401 1900). The two areas studied are shown in gray on panel A. The solid lines correspond to the multimodal
 402 mean value and the colored areas represent the intermodel standard deviation. On panel B, the dashed
 403 lines represent the linear regression of the PF position anomaly (over 65-70°E) with global warming for
 404 the different scenarios. On panel C, the vertical dashed line indicates the mean value, across the different
 405 models and scenarios, of the global warming threshold for which the PF position anomaly in absolute

406 starts to be permanently greater than 0.4° latitude (that is twice the natural variability of the PF position
407 east of the Kerguelen Plateau ; referred to as GWL threshold).

408

409 We next investigate how the remaining WWs shifted southward are affected by local warming under the
410 different global warming levels. Under all future warming levels, WWs are projected to warm (Figure
411 8). When averaged over the area 20-120°E, 70-30°S, the mean change of temperature (relative to 1850-
412 1900) for the multimodel mean is 0.6°C ($\pm 0.3^\circ\text{C}$, regional mean intermodal standard deviation), 0.8°C
413 ($\pm 0.4^\circ\text{C}$), 1.1°C ($\pm 0.5^\circ\text{C}$), 1.4°C ($\pm 0.6^\circ\text{C}$) for respectively GWLs 1.5°C, 2°C, 3°C and 4.5°C (Figure
414 8). Compared to the warming, the overall projected deepening of WWs under global warming is
415 relatively weak and not significant for a large proportion of our region of interest, especially east of the
416 Kerguelen Plateau (Supplementary Material S4). The area-average deepening ranges from 5 to 9 m
417 between GWL 1.5°C and 4.5°C but changes in WWs depth vary widely spatially within a single model
418 and between models (Supplementary Material S4).

419



420

421

422 Figure 8: Change in winter waters' temperature for a global warming level of 1.5°C, 2°C, 3°C and 4.5°C
423 relative to 1850-1900 using 12 CMIP6 models and SSP1-2.6, SSP2-4.5 and SSP5-8.5. Only mean
424 values obtained from more than 80% of the simulations are shown (as winter waters shift differently

425 depending on models). Hatching indicates areas where the intermodel standard deviation is superior to
426 the multimodel mean.

427

428 4. DISCUSSION

429

430 4.1. Rapid winter waters variability associated with marine heatwaves

431

432 Our study shows that MHWs can be associated either with a replacement of WWs or with warmer and
433 deeper WWs (see section 3.1).

434

435 Our findings suggest that MHWs in the Southern Indian Ocean can be related to the regional mesoscale
436 activity. Surface mean MHW intensity patterns show that the most intense MHWs are located along the
437 northern boundary of the ACC (as defined in Park et al., 2019) in areas of high SST variability but also
438 east of the Kerguelen Plateau in high eddy kinetic energy areas (Su et al., 2021; Azarian et al., 2023).
439 Consistently, Su et al., 2021 show, using an eddy-resolving model and NOAA-OI observations, the
440 similarity between patterns of surface temperature anomalies and of sea level variability, used as a proxy
441 for eddy activity, east of the Kerguelen Plateau. East of the Kerguelen Plateau (80-100°E; 55-45°S), we
442 observe that MHWs sampled by elephant seal are shallower and less intense (Figure 5). This area east of
443 Kerguelen is a major foraging zone for elephant seals females and juveniles (*Mirounga leonina*) whose
444 behavior is related to mesoscale activity near the Polar Front (Bailleul et al., 2010; Dragon et al., 2010;
445 Cotté et al., 2015 ; Cox et al., 2020). Elephant seals were found to avoid the interior of anticyclonic
446 structures for capturing prey (Dragon et al., 2010). The observed bias of subsurface MHWs
447 characteristics with MEOP-CTD datasets compared to Argo floats data (Figure 5) is thus consistent with
448 MHWs being strongly associated with anticyclonic eddies. Also, Argo-derived MHW presence is found
449 consistently in locations with higher eddy kinetic energy compared with profiles outside MHWs,
450 especially in winter (Kolmogorov-Smirnov statistic-test=0.12, p-value= $2.4 \cdot 10^{-22}$; Supplementary
451 Material S5).

