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# 1 **Current and projected patterns of warming and marine heatwaves in the**

## 2 **Southern Indian Ocean**

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4 25 **Abstract**

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7 27 The Southern Indian Ocean (20-120°E, 70-30°S) hosts an exceptional biodiversity that contributed to  
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9 28 the inscription of the French and Australian natural reserves on the UNESCO World Heritage List. This  
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11 29 region is a “hot spot” for ocean heat uptake and already experiences intense marine heat waves (MHW),  
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13 30 as evidenced in 2011/2012 over the Kerguelen Plateau. In the coming decades, this region is also  
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15 31 expected to face supplemental anthropogenic warming, depending on future greenhouse gas emissions,  
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17 32 with unknown consequences for its marine ecosystems. Here, we present a regional analysis of ocean  
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19 33 warming and MHW based on the analyses of historical observations and Coupled Model  
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21 34 Intercomparison Project Phase 6 (CMIP6) climate projections. Consistent with observations over the  
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23 35 last decades, we find an intensification through the 21st century of surface warming and MHW over a  
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25 36 band located between 40°S and 55°S within the Antarctic Circumpolar Current region. CMIP6 models  
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27 37 also project much faster climate velocities (i.e. the speed and direction at which isotherms drift in the  
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29 38 wake of climate change) in the mesopelagic (200-1000m) than at the surface (0-200m). Lastly, a  
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31 39 comparison between the two Shared Socioeconomic Pathways (SSP1-2.6 and SSP2-4.5) analysed in  
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33 40 this study shows much larger changes in the second half of the 21st century for the higher emission  
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35 41 scenario. These results suggest that the subantarctic islands will probably be mostly affected by  
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37 42 warming and MHW under both scenarios, although committing to SSP1-2.6 could substantially  
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39 43 alleviate the pressure on ecosystems in the long term. This study also highlights the need to consider a  
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41 44 tri-dimensional environment that may evolve at different paces when designing efficient conservation  
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43 45 measures.  
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54 47 **Keywords**

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49 global climate models, ocean warming, ocean extremes, Southern Indian Ocean

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## 51 1 Introduction

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53 **Ocean circulation.** The Southern Indian Ocean (20-120°E, 70-30°S) is characterized by dynamic jets  
54 and a system of fronts associated with the Antarctic Circumpolar Current (ACC). The ACC is a strong  
55 eastward current (Donohue et al., 2016), driven by strong westerly winds (Rintoul and Naveira  
56 Garabato, 2013). As the ACC encounters the Kerguelen Plateau, it divides in several branches, with  
57 most of the ACC transport passing north of the Plateau (Park et al., 1991,1993, 2009). A strong jet is  
58 also observed through the Fawn Trough, a deep passage across the Plateau at 56°S (Park et al., 2008;  
59 Roquet et al., 2009; Van Wijk et al., 2010; Vivier et al., 2015; Figure 1). Northwest of the Southern  
60 Indian Ocean, the Agulhas Current, a western boundary current, flows southward along the east coast  
61 of Africa. At around 40°S, this flow is split with the Agulhas Return Current transporting water eastward  
62 (Lutjharms et al., 2006) and the Agulhas leakage transporting water to the South Atlantic (Schmidt et  
63 al., 2021). Generally, the frontal system and the circulation in the Southern Indian Ocean is an important  
64 biogeographical driver of phytoplankton and zooplankton communities which are at the basis of rich  
65 ecosystems (Hunt et al., 2001; Matsuno et al., 2020; Mishra et al., 2020; Venkataramana et al., 2020;  
66 Cotte et al., 2022).

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68 **Conservation efforts to protect a rich biodiversity.** The Southern Indian Ocean region hosts several  
69 endemic species, including large populations of megafauna of high patrimonial and economical value  
70 like king penguins, yellow-nosed albatrosses, southern elephant seals, krill, toothfish, and many others  
71 (Delord et al., 2014). To protect the rich biodiversity of the Southern Indian Ocean, conservation  
72 measures have been implemented both in the exclusive economic zones (EEZs) of the subantarctic  
73 islands and in the areas under the Commission for the Conservation of Antarctic Marine Living  
74 Resources (CCAMLR). Part of EEZs of the following territories, Prince Edward, Crozet, Kerguelen



75 and Heard and McDonald's islands, are managed through Marine Protected Areas (MPAs). The French  
76 national natural reserve (i.e. managed area with zones under strong or integral protection) within Crozet,  
77 Kerguelen and Saint-Paul and Amsterdam EEZ was created in 2006 and extended in 2016. The South  
78 African MPA around Prince Edward Islands have been officially implemented in 2013 and according  
79 to CCAMLR it contributes to a representative system of MPAs, to be used as a scientific reference for  
80 future management plans, to foster the recovery of Patagonian toothfish populations and to reduce the  
81 bycatch of toothfish fishery on marine seabirds. The Australian MPA around Heard and McDonald  
82 Islands was created in 2002 and has been extended in 2014. In total, 5.8% of the Southern Indian Ocean  
83 is covered by MPAs and only within EEZs. The new frontier for conservation is now the vast open  
84 ocean region that extends beyond EEZs (Della Penna et al. 2017), known as the "High Seas". A  
85 workshop held in 2019 organized by the CCAMLR Scientific Committee developed a scientific work  
86 program for pelagic spatial planning in the eastern subantarctic region to investigate the relevance of  
87 adding new subantarctic spatial conservation tools in the High Seas of the CCAMLR area (Makhado et  
88 al., 2019).

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90 **Conservation and climate change.** One key step in the design of a conservation plan is the evaluation  
91 of threats, including climate change (Meredith et al., 2019). The sector directly northward and within  
92 the Antarctic Circumpolar Current (ACC), corresponding to the latitudinal band 30°-50°S, in the  
93 Southern Indian Ocean is one of the regions of the world that has experienced the largest increase in  
94 ocean heat content in recent decades (Llovel & Terray, 2016; Roemmich et al., 2015; Sallée, 2018; Fox-  
95 Kemper et al., 2021). This large heat content increase has been explained by an increased heat uptake  
96 in the subpolar region transported northward by Ekman transport and subducted within and north of the  
97 ACC (Armour et al., 2016; Frölicher et al., 2015; Morrison et al., 2016; Sallée, 2018). In addition to  
98 large-scale processes (> 100 km), finer scale processes (1-100 km), which are key for the Southern  
99 Indian Ocean circulation (Kostianoy et al., 2004) and can be expected to intensify (Martinez-Moreno  
100 et al., 2019; Martinez-Moreno et al., 2021), could also potentially modulate climate change signal  
101 locally, maybe inducing important spatial heterogeneity in the temperature trends (e.g. anomalous

102 vertical heat transport driven by submesoscale fronts altering oceanic heat uptake, Siegelman et al.,  
103 2020).

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105 In the Southern Indian Ocean, species distributions are strongly shaped by the large meridional  
106 temperature gradient characterizing the region, which covers a transition zone from the subtropic to the  
107 Antarctic. Some species are even living close to their thermal tolerance limit (e.g., icefish, Kock &  
108 Everson, 2003; Collins et al., 2010) and it has been observed that warming could have a negative impact  
109 on the abundance of subantarctic krill, flagellates and Notothenioid fish (Constable et al. 2014) or even  
110 potentially on the juvenile recruitment of Patagonian toothfish (Belchier and Collins, 2008). Climate  
111 velocity, that is, the speed and direction at which isotherms drift in the wake of climate change (Loarie  
112 et al., 2009), can be a useful tool to study biodiversity redistributions due to climate change (Garcia  
113 Molinos et al., 2016). Although there is no specific studies on the Southern Ocean using this tool, there  
114 are global studies that tend to show that the Southern Ocean may be a generally « slow-moving » basin  
115 compared to other regions (Burrows et al., 2014) but also that there may be an important spatial  
116 heterogeneity of this indicator (Brito-Morales et al., 2020).

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118 Given the rich biodiversity and the observed and projected warming trends in the Southern Indian Ocean  
119 (Fox-Kemper et al., 2021), there is an urgent need to integrate climate change in biodiversity  
120 conservation and management. However, if climate change is increasingly presented as one of the  
121 threats on biodiversity in conservation plans, such a threat is rarely quantified and no associated actions  
122 are indicated. This issue will also likely be raised in line with the momentum fostered by the  
123 negotiations of a treaty on the conservation and sustainable use of marine biodiversity in areas beyond  
124 national jurisdiction (BBNJ), notably for the development of MPAs in the High Seas (Ban et al., 2014;  
125 Maxwell et al., 2020; Crespo et al., 2020). Despite an increasing awareness that climate change might  
126 hinder conservation measures efficiency and despite increasing literature on the need to develop new  
127 dynamical tools (Tittensor et al., 2019; Crespo et al., 2020), conservation policies seem to remain only  
128 focused on managing direct anthropogenic pressures as long as policy-makers have no concrete and  
129 operational courses of action to take into account the impacts of climate change (Wilson et al., 2020).

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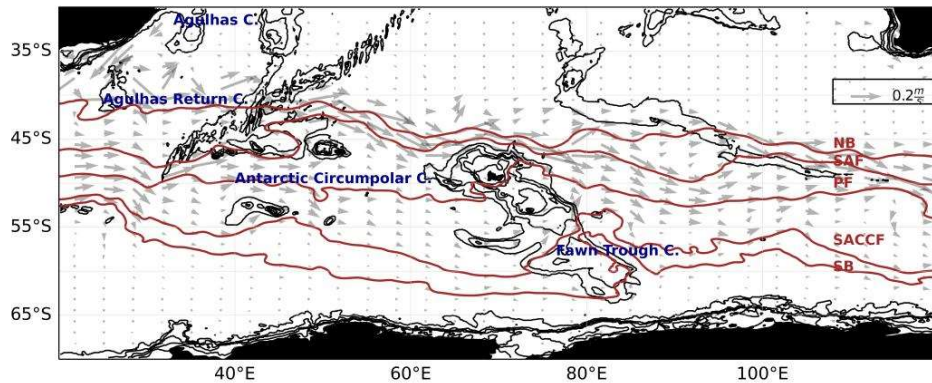
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2 131 **Current lack of relevant knowledge on climate change for policy-makers.** Levers for potential  
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4 132 action remain today unclear at the regional level and require a better understanding of climate change  
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6 133 related hazards at relevant spatial and temporal scales for conservation (Wiens and Bachelet, 2010 ;  
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8 134 Carr et al., 2011; Butt et al., 2016; Jones et al., 2016). Today, a gap remains in a systematic description  
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11 135 of local observed and future changes over the entire Southern Indian Ocean.

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14 136 In this study, we aim at addressing this shortcoming, by presenting a regional analysis of past and future  
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16 137 ocean warming based on historical observations and climate projections under different scenarios. Here,  
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18 138 we use a combination of decadal observations and CMIP6 simulations over the entire Southern Indian  
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20 139 Ocean to estimate current trends and analyse projections to help identifying areas that are most likely  
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22 140 to undergo significant temperature changes under two future emission scenarios : Shared  
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24 141 Socioeconomic Pathways (SSPs) 1-2.6 (high mitigation scenario) and 2-4.5 (modest mitigation  
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26 142 scenario; projected to lead to a global warming in 2100 similar to modelled pathways assuming  
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28 143 continuation of policies implemented by the end of 2020; IPCC, 2022). We estimate the average  
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30 144 temperature trends and extreme events, both listed as “climatic impact-drivers” of marine ecosystems  
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32 145 according to the IPCC Assessment Report 6 (Chen et al., 2021; Cooley et al., 2022). We document  
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34 146 average temperature trends in terms of warming patterns (°C/decade) as well as climate velocities  
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36 147 (km/decade). This analysis is performed for the ocean surface (0-200 m) and for the mesopelagic (200-  
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38 148 1000 m) regions. Extreme events are characterized in terms of marine heatwaves (MHW, Hobday et  
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41 149 al., 2016; Frölicher et al., 2018). Su and co-authors (2021) characterized MHW but focusing only on  
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43 150 the northern part of the Kerguelen Plateau. Our study extends the MHW analysis to the Southern Indian  
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45 151 Ocean and uses CMIP6 models to project the evolution of MHW throughout the 21st century.

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54 153 Figure 1: Ocean circulation in the Southern Indian Ocean. The mean geostrophic velocity between 1993  
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56 154 and 2020 using AVISO product (<https://doi.org/10.48670/moi-00148>) is shown (grey arrows). Some  
57  
58 155 specific currents are indicated in blue and the Antarctic Circumpolar Current (ACC) fronts, the Northern  
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156 Boundary (NB), Subantarctic Front (SAF), Polar Front (PF), Southern ACC front (SACCF) and the  
1 Southern Boundary (SB) are shown in brown (constructed from mean dynamic topography, source:  
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4 158 Park and Durand, 2019, Park et al., 2019).

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## 42 161 2 Material and Methods

### 45 162 2.1 Data

#### 47 163 2.1.1 Observations

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53 165 The Operational Sea Surface Temperature and Ice Analysis (OSTIA) system run by the UK's Met  
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55 166 Office (Good et al., 2020) provides daily sea surface temperature free of diurnal variability at a 0.05deg.  
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57 167 x 0.05deg. horizontal grid resolution between 1982 and 2019 (available at  
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168 <https://marine.copernicus.eu/>). This product combines satellite measurements from both infrared and  
169 microwave radiometers with in-situ measures from ships, and drifting and moored buoys.

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171 The National Oceanic and Atmospheric Administration Daily Optimum Interpolation Sea Surface  
172 Temperature (NOAA OI SST V2 High Resolution) dataset, provided by the NOAA PSL (available  
173 from their website at <https://psl.noaa.gov>), combines sea surface temperature observations (SST at 0.2  
174 m) from different platforms (satellites, ships, buoys and Argo floats) with a 0.25deg x 0.25deg  
175 horizontal grid resolution between 1982 and 2019 (Reynolds et al. 2007; Banzon et al. 2016). Contrary  
176 to OSTIA dataset, OISST does not include satellite measurements from microwave radiometers as SST  
177 inputs (Yang et al., 2021).

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### 179 2.1.2 Global climate models – CMIP6

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181 Models from the Coupled Model Intercomparison Project 6 (CMIP6; Eyring et al., 2016) are used in  
182 this study (Table 1). These are coupled ocean-atmosphere models developed by 49 different climate  
183 modelling groups<sup>1</sup> that have been used to carry out historical and projection simulations notably to  
184 investigate how the Earth system responds to forcing (Eyring et al., 2016).

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<sup>1</sup> [https://wcrp-cmip.github.io/CMIP6\\_CVs/docs/CMIP6\\_institution\\_id.html](https://wcrp-cmip.github.io/CMIP6_CVs/docs/CMIP6_institution_id.html)

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3 186 Table 1: CMIP6 models used, using yearly data over multiple depths and daily data at the surface and  
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5 187 scenarios associated. CMIP6 models outputs are available at : [https://esgf-](https://esgf-node.llnl.gov/projects/cmip6/)  
6  
7 188 [node.llnl.gov/projects/cmip6/](https://esgf-node.llnl.gov/projects/cmip6/).

