

1 **Characterization of Past Marine Heatwaves around South**
2 **Pacific Island Countries: What really matters?**

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25 **Abstract**

26

27 Marine heatwaves (MHWs) can have devastating and lasting impacts on marine ecosystems. We investigated
28 past MHW characteristics around 12 southwestern Pacific Island countries and territories (PICTs) using two
29 observed sea surface temperature products and an ocean reanalysis product. PICTs are highly dependent on
30 their marine resources for their livelihoods: a better understanding of MHW characteristics is needed for
31 planning and adaptation to risks associated with MHWs. Our research builds on previous studies where
32 MHWs have been detected and described using a point-based definition. We first revisit past MHW
33 characteristics based on their spatial extent, vertical extent and seasonality. We show that filtering MHWs by
34 size (spatial extent) and seasonality can greatly affect their characterisation and help trace their physical
35 drivers. We then characterise past events inside each EEZ (Economic Exclusive Zone) and at the coast with
36 MHW indices tailored to benefit Pacific Island stakeholders. We consider two types of events: large-scale
37 events, covering a large part of the EEZ, likely to affect pelagic fisheries, and events affecting coastal zones
38 and ecosystems. We distinguish between events occurring in the hot season (November to April), and in the
39 cold season (May to October). We show that all 12 PICTs experienced MHWs in the past 30 years that are
40 getting more frequent with greater spatial extents, longer durations, explained by the long-term warming
41 trend in sea surface temperature, but with lower maximum intensity. New Caledonia, Vanuatu, Fiji and Tonga
42 appear to be more exposed to MHWs with longer duration, higher maximum intensity, and deeper extent
43 compared to other countries.

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46 **1 Introduction**

47 Marine heatwaves (MHWs) are warm ocean temperature extremes, often characterised in terms of
48 anomalously warm sea surface temperatures that persist above some threshold value. MHWs have gained

49 traction in recent years by both scientists and the general public due to their detrimental impacts on ecology
50 and the economy. MHWs affect marine life both directly and indirectly, and can reverberate up the food
51 chain. Some iconic events have had devastating effects on coastal species, open-ocean resources and
52 economies at local through to global scales (Hobday et al., 2018; Smith et al., 2021). The 2011 Western
53 Australian event affected several ecological communities including corals, seaweeds, sea grass and
54 commercially important species such as king and tiger prawns, blue crabs and scallops (Caputi et al., 2016;
55 Moore et al., 2012; Thomson et al., 2015; Wernberg et al., 2013). The 2015 northeast Pacific Blob resulted
56 in massive die off in seabirds and mammals, changes in community structure of phytoplankton and
57 zooplankton, and fisheries closures due to harmful algal blooms (Cavole et al., 2016; Jones et al., 2018). The
58 2012 northwest Atlantic event saw shifts in the distribution and phenological changes in commercially
59 important lobster species, resulting in serious consequences for the lobster fishery in the US and Canada
60 (Mills et al., 2013). Smith et al. (2021) estimate that the economic cost of certain MHW events can exceed
61 several million US dollars (USD) (e.g. \$38 million, 2012 northwest Atlantic event) in direct losses and several
62 billion USD per annum in indirect losses for events lasting multiple consecutive years.

63

64 Significant efforts have been made recently to better understand these extreme events, with the ultimate goal
65 to provide useful information to stakeholders to enable effective adaptation measures. As a first step, the need
66 to have a common definition of a MHW, which was valid for both summer and winter seasons and for various
67 areas with different sea surface temperature (SST) variability, was recognised (Hobday et al., 2016, hereafter
68 Hob16). Building on an existing definition developed from the concept of atmospheric heatwave community,
69 Hob16 developed a definition for MHWs. In this now widely used definition, a MHW occurs when ocean
70 (here, sea surface) temperatures are warmer than the daily climatological 90th percentile threshold based on
71 a 30-year historical baseline for a period of five or more days. To better account for the maximum intensity
72 and possible impacts of a MHW, Hobday et al. (2018) further defined MHW categories as integer multiples
73 of the difference between the 90th percentile and the climatological value: these are Moderate (Category 1,
74 between 1 and 2 integer multiple), Strong (Category 2, 2-3 integer multiples), Severe (Category 3, 3-4 integer
75 multiples) and Extreme (Category 4, above 4). This definition has been used in many subsequent studies, and
76 statistics obtained on past and future MHWs for the global ocean often rely on this definition, albeit with
77 slight modifications (for example in Oliver et al., 2021; Sen Gupta et al., 2020; Plecha & Soares, 2020).
78 These studies show that all regions in the ocean have been experiencing MHWs in the past decades, with
79 projected increases in MHW maximum intensity, duration and frequency in the coming decades (Oliver et
80 al., 2021).

81

82 Although the southwestern Pacific has been less studied than other regions such as the northeastern Pacific,
83 it has not been spared by MHWs. This region is composed of a myriad of vulnerable islands and atolls, with
84 marine ecosystems and coral reef environments highly sensitive to increasing temperatures, threatening the
85 entire ecosystem and causing concerns for food security, tourism and fish catch rates (Andrefouet et al., 2015;
86 Holbrook et al., 2022; Uthicke et al., 2015; Wyatt et al., 2023, Smith et al., 2021). With the projected increase
87 of temperature, and MHWs frequency with climate change (IPCC, 2023) there are concerns that such
88 ecosystems may disappear completely by 2050 (Dixon et al., 2022; Hughes et al., 2018; van Hooidek et al.,
89 2013). Holbrook et al. (2022), hereafter H22, examined past MHW characteristics and climate change
90 projections of MHW metrics (frequency, maximum intensity and duration) in the tropical western and central
91 Pacific region. In the whole region (except along the equator), H22 showed that there are on average 1 to 3
92 MHW events per year at any particular location, typically lasting from 8 to 13 days, with a mean maximum
93 intensity of 1.1°C to 1.7°C. H22 also suggested that MHWs days are projected to significantly increase in
94 the coming decades, with rates depending on the carbon emissions scenario. H22 also investigated 3 main
95 events over the past period: February 2016 event in Fiji, the 2015 mass coral bleaching event in Samoa, and
96 the 2010 mass coral bleaching event in Palau.

97

98 These analyses are a useful first step for Pacific Island countries towards becoming aware of the past and
99 future risk of exposure to MHWs of varying intensities, frequencies and durations. Yet, the information that
100 decision makers could extract from these metrics is often insufficient to allow them to fully understand MHW
101 impacts on ecosystems, and to take effective action. We illustrate this through the following four points. First,
102 as Hob16's detection method is performed independently at each location, it does not consider MHW spatial
103 extent and does not distinguish between large events and smaller, more localised events. Secondly, in most
104 studies, the detection is done at the surface, and does not consider the MHW vertical extent. These metrics
105 alone do not fully measure all ecosystem exposure. Highly mobile pelagic species, such as tunas, are likely
106 not affected in the same way by very localised events as compared to sessile species. The extent of exposure
107 for mobile species is likely more linked to large-scale events covering hundreds or thousands of square
108 kilometres. Many pelagic species also regularly move vertically through the water column to track prey
109 resources and/or meet oxygen demands (Briand et al. 2011; Arrizabalaga et al. 2015; Nikolic et al. 2017),
110 and metrics measuring the depth of MHWs are needed to capture this exposure. Thirdly, seasonal distinctions
111 are essential as MHWs' impacts on ecosystems depend on their thermal tolerance levels, thus on the time of
112 year of occurrence (summer or winter). Finally, time-mean statistics for MHWs alone do not inform decision
113 makers on the strongest events that occurred in the past, nor on the statistical distributions of events, to better
114 anticipate the types of future events that are likely to occur in the countries' waters.

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116 Here, we aim to go beyond these limitations. We characterise past MHWs (1981-2023) for 12 Pacific Island
117 countries and territories (PICTs) within their EEZs, so that the results can be more easily usable for marine
118 management and decision making in each PICT. We consider two different types of events that can
119 significantly affect Pacific Island ecosystems and economies: (i) large-scale events, henceforth referred to as
120 ‘Macroscale events’, covering a large part of the EEZ, with potentially significant impacts for pelagic
121 fisheries, and (ii) coastal events, that may have smaller spatial extents, yet may impart significant impacts on
122 reef ecosystems and coastal resource management. We distinguish between events occurring in summer and
123 in winter months. We extract the vertical extents of surface MHWs to gain an understanding of the volume
124 of water that may be subjected to heat stress during MHW events. Finally, we also explore climate trends in
125 MHW properties.

126

127 This paper is organised as follows. In section 2, we present the data used, and the methodology applied. In
128 the same vein as some recent studies (Sun et al., 2023; Bonino et al., 2023), we propose an easy and simple
129 way to quantify the spatial extent of surface MHWs by calculating areas of connected points. In section 3,
130 we explore the spatial extent of MHWs in the whole southwest Pacific region, and show that the MHW
131 metrics, when excluding small scale events, change substantially from what has been previously published
132 (H22; Oliver et al., 2021). We also show that discussing MHW statistics in terms of sizes helps to infer the
133 underlying physical drivers. In section 4, we provide information on past MHW characteristics for PICTs.
134 For each PICT, we provide past MHW metrics for the two types of events (macroscale and coastal events),
135 separately. We conclude and provide perspectives in section 5 on what should now be done, with this
136 information, to better assess the vulnerability of PICTs to future MHWs.

137

138 **2 Data and Methods**

139 The study region extends from 2.4°S to 34.8°S and 145°E to 151°W (Fig. 1 a). It contains the eastern coastline
140 of Australia and Papua New Guinea and full EEZs of 12 PICTs; on the western side, Solomon Islands, New
141 Caledonia, Vanuatu; in the centre, Tuvalu, Fiji, Wallis and Futuna, Tonga; and on the eastern side, Tokelau,
142 Samoa, American Samoa, Niue and Cook Islands.

143

144 **2.1 Temperature datasets**

145 We used three ocean temperature products to detect MHWs over the study region. We first used the NOAA-
146 OISST version 2.1, which is a blended daily SST product (representing temperatures at 0.2m depth) mixing
147 satellite and in situ SST data. These data are mapped onto a 0.25° grid for the period 1981-09-01 to 2023-06-
148 26 (Huang et al., 2021).

149 We also used ocean temperatures from GLORYS12, an ocean reanalysis product with a 1/12° horizontal
150 resolution and 50 vertical levels (Lellouche et al., 2021). For comparison with NOAA-OISST, the
151 GLORYS12 data was regridded to 0.25° and the first depth level was used (0.49m) for the period 1993-01-
152 01 to 2019-12-31 for open ocean events. The advantage of GLORYS12 is that it allows us to explore the
153 vertical extent of MHWs. For investigation of the MHW events at the coast (Section 4), grid cells closest to
154 the land mask of the 12 PICTs in waters deeper than 200m depth were used at 1/12° horizontal resolution
155 and at the first depth level (0.49m) for the period 1993-01-01 to 2023-10-24. As GLORYS12 does not resolve
156 processes in very shallow coastal waters adequately, a depth of 200m allowed MHW detection to be made in
157 sufficiently deep waters outside the lagoon but close enough to the coast so that inferences could be made
158 about MHW events that could have affected coastal waters.

159 Finally, we use the Operational Sea Surface Temperature and Ice Analysis (OSTIA) product to validate and
160 compare robust features in coastal MHWs with GLORYS12 over the 1993-01-01 to 2023-10-24 period.
161 OSTIA is a 0.05° horizontal resolution, blended SST product using in-situ and satellite data from both
162 infrared and microwave radiometers (Good et al., 2020).

163

164 **2.2 MHW detection method and product intercomparison**

165 MHWs were detected using all products, based on the Hob16 definition at each pixel in the tropical southwest
166 Pacific (Fig. 1 a). A 90th percentile threshold was used with the 1993-2019 climatological period. This
167 baseline was chosen since it was common to all products and for consistency, as the detection method is quite
168 sensitive to the baseline chosen (Amaya et al., 2023). No trend was removed to understand the impact of total
169 heat exposure (to account for both temporary extreme heat events and long-term warming (see also discussion
170 in Section 5.3)). To understand if the trends that we are seeing is due to long term warming, we detrended the
171 SST and calculated trends on MHWs detected on the detrended SST (Fig. 7, 8).

172 The marineHeatWaves package available in Python (<https://github.com/ecjoliver/marineHeatWaves>, last
173 access: 24 September 2024) was used for the detection of MHWs and calculation of key MHW parameters
174 such as duration, intensities, onset and decline rates.

175 We also computed linear trends for the annual number of MHW days, duration, maximum intensity, vertical
176 extent and their significance using linear least-squares regression from the Scipy Package in Python. For the
177 detection and calculation of trends, annual mean time series of these variables were used for full years from
178 1982 to 2022 for NOAA-OISST and 1993 to 2022 for GLORYS12 and OSTIA coastal events.

179 The statistical significance of the slope was obtained with the parametric Wald Test (<https://docs.scipy.org/doc/scipy/reference/generated/scipy.stats.linregress.html>, last access: 6 July 2024).

181

182 **2.3 MHW spatial extent**

183 Here we present a simple and easy way to measure the daily spatial extent of MHWs, using contours drawn
184 over spatially connected MHW patches. It is an intuitive method, easy to follow and sufficient for the
185 purposes of this paper, allowing MHWs to be described in a way complementary to the parameters originally
186 presented in Hob16. As in the method used by Bonino et al. (2023), our method does not consider the physical
187 processes behind an event, it just calculates the area occupied by connected pixels in active MHW state.

188 After MHWs were detected at each grid cell in the study area (Fig. 1 a), a boolean 1 was assigned to each
189 day in an active MHW state at each location and a 0 otherwise. Contours were drawn over regions with 1s
190 and 0s. The closed contours were then turned into polygons and the area of the polygons were calculated. In
191 the case where non-MHW areas were enclosed by MHW areas, the area occupied by the non-MHW polygon
192 was subtracted from the MHW polygon. Each grid cell within a particular MHW polygon was assigned a
193 value equal to the area of that MHW polygon (Fig. 1 b). Polygons greater than 25 square degrees were
194 categorised as ‘macroscale’ events and polygons smaller than 25 square degrees as ‘microscale’ events on
195 each day. This was done for each day separately. This choice follows Sun et al. (2023) and allows the
196 elimination of the MHWs linked to the passage of mesoscale eddies, which occupy areas of around 1-2 square
197 degrees, with diameters between 50-500 km in the region (Keppler et al., 2018). The micro and macroscale
198 spatial extents were then used as masks to filter MHW properties described in Section 2.2 (MHW detection
199 method and product intercomparison) by their sizes (spatial extent), every day independently. Once
200 information relevant to events of particular sizes (spatial extent) were obtained, comparisons between the
201 MHW properties related to microscale and macroscale sized events were made by sizes and seasons.
202 Properties associated with macroscale events were then clipped with country EEZs to obtain relevant country

203 level information as macroscale sized events have higher chances of affecting large ocean areas and their
204 marine resources.

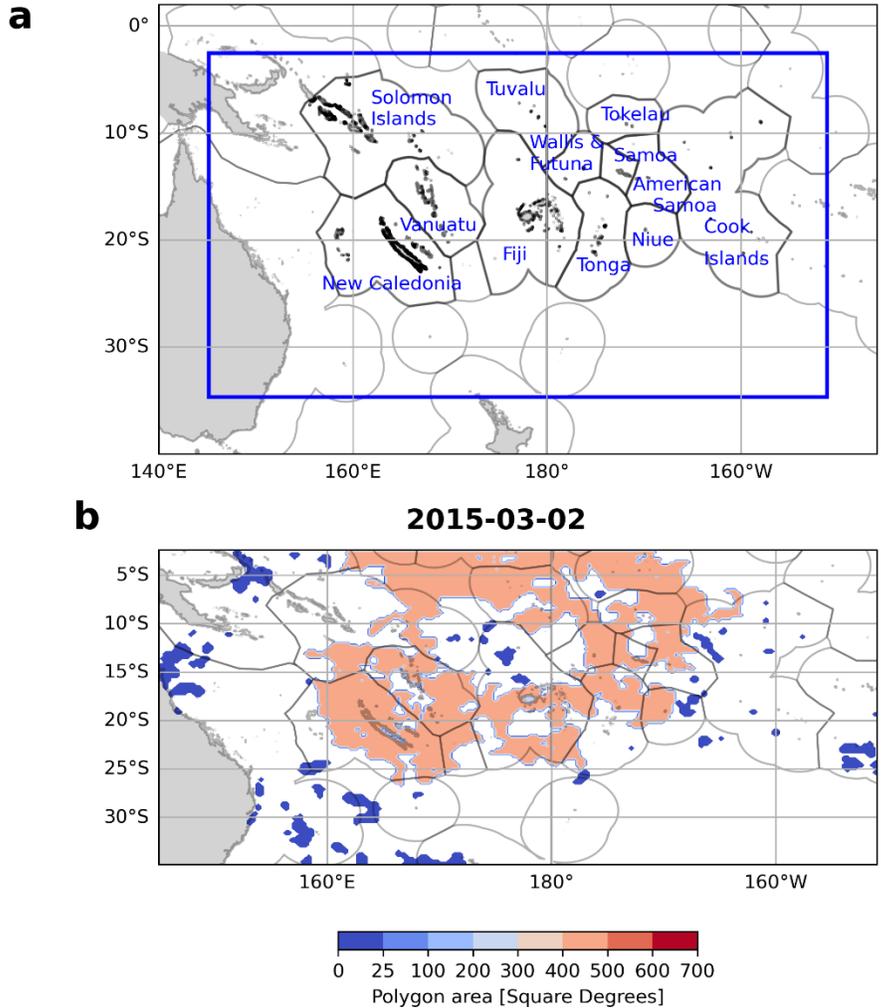
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206 **2.4 MHW vertical extent**

207 MHWs were identified independently at each of the upper ocean 38 depth levels available in GLORYS12
208 from 0.49 to 1500m, as has been done by others (Schaeffer et al., 2023; Schaeffer & Roughan, 2017). We
209 only consider events detected at the surface. Then, the maximum depth of MHW detection without
210 interruption from the surface in MHW detection, was recorded as the vertical extent of the surface MHW
211 event at that location. This method does not allow for the identification of subsurface-only MHWs (Schaeffer
212 et al., 2023). Vertical extents associated with microscale and macroscale events were explored in terms of
213 their seasonality and trends. Macroscale events were clipped with country EEZs to obtain relevant country
214 level information.