452 |

453 | In this study, we show that MHW occurrence is positively correlated to a southward advection of water,
454 especially at the northern boundary of the ACC (correlation coefficient up to 0.87; Figure 3). The
455 advection of water parcels showed that MHW are associated with southward latitudinal displacements
456 that, on timescales of the order of a MHW duration (15 days), can be more than 110 km further than
457 usual (Figure 3B). This observation highlights the role of advective processes on MHWs.

458

459 The link described above between the mesoscale circulation and the presence of MHWs may also
460 explain MHWs' subsurface signal. Surface temperature anomalies can be advected southward by eddies
461 and penetrate deeper in the water column. Eddies can also trap and advect northern water masses
462 southward, forming an anticyclonic meander in the Polar Front, and eventually generating a temperature
463 anomaly across the water column. MHWs could be triggered by the southward advection of water
464 masses across the Polar Front, e.g. within mesoscale eddies or front meanders, which would essentially
465 drive WWs distribution further southward. This study shows that indeed MHWs are associated with a
466 lower probability of presence of WWs (Figure 4A). WWs northernmost extension (at least 80% of
467 probability of presence) is shifted southward by around 1.4° latitude on average during MHWs in the
468 Southern Indian Ocean. MHWs can therefore be associated with the variability of the Polar Front
469 position, if the definition is taken of the Polar Front as the northernmost boundary of WWs. Such
470 relation between MHWs and front shifts has already been observed in other regions (e.g. East Asian
471 Marginal Seas, Choi et al., 2022, or the Kuroshio-Oyashio system, Du et al., 2022). The observed
472 warming and deepening of WWs, also across all longitudes (Figure 4 B and C) is not contradictory with
473 advective processes, as the southward shift of WWs distribution can lead to deeper and warmer WWs
474 replacing shallower and colder WWs.

475 |

476 | In addition to advective processes, locally enhanced mixing could contribute to extending temperature
477 anomalies at depth, especially in highly energetic regions such as east of the Kerguelen Plateau (Dove et
478 al., 2022). The observed warming of WWs (Figure 4C) can also be due to vertical mixing of the cold
479 subsurface water mass with warmer surface water (Giddy et al., 2023). Giddy et al., (2023) show that a

480 warming trend of 0.2°C over 28 days in the WW layer was driven by a convergence of heat flux from
481 both above and below the WW layer; since in our study we find WWs temperature anomalies of 0.33°C
482 during MHWs (Figure 4C), diffusive processes may not be negligible.

483

484 4.2. Projected southward shift and warming of WWs in CMIP6 models

485

486 Intensity, duration, and extension of MHWs are expected to increase in the future both globally and in
487 the Southern Indian Ocean. At the global scale, the average global number of MHW days is projected to
488 increase by a factor of 16 even in a 1.5°C warming world (Frölicher et al., 2018). In addition, MHWs are
489 projected to be more intense and to last longer, mostly due to ocean warming, especially in the
490 subantarctic Indian Ocean (Azarian et al., 2023). An almost permanent state of MHW, relative to the
491 historical period (1984-2014), is almost reached west of the Kerguelen Plateau (311.8 annual MHW
492 days) at the end of the century using CMIP6 models under SSP2-4.5 (Azarian et al., 2023). Here we
493 discuss the potential shift and warming of WWs under global warming on decadal timescales in both
494 observations and CMIP6 analysis.

495

496 4.2.1. Comparing CMIP6 projections to past observations and paleoceanographic reconstructions

497

498 Our study shows a southward shift of WWs under global warming and thus of the Polar Front if this
499 front is defined as the northernmost extension of WWs, using WWs probability of presence as an
500 indicator (see section 3.2). The amplitude of this shift varies depending on the models but it can already
501 be observed for a GWL 1.5°C. In a 1.5°C warming world, a maximum shift of around 4° latitude
502 southward is found at 72°E (i.e. over the Kerguelen Plateau; compared to its preindustrial position;
503 Figure 7).