	<b>Yearly data – multiple depth levels</b>	<b>Daily data - surface</b>	<b>Ocean horizontal resolution (before interpolation)</b>	<b>References</b>
<b>ACCESS-CM2</b>	Historical,ssp1 26,ssp245	Historical, ssp126, ssp245	1°	Bi et al., 2020
<b>ACCESS-ESM1-5</b>	Historical, ssp126, ssp245	Historical, ssp126, ssp245	1°	Ziehn et al., 2020
<b>BCC-CSM2-MR</b>	Historical, ssp126,ssp245	Historical, ssp126, ssp245	1°	Wu et al., 2019
<b>CAMS-CSM1-0</b>	Historical, ssp126,ssp245	/	1°	Rong et al., 2019
<b>CanESM5</b>	Historical, ssp126, ssp245	Historical, ssp126, ssp245	1°	Swart et al., 2019; Christian et al., 2021
<b>CanESM5-CanOE</b>	Historical, ssp126, ssp245	/	1°	Swart et al., 2019; Christian et al., 2021
<b>CESM2</b>	Historical, ssp126, ssp245	Historical, ssp126, ssp245	1°	Danabasoglu et al., 2020

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<b>CESM2-WACCM</b>	Historical, ssp126, ssp245	Historical, ssp126, ssp245	1°	Danabasoglu et al., 2020
<b>CMCC-CM2-SR5</b>	Historical, ssp126, ssp245	Historical, ssp126, ssp245	1°	Cherchi et al., 2019
<b>CMCC-ESM2</b>	Historical, ssp126, ssp245	Historical, ssp126, ssp245	1°	Lovato et al., 2022
<b>CNRM-CM6-1</b>	Historical, ssp126, ssp245	Historical,ssp12 6,ssp245	1°	Voldoire et al., 2019
<b>CNRM-CM6-1-HR</b>	/	Historical,ssp12 6,ssp245	0.25°	Voldoire et al., 2019
<b>CNRM-ESM2-1</b>	Historical, ssp126, ssp245	Historical, ssp126, ssp245	1°	Séférian et al., 2019
<b>GFDL-CM4</b>	Historical, ssp245	Historical, ssp245	0.25°	Held et al., 2019; Dunne et al., 2020
<b>GFDL-ESM4</b>	Historical, ssp126, ssp245	/	0.5°	Dunne et al., 2020
<b>HadGEM3-GC31-LL</b>	Historical, ssp126,ssp245	/	1°	Kuhlbrodt et al., 2018; Andrews et al., 2020
<b>EC-Earth3</b>	/	Historical, ssp126, ssp245	1°	Döscher et al., 2021

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<b>EC-Earth3-CC</b>	Historical, ssp245	/	1°	Döscher et al., 2021
<b>EC-Earth3-Veg</b>	Historical, ssp126, ssp245	/	1°	Döscher et al., 2021
<b>IPSL-CM6A-LR</b>	Historical, ssp126, ssp245	Historical, ssp126, ssp245	1°	Boucher et al., 2020
<b>MIROC-6</b>	/	Historical, ssp126, ssp245	1°	Tatebe et al., 2019
<b>MIROC-ES2L</b>	Historical, ssp126, ssp245	/	1°	Hajima et al., 2020
<b>MPI-ESM1-2-HR</b>	Historical, ssp126, ssp245	Historical, ssp126, ssp245	0.4°	Müller et al., 2018; Mauritsen et al., 2019
<b>MPI-ESM1-2-LR</b>	Historical, ssp126, ssp245	Historical, ssp126, ssp245	1.5°	Mauritsen et al., 2019
<b>MRI-ESM2-0</b>	Historical, ssp126, ssp245	Historical, ssp126, ssp245	1°x0.5°	Yukimoto et al., 2019
<b>NESM3</b>	Historical, ssp126, ssp245	Historical, ssp126, ssp245	1°	Cao et al., 2021
<b>UKESM1-0-LL</b>	Historical, ssp126, ssp245	/	1°	Sellar et al., 2019

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191 Historical and projection simulations from the ScenarioMIP experiments are used. Historical  
192 simulations cover the period 1850-2014 and use historical forcing, mostly based on observations, that  
193 includes among others greenhouse gas, aerosol concentrations and solar forcing (Eyring et al., 2016).  
194 Projection simulations from the ScenarioMIP experiments cover 2015-2100 and over multiple emission  
195 trajectories, described through so-called Shared Socioeconomic Pathways (SSPs). More specifically,  
196 SSPs describe development pathways according to different economic and political strategies (O'Neill  
197 et al., 2017), and subsequent forcing levels similar to the ones used in CMIP5, that are the  
198 Representative Concentration Pathways (RCPs). However, SSPs represent an improvement in the sense  
199 that those scenarios include updated data on recent emission trends (O'Neill et al., 2016) and allow to  
200 explore the implication of different climate change mitigation policies (Riahi et al., 2017). In this study,  
201 for all analyses, two projection scenarios are considered: the SSPs 1-2.6 and 2-4.5. The SSP1-2.6  
202 describes a world that shifts to a more sustainable path leading to an estimated warming of 1.8 °C by  
203 the end of the century (as compared to pre-industrial) whereas SSP2-4.5 represents a path in which  
204 socio-economic trends do not shift significantly from the historical patterns, with an estimated warming  
205 of 2.7 °C by the end of the century. The focus on those two scenarios allows the comparison between  
206 two possible futures whose occurrence will depend on countries' commitments to reduce their net  
207 greenhouse gas emissions (Hausfather & Peters, 2020).

208 Depending on the analysis, the variable considered is either *thetao* (sea temperature across different  
209 depth levels) or *tos* (sea surface temperature) as only *tos* was available daily. Each model output is  
210 regridded to the same regular 1°-1° horizontal grid using distance weighted average remapping (using  
211 climate data operators « cdo » remapdis) as in Kwiatkowski et al., 2020. Each model output is also  
212 regridded vertically following the World Ocean Atlas standard discretization (33 vertical intervals from  
213 the surface (0 m) to the abyssal seafloor (5500 m)).

214 There are several ways to combine the results from multiple models. The traditional approach used by  
215 the IPCC, which is the main method used here, is to use a model ensemble mean, all models being  
216 weighted equally, and then to study the projections for fixed future periods. For changes in temperature  
217 and projected MHW characteristics, future periods of 20 years are considered: the near term (2021-

218 2040), the mid term (2041-2060) and the long term (2081-2100) as in the IPCC Assessment Report 6  
1  
2 219 (Chen et al., 2021). An alternative method is also considered to further support the projected trends  
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4 220 obtained with the traditional method: the time-shift approach (Herger et al., 2015; Chen et al. 2021; Lee  
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6 221 et al., 2021). Instead of specifying a fixed time period, this approach specifies a fixed global warming  
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8 222 value compared to pre-industrial, typically 1.5°C, 2°C and 3°C (hereafter referred to as « global  
9  
10 223 warming levels » or GWL 1.5°C, 2°C and 3°C, respectively). These GWLs are in general reached at  
11  
12 224 different time periods depending on the models and on the scenarios. This method allows to account for  
13  
14 225 the different climate sensitivities of the models and facilitates the comparison between global warming  
15  
16 226 and regional spatial patterns. For each model and under each SSP, warming levels are defined as 20-  
17  
18 227 year running means of globally averaged atmospheric surface temperature anomaly compared to the  
19  
20 228 pre-industrial period (1850-1900). Then the change in a given metric (temperature, MHW indicator) is  
21  
22 229 estimated using a climatology of 20 years centred on the first year for which the warming level exceeded  
23  
24 230 a given threshold (e.g., 1.5°C), relative to the 1850-1900 reference value. These results are then  
25  
26 231 averaged over the model ensemble and over the SSPs considered, all simulations being weighted  
27  
28 232 equally. This method is applied to estimate the spatial patterns in warming and in MHW intensity for  
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30 233 GWL 1.5°C, GWL 2°C and GWL 3°C. To be able to investigate GWL 3°C, given that not all models  
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32 234 for SSP1-2.6 and SSP2-4.5 may reach this threshold, outputs from SSP5-8.5 are also used  
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34 235 (Supplementary Figure S1).  
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44 237 Models are also confronted with observations over the historical period for evaluation purposes. More  
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46 238 precisely, we evaluate how well the spatial patterns and mean trends are reproduced by the models and  
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48 239 compared to observations. This comparison is used as an indicator of what processes affecting trends  
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50 240 may be or may not be reproduced by the model ensemble. Such information contributes to the  
51  
52 241 interpretation of projections and uncertainties. Models and observations warming rates and MHW mean  
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54 242 intensity are compared respectively over 1982-2019 (to account for natural interannual variability) and  
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56 243 1984-2014 (MHW analysis requiring 30 years of data). CMIP6 historical outputs are thus completed  
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58 244 with SSP2-4.5 outputs until 2019, since SSP2-4.5 is most representative of today's emission pathway  
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245 (Fricko et al., 2017; Hausfather and Peters, 2020). The temperature trends significance is determined  
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2 246 using the coefficient of determination ( $R^2$ ) of the linear regression as well as a signal-to-noise ratio  
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4 247 (SNR) comparing the trend to the interannual variability of the anomaly between the expected (from  
5  
6 248 the linear regression) and observed temperature, as defined in Auger et al., 2021.  
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10 249 To quantify the impact of natural variability on the projected trends, we also exploit additional  
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12 250 simulations using the IPSL-CM6A-LR model, which exhibits an important centennial climate  
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14 251 variability (Bonnet et al., 2021), through the analysis of the temperature trends of 11 members (r1i1p1f1,  
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16 252 r2i1p1f1, r3i1p1f1, r4i1p1f1, r5i1p1f1, r6i1p1f1, r10i1p1f1, r11i1p1f1, r14i1p1f1, r22i1p1f1,  
17  
18 253 r25i1p1f1). These members were all initialized in 1850, but with distinct initial conditions, mostly  
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20 254 covering different states regarding the initial trend of the Atlantic Meridional Overturning Circulation  
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22 255 (Bonnet et al., 2021). First, the temperature trends over the historical period (1975-2015) of the different  
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24 256 members are compared. Second, projected changes in surface temperature for the near, mid and long  
25  
26 257 term periods are compared. Finally, Pearson correlation coefficients between spatial patterns of changes  
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28 258 in surface temperature for each member simulation relative to the r1i1p1f1 simulation over each year  
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30 259 between 2015 and 2100 in SSP2-4.5 are estimated. The aim is to determine whether the initial  
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32 260 conditions of the simulations and natural variability still play an important role in determining the  
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34 261 regional characteristics of the projected trends compared to the radiative forcing.  
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## 41 42 43 263 **2.2 Climate velocity**

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48 265 For climate velocity we use the classical definition as the ratio between the warming rate and the local  
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50 266 spatial gradient of a variable as in Loarie et al., 2009 and Brito-Morales et al., 2018. The intensity of  
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52 267 horizontal climate velocity  $v$  for temperature (T) is thus here defined as  
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56 268 
$$v = \frac{\frac{\partial T}{\partial t}}{||\nabla T||}$$

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270 By convention,  $v$  is positive in case of a warming ( $\frac{\partial T}{\partial t} > 0$ ) and negative in case of a cooling.

271 The climate velocity vector  $\vec{v}$  is then defined as

$$\vec{v} = \frac{-\partial T}{\partial t} \left[ \frac{\frac{\partial T}{\partial x}}{\|\nabla T\|^2} \cdot \vec{u}_x + \frac{\frac{\partial T}{\partial y}}{\|\nabla T\|^2} \cdot \vec{u}_y \right].$$

273 By convention,  $\vec{u}_x$  (longitudinal unit vector) is positive eastward and  $\vec{u}_y$  (latitudinal unit vector) is  
274 positive northward.  $\vec{v}$  points to the direction to follow to remain at the same temperature.

275

276 For CMIP6 outputs, climate velocity is estimated over different historical periods of 50 years (1850-  
277 1900, 1950-2000, 1955-2005 and 1965-2015) to check the sensitivity of the pre-industrial or historical  
278 climate velocity that could be used as a baseline for comparison with the projected climate velocities.  
279 Then climate velocity is estimated over 2015-2065 and 2050-2100 for SSP1-2.6 and SSP2-4.5,  
280 respectively. Climate velocity is estimated for different depth zones: surface (0-200 m) and mesopelagic  
281 (200-1000 m). The average temperature weighted by the thickness of each standard depth layer is used  
282 to calculate a horizontal climate velocity. The climate velocities obtained from each model are then  
283 averaged to get the mean-ensemble results.

284

### 285 2.3 Marine heatwaves

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287 The definition of a marine heatwave (MHW) as a "discrete prolonged anomalously warm water event"  
288 was introduced in Hobday et al., 2016 to allow for comparison with other studies increasingly adopting  
289 this standardized definition. In this work, a MHW is detected when the temperature is above a given  
290 threshold for at least 5 days. This threshold is defined as the 90<sup>th</sup> (for model evaluation) or the 99<sup>th</sup>  
291 percentile (for projections, to focus on the most intense events) of the data distribution. The climatology

292 and threshold are estimated for each grid point of the region of interest and for each day of the year  
293 using an 11-day window. The threshold is also smoothed by applying a 30-day moving average. The  
294 climatology is estimated over at least 30 years of data, in order to smooth out climate mode of variability  
295 (e.g., ENSO, AMO; Scannell et al., 2016).

296 MHW can be quantified by different metrics. The definition of MHW intensity varies and can be  
297 determined relative to the seasonal climatology or to a chosen threshold (Hobday et al., 2016). Here we  
298 define MHW intensity relative to the threshold (90th percentile for model evaluation, 99th percentile  
299 for projections) and the mean intensity is weighted by the number of days affected. In addition, the  
300 mean number of days affected by MHW per year, also called mean annual MHW days, has been found  
301 strongly correlated to some observed ecological performance in the marine environment (e.g., seagrass  
302 density, Smale et al., 2019). The two metrics, mean MHW intensity and mean MHW annual days, are  
303 therefore used here to characterize MHW as potential climatic impact-drivers of marine ecosystems.

304

## 305 **3 Results**

### 306 **3.1. Historical warming trends and marine heatwaves**

#### 307 *3.1.1. Warming trends*

308

309 The mean warming rate observed over the Southern Indian Ocean (20°-120°E, 70°-30°S) between 1982  
310 and 2019 is 0.03°C/decade ( $\pm 0.08^\circ\text{C}/\text{decade}$ , spatial standard deviation), as estimated by a linear  
311 regression of observation-based sea surface temperature from the OSTIA product, and 0.07°C/decade  
312 ( $\pm 0.09^\circ\text{C}/\text{decade}$ ) using OISST dataset (See Section 2.1.1). Such regional averaged temperature trend  
313 hides important east/west contrasts (Figure 2, also for OISST as shown in Supplementary Figure S2)  
314 with warming trends north of the area and east of the Kerguelen Plateau between 0.1 and 0.3 °C/decade  
315 that are found significant ( $R^2$  between 0.4 and 0.5,  $\text{SNR} > 1$ ). The cooling pattern west of the Kerguelen

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316 Plateau is not found significant, but has also been obtained on different observational datasets (Yang et  
317 al., 2021), suggesting high temporal variability in this area.

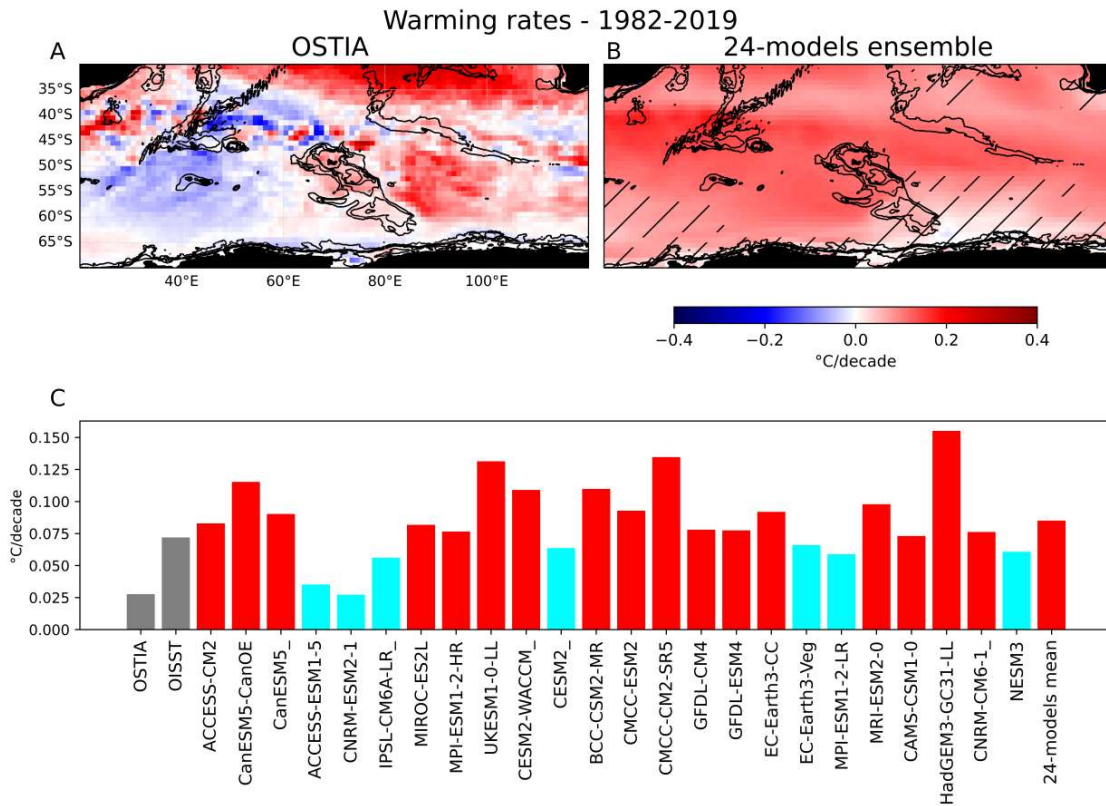
318 In comparison, the 24-single-member-CMIP6-models produces an ensemble mean warming rate from  
319 1982 to 2019 close to the one obtained with OISST dataset ( $0.085 \pm 0.053$  °C/decade, spatial standard  
320 deviation). A majority of CMIP6 models (17 over 24) simulate higher mean warming rates than the  
321 observed one with OISST dataset but none shows an averaged cooling in the region (Figure 2,  
322 Supplementary Figure S3). The simulated spatial patterns of temperature trends are quite different  
323 between different model simulations, but also between different ensemble members of the same model  
324 (IPSL-CM6A-LR, Supplementary Figure S5A). The initial conditions of the simulations as well as  
325 decadal and/or multidecadal variability might thus play an important role in the regionalisation of  
326 temperature trends over the historical period.