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218 **Figure 1** Map showing the study area, tropical South Western Pacific enclosed by the blue box. The 12
 219 **PICTs** explored in depth in this study with their Exclusive Economic Zones (EEZs) are labelled in blue
 220 and outlined in black inside the blue box, from left to right Solomon Islands, New Caledonia, Vanuatu,
 221 Tuvalu, Fiji, Wallis and Futuna, Tonga, Tokelau, Samoa, American Samoa, Niue and Cook Islands.
 222 Other PICTs and their EEZs in the region are outlined in grey. **b.** MHW polygon areas on 2015-03-02.
 223 MHWs detected using NOAA-OISST from 1981-09 to 2023-06.

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227 **3 Revisiting past MHW metrics in the southwest Pacific in terms of spatial extent and seasonality**

228 **3.1 MHW spatial extent**

229 Before characterising “macroscale” MHW events, we first investigate the distribution of MHW polygon sizes
230 in the study region. Figure 2 shows histograms of MHW polygons, by size, for both NOAA-OISST and
231 GLORYS12 products, and separately for cold season (May to October) and hot season (November to April).
232 A large majority of the MHW events (80% for GLORYS12, 72% for NOAA-OISST) detected daily are of
233 very small spatial extent, less than one square degree (Fig. 2 a). The two products give quite different results
234 for the number of small-scale events, highlighting the dependence of the Hob16 detection method on the
235 product used. Hob16 have acknowledged that the method is sensitive to the product chosen, and differences
236 may arise in terms of MHWs statistics among products, even when using the same baseline (see Appendix
237 1). This is particularly true in the cold season, when there are more than twice as many events smaller than 1
238 square degree identified using GLORYS12 compared with the NOAA-OISST product (Fig. 2 a). This might
239 also be related to higher energy of fine-scale processes in the cold season in the region (Rocha et al., 2016;
240 Sérazin et al., 2019) represented in the 1/12° GLORYS simulation. Interestingly, the differences in the
241 number of macroscale polygons (i.e. polygons greater than 25 square degrees) between the two products is
242 strongly reduced (17% difference between NOAA-OISST and GLORYS12 compared to 94% difference for
243 sizes smaller than 25 square degrees, not shown). This is an important result, since it lowers the dependence
244 of the method on the product used when examining properties of macroscale events. Up to 20 square degrees,
245 microscale events are more numerous in the cold season than in the hot season (18% and 60% more, for
246 NOAA-OISST and GLORYS12, respectively, Fig. 2 b). The contrary is true for macroscale events: there are
247 more macroscale events in the hot season than in the cold season (37% and 32% more, for NOAA-OISST
248 and GLORYS12, respectively, Fig. 2 b) as will be discussed later.

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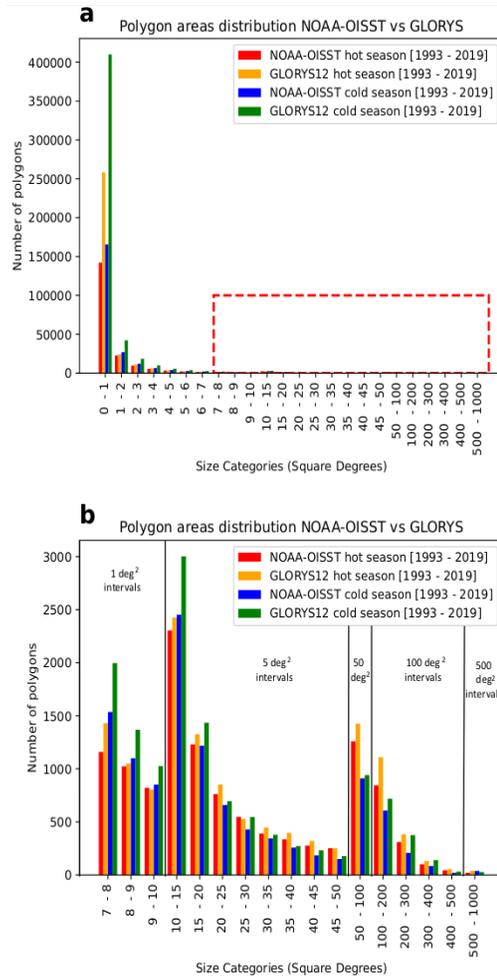


Figure 2 Bar chart showing the number of MHW polygons belonging to various size categories in the hot (November to April) and cold (May to October) seasons. **a**, Shows all the size categories from 0 to 1000 square degrees. The red dashed rectangle is to indicate the zoom used in **b**. **b**, is a zoom in on sizes 7 to 1000 square degrees. Polygon areas were calculated from MHWs detected using NOAA-OISST and GLORYS12 from years 1993 to 2019.

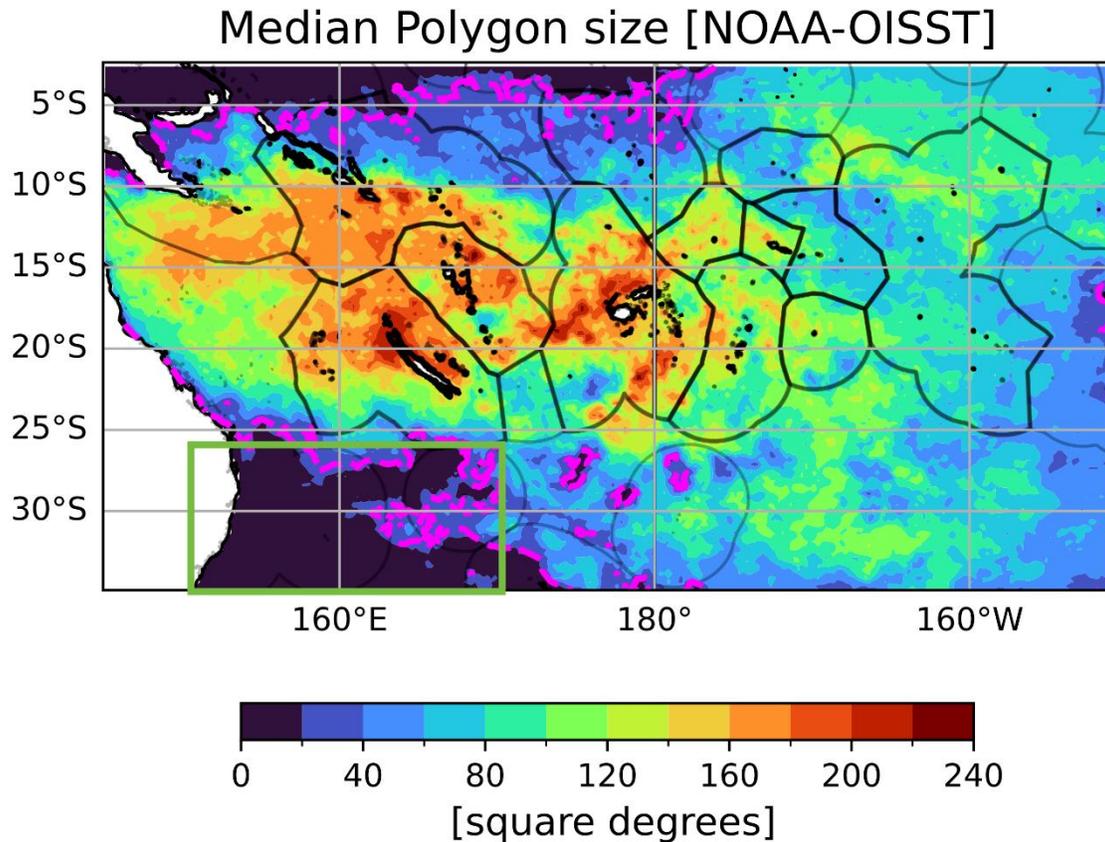
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258 Figure 3 shows the median size of the MHWs occurring in the southwest Pacific region. MHWs have highly
259 variable spatial extents throughout the region. The majority of events occurring around New Caledonia,
260 Vanuatu and Fiji are large-scale events of more than 160 square degrees (Fig. 3). This suggests that for these
261 areas, the underlying processes could be linked to drivers impacting large-scale atmospheric or oceanic
262 conditions, such as ENSO or MJO (Madden Julian Oscillation), as suggested previously (Dutheil et al., 2024;
263 Holbrook et al., 2019; Sen Gupta et al., 2020; Vogt et al., 2022). MHWs become slightly smaller towards the
264 east, with a median size of less than 100 square degrees. In the eddy-rich region (green box, Fig. 3) (Qiu &
265 Chen, 2004), associated with the East Australian Current and its retroflection (west of $\sim 170^\circ\text{E}$ and south of
266 25°S), MHWs are all small sized, with the median being smaller than the 25 square degrees limit (marked in
267 dashed lines in magenta, Fig. 3). They are mostly associated with the occurrence of mesoscale eddies (Everett
268 et al., 2012; Keppler et al., 2018). MHWs are also small in the Warm Pool region, equatorward of 5°S (Fig.
269 3).



270

271 **Figure 3** Map showing median MHW polygon size with a dashed contour line at 25 square degrees in
 272 **magenta**. MHWs detected using NOAA-OISST from 1981-09 to 2023-06. The green rectangle marks
 273 **the eddy rich region, where eddies shed the southern extent of the East Australian Current.**

274

275 **3.2 Properties of MHWs filtered by size and season**

276 Investigating the properties of MHWs (number of MHW days, mean duration, mean maximum intensity and
 277 vertical extent) as a function of size and season revealed patterns resembling dominant ocean-atmosphere
 278 processes in regions within the study area. The climate of the region is largely influenced by the presence of
 279 the South Pacific Convergence Zone (SPCZ), a band of low-level atmospheric convergence, cloudiness and
 280 rainfall, roughly extending from the Solomon Islands southeastward toward French Polynesia (Brown et al.
 281 2020; Vincent et al., 2014). In the northern part of the region, equatorward of ~10°S, the waters are warmer
 282 than 29°C, forming the western Pacific Warm Pool (Cravatte et al., 2009). The region south of 20°S, in the
 283 area of the Subtropical Counter Current and in the area of the meandering East Australian Current, is

284 characterized by ubiquitous, long lived, deep extending mesoscale eddies (Keppler et al., 2018; Qiu et al.,
285 2009).

286 We chose to divide the study area into five subregions. The subregion division was inspired by Longhurst
287 (2007) and Houssard et al. (2017). While these authors made the divisions based on ecological reasons for
288 example due to nitrogen biochemistry at the base of marine food chains, ours has been modified to consider
289 important climatological processes in the region, including the expected location of the SPCZ (subregions 1,
290 2, South-SPCZ and North-SPCZ), the transition between the western Pacific and the central eastern Pacific
291 (subregion 3, Equatorial central region), presence of high energy eddies generated by the Eastern Australian
292 Current (subregion 4, Southeastern Australian eddy region) and the more homogenous subtropical region
293 (subregion 5, Subtropical region), which is part of the south Pacific subtropical gyre in Longhurst (2007) and
294 Houssard et al. (2017). We have named our subregions to reflect our choice of classification. These also
295 correspond to different properties in MHW metrics, as seen in Figures 4, 5 and 6. Figure 4 shows mean MHW
296 characteristics for all events, and also separately for microscale (0-25 square degrees) and macroscale events
297 (25-700 square degrees). Figure 5 further shows these properties for the hot and cold seasons for macroscale
298 events. Figure 6 shows the mean vertical extent of the MHWs for both micro and macroscale events for the
299 two seasons.

300 Across the whole study area, there are between 10 to 30 days of MHWs per year (Fig. 4 a), with contrasting
301 properties within the domain. Subregion 2 stands out with less MHW days than the rest of the region (around
302 12 to 18 days per year), with a similar amount of microscale and macroscale events all year around, i.e., in
303 both the cold season and hot season (Fig. 5 for macroscale only, microscale not shown). There, MHWs are
304 of short duration (typically 5 to 10 days), and of small maximum intensities (+1.4°C). This subregion
305 corresponds to the location of the warmest surface waters of the Warm Pool, where temperatures are greater
306 than 29°C in the mean (blue contour in Fig. 4 a), and where the cloud cover is important. MHWs here extend
307 from 40 to 80m depth in the hot season, deeper than the mean mixed layer depth, and even deeper in colder
308 months (Fig. 6).

309

310 In contrast, subregion 3 (the equatorial region east of 180°central region) is exposed to MHWs around 25 to
311 30 days per year (Fig. 4 a). There, the majority of MHWs are large-scale events (compare Fig. 4 d and g) and
312 most present during the hot months (Fig. 5). These MHWs are of longer duration (on average 40 days) and
313 of higher intensities (approx. +2°C) closer to the equatorial band and they extend quite deeply (down to 80
314 to 100 m depth, Fig. 6 c, d). We isolated the long duration, large-scale MHWs in this region and found
315 episodes in 1982-83, 1987, 1991-92, 1997-98, 2009, 2010, and 2015-2016 (not shown). They are thus
316 systematically associated with El Nino events, in accord with Sen Gupta et al. (2020), and consistent with

317 processes associated with the eastward displacement of the Warm Pool waters and deepening of the
318 thermocline in the region during the development of El Niño events (e.g. Picaut et al. 2001).

319 Subregion 1, the “South-SPCZ region” is, interestingly, the region which is more exposed to MHWs, with as
320 much as 30 days of MHWs per year on average. This area encompasses the Solomon Sea and the Coral Sea,
321 and extends eastward to the Fiji archipelago. There, the MHWs are mostly of large scale (compare Fig. 4 d
322 and g, see also Fig. 3), and associated with long durations (more than 30 days on average, Fig. 4 h). Their
323 maximum intensity is slightly greater for macroscale events than microscale, typically being around +1.6 to
324 +2°C. In the hot season, macroscale events are more numerous but of shorter duration compared to the cold
325 season. Their depth corresponds to the mean seasonal depth of the mixed layer, typically from 20 to 40m in
326 the hot season and from 40 to 80m in the cold season (Fig. 6). In the cold season, macroscale events are less
327 numerous, but last longer: some can last up to one year (see Fig. 5 e). They are slightly deeper, typically from
328 40 to 80m, also mirroring the winter depth of the mixed layer (Fig. 6). The very long events in the cold season
329 correspond to the recent La Niña years, as will be discussed later, and to the associated warmer anomalous
330 SST conditions in the southwest Pacific. More studies will be required to characterise the processes driving
331 other MHW events, but the characteristics described here argue for mixed layer dynamics and large-scale
332 atmospheric forcing events.

333 Subregion 4, the “Southeastern Australia eddy region”, is characterised by 15 to 25 MHW days per year. In
334 this eddy-rich area, associated with the retroflection of the energetic East Australian Current, MHWs events
335 are all of small size and short duration (10 to 25 days). They have large maximum intensities, reaching above
336 3.5°C south of the domain. These microscale MHWs exhibit substantial vertical extent, much deeper than
337 the mixed layer depth, both in the hot season (100 to 150m) and in the cold season (more than 200m)
338 suggesting that they are mostly associated with passing eddies (see Fig. 6) with deeper impacts in winter
339 (Bian et al., 2023).

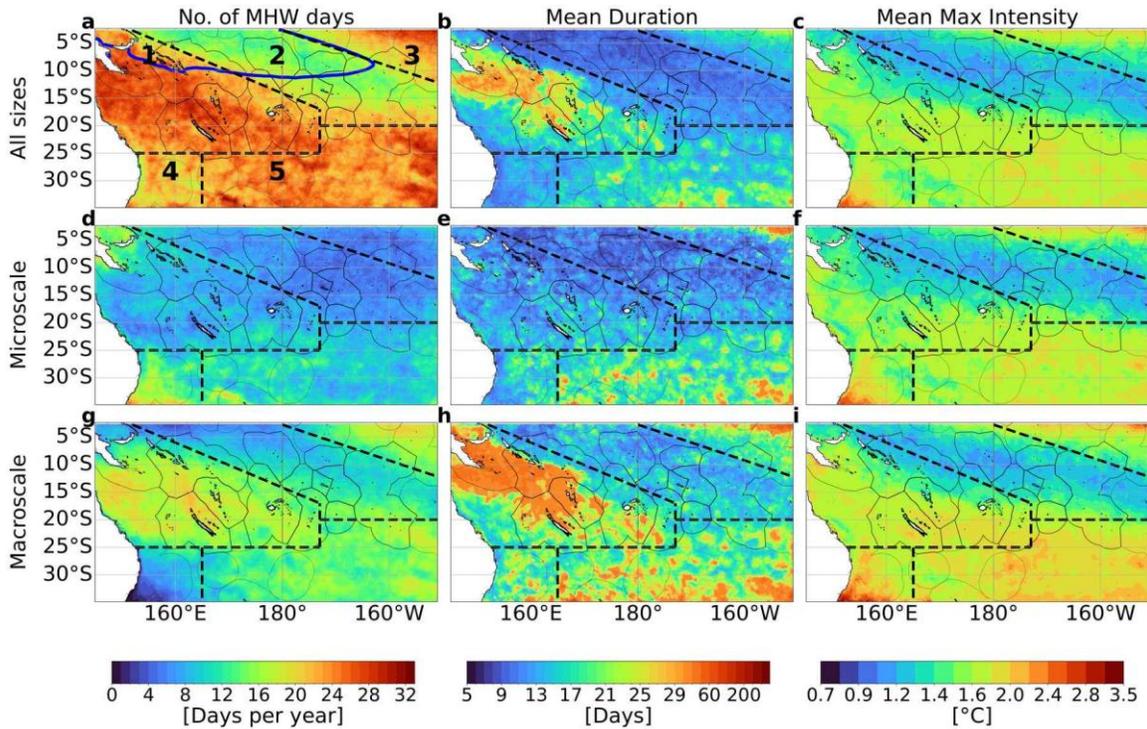
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341 Finally, subregion 5, the “subtropical region”, is a mix between subregions 1 and 4 in terms of MHW
342 properties. This area experiences between 20 and 32 days of MHWs each year (Fig. 4 a), both of large and
343 small scales. As with subregion 1, the macroscale events are more prevalent in the hot season (Fig. 5 a), with
344 short durations of 10 to 20 days, but large intensities (2 to 2.5°C), and shallow depths (20 to 40 m depth,
345 corresponding to the mean seasonal depth of the mixed layer, see Fig. 6). Very few macroscale events occur
346 in the cold season, but they do last longer than in summer and are on average of lower maximum intensity
347 (+1.4 to +2°C). It is worth noting that MHW properties are quite noisy here, with small-scale features of
348 longer duration, higher intensities, and overall much deeper extent (Fig. 6). It is probable that these MHWs
349 arise through several processes, with large-scale atmospheric forcing contributing to large-scale, shallow

350 events, and mesoscale eddies contributing to smaller scale events, with much deeper extents, as also
 351 suggested by Bian et al. (2023).