504 |

505 | This climate change signal may not have emerged yet in the observations. Different results have been
506 found regarding actual trends in Polar Front shift depending on the front detection method used

507 (Chapman et al., 2020). There is a consensus today that there is no evidence of a southward shift of the
508 mean ACC position from observations (Gille, 2014; Chambers et al., 2018; Pauthenet et al., 2018 ;
509 Meredith et al., 2019). Over the past decades the Polar Front may have remained within its natural range
510 of latitude. This is also what is observed with the MERCATOR product using the definition of the Polar
511 Front applied in our study (i.e. northernmost boundary of WW). In particular, although an increase in
512 MHW occurrence is observed east of the Kerguelen Plateau over the period 1993-2019, using OSTIA
513 dataset, there is no significant increase in MHWs that are associated with a southward shift of WWs
514 (Supplementary Material S6). In this study, we also find no significant southward shift of WWs, using
515 MERCATOR reanalysis between 1993 and 2019 (Supplementary Materials S6). Instead, we do observe
516 a northward shift of around 2° latitude of the Polar Front west of the Kerguelen Plateau between 47° and
517 65°E (Supplementary Materials S6). However, also in this area, no causal relation between Polar Front
518 shift and occurrence of MHWs can be identified, because no significant trend in MHWs is observed
519 using the OSTIA dataset. We thus conclude that, over the last 30 years, the position of the Polar Front
520 and the SST may still be dominated by natural variability (Azarian et al., 2023).

521

522 However, a shift of the Polar Front, and thus of WWs, in the Southern Indian Ocean might have already
523 occurred in a warmer world in the past (Civel-Mazens et al., 2021). During peak-Interglacials, the Polar
524 Front was found to pass through the Fawn Trough instead of nearby Kerguelen Islands ; in our study, th
525 is regime shift of the Polar Front is also found at the end of the century in some models and for high
526 GWLs (e.g. 4.5°C; Figure 6D).

527

528 Such projected shift could be due to changes in air-sea interactions, advection and sea ice dynamics
529 which all drive WWs characteristics (Gordon and Huber, 1984; Sharma and Matthew., 1985; Toole et
530 al., 1981; Evans et al., 2018 ; Pauthenet et al., 2018). In particular, changes in freshwater fluxes, notably
531 due to Antarctic sea ice melting and change in sea-ice transport, could be an important driver of WWs
532 mass transformation (Abernathey et al., 2016; Haumann et al., 2016). Sea ice melting and meltwater
533 advection in summer contributes to making WWs colder than subantarctic summer surface water (Park

534 et al., 1998; Anilkumar et al., 2015). If sea ice volume decreases, so might the supply of WWs and
535 possibly their extension.

536

537 We remind that different metrics can be used to define the Polar Front (Chapman et al., 2020).
538 Therefore, whether the Polar Front may shift in the future might vary depending on the region studied
539 and the definition used. For instance, a water mass based definition of a front, or a surface temperature
540 contour, might not always be well suited to follow future change of the jet position, at least regionally
541 (Meijers et al., 2019). Jets and fronts of the Southern Indian Ocean could be controlled by different
542 dynamical and non dynamical processes, thus generating a decorrelation between the jets and the fronts
543 position under global warming but this would require further investigation.

544 |

545 | 4.2.2. Ecological implications of a projected asymmetrical southward shift of winter waters

546 |

547 | In the long term, a drastic change in the WWs extension, and thus of the Polar Front, could have a
548 significant impact on the composition and spatial distribution of the ecosystems. The changes caused by
549 extreme events will tend to become average states depending on the GWL (WWs southward shift and
550 warming; Figures 6 and 8), except for potential effects on WWs depth which are more uncertain (see
551 section 3.2; Supplementary Material S4).