327 Historical warming rates from the multimodel ensemble are more homogeneous than from any  
328 individual models or observations, despite greater warming rates being found between 40° and 50°S  
329 north and west of Prince Edward, Marion and Crozet islands (Figure 2). The multimodel ensemble mean  
330 underestimates warming trends north of the ACC and east of the Kerguelen Plateau. It shows a general  
331 warming throughout the area. A lower signal and/or lower agreement between models is found south  
332 of the Kerguelen Plateau near the Antarctic shelves.

333

334 Figure 2: Warming rates between 1982 and 2019 in the Southern Indian Ocean, using linear regression  
335 on surface temperature, using OSTIA observations (A) and a 24-single-member-CMIP6-model  
336 ensemble (B). Hatching indicates areas where the intermodel standard deviation of the warming rate is  
337 greater than the mean value, suggesting a low change or a low robustness of the output. For each model  
338 and for the 24-model ensemble, the mean warming rate over the area is also calculated and compared  
339 to the mean warming rates estimated from the OSTIA and OISST datasets (C). Bars colored in red  
340 indicate a higher warming rate than the one derived from OISST (gray bar) and in blue if it is a lower  
341 rate.

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### 3.1.2. Climate velocity

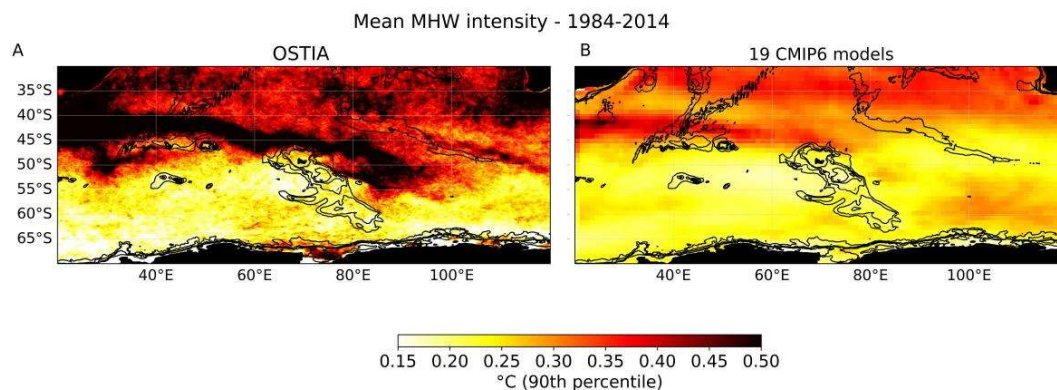
The mean climate velocity over the Southern Indian Ocean is 4.9 km/decade ( $\pm 27$  km/decade, spatial standard deviation) using OSTIA dataset and 10.64 km/decade ( $\pm 34$  km/decade) using OISST dataset between 1982 and 2019 (see Sections 2.1.1 and 2.2). An east/west contrast is observed similar to what is found in section 3.1.1. East of the Southern Indian Ocean ( $70^{\circ}$ - $120^{\circ}$ E,  $70^{\circ}$ - $30^{\circ}$ S), the mean climate velocity is around 12 km/decade using OSTIA dataset and around 18 km/decade using OISST dataset.

### 3.1.3. MHW intensity

The regional mean MHW intensity observed over the Southern Indian Ocean between 1984 and 2014 is  $0.35^{\circ}\text{C}$  above the 90th percentile of the local temperature distribution using the OSTIA dataset (Figure 3). Detection of MHW from the OSTIA dataset highlights a pattern of greater MHW intensity

357 north of the Kerguelen Plateau, in the region of influence of the ACC (Figure 3, pattern also identified  
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2 358 in Su et al., 2021). The 19-model ensemble, reproduced the spatial pattern with greater mean MHW  
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4 359 intensity north of the Plateau, notably over the Crozet Plateau, and the less intense MHW west of the  
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6 360 Kerguelen Plateau (Figure 3, Supplementary Figure S4).  
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10 361 However, the multimodel mean underestimates the intensity of MHW north of the ACC compared to  
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12 362 observations. The mean MHW intensity between 40°S and 30°S obtained from the multimodel mean is  
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14 363 26% lower than the one obtained from observations.  
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20 365 Figure 3: Mean Marine Heatwaves (MHW) intensity as defined by the anomaly above the threshold  
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22 366 (90th percentile) between 1984 and 2014 in the Southern Indian Ocean using OSTIA observations (A)  
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24 367 and a 19-single-member-CMIP6-model ensemble (B). Hatching indicates areas where the intermodel  
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26 368 standard deviation of the MHW intensity is greater than the mean value, suggesting a low robustness  
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### 3.2 Projected warming trends and marine heatwaves

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#### 3.2.1 *The impact of natural variability on the projected temperature trends*



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2 375 To quantify the impact of natural variability on the projected temperature trends, we first focus our  
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4 376 analysis on one model (IPSL-CM6A-LR), for which we use an ensemble of simulations and investigate  
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6 377 the similarity between members of the simulated patterns for historical and projected warming (see  
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9 378 Section 2.1.2).

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11 379 The mean warming rate over the Southern Indian Ocean varies from 0.031°C/decade to 0.11°C/decade  
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13 380 over 1975-2015 between the 11 members of IPSL-CM6A-LR (Supplementary Figure S5). Important  
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15 381 differences regarding the spatial patterns are found, with members producing a general warming  
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17 382 throughout the region (e.g. r6i1p1f1), others showing a cooling north of the area (e.g. r3i1p1f1,  
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19 383 r4i1p1f1, r22i1p1f1) or a cooling east of the Kerguelen Plateau (e.g. r2i1p1f1, r14i1p1f1, r25i1p1f1).

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23 384 Across the ensemble members, the mean change in surface temperature over the Southern Indian Ocean  
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25 385 in SSP2-4.5 ranges from 0.15°C to 0.44°C in the near term (2021-2040), from 0.43 to 0.66°C in the mid  
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27 386 term (2041-2060) and from 0.83°C to 1.06°C in the long term (2081-2100), as compared to the historical  
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29 387 period (1995-2014, Supplementary Figure 5B). The timeseries of Pearson correlation coefficient  
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31 388 relative to r1i1p1f1 member pinpoints the increased similarity between the members' patterns, notably  
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33 389 from 2050 onward (correlation coefficient mainly over 0.5, Supplementary Figure 5C). It could be that  
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35 390 the remaining differences between the members' projections is to be attributed to a non-deterministic  
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37 391 component in ocean response, notably intrinsic ocean variability (Dijkstra, 2016).

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42 392 This suggests that over the historical period the natural variability is strong and drives a large spread of  
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44 393 temperature trends between ensemble members. With increasing radiative forcing, this spread  
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46 394 decreases, suggesting that the projected long term spatial patterns are not dependent on natural  
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48 395 variability.

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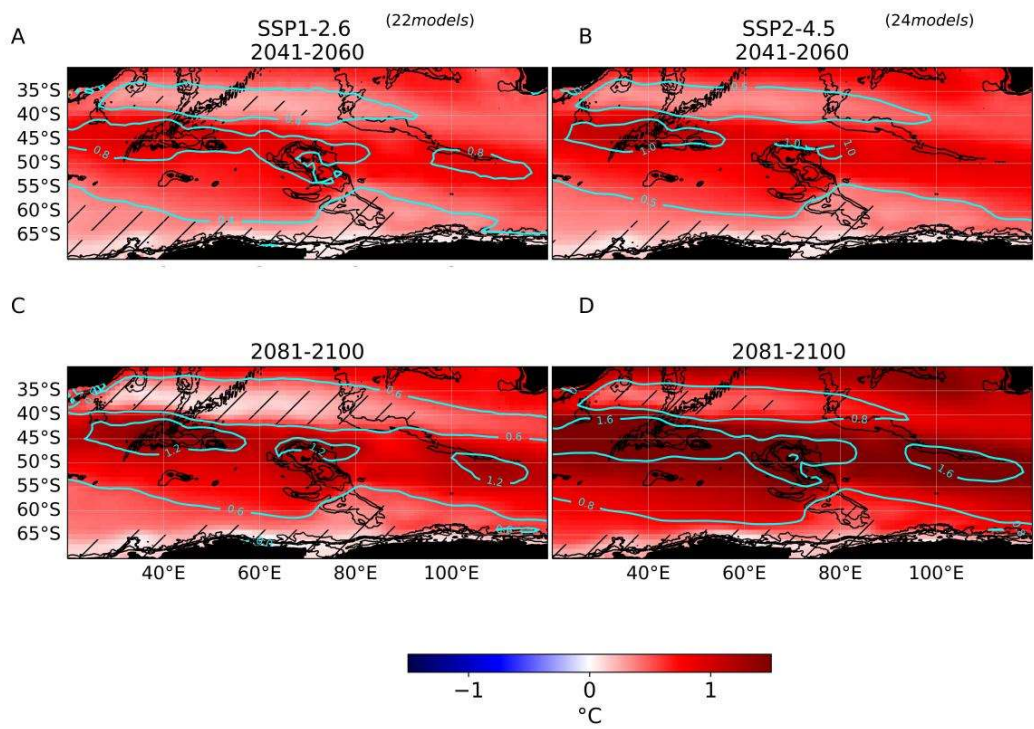
### 52 53 397 *3.2.2 Projected warming*

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57 399 Over the Southern Indian Ocean and for SSP2-4.5, the projected warming is 0.29°C ( $\pm 0.06^\circ\text{C}$ ,  
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59 400 intermodel variability) in the near term (2021-2040), 0.58°C ( $\pm 0.09^\circ\text{C}$ ) in the mid term (2041-2060)

1 401 and 1.05°C ( $\pm 0.15^\circ\text{C}$ ) in the long term (2081-2100), compared to the historical period (1995-2014).  
2 402 While the mean surface temperature change is similar in both scenarios in the near term, it is 1.2 and  
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4 403 1.7 times higher for SSP2-4.5 than for SSP1-2.6, in the mid and long term, respectively (Figure 7).  
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7 404 Using the 24-model ensemble, a larger warming is simulated between 40°S and 50°S and up to 55°S,  
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9 405 thus in regions including the Indian Ocean subantarctic Exclusive Economic Zones (EEZs, see Figure  
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11 406 4). This latitudinal band of large warming is located in the ACC and expands southward with time and  
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14 407 in SSP2-4.5.  
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17 408 Between 35° and 40°S, warming is lower than in the latitudinal band encompassing the subantarctic  
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19 409 island's EEZs (warming of 0.3-0.4°C in SSP2-4.5 mid term). South of 55°S, surface temperature  
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21 410 changes remain below 1°C even in the long term in SSP2-4.5. The region south of the ACC has been  
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23 411 shown to experience lower warming due to the local circulation and stratification change (Armour et  
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25 412 al., 2016; Haumann et al., 2020).  
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31 414 Figure 4: Surface temperature change from the historical period (1995-2014) for the mid-term (A and  
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33 415 B) and long term (C and D) projected periods under SSP1-2.6 (A and C) and SSP2-4.5 (B and D) using  
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35 416 CMIP6 multimodel mean. Contour lines of similar temperature change are indicated in cyan. Hatched  
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37 417 areas indicate where the intermodel standard deviation of the temperature change is higher than the  
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39 418 mean value, suggesting a less robust output.  
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### 3.2.3 Projected climate velocity

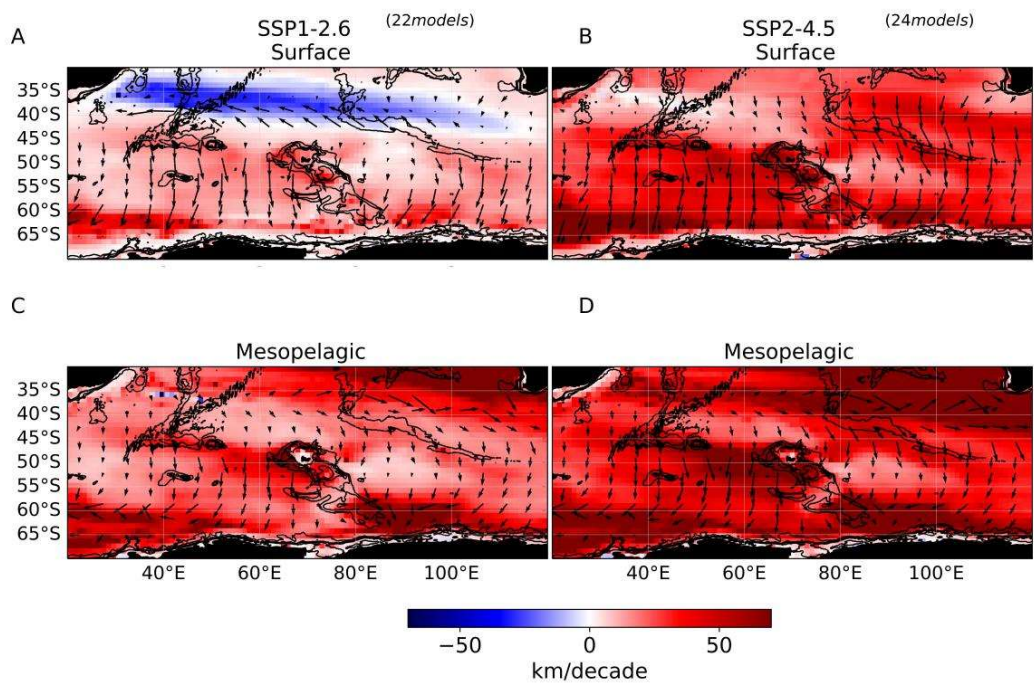
For the Southern Indian and in SSP2-4.5, the average climate velocities over 2015-2065 is 38.53 southward ( $\pm 5.8$ , intermodel variability) and 47.43 ( $\pm 8.1$ ) km/decade at the surface and in the mesopelagic, respectively. When averaged over 2050-2100, it is 31.62 ( $\pm 5.6$ ) and 57.46 ( $\pm 9.8$ ) km/decade, at the surface and in the mesopelagic, respectively. At the end of the century, surface (mesopelagic) climate velocities are expected to be 5.3 times (1.8 times) faster in SSP2-4.5 as compared to SSP1-2.6 (Figure 7). Mesopelagic climate velocities under both scenarios are also about 5 times faster for the period 2015-2065 compared to the historical period 1955-2005.