352 Overall, seasonality appears to play a very important role in the characterisation of MHW properties in the
 353 study region. For macroscale events, MHW properties have contrasting characteristics in different seasons.
 354 This suggests that the combination of drivers of MHW events in the hot and cold seasons may actually be
 355 quite different. In general, over the study area, there is a tendency for macroscale events to be of short duration
 356 and high maximum intensity during the hot season, while the opposite is true for the cold season. While
 357 microscale events tend to have higher variability in terms of vertical extent, and can extend deeper than
 358 macroscale events in some locations regardless of the season (compare Fig. 6 a, b to c, d), both microscale
 359 events and macroscale events are much shallower in the hot season and extend much deeper in the cold
 360 season. This is likely due to shoaling of the mixed layer depth (MLD) during the hot season (median MLD
 361 ~14-28m, Fig. 6 e), restricting surface related MHWs within the shallower mixed layer, and due to deeper
 362 MLD in the cold season (median MLD ~14-90m, Fig. 6 f) allowing greater mixing and MHWs to be detected
 363 without interruption over greater depths.

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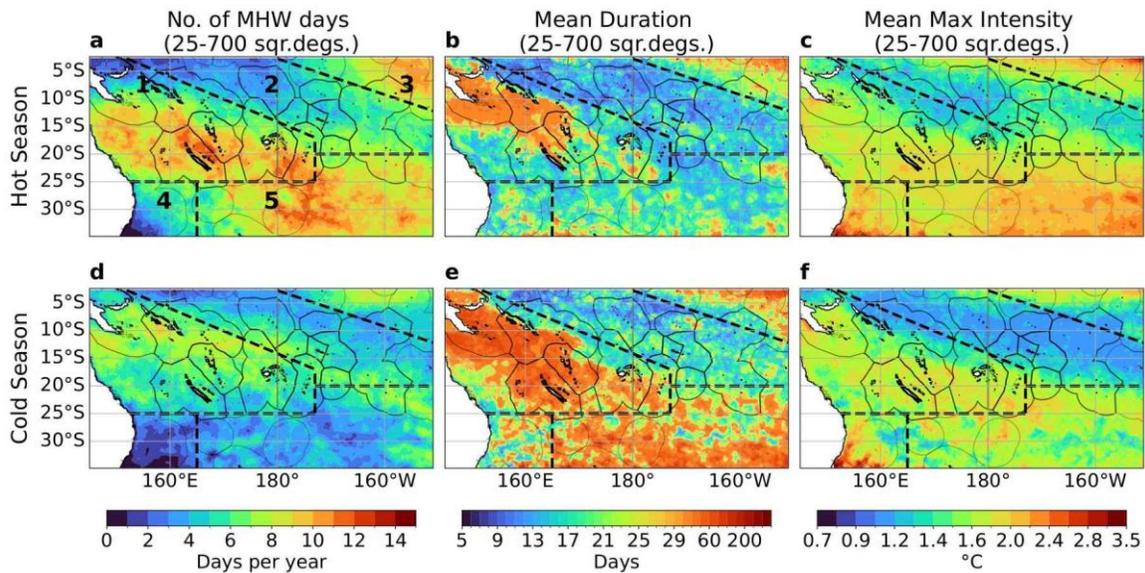
365

366 **Figure 4** Panel plots showing number of MHW days, mean duration and maximum intensity by spatial
 367 extent; a,b,c, for all sizes (0-700 square degrees), d,e,f, for microscale (sizes 0-25 square degrees), g,h,i

368 for macroscale (sizes 25-700 square degrees) respectively. MHWs detected using NOAA-OISST from
 369 1981-09 to 2023-06. Regions of special interest based on common ocean-atmospheric process
 370 demarcated with black dashed lines; 1. South-SPCZ region, 2. North-SPCZ region, 3. Equatorial
 371 central region, 4. Southeastern Australia eddy region and 5. Subtropical region. The blue line in a is
 372 the 29°C isotherm (mean temperature) showing the mean position of the western Pacific warm pool.

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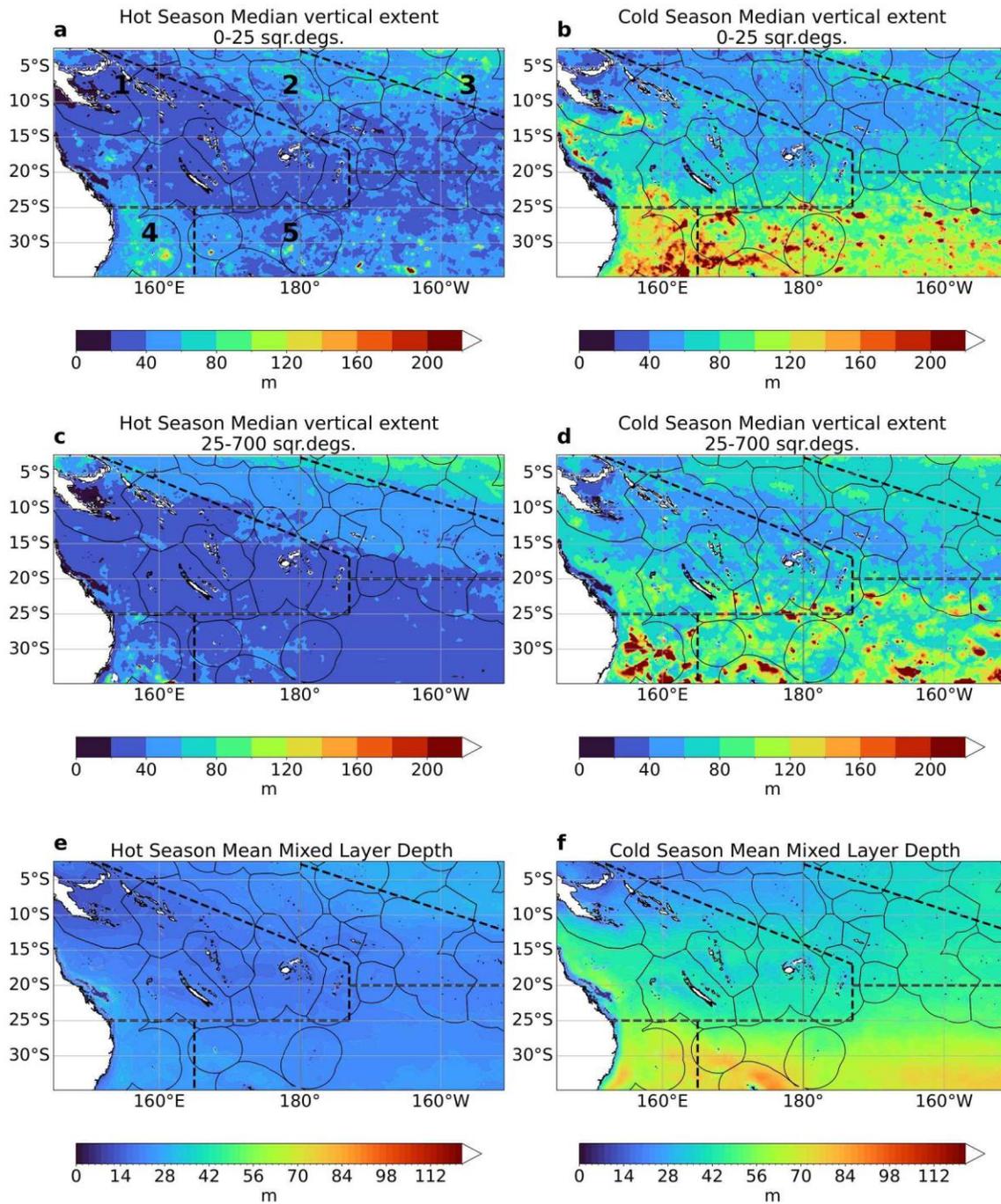


375

376 **Figure 5** Panel plots showing number of MHW days, mean duration and mean maximum intensity for
 377 macroscale events (25-700 square degrees); a,b,c in hot and d,e,f in cold season respectively. MHWs
 378 detected using NOAA-OISST from 1981-09 to 2023-06. Refer to Figure 4a for regions numbered 1 - 5,
 379 demarcated with black dashed lines.

380

381



382

383 **Figure 6 Median vertical extent of surface MHWs by spatial extent and seasons; a,b, microscale events**
 384 **(0-25 square degrees) in hot and cold seasons respectively. c,d, macroscale events (25-700 square**
 385 **degrees) in hot and cold seasons respectively. e,f, Mean mixed layer depth in hot and cold seasons**
 386 **respectively from GLORYS12. MHWs detected using GLORYS12 from 1993 to 2019. Refer to Figure**
 387 **4 a for regions numbered 1 - 5, demarcated with black dashed lines.**

388 3.3 Long term trends

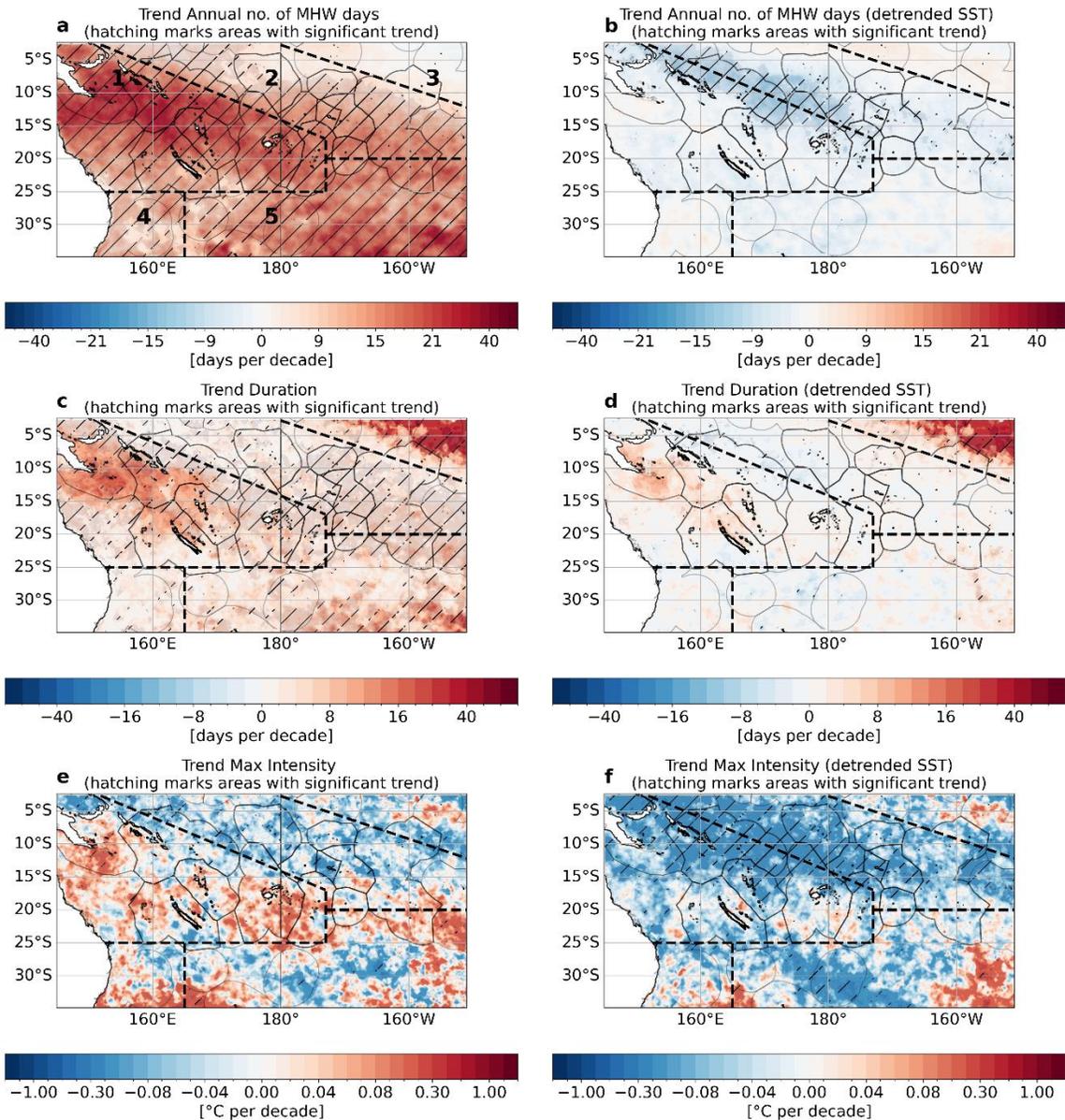
389 The previous figures showed the mean MHW properties over the 1981-2023 period. A key question now is
390 whether, if, and how, these properties have changed over time. This was investigated in H22. They found
391 that, except for the central equatorial subregion 3, there has been an increase in the number of events per
392 year, but with no strong nor consistent trend in maximum intensity or duration.

393 Figure 7 shows trends in annual number of MHW days, annual mean duration, annual mean maximum
394 intensity, with hatched areas indicating significant (p -value < 0.05). More specifically, for subregions 1, 2
395 and 5, the number of MHWs per year significantly increased over time in the original version and decreased
396 significantly between subregions 1 and 2 in the detrended version. As the 12 countries studied in detail are
397 located in these three regions, all countries also have experienced significant positive trends in the annual
398 number of MHW days in the past decades (Fig. 7 a). Region 1 experiences between 12 to 24 MHW days per
399 year on average (Fig. 4 g); this number was multiplied up to four times during the last 4 decades around the
400 Solomon Islands, New Caledonia and Vanuatu (Fig. 7 a). The same is true for the trend in MHW duration,
401 with MHW events becoming longer over the past decades (Fig. 7 c). Average MHW duration is between 5 –
402 30 days over most of the countries (Fig. 4). The mean duration has also largely increased, since 1982,
403 especially in subregion 1, in the Solomon Sea. On the contrary, and consistent with H22 findings, there is no
404 strong and significant trend in MHW maximum intensity (Fig. 7 e). The only significant pattern is a decreased
405 maximum intensity in the Warm Pool area (subregion 2), where the maximum intensity was already the
406 smallest in the whole region. No significant trends were observed over most parts of the study region in terms
407 of the vertical extent (Figure not shown).

408 We also present trends on the MHW properties for MHWs detected on the detrended SST. This allows us to
409 investigate if the trends observed are explained by the long warming trend only. The results obtained show
410 that the increase in the number of MHW days during the last decades is clearly due to the long-term warming
411 (compare Figure 7 a to Figure 7 b). A large part of the increase in MHW duration in subregion 1 seen in
412 Figure 7 c is also reduced or even disappears on the detrended version, Figure 7 d. Also, on the detrended
413 version, we now have a decrease in maximum intensity over the last decades in many areas, whereas there is
414 no significant trend on the initial version (compare Figure 7 e to f). The trends in MHWs metrics are thus
415 largely explained by the long-term warming trend.

416 Finally, Figure 8 shows the daily time series of the percentage of surface area of the study region in a MHW
417 state, for both GLORYS12 and NOAA-OISST. A significant trend of ~3.5 percent (~70 square degrees)
418 increase per decade is observed (Fig. 8 a). Over the past decade, there has not been a single day when at least

419 part of the region was not exposed to MHWs. Results obtained from the SST detrended version (Figure 8 b)
 420 indicates that the trend in spatial extent observed in Figure 8 a is also due to the long-term ocean warming.
 421
 422

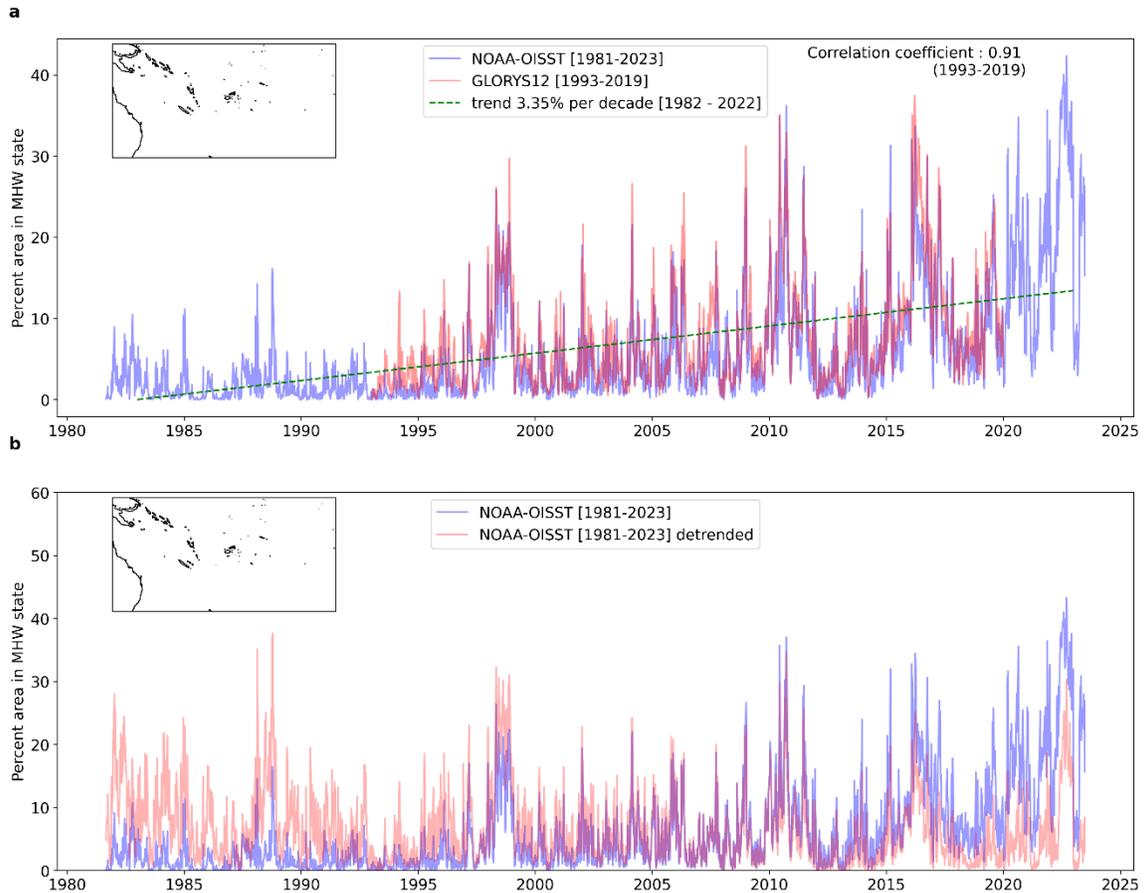


423

424 **Figure 7 Trends in MHW properties for MHW detection made of the full time series and the detrended**
 425 **time series. a, b, annual number of MHW days, c,d, duration , e,f, maximum intensity. MHWs detected**

426 using NOAA-OISST from 1982 to 2022. The regions demarcated in black are, 1. South-SPCZ region,
427 2. North-SPCZ region, 3. Equatorial central region, 4. Southeastern Australia eddy region and 5.
428 Subtropical region. The data in the maps refer to average changes in these metrics per decade over the
429 40 years.