552

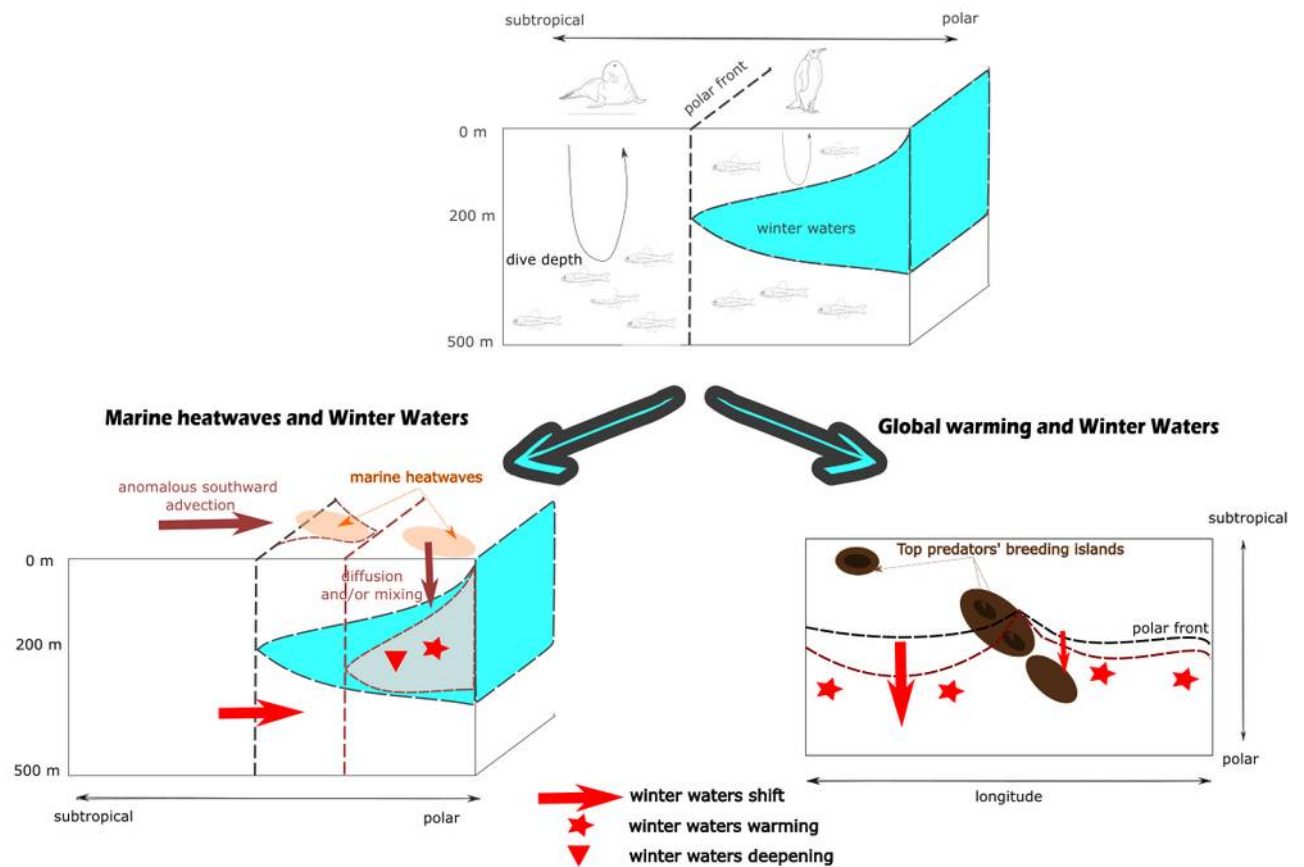
553 The asymmetry of the WWs southward shift in the CMIP6 models between the western side and the
554 eastern side of the Kerguelen Plateau (Figure 7) indicates that eastern ecosystems may be somehow
555 shielded by climate change. This buffering effect against climate change observed on the eastern side of
556 the Plateau could provide a “refuge” to some species of the Kerguelen Plateau. The concept of “climate
557 refugia” has been introduced to identify local areas undergoing limited or slower changes in climate, and
558 are typically potential candidates for protection (Burrows et al., 2014; Brito-Morales et al., 2018). In this

559 study, the spatial differentiation of climate change impacts observed in CMIP6 models could be useful
560 to guide conservation measures implemented in the French Southern Lands.