Negative surface climate velocities (i.e. northward) over 2050-2100, are found around 35°S in SSP1-2.6 (Figure 5), meaning that this area is expected to cool towards the end of the 21st century. This

1 431 cooling is only found at the surface and not at depth under SSP1-2.6, and is not projected under SSP2-  
2 432 4.5.  
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5 433 Important differences are found between surface and mesopelagic climate velocities. Mesopelagic  
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7 434 conditions might undergo faster climate velocities than at the surface and that, already over 2015-2050  
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9 435 (Figure 7). For the two projected periods and for both scenarios, mesopelagic climate velocities  
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11 436 averaged over the Southern Indian Ocean are between one and four times faster than surface climate  
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13 437 velocities. In contrast, for different periods of 50 years between 1850 and 2015, surface climate  
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15 438 velocities are found between 1.5 and 3.1 faster than mesopelagic climate velocities. Those differences  
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17 439 between climate velocities in the mesopelagic and at the surface are accentuated in some areas. Those  
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19 440 differences can reach up to 160 km/decade southwest of Australia, 120 km/decade west of Kerguelen  
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21 441 Plateau or vary between 40 and 70 km/decade north of Crozet Plateau in SSP2-4.5. Faster climate  
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23 442 velocities in the mesopelagic compared to the surface for a same location (Figure 5) can be due to the  
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25 443 weaker spatial temperature gradients at depth as it is for instance the case west of the Australian coast..  
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33 445 Figure 5: Surface (0-200m, A and B) and mesopelagic (200-1000m, C and D) climate velocities, defined  
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35 446 as the ratio between the warming rate and the temperature spatial gradient between 2050 and 2100 using  
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37 447 multimodel means under SSP1-2.6 (A and C) and SSP2-4.5 (B and D). It can be interpreted as the  
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39 448 velocity an individual should adopt to remain at the same temperature. By convention, positive climate  
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41 449 velocities correspond to warming trends and negative ones to cooling trends. Black arrows indicate the  
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43 450 direction of the climate velocity.  
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### 3.2.4 Projected marine heatwaves

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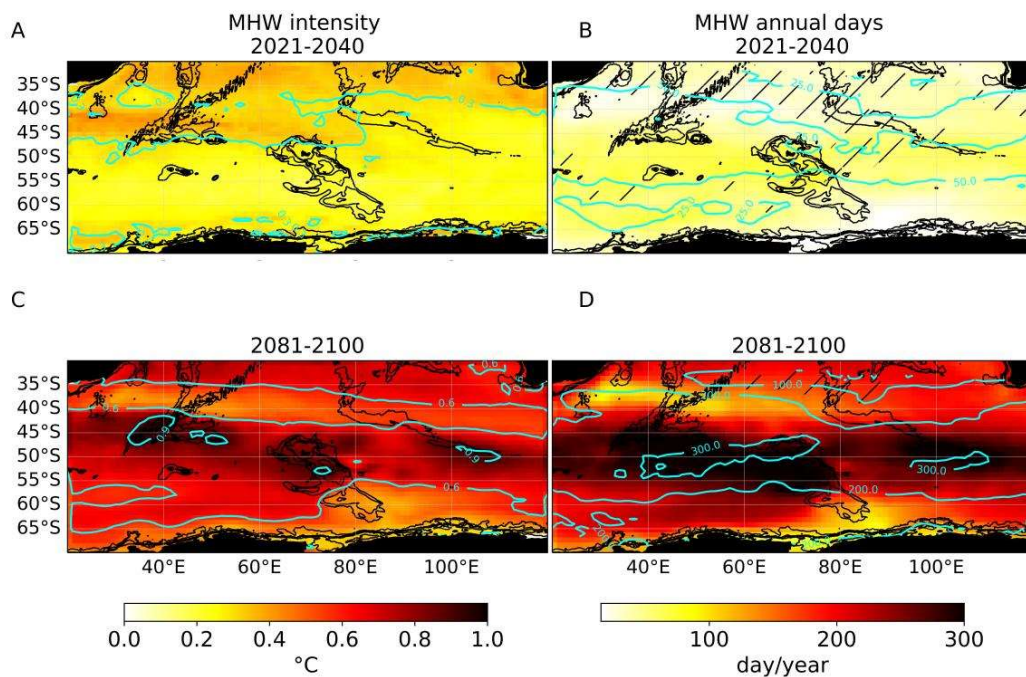
455 In the Southern Indian Ocean, the projected mean MHW intensity is 0.28°C (above 99th percentile  
 456 threshold) in the near term for both scenarios and 0.39°C or 0.63°C in the long term, respectively in  
 457 SSP1-2.6 or SSP2-4.5. The areas most affected by this intensification in the long term are located  
 458 between 40°S and 55°S and in particular over Prince Edward, Marion, Crozet, Kerguelen and Heard  
 459 and McDonald Islands (Figure 6). The spatial pattern of mean MHW intensity in SSP2-4.5 for the near  
 460 term is similar to the historical pattern (Figure 3). North of the ACC, mean MHW intensity, for this  
 461 scenario and time horizon, varies between 0.3 and 0.4°C. In the long term under SSP2-4.5, a maximum  
 462 MHW intensity of 0.97°C is found over Crozet Plateau and the zonal maximum MHW intensity is found  
 463 to be 0.81°C at 48°S. The pattern obtained is similar to the pattern of surface temperature change (Figure

464 4), suggesting that the detected MHW might be caused by a mean shift of the temperature distribution  
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2 465 rather than a change in the spread of the temperature distribution (as in Oliver et al., 2019a).  
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5 466 Additional analyses, investigating the daily temperature distribution shift in SSP2-4.5 relative to the  
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7 467 historical period, show that the relative shift in the mean of the temperature distribution south of 50°S  
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9 468 is much larger than the changes in the spread of the distribution, whereas north of 50°S similar orders  
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11 469 of magnitude of relative change are found in terms of increased mean temperatures and increased  
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13 470 distributions spread (Supplementary Figure S6). In particular, the area between 35° and 40°S shows a  
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15 471 larger relative change in the spread of the distribution than in the mean of the distribution, with increases  
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17 472 of respectively 9.98% and 7.60% in the long term compared to the historical period.  
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21 473 In the Southern Indian Ocean, the projected mean annual MHW days is 46.1 days/year in the near term  
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23 474 and 119.3 days/year in the long term in SSP1-2.6. These values increase to 42.8 days/year and 206  
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25 475 days/year respectively in SSP2-4.5 (Figure 6). Annual MHW days under both scenarios are similar in  
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27 476 the near term but it is 23% higher in the mid term and 73% higher in the long term in SSP2-4.5 compared  
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29 477 to SSP1-2.6 (Figure 7). Similar as for MHW intensity, the most impacted area is generally the latitudinal  
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31 478 zone between 40°S and 55°S in the ACC region. In SSP2-4.5, in the near term, the zonal number of  
32  
33 479 annual MHW days is maximum between 40°S and 55°S varying between 44.5 and 62.9 days, the  
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35 480 maximum being reached at 50°S. In the long term, the zonal number of annual MHW days is maximum  
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37 481 between 40°S and 57°S varying between 194 and 290 days, the maximum being reached at 51°S. A  
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39 482 permanent state of MHW is almost reached over the Kerguelen Plateau (312 days west of the Plateau).  
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41 483 When considering the relationship between changes in surface temperatures and MHW annual days for  
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43 484 the three projected time periods, it appears that over the whole area a permanent state of MHW could  
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45 485 be reached for a 2°C regional mean surface temperature change relative to the historical period  
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47 486 (Supplementary Figure S7).  
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56 488 Figure 6: Projected mean MHW intensity (as defined by the anomaly above the threshold of 99th  
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58 489 percentile relatively, A and C) and projected mean number of days per year affected by MHW (B and  
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490 D) under SSP2-4.5 using a 19-single-member-CMIP6-model ensemble for both 2021-2040 (A and B)  
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 2 491 and 2081-2100 (C and D). MHW were detected relative to a historical seasonally-varying climatology  
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 4 492 (1984-2014). Contour lines of similar metric are indicated in cyan. Hatching indicates areas where the  
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 6 493 intermodel standard deviation of the metric is greater than the mean value, suggesting a low robustness  
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 9 494 of the output.

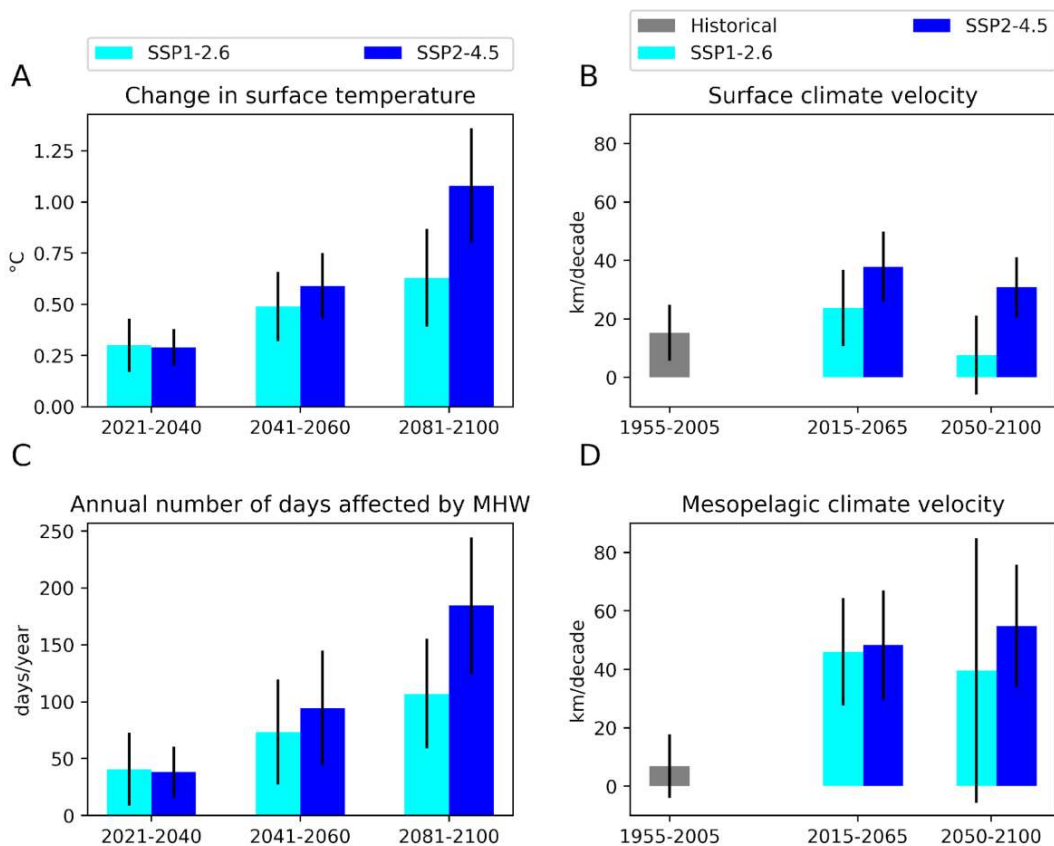
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 48 497 Figure 7: Synthesis of the different climate impact drivers metrics over the Southern Indian Ocean (20°-  
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 50 498 120°E 70°-30°S) : change in surface temperature (A, relative to 1995-2014); the annual number of day  
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 52 499 affected by MHW as defined using the 99th percentile threshold (C); average surface (B) and  
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 54 500 mesopelagic (D) climate velocities. The error bars correspond to the intermodel standard deviation for  
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 57 501 each metric.

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### 3.3 Patterns of warming-related climatic impact-drivers for GWL 1.5°C, 2°C and 3°C

Patterns of warming-related climatic impact-drivers are also investigated using a timeshift approach (see Section 2.1.2). Not only is this method used to confirm the robustness of the spatial patterns obtained through the traditional approach, but this method also contributes to describing future changes in accordance with targets defined in the Paris Agreement<sup>2</sup>, regardless of the mitigation pathway (Chen et al., 2021).

<sup>2</sup> [https://unfccc.int/sites/default/files/english\\_paris\\_agreement.pdf](https://unfccc.int/sites/default/files/english_paris_agreement.pdf)



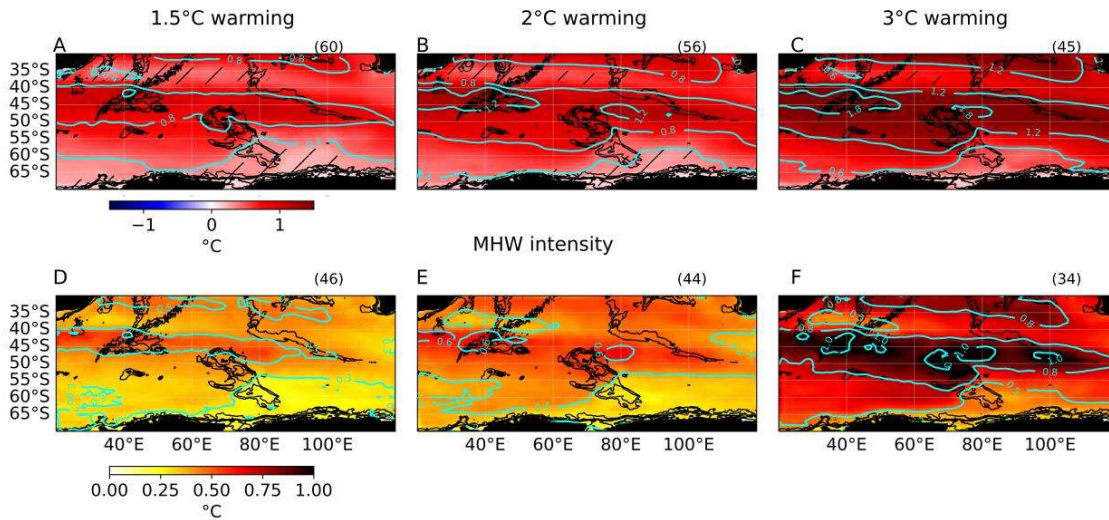
1 512 The mean sea surface temperature change over the Southern Indian Ocean is  $0.6^{\circ}\text{C}$  ( $\pm 0.2^{\circ}\text{C}$ , intermodel  
2 513 variability),  $0.7^{\circ}\text{C}$  ( $\pm 0.2^{\circ}\text{C}$ ) and  $1.1^{\circ}\text{C}$  ( $\pm 0.3^{\circ}\text{C}$ ) greater than in 1850-1900 for global warming levels  
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4 514 (GWLs, see Section 2.1.2) of  $1.5^{\circ}\text{C}$ ,  $2^{\circ}\text{C}$  and  $3^{\circ}\text{C}$ , respectively, as computed from the CMIP6 model  
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6 515 ensemble (Figure 8; we remind that GWLs are defined in respect to pre-industrial temperatures and not  
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8 516 in respect to the present). In the three cases, the patterns are similar, only the amplitude increases with  
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11 517 increasing global warming. Surface temperature changes are warmer than  $0.8^{\circ}\text{C}$  between  $40^{\circ}$  and  $50^{\circ}\text{S}$   
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13 518 for GWLs  $1.5^{\circ}\text{C}$  and  $2^{\circ}\text{C}$  and warmer than  $1.2^{\circ}\text{C}$  for GWL  $3^{\circ}\text{C}$  at the same latitudes. Surface  
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15 519 temperature changes stay below  $0.4^{\circ}\text{C}$  and  $0.6^{\circ}\text{C}$  near the Antarctic, respectively for GWLs  $2^{\circ}\text{C}$  and  
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17 520  $3^{\circ}\text{C}$ .

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20 521 The mean MHW intensity is  $0.37^{\circ}\text{C}$  ( $\pm 0.037^{\circ}\text{C}$ , intermodel variability),  $0.43^{\circ}\text{C}$  ( $\pm 0.050^{\circ}\text{C}$ ) and  
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22 522  $0.43^{\circ}\text{C}$  ( $\pm 0.050^{\circ}\text{C}$ ), for GWLs  $1.5^{\circ}\text{C}$ ,  $2^{\circ}\text{C}$  and  $3^{\circ}\text{C}$ , respectively (Figure 8). For GWL  $1.5^{\circ}\text{C}$ , the most  
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24 523 intense MHW are found in the subtropical region and north of the ACC ( $40^{\circ}$ - $45^{\circ}\text{S}$ ,  $20^{\circ}$ - $90^{\circ}\text{E}$ ) varying  
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26 524 between  $0.5^{\circ}\text{C}$  and  $0.6^{\circ}\text{C}$ . For GWLs  $2^{\circ}\text{C}$  and  $3^{\circ}\text{C}$ , mean MHW intensity between  $40^{\circ}$  and  $50^{\circ}\text{S}$  can be  
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28 525 warmer than respectively  $0.5^{\circ}\text{C}$  and  $0.8^{\circ}\text{C}$ . For both warming trends and MHW characteristics, the  
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30 526 patterns obtained here using GWLs are similar to the ones obtained using projections on fixed future  
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32 527 periods (Section 3.2).