430



431

432 **Figure 8 a.** Time series showing percent of study region in MHW state, with a statistically significant
433 trend line (p -value < 0.05) in green calculated between 1982 to 2022 for NOAA-OISST and Pearson
434 correlation coefficient calculated between 1993 and 2019 for NOAA-OISST and GLORYS12 (p -value
435 < 0.05). **b.** Time series of percent of study region in MHW state using the NOAA-OISST and the
436 detrended NOAA-OISST from 1982 to 2022.

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440

441 **4 Past MHWs for each Pacific country**

442 **4.1 Macroscale events: statistics for each country**

443 Section 3 discussed MHW properties at the regional scale. To provide more usable information for PICTs,
444 we now investigate statistics of past macroscale events that affected each EEZ separately. Figure 9 shows the
445 mean and standard deviation of the mean duration and mean maximum intensity in the 12 PICTs studied.
446 PICTs in the western and south-central part of the study region: Solomon Islands, New Caledonia, Vanuatu,
447 Fiji and Tonga appear to be more exposed to MHWs of higher duration (Fig. 9 a) but with a large variability
448 in MHW duration (Fig. 9 b). These PICTs are also exposed to higher maximum intensity events (Fig. 9 c)
449 with a higher standard deviation (Fig. 9 d) compared to other PICTs (Fig. 9), suggesting that the types of
450 MHWs to which they are exposed are more diverse in terms of features and possible drivers. Figure 10
451 illustrates the seasonal distribution of macroscale MHW properties (i.e. MHW duration, maximum intensity,
452 onset rate, decline rate and vertical extent) inside the EEZs of each of the 12 PICTs. These properties have
453 been chosen for their relevance for marine ecosystem management and to help guide adaptation planning
454 across the Pacific region. Maximum intensity and onset and decline rates (two MHW metrics describing how
455 quickly a MHW develops or dissipates) are of particular interest (Jessica Randall per. communication) as
456 these parameters allow managers to gauge the amount of time they would need to better prepare for MHWs,
457 and the potential severity of their impacts (Spillman et al., 2021; Jessica Randall per. communication).

458 Figure 10 confirms, at EEZ scales, and similar to the results presented in section 3, that in the hot season,
459 most of the macroscale events in all countries are of short duration. Half of the MHW events lasted < 10
460 days, 75% of the events were < 20 days (Fig. 10 a), and for most of the PICTs, 90% of the MHWs lasted <
461 30 days. However, there is some variability among the PICTs; 90% of the MHWs events affecting Tuvalu
462 were < 20 days, whereas 10% of the events affecting Vanuatu were > 50 days. (Fig. 10 a). In the cold season,
463 the MHW duration is more variable, and events can last much longer. This is especially true for PICTs within
464 subregion 1 (New Caledonia, and Vanuatu) which experienced 25% of events > 40 days and 10% of the
465 events lasting up to 4 to 5 months (Fig. 10 a). New Caledonia and Vanuatu also experienced the highest
466 maximum intensities compared to other PICTs, followed by Tonga and Fiji.

467

468 For PICTs located in the eastern part of the region, the median maximum intensities are between 0.25 to
469 0.5°C higher in the hot season than in the cold season, for example in American Samoa, Cook Islands, Niue,

470 Samoa, Tokelau and Tuvalu (Fig. 10 b). For PICTs located in the western side of the study region (Fiji, New
471 Caledonia, Solomon Islands, Tonga and Vanuatu), the maximum intensities are similar in hot and cold
472 seasons (Fig. 10 b). As shown also in section 3, for all PICTs, MHWs are much deeper in winter than in the
473 hot season, with 10% of the MHW events reaching depths more than $> 200\text{m}$ around Fiji and Tonga.

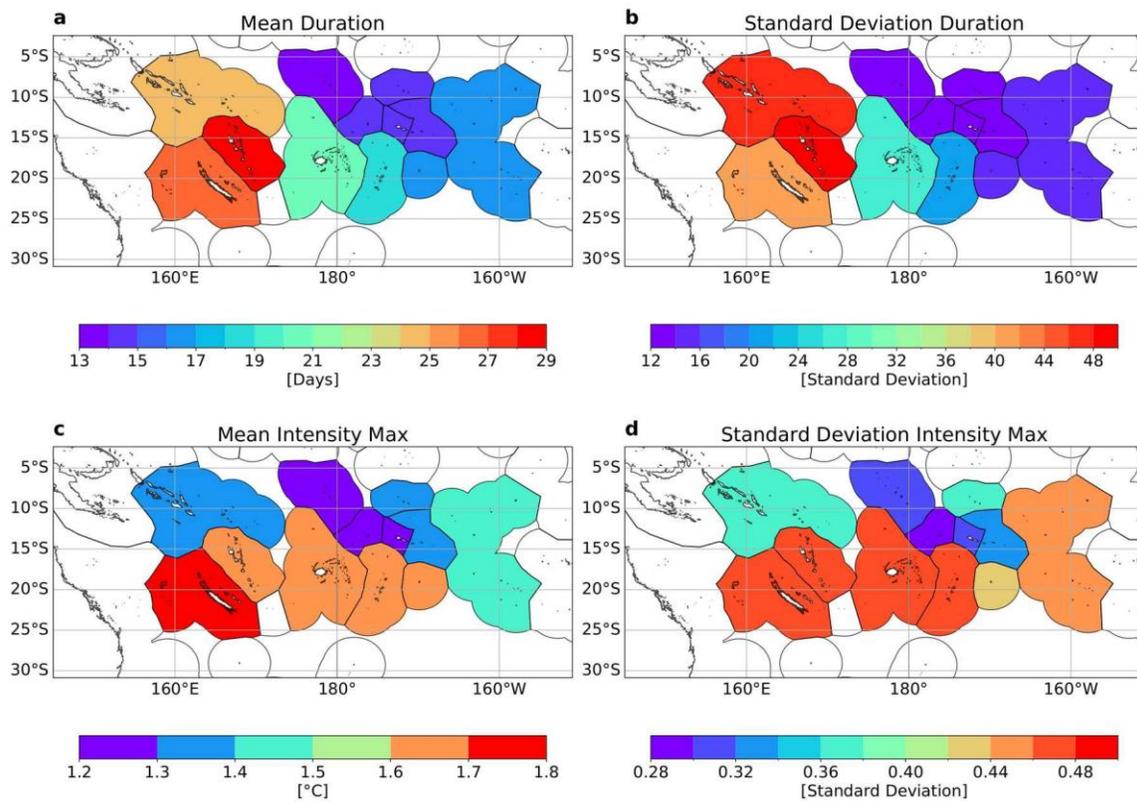
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475 Finally, the onset and decline rates are also shown. The faster the onset rate is, the quicker the MHW emerges,
476 and the shorter the reaction window for management responses is. The slower the decline rate is, the longer
477 it takes for the MHW to dissipate, and the slower heat is removed. Clearly, the onset rate is higher during the
478 hot season and lower in the cold season for all PICTs (Fig. 10 c, d). The median value is around $1.14\text{ }^{\circ}\text{C}/\text{day}$,
479 and 25% of all onset rates are $>+ 0.3\text{ }^{\circ}\text{C}/\text{day}$ (Fig. 10 c), which is consistent with the results of Spillman et al.
480 (2021), but in the medium to high range compared to other regions (compare the values shown here with
481 Figure 3 from Spillman et al. (2021)). This is true for all PICTs, especially for Niue and Tokelau. In these
482 PICTs, where MHWs are typically of short duration (Fig. 4 a), summer MHWs develop quickly, and marine
483 managers have little time to react. This also indicates rapid warming of the upper, shallow mixed layer (see
484 Fig. 6 e, f).

485 The pattern in the decline rate is similar to the onset rate. For all PICTs except Tuvalu, the decline rate is
486 larger in the hot season than in the cold season. This means that MHWs also dissipate more quickly in the
487 hot season, and prevent heat from stagnating.

488 The , we have found that Fiji, New Caledonia, Vanuatu and Tonga experience higher maximum intensity
489 events compared to other countries in the study region and longer lasting events, especially in the cold season,
490 with deeper vertical extent. In the hot season, all countries experience MHWs of similar duration (less than
491 25 days). These are short duration events but of maximum intensity comparable or slightly higher than cold
492 season (central and eastern Pacific countries). The results suggest that these cold-season, long-duration, high-
493 intensity events may or may not translate into ecological disturbances in the Solomon Islands, Fiji, New
494 Caledonia, Vanuatu, and Tonga, and therefore warrant continued monitoring.

495



496

497 **Figure 9 Mean and standard deviation of MHW duration a, b and mean maximum intensity c, d, inside**
498 **EEZs from Macroscale events. MHWs detected using NOAA-OISST from 1981-09 to 2023-06.**

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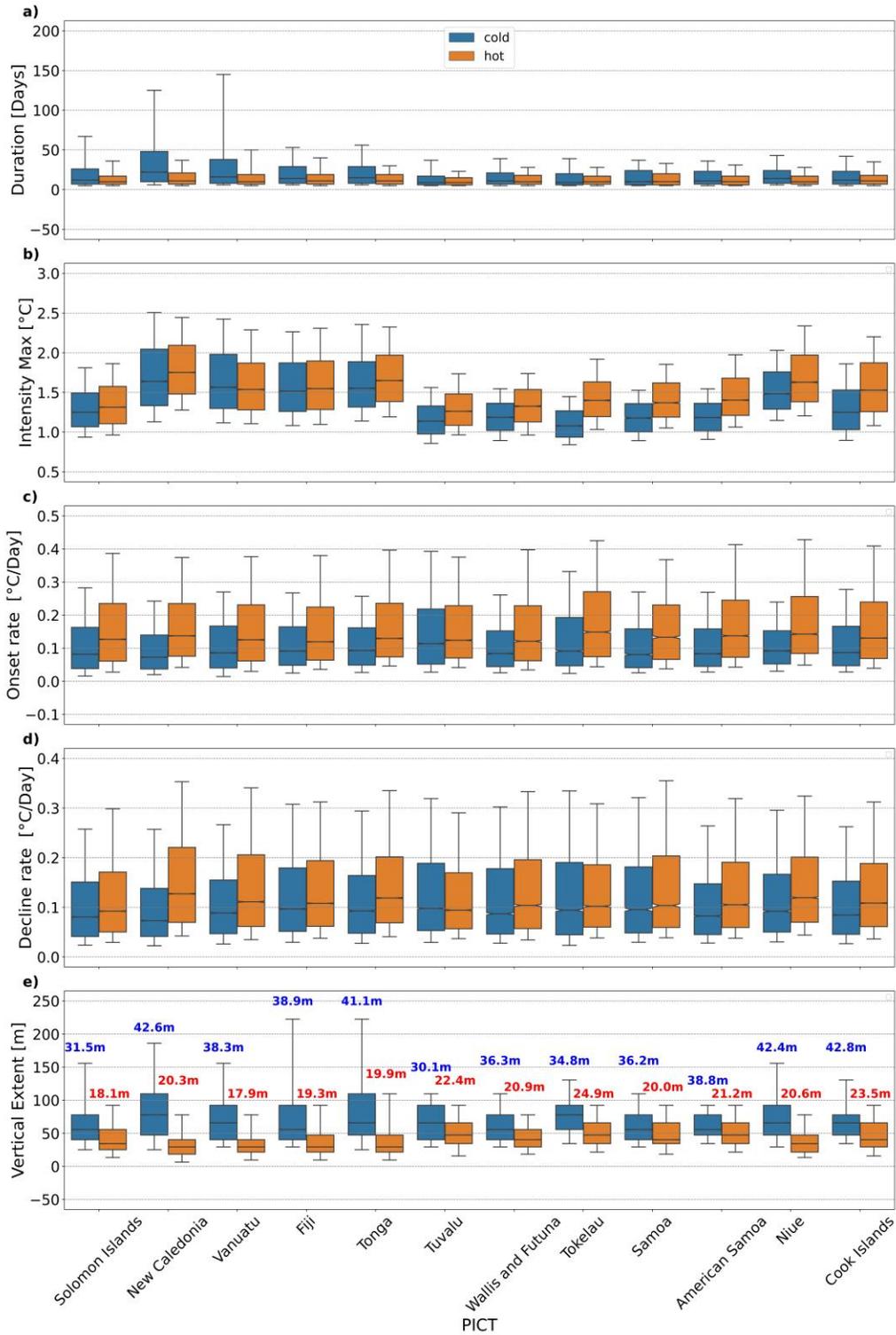
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508 **Figure 10** Box whisker plots showing MHW properties for macroscale events by Pacific Island Country and
509 Territory (PICT) and seasons a, Duration, b, Maximum Intensity, c, Onset rate, d, Decline rate and e, vertical
510 extent. The red and blue texts in e are the mean mixed layer depth (MLD) in hot and cold season respectively.
511 Lower edge of whisker marks 10th percentile, lower edge of box marks 25th percentile, the line in the middle
512 marks the median, the upper edge of the box marks 75th percentile and the upper edge of the whisker marks 90th
513 percentile. MHWs detected using NOAA-OISST from 1981-09 to 2023-06. MHW Vertical extents and mean Mixed
514 Layer Depth obtained from GLORYS12 for period 1993 to 2019.

515 Figure 11 also shows the time series of the percentage fraction of EEZ in a MHW state, for two examples,
516 New Caledonia and Fiji. This figure allows the identification of the main events that have impacted a large
517 portion of the territory of each PICT, in both seasons. Some events – for example between 1997–1999,
518 2010/11, 2015/16, 2020, and 2022, – covered more than 80% of the New Caledonia EEZ (Fig. 11 a). In the
519 hot season, the largest events occurred in 1993, 2002, 2004, 2009, 2015, 2016 and 2022. These events,
520 however, were short lived. In Fiji, the events of 2010, hot season events from 2014 to 2017, and the events
521 of 2022, were most striking (Fig. 11 c).

522

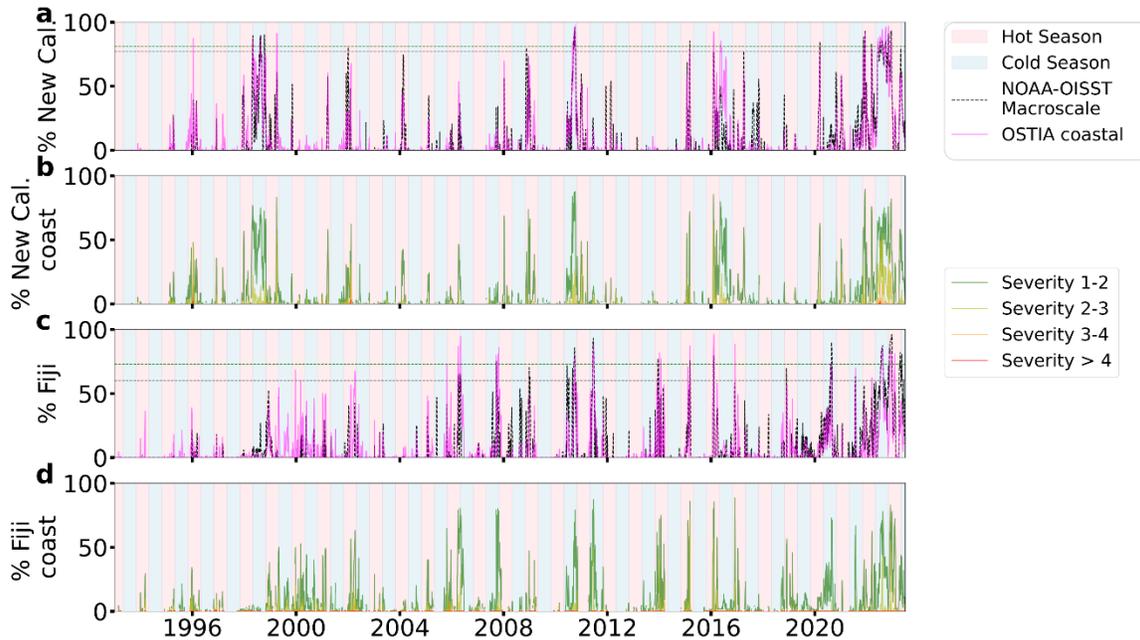
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524 **4.2 Coastal events: spatial structures**

525 We now investigate past MHW events around each country close to the coast, to provide answers to the
526 following questions: (1) are open ocean events observed at the coastal level too? (2) Which coastal areas
527 have been more impacted in the last decades? (3) Are there any refugia areas, less impacted by MHWs? (4)
528 Are coastal MHWs longer now or of stronger maximum intensity compared with the past, and if so, where?

529

530 To answer questions (2) and (3), Figure 12 and 13 show MHW properties around the coast of New Caledonia
531 and the Fijian archipelago, as examples, for both the cold and hot seasons using the OSTIA product, which
532 better resolves at the coastal scale. The same plots showing MHW properties at the coast, but using
533 GLORYS12, are also shown to estimate the robustness of the signals, and evaluate the ability of the
534 GLORYS12 reanalysis to detect MHWs near the coast. The Fiji and New Caledonia coastlines are used here
535 as examples because they provide interesting insights into the nature of MHWs along large coastline oceanic
536 islands. Their long coastlines offer diverse interactions between MHWs and local oceanographic conditions
537 allowing us to gain further insights into the nature of coastal MHW events. Coastal MHWs for Solomon
538 Islands, Vanuatu and Tonga are shown in Supplementary Figs. S1–S3. As shown in section 3, the small-
539 scale MHWs events detected can be quite different depending on the product, especially in the cold season.
540 Here, only the robust patterns shown in both products (OSTIA and GLORYS12) will be discussed.