561 |

562 | This contrast between the west and the east of Kerguelen Plateau also echoes the differences in
563 vulnerability to a warming ocean observed between Crozet and Kerguelen king penguins' populations (
564 *Aptenodytes patagonicus*, Bost et al., 2015 ; Brisson-Curadeau et al., 2022). It was found that, over the
565 last 25 years, king penguins from Crozet were more sensitive to prey distance to the colony, associated
566 with the fluctuations of the Polar Front position, than king penguins from Kerguelen. It was suggested
567 that this latter population can be positively impacted by a warming ocean, through an increase in prey
568 abundance and growth rates, as foraging areas east of Kerguelen are more stable (Bost et al., 2015;
569 Brisson-Curadeau et al., 2022). However, these studies did not take into account that there may be a
570 warming threshold (around 2.6°C, see section 3.2; Figure 7C) when the Polar Front might no longer be
571 stable east of the Kerguelen Plateau. An ocean warmer than 2.6°C could then have dire consequences on
572 the Kerguelen king penguins and on other predators that rely on WWs in the vicinity of their colonies.
573 Note that this warming threshold is higher than the 1.5°C target of the Paris Agreement, which illustrates
574 how committing to strong mitigation policies could significantly alleviate climate change pressure on
575 biodiversity.

576



577
578

579 Figure 9: Summary of the impacts of marine heatwaves and long-term global warming on winter waters,
580 whose presence and characteristics play an important ecological role, notably for Southern Indian Ocean
581 land-based top predators.

582

583 5. Conclusion

584

585 Winter Waters (WWs) refers to a subsurface water mass, characterized by a temperature minimum
586 between 100 m and 400 m. This water mass plays an important ecological role in the Southern Indian
587 Ocean, often constraining the foraging areas of several predator species. In the context of climate
588 change, the aim of this study is to shed light on the impact of a warming climate on WWs. We found that

589 WWs presence, temperature and depth can strongly be impacted by warming at different timescales
590 (Figure 9). In the recent decades (most recent 30 years), extreme local warming events (MHWs) are
591 found to be related to changes in the distribution of WWs: their northernmost extension (at least 80% of

592 probability of presence) is shifted southward by around 1.4° latitude during MHWs. Under global
593 warming, this southward shift of WWs could be increased and maintained in the long term. In particular,
594 WWs northernmost extension is projected to shift southward by around 2.5° latitude under a 2°C
595 warming world between 50° and 90°E using 12 CMIP6 models.

596 If MHWs ecological impacts can generally be limited in time and space, major extreme events such as
597 the 1997 MHW (Bost et al., 2015) have been associated with dramatic consequences on land-based
598 marine top predators. Impacts during such extreme events may foreshadow long-term changes for
599 ecosystems in the future. WWs response to warming, however, is not homogeneous in our study area.
600 CMIP6 projections suggest that the position of WWs east of the Kerguelen Plateau is relatively more
601 stable, at least up to 2.6°C global warming. The presence of WWs nearby Kerguelen's colonies of top
602 predators could therefore be preserved under a Paris Agreement scenario.

603 This study therefore points out how warming can affect ecologically significant subsurface physical
604 features which are crucial for pelagic ecosystems. Understanding how such features might change
605 spatially and at different timescales could be useful for policy-makers to account for climate change
606 impacts in conservation and for mitigation strategies.

607

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609 Publicly available datasets were analyzed in this study. The OSTIA, AVISO and Mercator reanalysis
610 products were downloaded from copernicus marine service (<https://marine.copernicus.eu/>). The Argo
611 data were downloaded from Argo GDAC Data Browser
612 (https://www.usgodae.org/cgi-bin/argo_select.pl), and these data are collected and made freely
613 available by the International Argo Program and the national programs that contribute to it
614 (<https://argo.ucsd.edu>, <https://www.ocean-ops.org>). The Argo Program is part of the Global Ocean
615 Observing System. The elephant seal data are collected and made freely available by the International
616 MEOP Consortium and the national programs that contribute to it (<http://www.meop.net>). Both French
617 and Australian MEOP data were used. The Australian seal tracking data are collected by the Integrated

618 Marine Observing System (IMOS). IMOS is a national collaborative research infrastructure, supported
619 by the Australian Government. It is operated by a consortium of institutions as an unincorporated joint
620 venture, with the University of Tasmania as Lead Agent. CMIP6 models outputs are publicly available
621 here: <https://esgf-node.llnl.gov/projects/cmip6/>.

622

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633

634 **Appendix A : Supplementary Materials**

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636

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