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40 529 Figure 8: Change in surface temperature for global warming levels (GWLs)  $1.5^{\circ}\text{C}$  (A),  $2^{\circ}\text{C}$  (B) and  $3^{\circ}\text{C}$   
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42 530 (C) and mean MHW intensity for GWLs  $1.5^{\circ}\text{C}$  (D),  $2^{\circ}\text{C}$  (E) and  $3^{\circ}\text{C}$  (F) warming world relative to the  
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44 531 pre-industrial period (1850-1900) using a time-shift approach and CMIP6 mean ensembles. The number  
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46 532 of simulations used (using SSP1-2.6, SSP2-4.5 and SSP5-8.5) in each case is indicated in  
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48 533 parentheses. Contour lines of similar temperature change or MHW intensity are indicated in cyan.  
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50 534 Stapling indicates areas where the intermodel standard deviation is higher than the mean value,  
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52 535 suggesting a less robust output.

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Change in surface temperature



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## 538 4 Discussion

### 539 4.1. Regional characteristics of temperature-related climatic impact-drivers

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541 This study presents a regional analysis of current and projected trends of temperature-related climatic  
542 impact-drivers in the Southern Indian Ocean: temperature change, temperature-driven climate  
543 velocities and marine heatwaves (MHW). Our main findings can be summarized as follows.

544

545 **Warming patterns are spatially heterogeneous in the region.** Global ocean surface warming rates  
546 have been estimated at around 0.08°C/decade between 1880 and 2020 (NOAA, 2022) and the IPCC  
547 Assessment Report 6 has indicated a 0.60°C increase in global SST from 1980 to 2020 (Fox-Kemper et  
548 al., 2021). In the Southern Indian Ocean, a greater warming north of the Antarctic Circumpolar Current

549 (ACC) of around 0.11°C/decade has been observed between 1950 and 2012, while cooling patterns  
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2 550 have been observed near the Antarctic (Armour et al., 2016; Sallée et al., 2018). The mean warming  
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4 551 trend here in the Southern Indian Ocean between 1982 and 2019 is lower, between 0.03°C/decade and  
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6 552 0.07°C/decade (Figure 2, Supplementary Figure S2). Observed warming trends are significant in the  
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9 553 northern part of the region and east of Kerguelen Plateau and could vary between 0.1 and 0.3°C/decade.

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15 555 **Climate velocities are faster over Kerguelen Plateau as compared to global ocean averages.** The  
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17 556 global ocean median climate velocity has been estimated around 13 km/decade over 1900-2010 (Gupta  
18  
19 557 et al., 2015) or 12 km/decade over 1955-2005 (Brito-Morales et al., 2020) at the surface and around 6.3  
20  
21 558 km/decade in the mesopelagic layer over 1955-2005 (200 - 1000 m). The mean surface climate velocity  
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24 559 over the Southern Indian Ocean is found between 4.9 and 10.6 km/decade between 1982 and 2019 using  
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26 560 OSTIA and OISST datasets. In particular, surface climate velocities are particularly fast over Heard and  
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29 561 McDonalds Islands EEZ (20.3 km/decade, using OSTIA dataset ; 44.0 km/decade, using OISST  
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31 562 dataset), Saint-Paul and Amsterdam EEZ (12.9 km/decade ; 24.4 km/decade) and Kerguelen EEZ (11.8  
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33 563 km/decade ; 27.4 km/decade) while they are slower than global estimates or more variable over Crozet  
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35 564 EEZ (-2.6 km/decade ; 18.2 km/decade) and Prince Edward Islands EEZ (-5.8 km/decade ; 5.9). Crozet  
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37 565 and Prince Edward Islands EEZ are located in the area which seems to undergo a local cooling that  
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39 566 could be associated with high temporal variability (Figure 2, Supplementary Figure S2). However, the  
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42 567 analyses using IPSL-CM6A-LR members (see Sections 2.1.2 and 3.2.1) suggest that in the long term,  
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44 568 radiative forcing will likely dominate warming trends compared to internal variability, and an important  
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46 569 warming as well as fast climate velocities are projected over the Crozet Plateau (Section 3.2).

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53 571 **MHW events are particularly intense at the ACC northern boundary between 20°E and 95°E**  
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55 572 **(north of the Kerguelen Plateau).** The patterns of MHW mean intensity between 1984 and 2014  
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57 573 obtained with the OSTIA dataset (Figure 3) are consistent with past estimates (Su et al., 2021).  
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59  
60 574 However, zooming out from the northern part of the Kerguelen Plateau shows not only that the MHW

575 are more intense at the northern boundary of the ACC, but also that MHW are generally more intense  
1  
2 576 northward up to the subtropical zone. The global ocean mean intensity of MHW estimated from NOAA  
3  
4 577 observations and defined as the anomaly of temperature compared to the 90th percentile threshold is  
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6 578 around 0.35 °C (Plecha & Soares, 2020) when it can reach 1.2°C north of Crozet EEZ.  
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13 580 **Over the historical period, no significant spatial contrasts in mean annual MHW days are**  
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15 581 **observed in the Southern Indian Ocean north of 60°S.** The global ocean mean annual number of  
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17 582 days affected by MHW has been estimated from around 30 days/year in 1900 to around 60 days/year  
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19 583 in 2020 (Holbrook et al., 2020, using observations and models). Between 1984 and 2014 using OSTIA  
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21 584 dataset, a mean number of around 24 days per year affected by MHW (90th percentile) is observed  
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23 585 north of 60°S, with in average 23 annual MHW days over Kerguelen and Crozet EEZ (data not shown).  
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25 586 South of 60°S, the mean annual MHW days is lower (16 days/year).  
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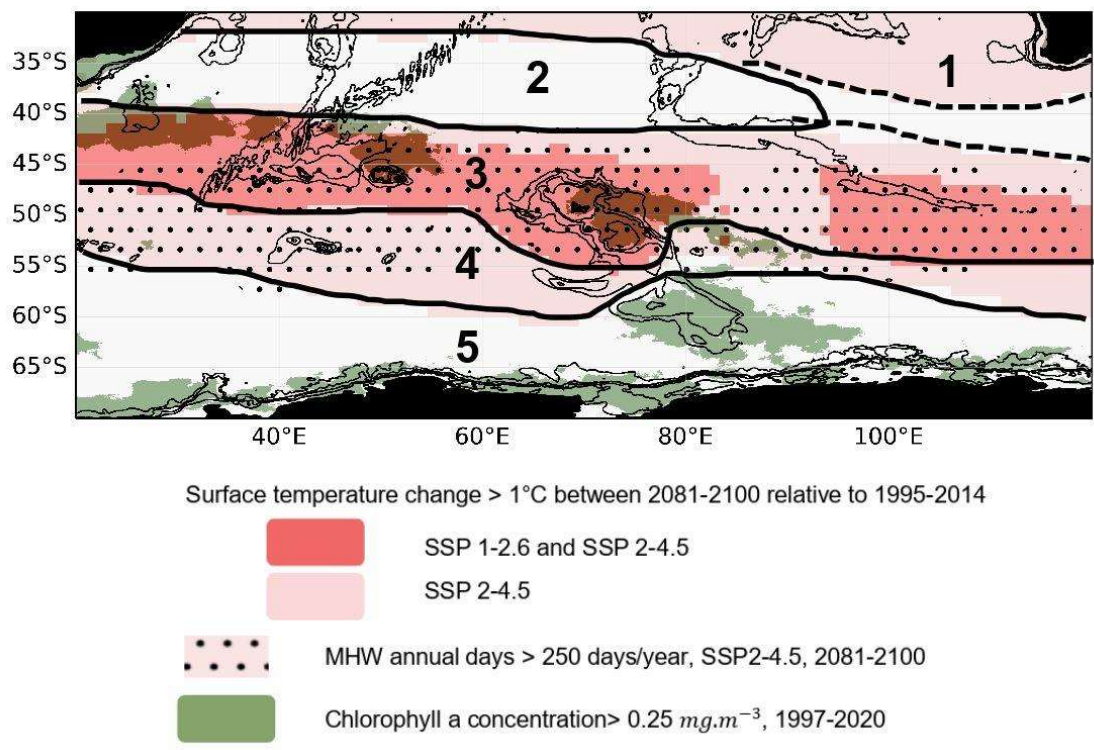
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33 588 **Five contrasted zones emerge.** When comparing the projected regional characteristics of both  
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35 589 warming and MHW characteristics (climatic impact-drivers), five zones (from the subtropics to the  
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37 590 Antarctic continent) associated with specific dynamical features stand out relative to the level of change  
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39 591 expected to occur (Figure 9). The first (north of 35°S, subtropical region) and fourth (between 50°S and  
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41 592 55°S, southern part of the ACC) zones are affected by intermediate amplitudes of warming-related  
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43 593 climatic impact-drivers. The second (between 35°S and 40°S, under the influence of the Agulhas Return  
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45 594 Current) and fifth (south of 55°S, Antarctic colder water) zones have weaker warming and weaker  
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47 595 changes in mean MHW intensity and in mean annual MHW days. Finally, the third zone (north of the  
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49 596 ACC and covering subantarctic islands) is the one with the most important magnitudes of warming-  
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51 597 related climatic impact-drivers, especially over topographic features: the Crozet Plateau, Kerguelen and  
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53 598 the Southeastern ridge.  
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599 **The projected mean MHW intensity might be underestimated in CMIP6.** It can be noted that the  
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2 600 projected mean MHW intensity might be underestimated, as it was found over the historical period  
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4 601 relative to observations (Figure 3) and in global studies using CMIP6 models (Pilo et al., 2019; Plecha  
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6 602 et al., 2020). Since the observations suggest that the most intense MHW are related to mesoscale activity  
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9 603 and that this mesoscale activity is not always well reproduced by climate models (Pilo et al., 2019; Su  
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11 604 et al., 2021), but could be expected to intensify (Hogg et al., 2015; Patara et al., 2016; Martinez-Moreno  
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13 605 et al., 2019; Martinez-Moreno et al., 2021), projections in terms of MHW intensity may be  
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15 606 underestimated.  
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22 608 Figure 9: Representation of the 5 zones identified in this study in terms of climatic impact-drivers'  
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24 609 trends (warming and marine heatwaves) along with the identification of areas for which surface  
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26 610 temperature increases by more than 1°C at the end of the century relative to 1995-2014 under SSP1-2.6  
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29 611 and SSP2-4.5; and areas for which mean MHW annual days are higher than 250 day/year at the end of  
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31 612 the century under SSP2-4.5 using CMIP6 models. Areas of chlorophyll a concentration greater than  
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33 613 0.25 mg.m-3 (using Copernicus-GlobColour product provided by ACRI-ST company, between 1997  
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35 614 and 2020) are identified in green to allow for comparison between spatialised climate trends and  
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37 615 spatialised biological characteristics.  
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**4.2 Implications of climate mitigation**

This study also shows how regional patterns of temperature change and marine heatwaves can differ between SSP1-2.6 and SSP2-4.5. Not only can the magnitude of changes be mitigated in SSP1-2.6 but some patterns may be reversed at the end of the century, for instance through the surface cooling obtained around 35°S. However, the major differences between SSP1-2.6 and SSP2-4.5 mainly occurred in the long term.

The consequences of following one SSP instead of another can also be identified at the EEZ scale, both in terms of emerging trends and of magnitude of change. The projected changes in surface temperature over Saint-Paul and Amsterdam EEZ in SSP1-2.6 remain in the range of the observed interannual variability at that location, even in the long term, which is not the case for the other EEZs. Already in the mid term in SSP1-2.6 Crozet, Heard and McDonalds Islands, Kerguelen and Prince Edward Islands

631 EEZ changes in surface temperature are found to be respectively 2.6, 2.5, 2.8 and 3.1 times higher than  
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2 632 the observed (using OSTIA) interannual variability in sea surface temperature (Figure 10). This  
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4 633 indicates that emerging warming trends will also occur in a high mitigation scenario (SSP1-2.6) for  
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6 634 subantarctic islands.  
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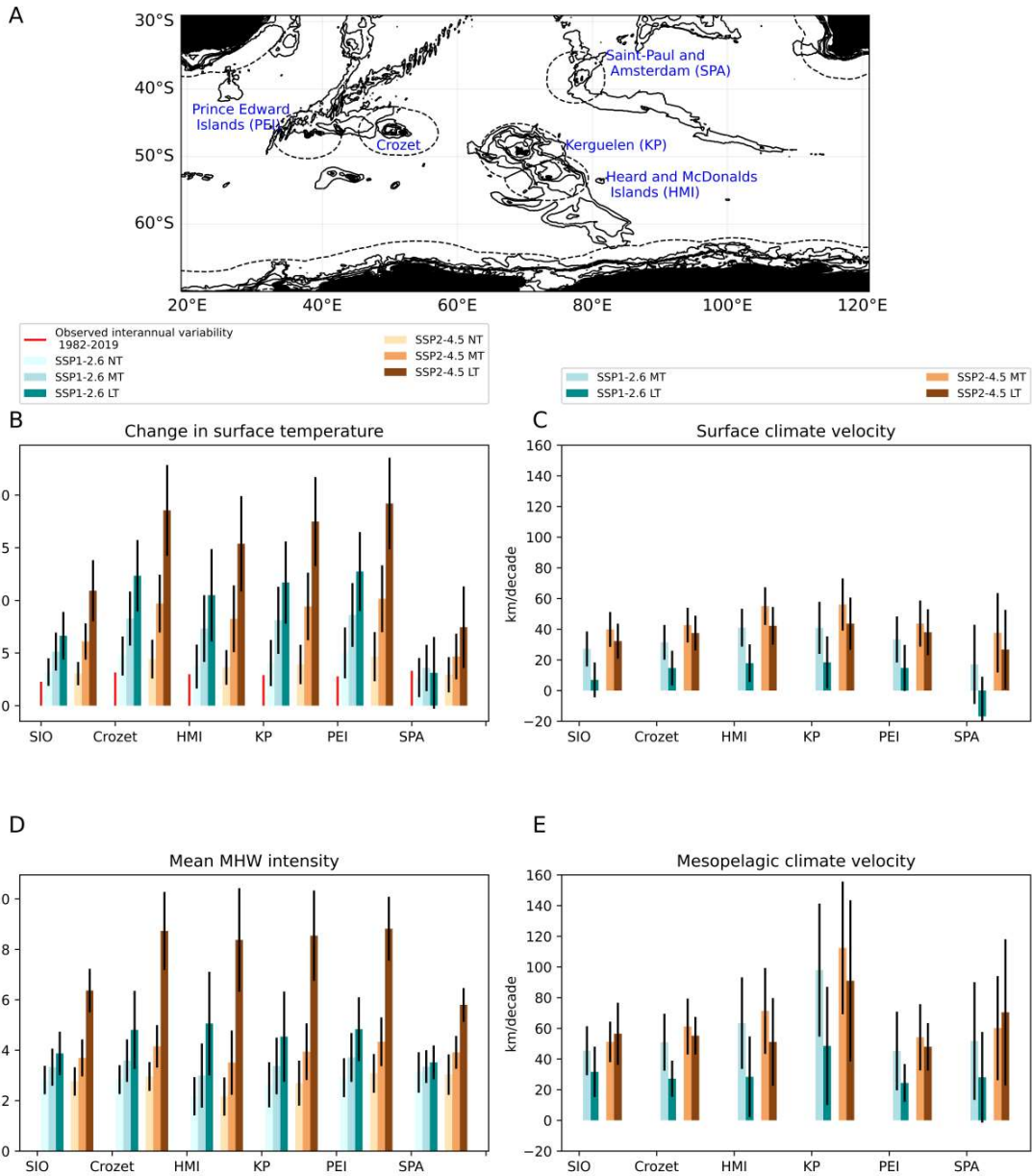
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10 635 At the EEZ level, major differences between the two SSPs used in this study mainly occur in the long  
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12 636 term. In the long term , the change in surface temperature is 0.62°C , 0.49°C , 0.58°C , 0.65°C and  
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14 637 0.43°C warmer in SSP2-4.5 compared to SSP1-2.6 for Crozet, Heard and McDonalds Islands,  
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16 638 Kerguelen, Prince Edward Islands and Saint-Paul and Amsterdam EEZ, respectively. In the long term,  
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18 639 mean MHW intensity is 0.39°C , 0.33°C, 0.40°C, 0.40°C and 0.23°C warmer in SSP2-4.5 compared to  
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20 640 SSP1-2.6 for respectively Crozet, Heard and McDonalds Islands, Kerguelen, Prince Edward Islands  
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22 641 and Saint-Paul and Amsterdam EEZ (Figure 10).  
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26 642 This study therefore shows that the choice of a mitigation strategy and socio-economic development  
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28 643 pathway can have direct regional consequences on climate change patterns in the long term, even at the  
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30 644 scale of EEZs.  
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38 646 Figure 10: Map of subtropical and subantarctic islands' exclusive economic zones (EEZs) in the  
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40 647 Southern Indian Ocean (A). Change in surface temperature relative to 1995-2014 (B), mean MHW  
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42 648 intensity (D) and surface (C) and mesopelagic (E) climate velocities averaged over the Southern Indian  
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44 649 Ocean (SIO) and different EEZs : Crozet, Heard and Mc Donald Islands (HMI), Kerguelen (KP), Prince  
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46 650 Edward Islands (PEI) and Saint-Paul and Amsterdam (SPA), for SSP1-2.6 and SSP2-4.5. Changes in  
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48 651 surface temperature and mean MHW intensity are estimated over 2021-2040 (NT), 2041-2060 (MT)  
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50 652 and 2081-2100 (LT). Climate velocities were estimated over 2015-2065 (MT) and 2050-2100 (LT).  
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52 653 Change in surface temperature results are compared to the observed interannual variability in sea  
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54 654 surface temperature in each location calculated from the OSTIA dataset between 1982 and 2019.  
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657 **4.3 Coherence with known physical mechanisms and remaining questions**

658 The aim here is to better understand the projected intensities and patterns of warming and marine  
 659 heatwaves in the Southern Indian Ocean. This requires an evaluation of the models and a mechanistic  
 660 understanding of the potential heat uptake and redistribution processes.