541

542 **Figure 11 a,c, Time Series of % EEZ (in black dashed line) and % coastline (in magenta dashed line) in MHW**
 543 **state for New Caledonia and Fiji respectively. The horizontal green and gray dashed lines mark the 95 percentile**
 544 **of % EEZ covered by macroscale events and the 95 percentile of the % coastline in MHW state, respectively. b,**
 545 **Time Series of % coastline with 4 levels of severity for New Caledonia and Fiji respectively. Green line for**
 546 **severity 1 to 2, yellow for severity 2 to 3, orange for severity 3 to 4 and red for severity greater than 4. Coastal**
 547 **MHW and severity detected using OSTIA from 1993 to 2023, macroscale MHWs detected using NOAA-OISST**
 548 **from 1993 to 2023. In all panels a - d, the alternating pink and blue background colours represent the hot and**
 549 **cold season respectively.**

550

551 As expected, the absolute number of MHW days at the coast are different among the two products, with
 552 GLORYS12 showing higher number of MHW days (approx. 2 more days) in the cold season around New
 553 Caledonia's reef and higher mean duration (upto 10 days) (compare a to g and b and e to h and k in Fig. 12).
 554 These findings (more MHWs days of longer duration in GLORYS12 compared to OSTIA) are consistent
 555 with the conclusions from Chevillard et al. (submitted) that compared SST products, and can be explained
 556 by a larger variance of the high frequency SST signal (from 2 to 15 days) in OSTIA, compared to a smoother
 557 GLORYS12 product. In both products, significant contrasts between the various islands exist. The eastern
 558 coast of New Caledonia's main island, Grande Terre, experiences generally longer but less intense MHWs
 559 than the western coast, both in the hot and cold seasons. MHWs there are longer in the cold season, lasting >
 560 25-30 days on average (Fig. 12 b, e, h, k). The southwest coast of Grande Terre is exposed to short (< 15
 561 days), but very intense (+2.5°C of maximum intensity) MHWs in the hot season (Fig. 12 b, c, e, f). In these
 562 areas, southeasterly trade winds along the coast favour occasional coastal upwelling events bringing colder
 563 waters to the surface, whose signature in SST is modulated by the seasonal stratification (Alory et al., 2006;

564 Marchesiello et al. (2010)). The MHW occurrence might be related to occasional cessation of upwelling
565 explaining the short time scales of these events and the high amplitude in a region with usually much colder
566 (upwelling) conditions; this deserves more investigation.

567

568 The northeastern part of the New Caledonian archipelago, equatorward of 19.5°S, comprising the north coast
569 of Grande Terre, the northern part of the Chesterfield Islands, and Entrecasteaux reefs, seem to be less exposed
570 to MHWs than the rest of New Caledonia, with less MHWs days, both in the cold and hot seasons, with small
571 maximum intensities (around +1.2-1.5°C). The southern part of the Chesterfields Islands is more exposed,
572 with more MHW days, of longer duration in the cold season, but of moderate maximum intensity (+1.6°C in
573 the hot season, +1.4°C in the cold season).

574 Figure 13 presents MHW properties around coastal Fiji. Coastal Fiji experiences between 11 and 18 MHW
575 days per year, with certain parts of the Yasawas, parts of the Lau group and Kadavu having higher values in
576 the hot season compared to the cold season (Fig. 13 a, d). The opposite is true for GLORYS, where the
577 number of MHW days is generally higher in the cold season compared to the hot season. Generally, the mean
578 MHW duration around coastal Fiji is similar everywhere. In the hot season it is between 12 and 15 days and
579 between 12 and 20 days in the cold season (Fig. 13 b, e, h, k). These values are much shorter than what is
580 experienced along coastal New Caledonia. The patterns in mean maximum intensity are quite similar between
581 the hot and cold seasons in coastal Fiji (between +0.8 to +1.6°C, Fig. 13, c, f, i, l), with the southern part of
582 the country experiencing more intense MHWs in both the hot and cold seasons.

583

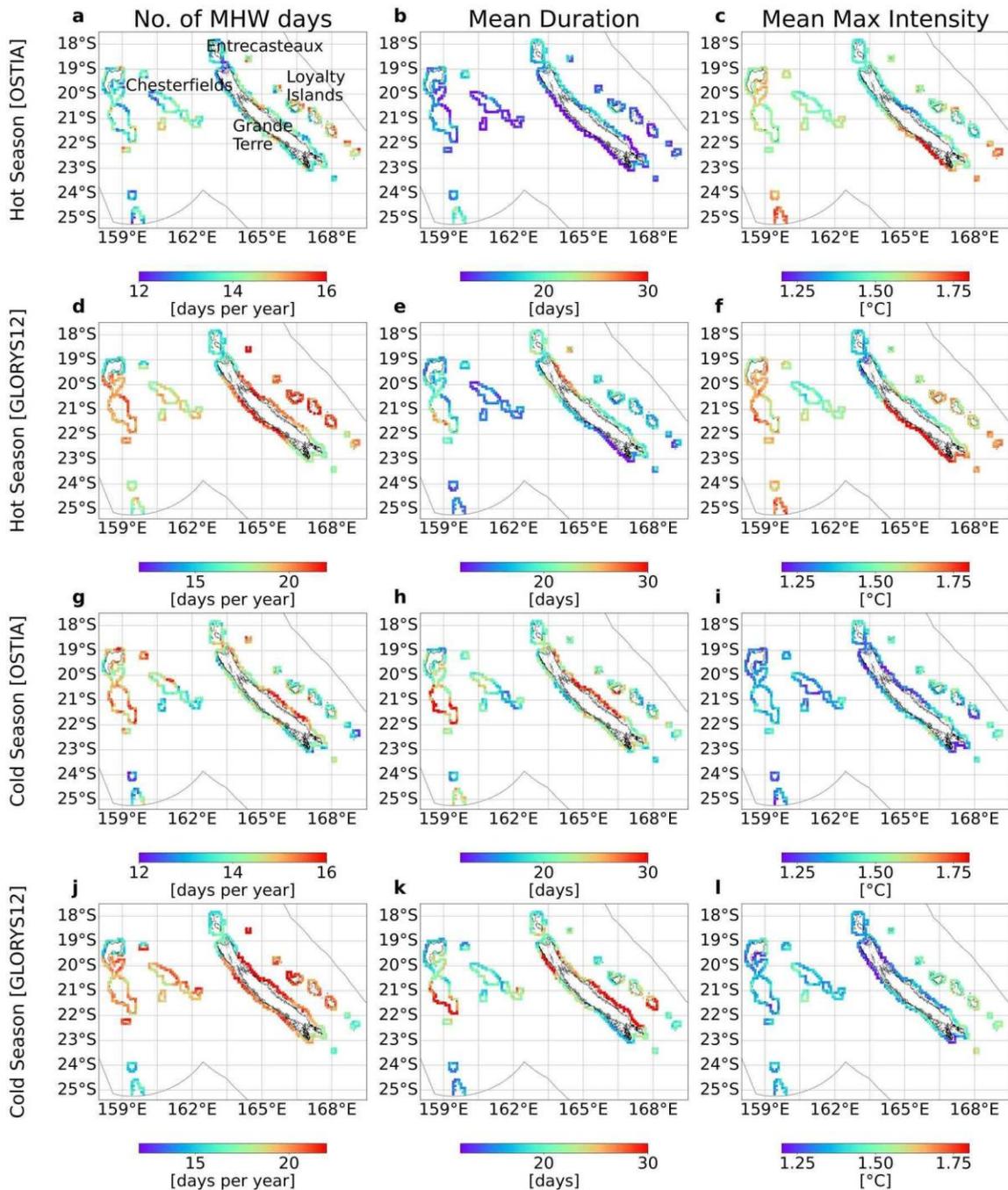
584 To answer question (4), Figure 14 shows locations with significant trends in annual number of MHW days
585 around coastal New Caledonia and Fiji for the OSTIA product. Similar trends are found with GLORYS12
586 (not shown). Significant trends in annual number of MHW days were observed around most of the coastlines
587 of the PICTs studied (Fiji, Fig. 14 b and Solomon Islands, Vanuatu and Tonga in Fig. S4; other PICTs not
588 shown). In New Caledonia, the only significant trends in MHWs days are found north of 20°S, especially
589 along the northeast coast of Grande Terre, which has significant positive trends of around 23 days of MHWs
590 per decade (Fig. 14 a), 1.5 times the typical number of current annual MHW days (approx. 14 MHW days
591 per year averaging over the seasons, Fig. 12 a, d). The trends in maximum intensity and other MHW
592 parameters were not significant around most parts of New Caledonia (not shown). In Fiji, most of the
593 coastline shows a significant increasing trend of around 8 to 15 MHW days per decade (Fig. 14 b). However,
594 the southern coast of Viti Levu, all the way from coastal Suva to Lautoka and Rotuma, exhibits a stronger

595 positive trends in annual number of MHW days (between 18 and 20 days per decade) (Fig. 14 b), about 1.3
596 times the typical number of MHW days per year (approx. 15 days per year from Fig. 13 a, d).

597

598 Are open ocean marine heatwaves also observed at the coast? To answer this question (1), Figure 11 shows
599 the percentage of the coastline (dashed line in magenta) in MHW state for New Caledonia and Fiji,
600 superimposed on the percentage of each EEZ (dashed line in black) in MHW state. The green and black
601 horizontal dashed lines indicate the 95 percentile of the percent of EEZ covered by macroscale events and
602 percent of coastline in experiencing MHW events respectively. For the period between 1993 and 2023, most
603 of the MHWs with large EEZ spatial coverage were observed along large parts of the coastline as well (Fig.
604 11 a, c). In New Caledonia, 77% of days with large macroscale events (greater than 80% of the EEZ,
605 corresponding to the 95 percentile) also experienced coastal events of large spatial extents (71% of the
606 coastlines, corresponding to the 95 percentile). 53% of MHW events that affected a large part of the
607 coastlines, remained uniquely coastal, that is, not occurring together with large macroscale events in the EEZ
608 (Fig. 11 a). Coastal MHWs with large spatial extents are more prevalent than large macroscale events in New
609 Caledonia EEZ. A similar pattern was observed in Fiji. Sixty eight percent of large macroscale events in Fiji
610 EEZ coincided with a large part of the coastline being in a MHW state as well, with 60% of large-scale
611 coastal events (greater than 60% of the coastlines, corresponding to the 95th percentile) not detected as
612 macroscale events in the EEZ (Fig. 11 c). The events of 1997-1999, 2010/11 and 2022, affected large parts
613 of the EEZ and the coastline in both New Caledonia and Fiji. While the events seem to peak in the hot season,
614 some large scale events extend across several seasons (including the cold season), for example, the 1997-
615 1999 and 2022 events in New Caledonia and the 2022 event in Fiji. The severity of coastal MHW events are
616 usually between 1 and 3 (Fig. 11 b, d) which corresponds to Moderate to Strong events according to naming
617 criteria established by Hobday et al. (2018). While it is known that high severity index events in the hot
618 season may have detrimental effects on coastal ecosystems, for example fish kills in coastal Fiji in February
619 2016 noted in H22 (high percentage of high severity events in the 2016 hot season around Fiji, Fig. 11 d), it
620 is uncertain if high severity index events in the cold season detrimentally affected coastal ecosystems as no
621 bleaching events were observed along coastal New Caledonia in the cold season of 2022, despite the severity
622 index being higher than usual around that time (Fig. 11 b).

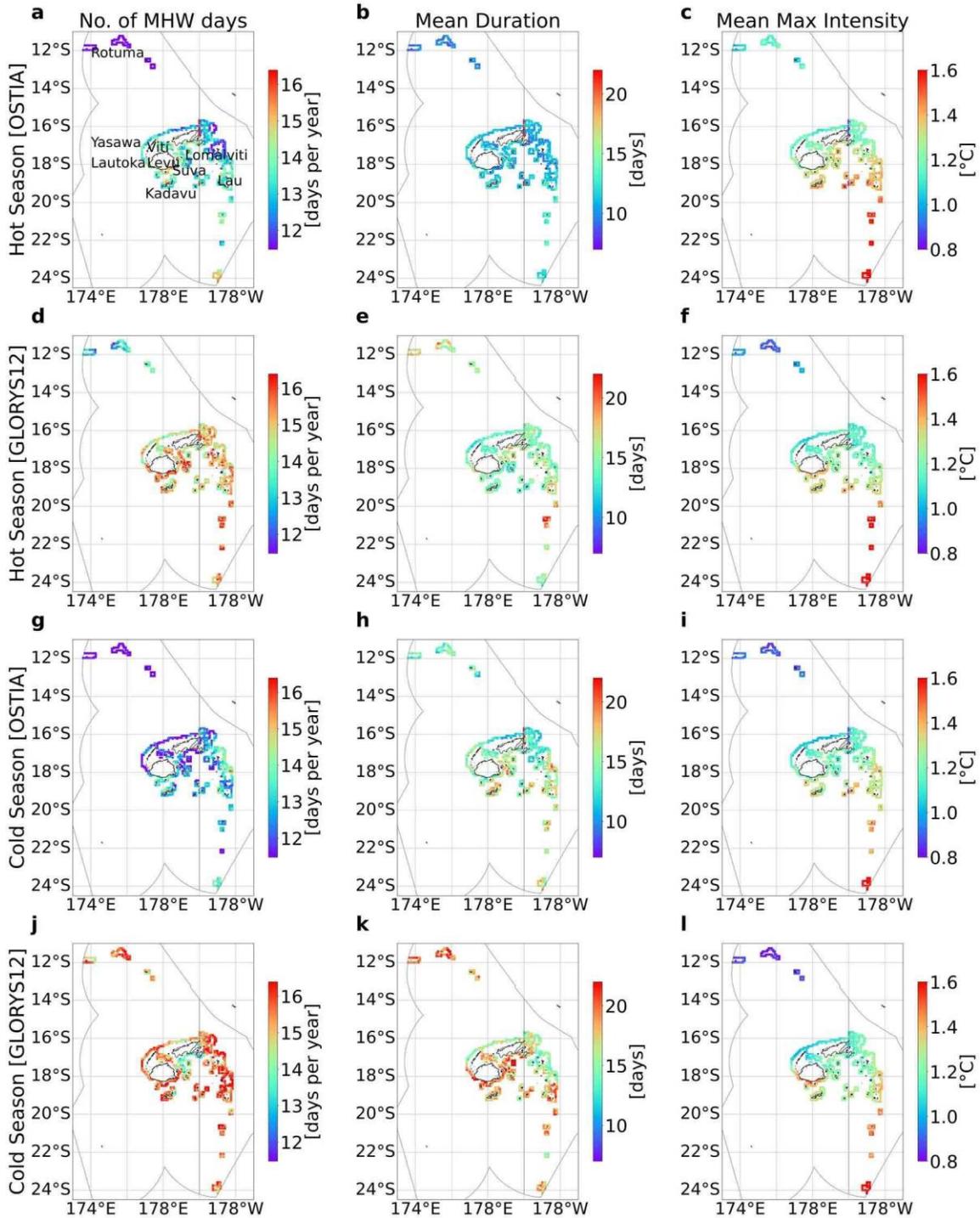
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624

625 **Figure 12 Total number of MHW days, mean Duration and mean Maximum Intensity in coastal New**
 626 **Caledonia: a,b,c in OSTIA and d,e,f in GLORYS12, hot season; g,h,i in OSTIA and j,k,l in GLOSYS12,**
 627 **cold season. The colorbar in a,g have been adjusted to reflect the spatial variability in the number of**
 628 **MHW days in OSTIA's hot and cold season for New Caledonia coastline.**

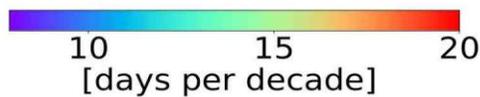
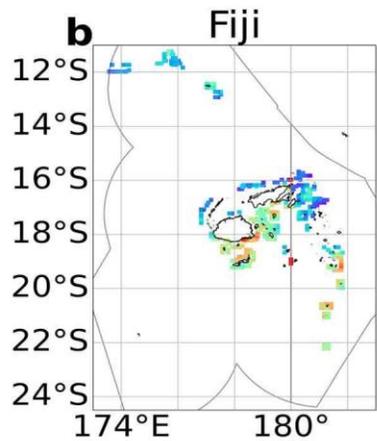
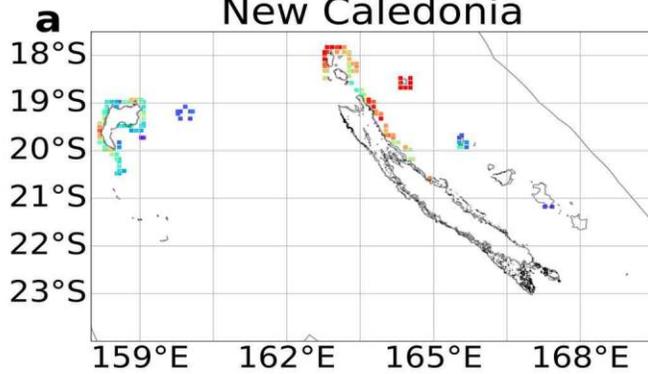
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630

631 **Figure 13** Total number of MHW days, mean Duration and mean maximum intensity in coastal Fiji ,
 632 a, b, c, in OSTIA , d,e,f, in GLORYS12 in hot season and g,h,i in OSTIA, j,k,l, in GLORYS12 in cold
 633 season. MHWs detected using OSTIA and GLORYS12 from 1993-01 to 2023-10.