661 It can be firstly noted that CMIP6 models have improved compared to CMIP5 models for some key  
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2 662 metrics in the Southern Ocean, such as the Antarctic Circumpolar Current (ACC) strength or the  
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4 663 representation of differences in density across latitudes of the ACC (Beadling et al., 2020). In addition,  
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6 664 the spatial patterns and interannual variability of MHW are better represented in CMIP6 compared to  
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9 665 CMIP5 models, and more generally tend to be better represented in higher resolution climate models  
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11 666 (Qiu et al., 2021).

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14 667 There are at least three ways to evaluate a climate model: 1) to compare the model outputs to  
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16 668 observation-based products, 2) to verify the agreement between multiple models and/or models'  
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18 669 versions (this is done here by using an ensemble of models) and 3) to confront the projections to known  
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21 670 physical mechanisms (Baumberger et al., 2017). Given the important role of natural variability for  
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23 671 shaping the spatial patterns of historical warming trends, it is difficult to evaluate the quality of the  
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25 672 CMIP6 ensemble in simulating warming trends in the Southern Indian Ocean by simply comparing  
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27 673 them to past observations (Raäisaänen, 2007; Baumberger et al., 2017; Gopika et al., 2020). We  
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30 674 therefore focus here on determining whether the projected patterns of warming and marine heatwaves  
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32 675 are coherent with known or potential heat redistribution processes.

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35 676 The intensity of the Southern Indian Ocean warming is not directly correlated to the intensity of global  
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37 677 warming. The models used in our study have a wide range of Equilibrium Climate Sensitivities (ECS;  
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39 678 defined as the long term global warming obtained after a doubling of the atmospheric  $CO_2$  above its  
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41  
42 679 pre-industrial concentration; Charney et al., 1979; Forster et al., 2021). The ECS of the model ensemble  
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44 680 we used in this study vary from 2.29 to 5.62 °C (Forster et al., 2021). However, no correlation was  
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46 681 found between the mean ocean warming in the region and the model ECS, that is, models displaying  
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48 682 greater warming are not necessarily the ones with greater ECS (data not shown), suggesting that the  
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50  
51 683 regional warming in the Southern Indian Ocean is sensitive to local processes, reproduced differently  
52  
53 684 in different models. It is therefore particularly important to investigate whether the projected warming  
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55 685 and marine heatwaves patterns in the Southern Indian Ocean can be explained by known physical  
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57  
58 686 processes active in the region.

687 The coherence of the projected patterns of warming-related climatic impact-drivers with known or  
688 potential heat redistribution processes is discussed here to both assess the adequacy of the models  
689 (Baumberger et al., 2017) and understand their main physical drivers.

690

691 *4.3.1 The impact of winds and local circulation on warming-related climatic*  
692 *impact-drivers' patterns*

693

694 CMIP6 projections, either through the traditional or the time-shift approaches (i.e. using GWLs, see  
695 Section 2.1.2), suggest an intensification of MHW and warming mostly in the region of influence of the  
696 ACC, in the subantarctic latitudinal band between 40° and 55°S. Such result is consistent with the  
697 observed increased heat uptake in the subpolar region transported northward by Ekman transport and  
698 subducted within and north of the ACC (Armour et al., 2016; Frölicher et al., 2015; Morrison et al.,  
699 2016; Sallée, 2018; Huguenin et al., 2022). The strength of this northward Ekman transport is modulated  
700 by the position and strength of the westerlies which is particularly strong over the Indian sector of the  
701 Southern Ocean (Lin et al., 2018). The westerlies are expected to intensify and to shift poleward (Lee  
702 et al., 2021) and thus the associated northward transport of heat content anomaly (anomaly caused by  
703 warming) may be strengthened, accumulating heat over the subantarctic (Swart et al., 2018; Fox-  
704 Kemper et al., 2021; Silvy et al., 2022). In addition, southward heat transport also occur through eddy  
705 advection, partly compensating the Ekman northward heat transport (Farneti et al., 2010; Saenko et al.,  
706 2018), but there are still uncertainties on the degree of this compensation (Fox-Kemper et al., 2021).

707 Another pattern that stands out in this study is the lesser intensification of warming and marine  
708 heatwaves between 35° and 40°S. This latitudinal band is mostly under the influence of the Agulhas  
709 Current system, which consists in the Agulhas Current, a western boundary current flowing southward  
710 along the African coast, which brings warm waters into the Indian Ocean at around 40°S through the  
711 Agulhas Return Current up to 70°E (Lutjharms et al., 2006). The remaining waters are transported to

1 712 the South Atlantic between 32°S and 42°S and this westerward inflow of relatively warm and salty  
2 713 water exiting the Indian sector is called the Agulhas leakage (Schmidt et al., 2021). Projections from  
3  
4 714 global climate models suggest an increase in Agulhas leakage (Rouault et al., 2009; Backeberg et al.,  
5  
6 715 2012; Biastoch & Böning, 2013), and a decrease of Agulhas Current transport by 11 to 23% at the end  
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8 716 of the century (Stellema et al., 2019; Ma et al., 2020; Sen Gupta et al., 2021). If we assume that the  
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10 717 decreasing Agulhas Current feeds both the increasing Agulhas leakage and the Agulhas Return Current,  
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12 718 and that the Agulhas Current is the main source of water for the Agulhas Return Current, then the  
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14 719 Agulhas Return Current would have to decrease. A decreasing Agulhas Return Current would slow  
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16 720 down a large heat transport source in the northern part of the Southern Indian Ocean, which could  
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18 721 potentially explain the lesser warming projected in this area.  
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23 722 The Agulhas Current system transport is also modulated by the position and strength of the westerlies.  
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25 723 Indeed, an equatorward shift of the westerlies (as observed in summer in SSP1-2.6, Bracegirdle et al.,  
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27 724 2020) can be associated with an increase of the Agulhas leakage (Durgadoo et al., 2013).  
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31 725 Latitudinal differences in projected warming trends and climate velocities seem therefore consistent  
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33 726 with known mechanisms in the region. In particular, the position and strength of the westerlies can have  
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35 727 a different effect on a specific zone, depending on how westerlies impact the local circulation.  
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42 729 *4.3.2 Remaining questions: on the role of unresolved spatial scales and*  
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44 730 *modes of variability*  
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51 732 The projected trends in warming and marine heatwaves therefore seem consistent with potential  
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53 733 mechanisms of heat uptake and transport but some key questions remain. Uncertainties remain  
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55 734 concerning the role of the ocean mesoscale circulation and the role of the decadal and longer variability.  
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736 Finer scale processes (meso- and submesoscale) have the potential to impact warming trends. Eddies  
737 can play a significant role in meridional heat transport (Morrison et al., 2016) and can for instance  
738 contribute to modulate heat uptake through submesoscale ventilation (Dove et al., 2021). Increased  
739 upward heat transport at submesoscale fronts can also alter surface heat uptake capacity (Siegelmann  
740 et al., 2020) but the impact of such a process on warming trends locally is yet to be studied. In a changing  
741 climate with intensifying winds, it is expected that mesoscale activity might change (Martinez-Moreno  
742 et al., 2019; Martinez-Moreno et al., 2021). However, it remains unclear how such changes might also  
743 impact the projected warming trends. To investigate whether resolution could play a role in determining  
744 the patterns of projected temperature changes, we focus on two models, GFDL-CM4 and MPI-ESM1-  
745 2-HR with a resolution of 0.25° and 0.4° respectively. As for the model ensemble, a pattern of greater  
746 surface warming over the subantarctic is observed (Supplementary Figure S8). This suggests that the  
747 influence of smaller scale processes on the warming patterns may remain limited, at least for the larger  
748 eddies represented in higher resolution CMIP6 models. The net impact of eddies on the heat budget and  
749 how it will evolve under climate change remain an active field of research (Hewitt et al., 2022).

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751 Internal variability is not negligible in the Southern Indian ocean between 1982 and 2019 but it is  
752 challenging to evaluate whether the representation of decadal and multidecadal variability modes and  
753 their interaction with the local circulation in the models is accurate. The Southern Indian Ocean is  
754 indeed under the influence of various modes of natural variability but depending on the time scale of  
755 interest, for instance for policy-makers, different modes of natural variability are to be considered. The  
756 Indian Ocean Subtropical Dipole (IOSD) and the El-Niño-Southern Oscillation (ENSO) can influence  
757 patterns of SST anomaly (Behera and Yamagata, 2001; Huang and Shuckla, 2008; Morioka et al., 2010)  
758 on decadal timescales and the Southern Annular Mode (SAM) on even shorter timescales (Sallée et al.,  
759 2010). As the above-mentioned climatic modes of variability may not be in the same phase in reality  
760 and in the climate models, this increases the uncertainty on near-term climate projections (Hurrell et al.,  
761 2010; Chen et al., 2021).

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762 Multidecadal variability may also not be negligible in the Southern Indian Ocean and could potentially  
763 impact projected trends on longer timescales (Zhang et al., 2018). Indeed, the natural variability  
764 observed in this study is important over a 37-year period. The east/west contrast obtained in the  
765 observations (Section 3.1.1) could result from the response to the positive-to-negative phase transition  
766 of the Atlantic Multidecadal Variability (AMV) but the teleconnexion processes associated may not be  
767 well represented in climate models (Chung et al., 2022). There are therefore uncertainties on how  
768 natural modes of variability and their interactions with the local circulation will evolve, and whether  
769 they will enhance, buffer or mask the projected changes.

#### 771 **4.4 Potential impacts on ecosystems**

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773 Using the warming-related climatic impact-drivers regional characteristics, it is then important to make  
774 the link with the regional ecological characteristics. Here, based on the observed and projected trends  
775 in warming and MHW and based on knowledge on the ecology of the Southern Indian Ocean, examples  
776 of potential impacts are discussed.

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778 Climate change might induce a shift in habitats for various species, thus potentially affecting the  
779 distribution of species with conservation and/or economic values (Reisinger et al., 2022). The region  
780 studied here covers three biogeochemical provinces (i.e. oceanographically and ecologically relatively  
781 homogeneous regions) as defined by Reygondeau et al., 2020, distributed latitudinally from north to  
782 south: the South Subtropical convergence, the Subantarctic water ring and the Antarctic (Reygondeau  
783 et al., 2020). Our results suggest that, as far as temperature interactions are concerned, a poleward shift  
784 of these provinces is expected and this shift is shown to be faster for the mesopelagic layer compared  
785 to the surface with potential ecological impacts for species living across multiple depth layers  
786 throughout their life cycle. Such shift between surface and mesopelagic conditions is particularly

1 787 relevant for the Saint-Paul and Amsterdam region which is currently located at the transition between  
2 788 different bioregions: the South subtropical convergence in the north and the Subantarctic water ring in  
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4 789 the south. By the end of the century, the temperature conditions south of Saint-Paul and Amsterdam  
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6 790 EEZ will probably be similar to the ones in the south subtropical convergence province. For the north  
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8 791 of the EEZ, the mesopelagic layer temperature conditions will shift faster and could be similar to the  
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10 792 ones in the Indian South Subtropical Gyre province. Our study helps identifying other areas that could  
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12 793 be undergoing an important shift between surface and mesopelagic conditions and therefore where long  
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14 794 term biophysical monitoring could be of special interest: the north-western side of Kerguelen Plateau,  
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16 795 slightly up to the southern part of the Crozet Plateau which has been identified as a foraging zone for  
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18 796 top predators (e.g. Pütz et al., 2002).

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23 797 The consequences of the long term shift of thermal conditions in top predators' foraging zones are  
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25 798 anticipated by extreme events in the near term (or in the past). The 1997 MHW that occurred in the  
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27 799 northern part of the Southern Indian Ocean has been associated with a southward shift of the Polar Front  
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29 800 south of the Crozet Plateau where king penguins (*Aptenodytes patagonicus*) from Crozet islands usually  
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31 801 forage. The temperature anomaly was so intense and associated with such a major shift of the foraging  
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33 802 zones that these zones were barely accessible to the penguins leading to important mortality of those  
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35 803 populations (Bost et al., 2015). Over the whole region, the mean MHW intensity of this event remained  
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37 804 greater than 0.5°C for 36 days (obtained using OSTIA dataset). Given models projections it appears  
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39 805 that such a drastic event may no longer be an extreme phenomenon and if associated with a significant  
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41 806 shift in the Polar Front position, it could lead to systematic mass mortality events for top predators.

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46 807 Intermediate levels of the food webs can also be affected by warming and MHW. Indeed, some  
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48 808 populations of fish are already living at the edge of their thermal tolerance. Low-antarctic (i.e. just south  
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50 809 of the Antarctic Polar Front) species can live in conditions above their upper optimal range of  
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52 810 temperature (1°C to 1.5°C) but further increases in temperature may become too physiologically  
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54 811 demanding, especially as the intensification projected appears to occur over their distribution areas  
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57 812 (Kock and Everson, 2003).

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813 Besides, a whole range of MHW potential impacts in the Southern Indian Ocean has not yet been  
814 covered. Such impacts could include primary production changes (Hayashida et al., 2020), changes in  
815 species growth and abundance (Oliver, 2019b; Smale & Wernberg, 2013), changes in population  
816 structure (Smale et al., 2017), behavioral changes, notably for reproduction and foraging (Fromant et  
817 al., 2021), changes in geographic distributions of species (Cure et al., 2017; Smale & Wernberg, 2013)  
818 or even genetic changes (e.g., Coleman et al., 2020). These impacts are yet to be studied in the Southern  
819 Indian Ocean.

#### 820 821 **4.5 Climate change and conservation**

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823 A regionalisation of temperature-related climatic impact-drivers, associated with further research on  
824 climate change impacts on ecosystems, should contribute to the further consideration of climate change  
825 impacts in conservation design and management. Increasing literature aims at addressing this issue and  
826 suggests management tools to help integrate climate resilience into MPA design (Tittensor et al., 2019;  
827 Crespo et al., 2020). However, efforts are needed to identify the risks posed by climate change at the  
828 regional scale. Our study of warming-related climatic impact-drivers mostly addresses the hazards  
829 dimension of a risk assessment (which would also include an analysis of the vulnerability and exposure  
830 of ecosystems, Chen et al., 2021) and points out the need to include the vertical analysis in the eco  
831 regionalisation process, since different layer depths may be impacted differently. In particular, this  
832 study shows that the relative difference between mesopelagic and surface climate velocity (a « climatic  
833 vertical shear ») is highest over Kerguelen Plateau and Saint-Paul and Amsterdam EEZ under both  
834 scenarios while it is the lowest over Heard and McDonalds Islands and Prince Edward Islands EEZ  
835 (Figure 10). Yet, mesopelagic climate velocities over Heard and McDonalds Islands and Prince Edward  
836 Islands EEZ are still between 20 and 30% faster than surface climate velocities in SSP2-4.5; and  
837 respectively between 50% and 60% and between 35% and 66% faster in SSP1-2.6 (Figure 10).

1 838 The 3D information provided by climate velocity could be further used to project potential changes in  
2 839 marine biodiversity distribution and help inform conservation management (Arafeh-Dalmau et al.,  
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4 840 2021). Through this type of methodology, other concepts related to climate velocity can be used to  
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6 841 understand the impact of climate change on species distribution, notably i) climate residence time  
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8 842 (Loarie et al., 2009) and ii) climate refugia (Burrows et al., 2014; Brito-Morales et al., 2018). Indeed, it  
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10 843 can be useful to know not only if certain environmental conditions will be found and where but also  
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12 844 how long these conditions will last in a specific area (climate residence time, Loarie et al., 2009). The  
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14 845 concept of climate refugia aims to identify areas that are relatively less impacted by climate change,  
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16 846 meaning low climate velocity and/or long climate residence time (Brito-Morales et al., 2018), but it can  
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18 847 also be based on the time of emergence of the climate change signal to identify temporary refugia  
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20 848 (Bruno et al., 2018). This concept could guide the development of surveillance programs to follow the  
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22 849 evolution of environmental conditions on specific zones that are particularly affected by climatic  
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24 850 impact-drivers. Climate velocity could also be used to anticipate future expansions of species and to  
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26 851 check if current MPA networks cover these expansions (Arafeh-Dalmau et al., 2021). Note that, to be  
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28 852 even more biologically meaningful, climate velocity should be combined with other constraints of  
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30 853 dispersion such as habitat permeability or connectivity (Brito-Morales et al., 2018). It may also be  
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32 854 important to consider multiple variables such as pH (acidification), primary production or zooplankton  
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34 855 abundance, since the interaction between multiple variables changes can result in multi-directional  
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36 856 distribution shifts (e.g., VanDerWal et al., 2013).

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38 857 From the characterisation of warming and marine heatwaves patterns presented here, it is difficult to  
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40 858 identify potential climate refugia. However, this study pinpoints areas that are scientifically interesting  
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42 859 to further study the impacts of climate change on ecosystems, for instance the area south of Crozet near  
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44 860 the Antarctic Polar Front and Saint-Paul and Amsterdam EEZ. Indeed, the area south of Crozet, in the  
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46 861 main zone of intensification identified in this study, is an important foraging zone for top predators (e.g.  
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48 862 Pütz et al., 2002) and is expected to undergo intense warming and increases in MHW intensity and  
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50 863 duration but it is also an area that can be subject to important natural variability (as seen on Figure 2).  
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52 864 It can therefore be very interesting to study whether this variability in the long term will be enough to  
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1 865 counteract warming trends and whether ecosystems in this area compared to similar ecosystems east of  
2 866 the Kerguelen Plateau (at the same latitudes) will develop different features as a response to different  
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4 867 changing conditions. The Saint-Paul and Amsterdam area can also be interesting to protect for further  
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6 868 scientific investigation on how the difference between surface and mesopelagic temperature changes  
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9 869 might affect endemic ecosystems.

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19 872 **5. Conclusion**

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22 873 The aim of this work is to provide a systematic description of observed and future temperature changes  
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24 874 and marine heatwaves over the entire Southern Indian Ocean and to compare the projections over this  
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26 875 region under two scenarios that reflect two possible socio-economic pathways.

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30 876 This analysis shows the spatial heterogeneity of temperature trends and marine heatwaves  
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32 877 characteristics at the regional scale, highlighting also some limits. The projected warming trends appear  
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34 878 to be consistent with warming mechanisms identified in the literature, notably related to the dynamic  
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36 879 of the ACC and the intensification and shifts of westerly winds. Concerning MHW intensity pattern, a  
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38 880 better spatial fit between the observations and the models was obtained, although intensities may be  
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41 881 underestimated in the models, mainly because of resolution limits, and current spatial patterns of MHW  
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43 882 intensity are expected to intensify.

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46 883 This intensification of both warming and marine heatwaves characteristics is expected to occur mostly  
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48 884 over the subantarctic islands, with consequences on endemic species and ecosystems that are still to be  
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51 885 further studied. It can be noted that the difference between SSP1-2.6 and SSP2-4.5 projections are  
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53 886 mostly significant in the long term, with changes in both scenarios that could be important for  
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55 887 ecosystems already in the near and mid term, highlighting the need to anticipate adaptation measures.  
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57 888 Such measures would need to also consider that surface and deeper conditions may evolve at different  
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59 889 pace.

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2 890 Through a regional example, this study also reaffirms the need to globally commit to strong mitigation  
3 891 strategies and to follow a sustainable socio-economic development pathway to alleviate the potential  
4 892 impacts of warming and MHW.  
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## 45 907 **Declaration of Competing Interest** 46 47 48

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52 909 The authors declare that they have no known competing financial interests or personal relationships that  
53 910 could have appeared to influence the work reported in this paper.  
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4 912 Appendix A : Supplementary material

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## Appendix A: Supplementary Materials

Figure S1: List of models used for the timeshift approach analyses for both SSP 245 and SSP585.

For changes in temperature (yearly data) 22 models	For MHW intensity (daily data) 17 models
ACCESS-CM2 ACCESS-ESM1-5 BCC-CMS2-MR CAMS-CSM1-0 CanESM5 CanESM5-CanOE CESM2-WACCM CMCC-ESM2 CMCC-CM2-SR5 CNRM-CM6-1 GFDL-CM4 GFDL-ESM4 HadGEM3-GC31-LL EC-Earth3-CC EC-Earth3-Veg IPSL-CM6A-LR MIROC-ES2L MPI-ESM1-HR MPI-ESM1-LR MRI-ESM2-0 NESM3 UKESM1-0-LL	ACCESS-CM2 ACCESS-ESM1-5 BCC-CMS2-MR CanESM5 CESM2-WACCM CMCC-ESM2 CMCC-CM2-SR5 CNRM-CM6-1 CNRM-CM6-1-HR GFDL-CM4 EC-Earth3 IPSL-CM6A-LR MIROC6 MPI-ESM1-HR MPI-ESM1-LR MRI-ESM2-0 NESM3

Figure S2 : Temperature trends between 1982 and 2019 in the Southern Indian Ocean (top panel), using linear regression on sea surface temperature, using OISST (left) and OSTIA (right) datasets. Timeseries of sea surface temperature for two areas (bottom panel): one west of the Southern Indian Ocean, covering Prince Edward Islands and Crozet (orange) and one north of Saint-Paul and Amsterdam (green) using OISST (full) and OSTIA (dashed) datasets

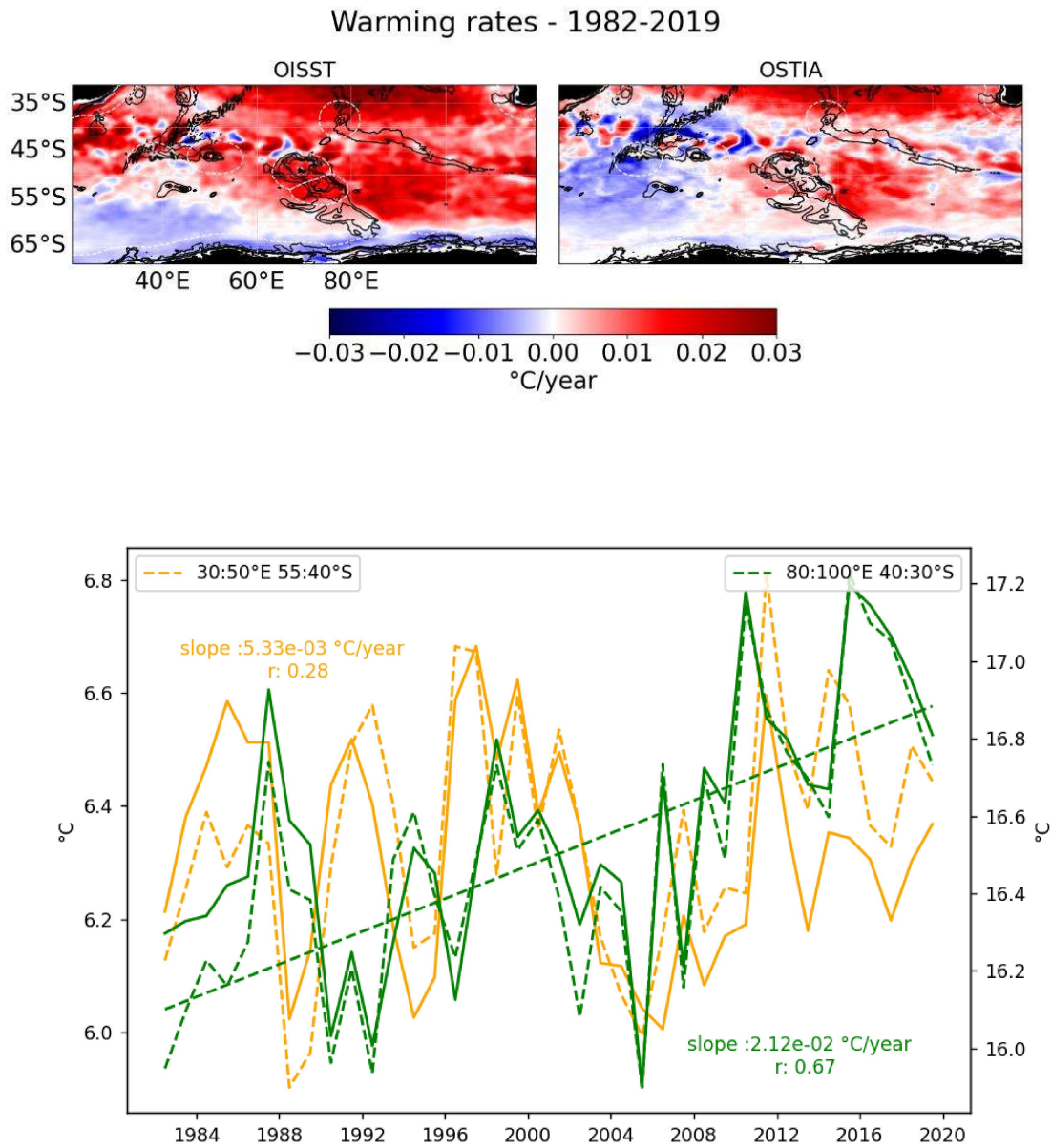
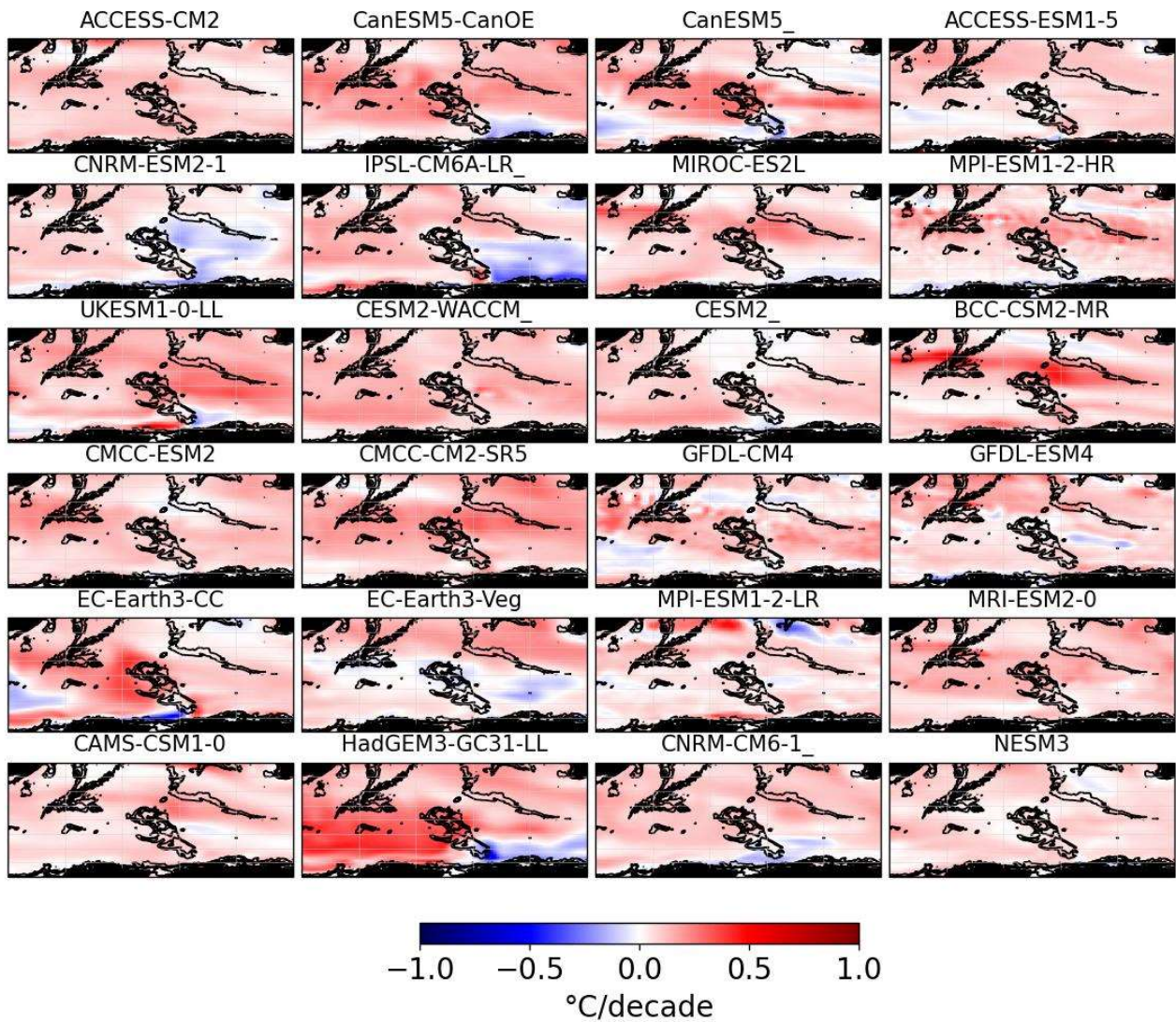


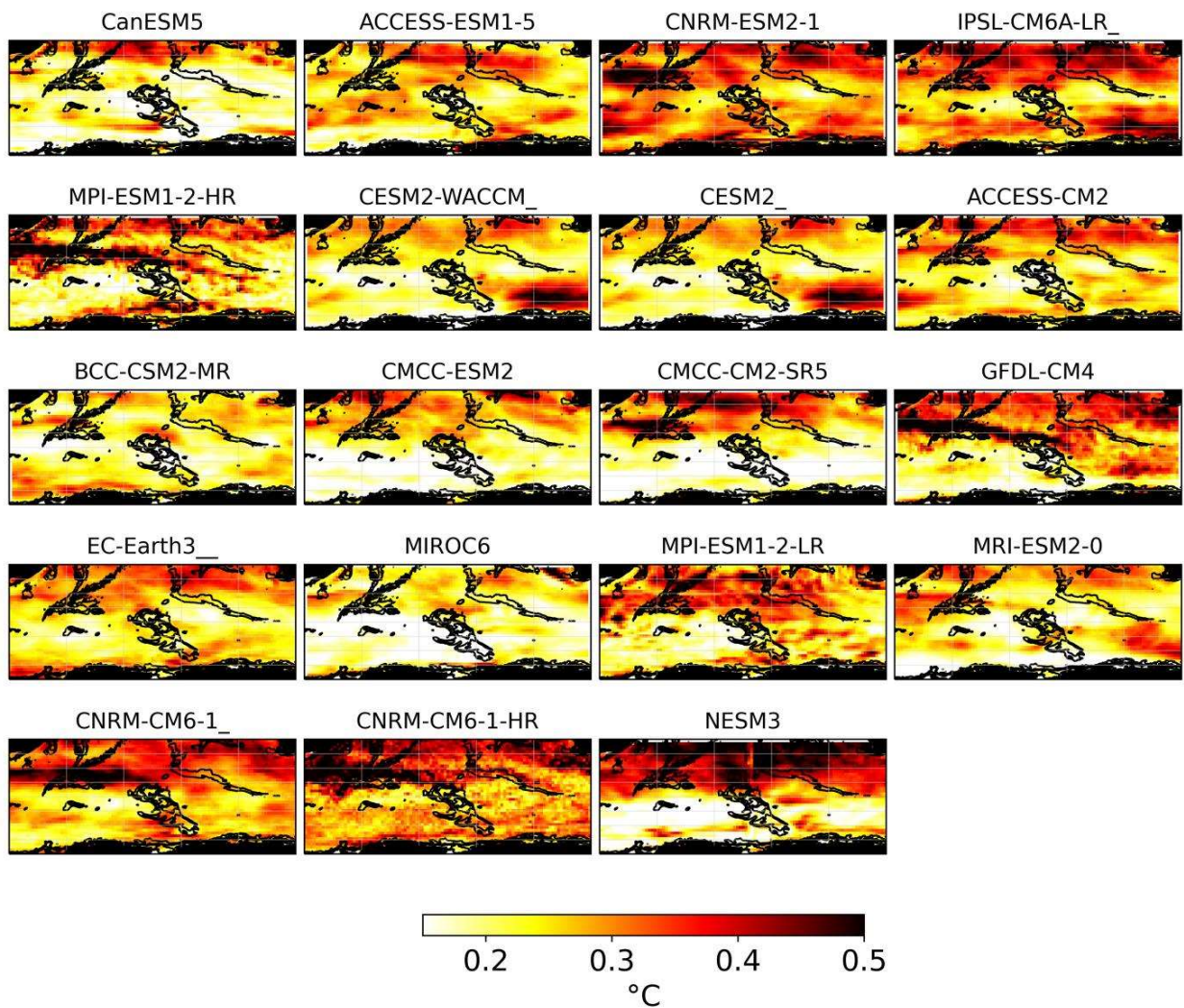
Figure S3: Warming rates between 1982-2019 for each of the 24 CMIP6 models studied.