Total annual MHW days trend per decade
New Caledonia



634

635 **Figure 14 Significant trends in annual number of coastal MHW days in New Caledonia, a and coastal**
636 **Fiji, b. MHWs detected using OSTIA from 1993 to 2022.**

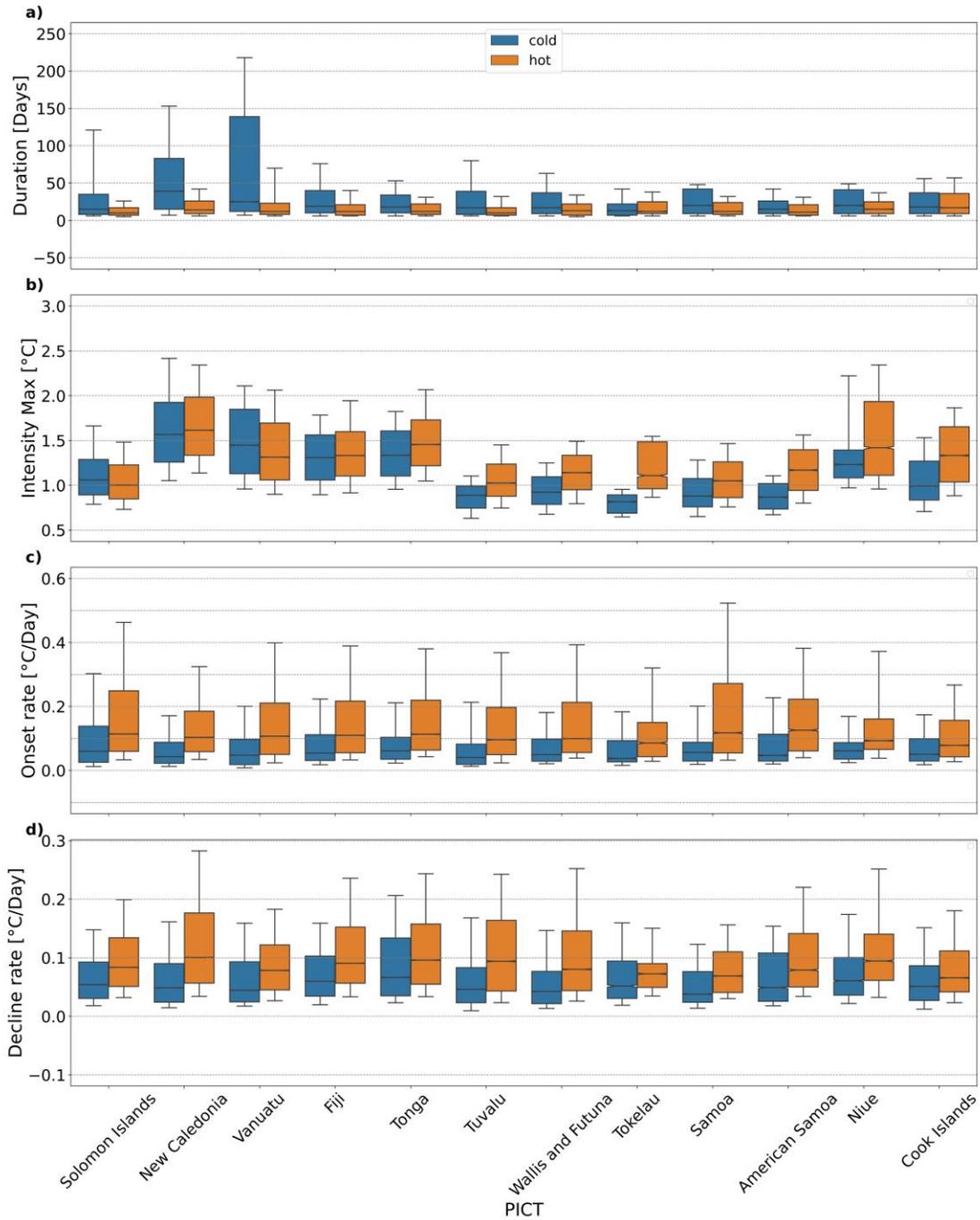
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638 **4.3 Coastal events: statistics for each country**

639

640 Figure 15 shows the seasonal distribution of coastal MHW properties (MHW duration, maximum intensity,
641 onset and decline rates) in the 12 PICTs studied in the form of box whisker plots for OSTIA. The duration

642 of MHWs can be much longer for coastal events compared to macroscale events. In the cold season, 75% of
643 the events have MHW durations of up to or longer than 80 days in New Caledonia, and Vanuatu (Fig. 15 a),
644 compared to up to 40 days during macroscale events (Fig. 10 a). The patterns and values in maximum
645 intensity are similar for coastal and macroscale events for all the 12 PICTs. The median maximum intensities
646 are typically higher in the hot season for all countries except Fiji, New Caledonia, Solomon Islands, Tonga
647 and Vanuatu, where the difference between the seasons is small or there are higher maximum intensities in
648 the cold season (Fig. 15 b). The statistical distribution of MHWs durations can display much longer MHWs
649 for coastal events (Figure 15) compared to macroscale events in the EEZ (Figure 10). In the cold season,
650 75% of the events (summed over the whole time period, and over all coastal points) have MHW durations of
651 up to or longer than 80 days in New Caledonia, and Vanuatu (Fig. 15 a), compared to up to 40 days during
652 macroscale events (Fig. 10 a). This is especially striking for Vanuatu, which is exposed along its coasts to
653 long duration MHWs. This is explained by the occurrence of long macroscale MHWs during winters of La
654 Nina years (not shown), that encompass all the coasts of Vanuatu Archipelago, but not its whole EEZ. The
655 onset and decline rates are smaller in value for the coastal events (Fig. 15 c, d) compared to macroscale events
656 (Fig. 10 c, d). This suggests that these PICTs could have a longer time to prepare (that is, the reaction window
657 is longer) for coastal MHWs compared to macroscale events. The slower onset and decline rates in coastal
658 MHWs could also be the reason why they have longer durations compared to macroscale events.



659

660 **Figure 15** Box whisker plots showing MHW properties for coastal events by Pacific Island Country
 661 and Territory (PICT) and seasons a, Duration, b, Maximum Intensity, c, Onset rate and d, Decline
 662 rate. Lower edge of whisker marks 10th percentile, lower edge of box marks 25th percentile, the line
 663 in the middle marks the median, the upper edge of the box marks 75th percentile and the upper edge
 664 of the whisker marks 90th percentile. MHWs detected using OSTIA from 1993-01 to 2023-10.

665 **5 Discussion**

666 In this paper, we investigated the characteristics of past MHWs in the Southwest Pacific. One novelty of this
667 work is that we revisited the past MHWs statistics by distinguishing between macroscale and microscale
668 events, and among hot and cold seasons. We also described the statistics of past MHWs for each PICT. For
669 each EEZ, we provided information on their vertical extent and on their signatures at the coast. This provides
670 important elements that allow both (i) a better understanding of the physical processes that generate MHWs,
671 and (ii) a better anticipation of their impacts on ecosystems.

672

673 **5.1 What does this paper tell us about possible physical drivers?**

674 We showed that the characteristics of past MHWs (duration, maximum intensity, and vertical extent) depend
675 on their size, and on the subregion considered. We now discuss what this can tell us in terms of the physical
676 processes driving the MHWs, and what governs these processes, for the five subregions identified. The spatial
677 extent of the MHW provides clues about its drivers: a large-scale event is likely driven by a large-scale
678 climate mode (e.g. Dutheil et al., 2024), while a small-scale event is more likely driven by a local advection
679 or atmospheric forcing process. While still in its infancy, the exploration of MHW vertical extent also
680 provides some interesting information on the MHW dynamics: shallow MHWs are more likely to be
681 generated by mixed layer depth dynamics, and deep MHWs by advection, or downwelling linked to planetary
682 waves or anticyclonic eddies. Recent work has led to the classification of the types of MHW events that can
683 occur in the vertical dimension (i.e. shallow, subsurface reversed/intensified, deep/extended events)
684 (Schaeffer et al., 2023; Zhang et al., 2023), characterisation based on surface features (e.g. block-like,
685 deepening, shoaling, multi-surfacing) (Köhn et al., 2024), as well as exploration of the mechanisms
686 underpinning such events (Elzahaby et al., 2021).

687 Previous studies investigating the physical processes and drivers generating MHWs have found ENSO to be
688 one of the important modulators of MHW activity (in terms of extent, duration and maximum intensity) in
689 this area (Sen Gupta et al., 2020). While El Nino has been found to enhance MHW occurrence in the central
690 Pacific region, it tends to suppress MHW occurrence in the western Pacific in a chevron shaped region
691 extending towards the east (opposite is true during La Nina) (Holbrook et al., 2019).

692 Some of our results are consistent with this view, but many other processes can generate MHWs. In subregion
693 3, the “Equatorial central region”, our results indeed showed that the MHWs detected are deep, of large scale
694 and long duration, and occur during El Nino events. MHW characteristics there are consistent with the
695 deepening of the thermocline in the region during the development of El Nino events. On the contrary, in

696 subregion 1, in the “South-SPCZ region”, MHWs exhibit a diversity of characteristics. Some of the large-
697 scale and long duration MHW, mostly occurring in winter, are related to La Nina years (not shown). Yet,
698 several other MHWs in the area occurring in summer are of shorter duration, are shallow and can occur
699 throughout the years independently of the ENSO phase. One of the most extensive MHW ever recorded in
700 the southwest tropical Pacific region occurred in February 2016, during El Nino (Dutheil et al., 2024) where
701 the El Nino was expected to induce cooler temperatures on average. That MHW event has been explained by
702 exceptionally clear skies and light winds allowing strong surface heating in response linked to the combined
703 effects of an El Nino and an MJO event (Dutheil et al. , 2024). More studies will be required to characterise
704 the various processes driving other MHW events, but our analyses suggest that mixed layer dynamics and
705 large-scale atmospheric forcing events are important factors.

706

707 On the contrary, in subregion 4 (the “Southeastern Australia eddy region”) , where it has been shown that
708 eddies are ubiquitous, most of MHWs detected are of small scale and short duration, and extend very deep.
709 As suggested by previous studies, MHWs in this subregion are often associated with mesoscale eddies (Bian
710 et al., 2023) and driven by advection (Zhang et al., 2023); surface heat flux driven MHWs (shallow to ~20
711 m or so) are also observed (Li et al., 2020; Gregory et al., 2024). In addition to mesoscale eddies, oceanic
712 downwelling Rossby waves, and downwelling-favourable winds are also MHW drivers near the Australian
713 coast (Li et al., 2023; Misra et al., 2021; Schaeffer & Roughan, 2017).

714 Finally, in subregion 5, the “subtropical region”, MHWs properties are a mix between subregion 1 and
715 subregion 4. In this area, the oceanic circulation is quite complex, with a zonally and vertically sheared
716 current system comprising the westward South Caledonian Jet in subsurface, the eastward Subtropical
717 Counter Current and EAC eastern extension. Mesoscale eddies are also ubiquitous (Keppler et al., 2018). It
718 is probable that MHWs are of mixed generation processes, with large-scale atmospheric forcing contributing
719 to large-scale, shallow events, and mesoscale eddies superimposed contributing to smaller scale events, with
720 much deeper extents, as also suggested by Bian et al. (2023). Investigating the oceanic heat budget to
721 understand the physical processes at play for the main MHWs events, in the different regions, will help to
722 better understand the various MHW types and will be done in a forthcoming study.

723

724 **5.2 What do our results on the different characteristics of MHW imply for ecosystem vulnerability?**

725 Distinguishing between macro and micro-scale MHWs events, and providing information on their vertical
726 extent, their seasonality and their signatures at the coast are also important outcomes from an ecosystem point
727 of view, both for open-ocean ecosystems and coastal ecosystems.

728 In the open ocean, highly mobile pelagic fishes like tunas are likely not affected in the same way by small-
729 scale and large-scale events covering a few, versus hundreds or thousands of square kilometres, respectively.
730 While tunas' mobility means that they can easily escape from the former, it is conceivable that such species
731 may sometimes be exposed to sub-optimal environmental conditions for extended periods during larger scale
732 events, necessitating long-range distributional shifts to more favourable areas (Bond et al. 2015; Walker et
733 al., 2020). Moreover, the consequences for affected individuals' physiology, feeding, growth and
734 reproductive success as well as overall fishery productivity can be substantial (e.g. Mills et al. 2013), yet
735 often remain uncertain, and hence unaccounted for in fisheries management (Jacox et al. 2020).

736 The PICTs located in subregion 1 – Papua New Guinea, Solomon Islands, New Caledonia, Fiji and Vanuatu
737 – each supporting commercially-important tuna fisheries and dependent economies (Vidal et al., 2024), have
738 all been exposed to macroscale MHWs over the past 40 years, affecting a large portion of their EEZ in both
739 cold and hot seasons. In the other PICTs, MHWs are generally of smaller size, potentially limiting the local
740 impact of MHWs on pelagic species like tunas; however, the cumulative impact of increasing regional MHW
741 maximum intensity, duration and time spent in MHW state on pelagic and coastal fisheries resources remains
742 unknown.

743 Dutheil et al. (2024) have shown that the 2016 MHW near New Caledonia deeply impacted surface
744 chlorophyll also and it is hence likely that during these events, all trophic levels will be impacted in addition
745 to oxygen and nutrients. Further research will have to investigate how these effects can combine to impact
746 the trophic web.

747 The vertical extent of MHWs is also important for predicting ecosystem vulnerability. The extension of warm
748 waters deeper is likely to affect both the fish species but also the fisheries. As an example, pelagic fishes like
749 bigeye tuna (*Thunnus obesus*), yellowfin tuna (*T. albacares*) and albacore tuna (*T. alalunga*) regularly move
750 vertically through the water column to track prey resources and/or meet oxygen demands (Briand et al. 2011;
751 Arrizabalaga et al. 2015; Nikolic et al. 2017). Data from tagging studies and fishery catch records both
752 demonstrate these species' propensity to dive to depths of several hundred metres (Williams et al. 2015;
753 Schaefer et al. 2011; Forget et al. 2015; Abascal et al. 2018; Scutt Phillips et al. 2019), thereby traversing
754 habitats likely to be severely affected by MHWs at-depth, such as those associated with the El Nino –
755 Southern Oscillation (ENSO) (Lehodey et al., 2020). Our results show that in the hot season, the majority of

756 macroscale MHWs are shallower than 50m depth; 90% of them are shallower than 100m for all PICTs. One
757 exception concerns the central equatorial Pacific, where pelagic species may be more impacted. In winter,
758 MHWs can extend deeper, especially around Solomon Islands, New Caledonia, Vanuatu, Fiji and Tonga. For
759 these PICTs, which are exposed to large-scale events, potential impacts on pelagic species are more likely.

760 The modification of the species habitat in the vertical also impacts species vulnerability to fisheries as they
761 may, for example and depending on the species, be able to escape (or inversely) the fishing gears more easily
762 in an extended (or reduced) favourable habitat. These considerations of modified fishing pressure versus fish
763 responses to MHW will have to be considered when estimating the impacts of MHWs on commercial fish.

764 For coastal ecosystems, the important thing is to know which MHW have formed at the coast. Some MHWs
765 can indeed affect a large part of an EEZ, but without forming at the coast, and therefore without any
766 significant impact on reef ecosystems, coastal fisheries or coastal resource management. Here, we have
767 provided information on past MHWs for each PICTs coast to help establish a link between observed and
768 reported impacts on coastal ecosystems (such as coral bleaching and mass mortality events), and to identify
769 key coastal MHW characteristics. For these ecosystems, already close to the thermal tolerance threshold,
770 summer MHWs may be particularly threatening, yet the consequences of such events remain highly
771 uncertain. A logical next next step is to work more closely with ecologists and coastal managers to
772 understand the impacts on, and to define relevant MHW indices and thresholds for coastal ecosystems across
773 the region. Such information could theoretically inform a risk assessment framework for coastal ecosystems
774 and guide country-led adaptation planning (e.g. Woods et al., 2022).

775

776 **5.3 Dependence of our results on the product and methodology**

777 In this paper, we used three different sea surface temperature products for the analyses (NOAA-OISST,
778 GLORYS12 and OSTIA). The choice of these three products was made either because they are widely used
779 (eg. NOAA-OISST), because they have a good spatial resolution at the coast (OSTIA) or because they
780 provide the subsurface structure and vertical extent (GLORYS). This choice has also been motivated by the
781 fact that these three products have a Near Real Time mode or are used in forecast mode (for GLORYS): as
782 such, they are used for warning systems for stakeholders and scientists. As shown by others (and illustrated
783 in Appendix 1), the MHWs detection method is highly sensitive to the product used. One of our important
784 results is that this sensitivity on SST products lessens when considering macroscale events: the confidence
785 in the results obtained for macroscale is thus higher. On the contrary, for coastal events, the results greatly
786 depend on the product used (see also Marin et al. 2021).

787 We briefly showed that different products and methods can result in different output in terms of MHW
788 characteristics. Here however, we only considered 2 SST products of different nature to illustrate the range
789 of uncertainties. We concentrated on identifying and discussing features that were robust across these 2
790 products. However, a recent paper (Chevillard et al., submitted to ocean science) specifically focussed on
791 quantifying the differences between different SST products and associated uncertainties in MHW metrics. In
792 that work, they systematically analyse MHW parameters across four gridded SST products, a reanalysis
793 product and an ensemble mean. The conclusions are that the dispersion among SST products can be very
794 high, especially for some metrics such as the onset and decline rates. Their recommendation is that MHW
795 studies should account for the uncertainty associated with SST product choice when reporting MHW metric
796 estimates. When feasible, the use of several SST datasets can substantially increase the robustness of the
797 results, by defining upper and lower bounds of metric estimates.

798

799 We also examined the MHWs long-term trends in the southwest Pacific, and showed that all 12 PICTs
800 experienced MHWs in the past 30 years and that these events are getting more frequent with greater spatial
801 extents, longer durations, but with lower maximum intensity. Moreover, the percentage of surface area of the
802 study region in a MHW state exhibits a significant increasing trend (Fig. 8). Over the past decade, there has
803 not been a single day when at least part of the region was not exposed to a MHW.

804 These results are essentially due to the choice of our fixed baseline (1993-2019), that is, the period of time
805 we used as a reference to compute the “normal” seasonal cycle. They are also due to the fact that we did not
806 remove any long-term trend in the temperature fields before applying the MHW detection method, as shown
807 by the comparison with results obtained when we first remove a long-term warming trend from the SST data.
808 As discussed by several others (see Amaya et al. 2023 for a comment), the choice of baseline matters, and
809 can modify the results significantly. We chose the fixed 1993-2019 baseline in order to capture total heat
810 exposure, encompassing both temporary extreme heat events and long-term trends. To characterise MHWs
811 in a future climate, both approaches (fixed baseline and shifting baseline) will be necessary. This will allow
812 managers to better anticipate the potential MHW impacts on species which will adapt quickly to a slow
813 temperature increase but will still be vulnerable to heat extremes, and those who are sensitive to absolute
814 thresholds (see Amaya et al., 2023).