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1 Figure S4: MHW intensity over 1984-2014 (90th percentile) for each of the 19 CMIP6 models studied.  
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46 Figure S5 : (A) Warming trends between 1975 and 2015 of 10 IPSL-CM6A-LR members. (B) Change  
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SSP2-4.5. (C)Time series of mean Pearson correlation coefficient, as an indicator of spatial similarity,

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for each 10 IPSL-CM6A-LR members relative to r1i1p1f1 member, under SSP2-4.5.

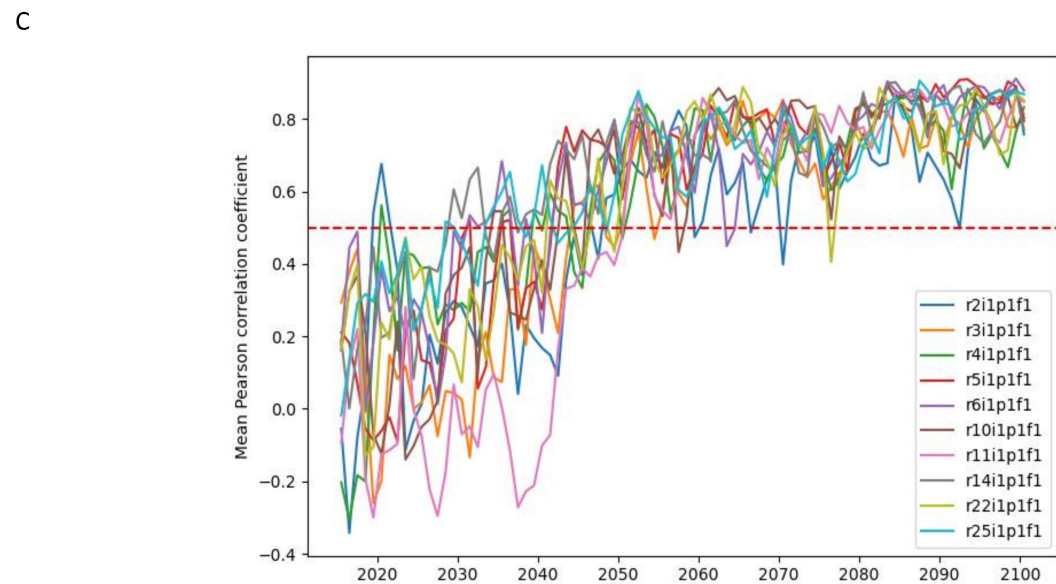
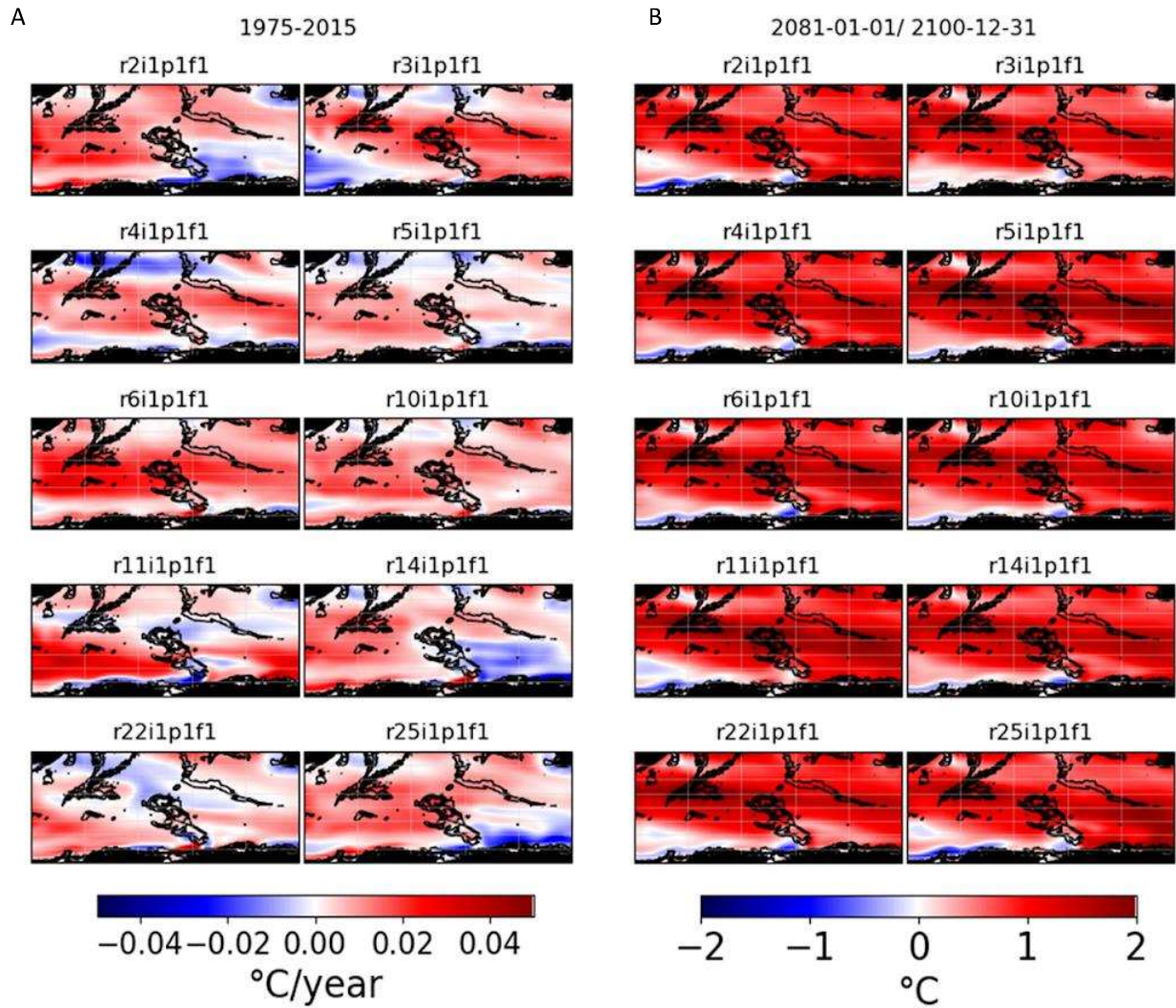


Figure S6: Relative increase in the mean (full) or spread (hatched) of the daily temperature distribution under SSP2-4.5 relative to historical period (1995-2014) from 19 CMIP6 models for 2021-2040 (near term, NT), 2041-2060 (mid term, MT) and 2081-2100 (long term, LT).

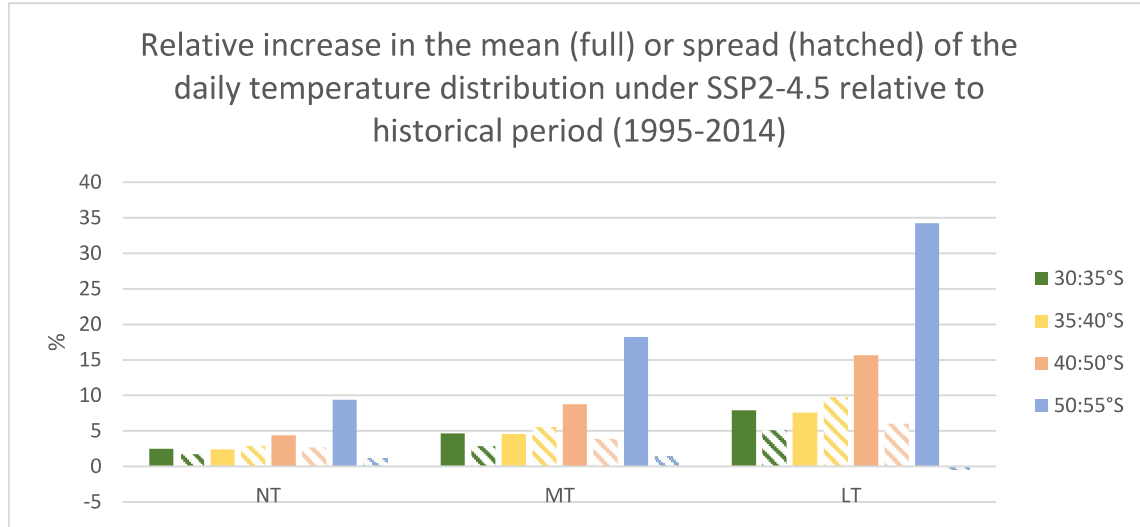




Figure S7: Relation between the change in surface temperature and MHW annual days for 20-year periods under SSP1-2.6 and SSP2-4.5 averaged over the area. Error bars correspond to intermodel variability.

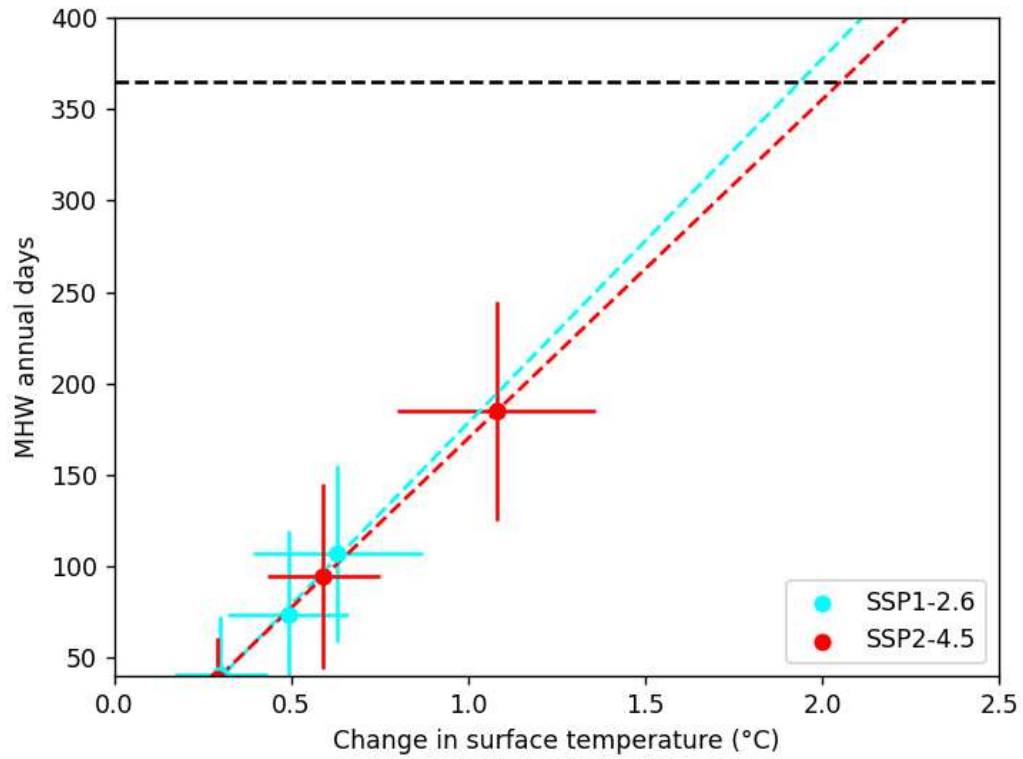
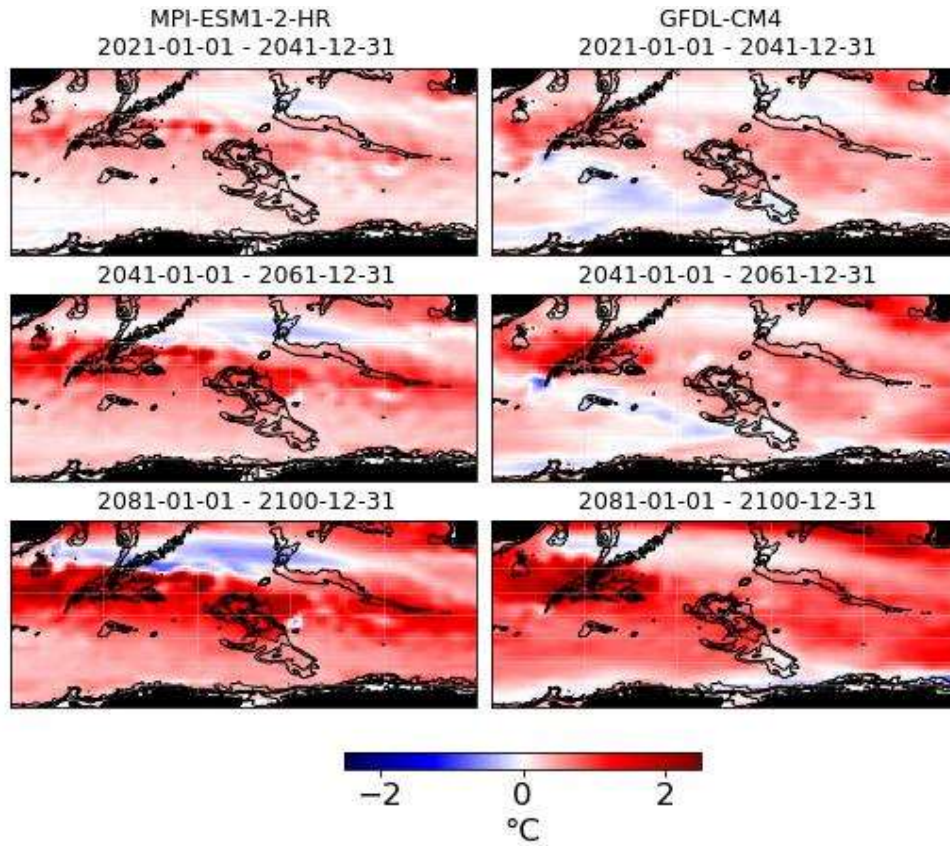


Figure S8: Change in surface temperature for the near-, mid- and long-terms under SSP2-4.5 for two high resolution models: MIP-ESM1-2-HR and GFDL-CM4.



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