815

816 **5.4 Responding to MHW threats**

817 Better knowledge of past MHW characteristics around each country allows us to relate past bleaching or
818 mass mortality events observed by the local populations to historical MHWs, or to other external

819 disturbances. It also helps to predict the types of MHWs that will occur in the future and their probability of
820 occurrence. By revealing which coastal areas experienced more MHWs, in which season, our results inform
821 the countries on the relative vulnerability of certain areas and ecosystems (e.g. those more susceptible to
822 coral bleaching, mass mortality of sessile marine species or thermal stress on resident, site-attached fishes).
823 For the macroscale events, our data on MHW vertical extent, and the percentage of the EEZ affected by
824 MHWs can help to better assess MHWs impacts on mobile pelagic fishes.

825 Here, we have provided detailed spatial maps of past MHW characteristics (number of MHW days, mean
826 duration, mean maximum intensity, Fig. 12, 13) along the coastlines of Fiji, New Caledonia and Tonga,
827 Solomon Islands and Vanuatu in Supplementary, indicative of potentially sensitive areas to ecological
828 impacts of MHWs. This is of strong interest to stakeholders in these PICTS as it points out to the fact that
829 not all coastal areas may be subjected to the same MHW maximum intensity impacts.

830 We also show the regions where significant climate trends in MHW characteristics arise (Fig. 14, Fig. S4)
831 pointing out also to regions of higher vulnerabilities to climate change when considering future management
832 of coastal ecosystems. Not all regions are affected similarly and such information is useful when prioritizing
833 areas for MHW impact management in the present and future climates.

834 In the context of Pacific Island communities, marine management would involve several stakeholders; the
835 local communities who claim rights and ownership over particular reef areas, resource users, local
836 government authorities, national government institutions, nongovernmental organisations and funding
837 bodies. Any species or area management plan therefore requires engagement of multiple stakeholders who
838 hold interests in that species or area. Unless it is certain that MHWs affect a species or resource, the
839 motivation to include MHW information for resource management may not be a priority. For many species,
840 the impact of MHWs may not be easily identified because of coarse resolution of temperature products used
841 in MHW detection, the definition of MHWs not being sensitive enough to capture MHWs and MHW
842 properties which are ecologically relevant or species and area showing resilience and no visible symptoms
843 of thermal stress. Without knowing which species are affected or what areas are affected and how, effective
844 conservation, management plans can't be made.

845 The results presented in this paper can help local authorities to conduct outreach and consultation with
846 stakeholders of reef areas that are showing a positive trend in MHW maximum intensity and MHW duration.
847 Citizen science initiatives can greatly help in surveillance of sensitive reef areas. As the concept of MHWs
848 is relatively new, having only been formally defined in 2016, many stakeholders may not yet be familiar with
849 it. Nonetheless, they may recall historical ecological impacts in vulnerable reef areas based on their lived
850 experiences, which need to be documented and compared with MHW event timelines from SST products.
851 These observations can help identify species that are prone to experiencing thermal stress so that conservation

852 plans can be made to understand and manage them better for greater reef resilience. Once the vulnerable
853 species and the nature of MHWs affecting them are identified, MHW forecast systems can be developed to
854 help inform local communities and resource users of forthcoming events, so that they can plan their fishing
855 effort and economic activities to offset the negative impact a MHW may bring.

856 In terms of early-warning systems to forecast the occurrence of MHW, products are increasingly being made
857 available to aid resource managers prepare for their occurrence (e.g. BoM-CSIRO Marine Heatwave Seasonal
858 Prediction Project by CSIRO and Bureau of meteorology, Coral reef watch made by NOAA, other forecast
859 products developed by Copernicus). They inform local communities and resource users of forthcoming
860 events, so that they can plan their fishing effort and economic activities to offset the negative impact a MHW
861 may bring. These tools typically track the formation and movement of pools and fronts of warm-water to
862 forecast out to 3-months. However, the ecological impact of forecasted MHWs may not be easily identified
863 because of coarse resolution of temperature products used in MHW detection. The mean, standard deviation
864 and trend values summarise the nature of the event but they do not imply ecological impact. Our results show
865 that the extent, maximum intensity and timing of MHW in the Pacific region can be more nuanced than just
866 the presence of warm-water. We expect that as these forecasting tools mature they will include greater clarity
867 on the expected impact of forecasted MHW (particularly as the forecast window shortens). Our results
868 identify additional parameters that can be used to build forecast systems with increased information of the
869 expected impact of MHW events.

870 When communities and stakeholders are prepared, the negative impacts of stressors can be lessened, or
871 sometimes mitigated (Woods et al., 2022). Hobday et al. (2023) proposed a table of action, which can be
872 used by researchers, industry, managers, policy makers and governments, to respond to potential MHW
873 arrival in several stages. The first step to take before any action plan is to assess the risk, revisiting past MHW
874 statistics for regions of interest, and determining, in particular, the reaction window. This is exactly what we
875 did here. Our findings indicate that the rate of onset of MHWs in summer, for all countries, is in the upper
876 range of the values observed at the global scale (Fig. 3 in Spillman et al. (2021)): MHWs develop quickly,
877 and the preparation window for countries is rather short. This preparation window is longer for coastal events,
878 and for winter MHWs. Marine managers should be prepared for rapid responses based on warning bulletins,
879 as MHWs develop and evolve.

880 The next steps will be to work closely with ecologists and anthropologists to identify the vulnerable species,
881 populations and ecosystems, and to define threshold limits and bio-cultural indicators to better assess the
882 risk. In the interdisciplinary project that supported this study, MaHeWa (<https://mahewa.fr>), we work closely
883 with biologists and anthropologists to produce adapted indices of MHWs impacts for Pacific Island countries,

884 useful for marine managers. Through the work presented in this paper, and these next steps, we hope to help
885 PICTs and their communities to become prepared for the threats that MHWs will represent in the near future.

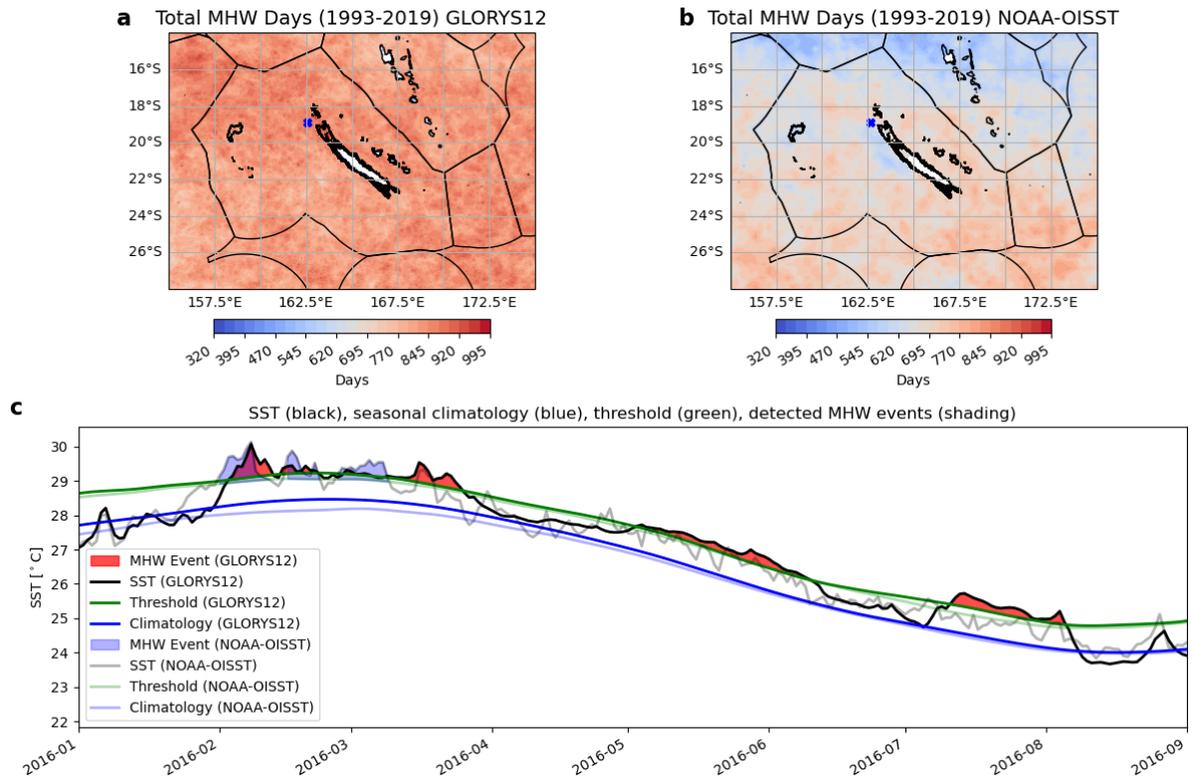
886

887

888 **Appendix A**

889 In this appendix, we illustrate how and why important differences may arise in MHW detection statistics
890 when applying the Hobday et al. (2016) detection method on two different, but similar, SST products. Figure
891 A1 (upper panels) shows the differences obtained in total MHW days between the two products, and Figure
892 A1 (lower) illustrates how such differences may arise during the year 2016. Even if the two climatologies
893 and 90th quantile levels are close, GLORYS12 is a smoother SST product than NOAA-OISST, and the
894 Hob16 method detects a greater number of longer duration MHWs events in GLORYS12, while it detects
895 fewer events and of shorter duration in NOAA-OISST.

896



898

899

900

901 **Figure A1: Upper panels: total number of MHWs days around New Caledonia for the period 1993-**
 902 **2019, detected at each point with the method from Hobday et al. (2016) using two different SST**
 903 **products: GLORYS12 reanalysis (upper left) and NOAA-OISST (upper right). Lower panel: Example**
 904 **of a timeseries at one particular location Latitude = -18.89° Longitude = 162.58° for the 01/2016 to**
 905 **09/2016 period for both products.**

906 **The darker colours and pink shading represent the MHW detected in GLORYS12 and the lighter**
 907 **colours and blue shading is for MHWs detected in NOAA-OISST. The SST time series are shown in**
 908 **black and grey lines for GLORYS12 and NOAA-OISST, respectively. The associated 1993-2019**
 909 **climatologies are shown in blue (dark and light), the 90th percentile threshold in green (dark and light).**

910

911 **Author Contributions**

912 SL, SC and CM led the design and implementation of the research, and wrote the first draft of the manuscript.
913 SL led the analyses and the preparation of the Figures. CD, JM, RL, IM, NH and SN contributed to text
914 sections. All authors contributed to manuscript revision, and read and approved the submitted version.

915

916 **Competing Interests**

917 The authors declare that they have no conflict of interest.

918

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926 GLORYS-12 and OSTIA from Copernicus Marine Services and Mercator Ocean International (MOI)
927 (https://data.Marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/description,[https://da](https://data.marine.copernicus.eu/product/SST_GLO_SST_L4_REP_OBSERVATIONS_010_011/description)
928 [ta.marine.copernicus.eu/product/SST_GLO_SST_L4_REP_OBSERVATIONS_010_011/description](https://data.marine.copernicus.eu/product/SST_GLO_SST_L4_REP_OBSERVATIONS_010_011/description)).

929

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938

939 **References**

940 Abascal, F. J., Peatman, T., Leroy, B., Nicol, S., Schaefer, K., Fuller, D. W., & Hampton, J. (2018).
941 Spatiotemporal variability in bigeye vertical distribution in the Pacific Ocean. *Fisheries Research*, 204, 371–
942 379. <https://doi.org/10.1016/j.fishres.2018.03.013>

943

944 Alory, G., Vega, A., Ganachaud, A., & Despinoy, M. (2006). Influence of upwelling, subsurface
945 stratification, and heat fluxes on coastal sea surface temperature off southwestern New Caledonia. *J.*
946 *Geophys. Res.*, 111. <https://doi.org/10.1029/2005JC003401>

947

948 Amaya, D., Jacox, M., Fewings, M., Saba, V., Stuecker, M., Rykaczewski, R., Ross, A., Stock, C., Capotondi,
949 A., Petrik, C., Bograd, S., Alexander, M., Cheng, W., Hermann, A., Kearney, K., & Powell, B. (2023). Marine
950 heatwaves need clear definitions so coastal communities can adapt. *Nature*, 616, 29–32.
951 <https://doi.org/10.1038/d41586-023-00924-2>

952

953 Arrizabalaga, H., Bruyn, P. de, Diaz, G. A., Murua, H., Chavance, P., Molina, A. D. de, Gaertner, D., Ariz,
954 J., Ruiz, J., & Kell, L. T. (2011). Productivity and susceptibility analysis for species caught in Atlantic tuna
955 fisheries. *Aquatic Living Resources*, 24(1), 1–12. <https://doi.org/10.1051/alr/2011007>

956

957 Bian, C., Jing, Z., Wang, H., Wu, L., Chen, Z., Gan, B., & Yang, H. (2023). Oceanic mesoscale eddies as
958 crucial drivers of global marine heatwaves. *Nature Communications*, 14(1), 2970.
959 <https://doi.org/10.1038/s41467-023-38811-z>

960

961 Bond, N. A., Cronin, M. F., Freeland, H., & Mantua, N. (2015). Causes and impacts of the 2014 warm
962 anomaly in the NE Pacific. *Geophysical Research Letters*, 42(9), 3414–3420.
963 <https://doi.org/10.1002/2015GL063306>

964

965 Bonino, G., Masina, S., Galimberti, G., & Moretti, M. (2023). Southern Europe and western Asian marine
966 heatwaves (SEWA-MHWs): A dataset based on macroevents. *Earth System Science Data*, 15(3), 1269–1285.
967 <https://doi.org/10.5194/essd-15-1269-2023>

968

969 Briand, K., Molony, B., & Lehodey, P. (2011). A study on the variability of albacore (*Thunnus alalunga*)
970 longline catch rates in the southwest Pacific Ocean. *Fisheries Oceanography*, 20(6), 517–529.
971 <https://doi.org/10.1111/j.1365-2419.2011.00599.x>

972

973 Brown, J. R., Lengaigne, M., Lintner, B. R., Widlansky, M. J., van der Wiel, K., Dutheil, C., Linsley, B. K.,
974 Matthews, A. J., & Renwick, J. (2020). South Pacific Convergence Zone dynamics, variability and impacts
975 in a changing climate. *Nature Reviews Earth & Environment*, 1(10), 530–543.
976 <https://doi.org/10.1038/s43017-020-0078-2>

977

978 Caputi, N., Kangas, M., Denham, A., Feng, M., Pearce, A., Hetzel, Y., & Chandrapavan, A. (2016).
979 Management adaptation of invertebrate fisheries to an extreme marine heat wave event at a global warming
980 hot spot. *Ecology and Evolution*, 6(11), 3583–3593. <https://doi.org/10.1002/ece3.2137>

981

982 Cavole, L. M., Demko, A. M., Diner, R. E., Giddings, A., Koester, I., Pagniello, C. M. L. S., Paulsen, M.-L.,
983 Ramirez-Valdez, A., Schwenck, S. M., Yen, N. K., Zill, M. E., & Franks, P. J. S. (2016). Biological Impacts
984 of the 2013–2015 Warm-Water Anomaly in the Northeast Pacific: Winners, Losers, and the Future.
985 *Oceanography*, 29(2), 273–285.

986

987 Chevillard, C. Le Gendre, R., Menkes, C., Izumo, T., Pagli, B., Van Wynsberge, S., and Cravatte, S.:
988 Sensitivity of marine heatwaves metrics to SST products, focusing on the Tropical Pacific, EGU sphere
989 [preprint], <https://doi.org/10.5194/egusphere-2025-5417>, 2025.

990

991 Cravatte, S., Delcroix, T., Zhang, D., McPhaden, M., & Leloup, J. (2009). Observed freshening and warming
992 of the western Pacific Warm Pool. *Climate Dynamics*, 33(4), 565–589. [https://doi.org/10.1007/s00382-009-](https://doi.org/10.1007/s00382-009-0526-7)
993 [0526-7](https://doi.org/10.1007/s00382-009-0526-7)

994

995 Darmaraki, S., Somot, S., Sevault, F., & Nabat, P. (2019). Past Variability of Mediterranean Sea Marine
996 Heatwaves. *Geophysical Research Letters*, 46(16), 9813–9823. <https://doi.org/10.1029/2019GL082933>

997

998 Dixon, A. M., Forster, P. M., Heron, S. F., Stoner, A. M. K., & Beger, M. (2022). Future loss of local-scale
999 thermal refugia in coral reef ecosystems. *PLOS Climate*, 1(2), e0000004.
1000 <https://doi.org/10.1371/journal.pclm.0000004>

1001

1002 Dutheil, C., Lal, S., Lengaigne, M., Cravatte, S., Menkès, C., Receveur, A., Börgel, F., Gröger, M.,
1003 Houlbreque, F., Le Gendre, R., Mangolte, I., Peltier, A., & Meier, H. E. M. (2024). The massive 2016 marine
1004 heatwave in the Southwest Pacific: An “El Niño–Madden-Julian Oscillation” compound event. *Science*
1005 *Advances*, 10(41), eadp2948. <https://doi.org/10.1126/sciadv.adp2948>

1006

1007 Elzahaby, Y., Schaeffer, A., Roughan, M., & Delaux, S. (2021). Oceanic Circulation Drives the Deepest and
1008 Longest Marine Heatwaves in the East Australian Current System. *Geophysical Research Letters*, 48(17),
1009 e2021GL094785. <https://doi.org/10.1029/2021GL094785>

1010

1011 Everett, J. D., Baird, M. E., Oke, P. R., & Suthers, I. M. (2012). An avenue of eddies: Quantifying the
1012 biophysical properties of mesoscale eddies in the Tasman Sea. *Geophysical Research Letters*, 39(16).

1013

1014 Forget, F. G., Capello, M., Filmlalter, J. D., Govinden, R., Soria, M., Cowley, P. D., & Dagorn, L. (2015).
1015 Behaviour and vulnerability of target and non-target species at drifting fish aggregating devices (FADs) in
1016 the tropical tuna purse seine fishery determined by acoustic telemetry. *Canadian Journal of Fisheries and*
1017 *Aquatic Sciences*, 72(9), 1398–1405. <https://doi.org/10.1139/cjfas-2014-0458>

1018

1019 Good, S., Fiedler, E., Mao, C., Martin, M. J., Maycock, A., Reid, R., Roberts-Jones, J., Searle, T., Waters,
1020 J., While, J., & Worsfold, M. (2020). The Current Configuration of the OSTIA System for Operational
1021 Production of Foundation Sea Surface Temperature and Ice Concentration Analyses. *Remote Sensing*, 12(4),
1022 Article 4. <https://doi.org/10.3390/rs12040720>

1023

1024 Gregory, C. H., Holbrook, N. J., Spillman, C. M., & Marshall, A. G. (2024). Combined Role of the MJO and
1025 ENSO in Shaping Extreme Warming Patterns and Coral Bleaching Risk in the Great Barrier Reef.
1026 *Geophysical Research Letters*, 51(13), e2024GL108810. <https://doi.org/10.1029/2024GL108810>

1027

1028 Hobday, A. J., Alexander, L. V., Perkins, S. E., Smale, D., Straub, S., Oliver, E. C. J., Benthuisen, J. A.,
1029 Burrows, M. T., Donat, M. G., Feng, M., Holbrook, N. J., Moore, P. J., Scannell, H. A., Sen Gupta, A., &
1030 Wernberg, T. (2016). A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, 141,
1031 227–238. <https://doi.org/10.1016/j.pocean.2015.12.014>

1032

1033 Hobday, A. J., Burrows, M. T., Filbee-Dexter, K., Holbrook, N. J., Sen Gupta, A., Smale, D. A., Smith, K.
1034 E., Thomsen, M. S., & Wernberg, T. (2023). With the arrival of El Niño, prepare for stronger marine
1035 heatwaves. *Nature*, 621(7977), 38–41. <https://doi.org/10.1038/d41586-023-02730-2>

1036

1037 Hobday, A., Oliver, E., Sen Gupta, A., Benthuisen, J., Burrows, M., Donat, M., Holbrook, N., Moore, P.,
1038 Thomsen, M., Wernberg, T., & Smale, D. (2018). Categorizing and Naming Marine Heatwaves.
1039 *Oceanography*, 31(2). <https://doi.org/10.5670/oceanog.2018.205>

1040

1041 Holbrook, N. J., Hernaman, V., Koshiba, S., Lako, J., Kajtar, J. B., Amosa, P., & Singh, A. (2022). Impacts
1042 of marine heatwaves on tropical western and central Pacific Island nations and their communities. *Global*
1043 *and Planetary Change*, 208, 103680. <https://doi.org/10.1016/j.gloplacha.2021.103680>

1044

1045 Holbrook, N. J., Scannell, H. A., Sen Gupta, A., Benthuisen, J. A., Feng, M., Oliver, E. C. J., Alexander, L.
1046 V., Burrows, M. T., Donat, M. G., Hobday, A. J., Moore, P. J., Perkins-Kirkpatrick, S. E., Smale, D. A.,
1047 Straub, S. C., & Wernberg, T. (2019). A global assessment of marine heatwaves and their drivers. *Nature*
1048 *Communications*, 10, 2624. <https://doi.org/10.1038/s41467-019-10206-z>

1049

1050 Huang, B., Liu, C., Banzon, V., Freeman, E., Graham, G., Hankins, B., Smith, T., & Zhang, H.-M. (2021).
1051 Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST) Version 2.1. *Journal*
1052 *of Climate*, 34(8), 2923–2939. <https://doi.org/10.1175/JCLI-D-20-0166.1>

1053

1054 Hughes, T. P., Anderson, K. D., Connolly, S. R., Heron, S. F., Kerry, J. T., Lough, J. M., Baird, A. H., Baum,
1055 J. K., Berumen, M. L., Bridge, T. C., Claar, D. C., Eakin, C. M., Gilmour, J. P., Graham, N. A. J., Harrison,
1056 H., Hobbs, J.-P. A., Hoey, A. S., Hoogenboom, M., Lowe, R. J., ... Wilson, S. K. (2018). Spatial and temporal
1057 patterns of mass bleaching of corals in the Anthropocene. *Science (New York, N.Y.)*, 359(6371), 80–83.
1058 <https://doi.org/10.1126/science.aan8048>

1059

1060 IPCC. (2023). Summary for Policymakers. (Climate Change 2023: Synthesis Report. Contribution of
1061 Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate
1062 Change, pp. 1–34). IPCC. doi: 10.59327/IPCC/AR6-9789291691647.001

1063

1064 Jacox, M. G., Alexander, M. A., Bograd, S. J., & Scott, J. D. (2020). Thermal displacement by marine
1065 heatwaves. *Nature*, 584(7819), Article 7819. <https://doi.org/10.1038/s41586-020-2534-z>

1066

1067 Jones, T., Parrish, J. K., Peterson, W. T., Bjorkstedt, E. P., Bond, N. A., Ballance, L. T., Bowes, V., Hipfner,
1068 J. M., Burgess, H. K., Dolliver, J. E., Lindquist, K., Lindsey, J., Nevins, H. M., Robertson, R. R., Roletto, J.,
1069 Wilson, L., Joyce, T., & Harvey, J. (2018). Massive Mortality of a Planktivorous Seabird in Response to a
1070 Marine Heatwave. *Geophysical Research Letters*, 45(7), 3193–3202. <https://doi.org/10.1002/2017GL076164>
1071

1072 Keppler, L., Cravatte, S., Chaigneau, A., Pegliasco, C., Gourdeau, L., & Singh, A. (2018). Observed
1073 Characteristics and Vertical Structure of Mesoscale Eddies in the Southwest Tropical Pacific. *Journal of*
1074 *Geophysical Research: Oceans*, 123(4), 2731–2756. <https://doi.org/10.1002/2017JC013712>
1075

1076 Köhn, E. E., Vogt, M., Münnich, M., & Gruber, N. (2024). On the Vertical Structure and Propagation of
1077 Marine Heatwaves in the Eastern Pacific. *Journal of Geophysical Research: Oceans*, 129(1), e2023JC020063.
1078 <https://doi.org/10.1029/2023JC020063>
1079

1080 Lehodey, P., Bertrand, A., Hobday, A. J., Kiyofuji, H., McClatchie, S., Menkès, C. E., Pilling, G., Polovina,
1081 J., & Tommasi, D. (2020). ENSO Impact on Marine Fisheries and Ecosystems. In *El Niño Southern*
1082 *Oscillation in a Changing Climate* (pp. 429–451). American Geophysical Union (AGU).
1083 <https://doi.org/10.1002/9781119548164.ch19>
1084

1085 Lellouche, J.-M., Greiner, E., Bourdallé-Badie, R., Garric, G., Melet, A., Drévilion, M., Clément, B., Hamon,
1086 M., Le Galloudec, O., Regnier, C., Candela, T., Testut, C.-E., Florent, G., Giovanni, R., Mounir, B., Drillet,
1087 Y., & Le Traon, P.-Y. (2021). The Copernicus Global 1/12° Oceanic and Sea Ice GLORYS12 Reanalysis.
1088 *Frontiers in Earth Science*, 9. <https://doi.org/10.3389/feart.2021.698876>
1089

1090 Li, J., Roughan, M., & Hemming, M. (2023). Interactions between cold cyclonic eddies and a western
1091 boundary current modulate marine heatwaves. *Communications Earth & Environment*, 4(1), 1–11.
1092 <https://doi.org/10.1038/s43247-023-01041-8>
1093

1094 Marin, M., Feng, M., Phillips, H. E., & Bindoff, N. L. (2021). A Global, Multiproduct Analysis of Coastal
1095 Marine Heatwaves: Distribution, Characteristics, and Long-Term Trends. *Journal of Geophysical Research:*
1096 *Oceans*, 126(2), e2020JC016708. <https://doi.org/10.1029/2020JC016708>

1097

1098 Mills, K. E., Pershing, A. J., Brown, C. J., Chen, Y., Chiang, F.-S., Holland, D. S., Lehuta, S., Nye, J. A.,
1099 Sun, J. C., Thomas, A. C., & Wahle, R. A. (2013). Fisheries Management in a Changing Climate: Lessons
1100 from the 2012 Ocean Heat Wave in the Northwest Atlantic. *Oceanography*, 26(2), 191–195.

1101

1102 Misra, R., Sérazin, G., Meissner, K. J., & Sen Gupta, A. (2021). Projected Changes to Australian Marine
1103 Heatwaves. *Geophysical Research Letters*, 48(7), e2020GL091323. <https://doi.org/10.1029/2020GL091323>

1104

1105 Moore, J. A. Y., Bellchambers, L. M., Depczynski, M. R., Evans, R. D., Evans, S. N., Field, S. N., Friedman,
1106 K. J., Gilmour, J. P., Holmes, T. H., Middlebrook, R., Radford, B. T., Ridgway, T., Shedrawi, G., Taylor, H.,
1107 Thomson, D. P., & Wilson, S. K. (2012). Unprecedented Mass Bleaching and Loss of Coral across 12° of
1108 Latitude in Western Australia in 2010–11. *PLOS ONE*, 7(12), e51807.
1109 <https://doi.org/10.1371/journal.pone.0051807>

1110

1111 Nikolic, N., Morandeau, G., Hoarau, L., West, W., Arrizabalaga, H., Hoyle, S., Nicol, S. J., Bourjea, J.,
1112 Puech, A., Farley, J. H., Williams, A. J., & Fonteneau, A. (2017). Review of albacore tuna, *Thunnus alalunga*,
1113 biology, fisheries and management. *Reviews in Fish Biology and Fisheries*, 27(4), 775–810.
1114 <https://doi.org/10.1007/s11160-016-9453-y>

1115

1116 Oliver, E. C. J., Benthuyssen, J. A., Darmaraki, S., Donat, M. G., Hobday, A. J., Holbrook, N. J., Schlegel, R.
1117 W., & Sen Gupta, A. (2021). Marine Heatwaves. *Annual Review of Marine Science*, 13(1), 313–342.
1118 <https://doi.org/10.1146/annurev-marine-032720-095144>

1119

1120 Phillips, J. S., Escalle, L., Pilling, G., Gupta, A. S., & Seville, E. van. (2019). Regional connectivity and
1121 spatial densities of drifting fish aggregating devices, simulated from fishing events in the Western and Central
1122 Pacific Ocean. *Environmental Research Communications*, 1(5), 055001. [https://doi.org/10.1088/2515-](https://doi.org/10.1088/2515-7620/ab21e9)
1123 [7620/ab21e9](https://doi.org/10.1088/2515-7620/ab21e9)

1124

1125 Picaut J, Ioualalen M, Delcroix T, Masia F, Murtugudde R, Vialard J (2001) The oceanic zone of convergence
1126 on the eastern edge of the Pacific warm pool: A synthesis of results and implications for El Niño-Southern
1127 Oscillation and biogeochemical phenomena. *J Geophys Res Oceans* 106(C2):2363–2386. doi:10.1029/2000
1128 JC900141

1129

1130 Plecha, S. M., & Soares, P. M. M. (2020). Global marine heatwave events using the new CMIP6 multi-model
1131 ensemble: From shortcomings in present climate to future projections. *Environmental Research Letters*,
1132 15(12), 124058. <https://doi.org/10.1088/1748-9326/abc847>

1133

1134 Qiu, B., & Chen, S. (2004). Seasonal modulations in the eddy field of the South Pacific Ocean. *Journal of*
1135 *Physical Oceanography*, 34(7), 1515-1527.

1136

1137 Qiu, B., Chen, S., & Kessler, W. S. (2009). Source of the 70-Day Mesoscale Eddy Variability in the Coral
1138 Sea and the North Fiji Basin. *Journal of Physical Oceanography*, 39(2), 404–420.
1139 <https://doi.org/10.1175/2008JPO3988.1>

1140

1141 Rocha, C. B., Gille, S. T., Chereskin, T. K., & Menemenlis, D. (2016). Seasonality of submesoscale dynamics
1142 in the Kuroshio Extension. *Geophysical Research Letters*, 43(21), 11,304-11,311.
1143 <https://doi.org/10.1002/2016GL071349>

1144

1145 Schaefer, K. M., Fuller, D. W., & Block, B. A. (2011). Movements, behavior, and habitat utilization of
1146 yellowfin tuna (*Thunnus albacares*) in the Pacific Ocean off Baja California, Mexico, determined from

1147 archival tag data analyses, including unscented Kalman filtering. *Fisheries Research*, 112(1), 22–37.
1148 <https://doi.org/10.1016/j.fishres.2011.08.006>

1149

1150 Schaeffer, A., & Roughan, M. (2017). Subsurface intensification of marine heatwaves off southeastern
1151 Australia: The role of stratification and local winds. *Geophysical Research Letters*, 44(10), 5025–5033.
1152 <https://doi.org/10.1002/2017GL073714>

1153

1154 Schaeffer, A., Sen Gupta, A., & Roughan, M. (2023). Seasonal stratification and complex local dynamics
1155 control the sub-surface structure of marine heatwaves in Eastern Australian coastal waters. *Communications*
1156 *Earth & Environment*, 4(1), 1–12. <https://doi.org/10.1038/s43247-023-00966-4>

1157

1158 Sen Gupta, A., Thomsen, M., Benthuisen, J. A., Hobday, A. J., Oliver, E., Alexander, L. V., Burrows, M.
1159 T., Donat, M. G., Feng, M., Holbrook, N. J., Perkins-Kirkpatrick, S., Moore, P. J., Rodrigues, R. R., Scannell,
1160 H. A., Taschetto, A. S., Ummenhofer, C. C., Wernberg, T., & Smale, D. A. (2020). Drivers and impacts of
1161 the most extreme marine heatwave events. *Scientific Reports*, 10(1), Article 1.
1162 <https://doi.org/10.1038/s41598-020-75445-3>

1163

1164 Sérazin, G., Marin, F., Gourdeau, L., Cravatte, S., Morrow, R., & Dabat, M.-L. (2019). Scale-dependent
1165 analysis of in situ observations in the mesoscale to submesoscale range around New Caledonia.
1166 <https://doi.org/10.5194/os-2019-124>

1167

1168 Smith, K. E., Burrows, M. T., Hobday, A. J., Sen Gupta, A., Moore, P. J., Thomsen, M., Wernberg, T., &
1169 Smale, D. A. (2021). Socioeconomic impacts of marine heatwaves: Global issues and opportunities. *Science*,
1170 374(6566), eabj3593. <https://doi.org/10.1126/science.abj3593>

1171

1172 Spillman, C. M., Smith, G. A., Hobday, A. J., & Hartog, J. R. (2021). Onset and Decline Rates of Marine
1173 Heatwaves: Global Trends, Seasonal Forecasts and Marine Management. *Frontiers in Climate*, 3.
1174 <https://doi.org/10.3389/fclim.2021.801217>

1175

1176 Sun, D., Jing, Z., Li, F., & Wu, L. (2023). Characterizing global marine heatwaves under a spatio-temporal
1177 framework. *Progress in Oceanography*, 211, 102947. <https://doi.org/10.1016/j.pocean.2022.102947>

1178

1179 Thomson, J. A., Burkholder, D. A., Heithaus, M. R., Fourqurean, J. W., Fraser, M. W., Statton, J., &
1180 Kendrick, G. A. (2015). Extreme temperatures, foundation species, and abrupt ecosystem change: An
1181 example from an iconic seagrass ecosystem. *Global Change Biology*, 21(4), 1463–1474.
1182 <https://doi.org/10.1111/gcb.12694>

1183

1184 Uthicke, S., Logan, M., Liddy, M., Francis, D., Hardy, N., & Lamare, M. (2015). Climate change as an
1185 unexpected co-factor promoting coral eating seastar (*Acanthaster planci*) outbreaks. *Scientific Reports*, 5,
1186 8402. <https://doi.org/10.1038/srep08402>

1187

1188 van Hooidek, R., Maynard, J. A., & Planes, S. (2013). Temporary refugia for coral reefs in a warming
1189 world. *Nature Climate Change*, 3(5), Article 5. <https://doi.org/10.1038/nclimate1829>

1190

1191 Vidal, T., Williams, P., & Ruaia, T. (2024, August 14). Overview of tuna fisheries in the Western and Central
1192 Pacific Ocean, including economic conditions – 2023—Rev.01 | WCPFC Meetings.
1193 <https://meetings.wcpfc.int/node/23098>

1194

1195 Vincent, E. M., Emanuel, K. A., Lengaigne, M., Vialard, J., & Madec, G. (2014). Influence of upper ocean
1196 stratification interannual variability on tropical cyclones. *Journal of Advances in Modeling Earth Systems*,
1197 6(3), 680–699. <https://doi.org/10.1002/2014MS000327>

1198

1199 Vogt, L., Burger, F. A., Griffies, S. M., & Frölicher, T. L. (2022). Local Drivers of Marine Heatwaves: A
1200 Global Analysis With an Earth System Model. *Frontiers in Climate*, 4.
1201 <https://doi.org/10.3389/fclim.2022.847995>

1202

1203 Walker, H. J., Hastings, P. A., Hyde, J. R., Lea, R. N., Snodgrass, O. E., & Bellquist, L. F. (2020). Unusual
1204 occurrences of fishes in the Southern California Current System during the warm water period of 2014–2018.
1205 *Estuarine, Coastal and Shelf Science*, 236, 106634. <https://doi.org/10.1016/j.ecss.2020.106634>

1206

1207 Wernberg, T., Smale, D. A., Tuya, F., Thomsen, M. S., Langlois, T. J., de Bettignies, T., Bennett, S., &
1208 Rousseaux, C. S. (2013). An extreme climatic event alters marine ecosystem structure in a global biodiversity
1209 hotspot. *Nature Climate Change*, 3(1), 78–82. <https://doi.org/10.1038/nclimate1627>

1210

1211 Woods, P. J., Macdonald, J. I., Bárðarson, H., Bonanomi, S., Boonstra, W. J., Cornell, G., Cripps, G.,
1212 Danielsen, R., Färber, L., Ferreira, A. S. A., Ferguson, K., Holma, M., Holt, R. E., Hunter, K. L., Kokkalis,
1213 A., Langbehn, T. J., Ljungström, G., Nieminen, E., Nordström, M. C., ... Yletyinen, J. (2022). A review of
1214 adaptation options in fisheries management to support resilience and transition under socio-ecological
1215 change. *ICES Journal of Marine Science*, 79(2), 463–479. <https://doi.org/10.1093/icesjms/fsab146>

1216

1217 Wyatt, A. S. J., Leichter, J. J., Washburn, L., Kui, L., Edmunds, P. J., & Burgess, S. C. (2023). Hidden
1218 heatwaves and severe coral bleaching linked to mesoscale eddies and thermocline dynamics. *Nature*
1219 *Communications*, 14(1), Article 1. <https://doi.org/10.1038/s41467-022-35550-5>

1220

1221 Zhang, Y., Du, Y., Feng, M., & Hobday, A. J. (2023). Vertical structures of marine heatwaves. *Nature*
1222 *Communications*, 14(1), 6483. <https://doi.org/10.1038/s41467-023-42219-0>

1223

1224

1225