

1 **Marine Heatwaves across the central South Pacific: characteristics,** 2 **mechanisms, and modulation by El Niño Southern Oscillation**

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14 **Abstract.** Marine heatwaves (MHWs) are intensifying with climate change, endangering ecosystems such as coral reefs. Yet
15 their regional characteristics and drivers remain poorly understood in many parts of the Pacific. Here we provide a
16 comprehensive assessment of MHWs in the central South Pacific and across the five archipelagos of French Polynesia (FP ;
17 representing more than 5 million km² of maritime area, a region as vast as Europe), using sea surface temperature
18 observations and an ocean reanalysis to investigate underlying mechanisms. MHW characteristics vary widely across the
19 region: its northern and southern parts (the Marquesas and Austral archipelagos respectively) experience the highest number
20 of MHW days and the strongest cumulative intensities, especially during the warm season (Nov-Apr). In contrast, its central
21 part (the Society, Tuamotu, and Gambier Islands) exhibits more moderate MHW characteristics. Heat budget analyses
22 highlight the seasonally and regionally diverse mechanisms shaping MHWs. In central FP during the warm season (austral
23 summer), most MHWs are driven by air–sea heat fluxes, while in the northern part, those driven by oceanic horizontal
24 advection dominate. During the cold season (austral winter), more MHWs driven by horizontal advection are observed in the
25 whole region since the thicker seasonal mixed layer reduces the proportion of MHWs driven by air-sea fluxes. El Niño–
26 Southern Oscillation (ENSO) strongly modulates MHW occurrences: El Niño favors MHW occurrences in northeastern FP,
27 while La Niña increases MHW occurrence in the southwest with different spatial extent depending on ENSO flavors
28 (Central or Eastern Pacific ENSO events). This modulation arises from reduced wind-evaporation cooling with reduced wind
29 speed, shoaled mixed layers, and enhanced horizontal heat advection, occurring primarily to the northeast of French
30 Polynesia during El Niño and to the southwest during La Niña. These results greatly improve our understanding of MHW
31 characteristics, dynamics and variability in this ecologically-fragile region.

32

33 **1- Introduction**

34 Extreme ocean temperature persisting in time, known as marine heatwaves (MHWs), have significant impacts on marine
35 ecosystems and, consequently, on island communities that rely on ecosystem services, fisheries, and tourism. Their
36 frequency and duration have increased over recent decades due to global ocean warming and are projected to continue rising
37 in the future (Oliver et al., 2018, 2019). Developing skillful forecasts of MHWs is therefore essential to anticipate their
38 impacts and, in turn, support effective mitigation. Such forecasts depend on a robust understanding of MHW characteristics,
39 their mechanisms, their physical drivers, and their variability (Holbrook et al., 2020). None of these aspects has yet been
40 studied in detail over the French Polynesia (FP) region where MHWs can lead to severe socioeconomic
41 consequences (Hédouin et al., 2020).

42 Some initial results regarding the mean characteristics and the dominant climate modes driving MHWs over FP can be
43 extracted from past studies conducted at broader spatial scales, such as the South Pacific or even globally. In the South-
44 Central Pacific, El Niño Southern Oscillation (ENSO) with its different phases El Niño (EN) and La Niña (LN) is known to
45 be an important driver of increased and suppressed MHW occurrence (Holbrook et al., 2019, 2022) and MHW intensity (Sen
46 Gupta et al., 2020). Additionally, the different flavors of ENSO (Capotondi et al., 2020) exhibit distinct connections with
47 MHWs across the Pacific Ocean in terms of both intensity and frequency. Using Linear Inverse Model (LIM) data, Gregory
48 et al., (2024) showed that these relationships vary between the Eastern Pacific (EP) and Central Pacific (CP) flavors of EN
49 and LN. In the tropical Pacific, both MHW intensity and occurrence tend to be consistent with sea surface temperature (SST)
50 anomalies during ENSO events, with maxima occurring in the central Pacific during CP EN events and in the eastern Pacific
51 during EP EN events.

52 Regarding the mechanisms of MHWs, global studies generally rely on numerical models to estimate the main physical
53 processes driving MHWs globally (Marin et al., 2022; Vogt et al., 2022; Bian et al., 2023, 2024). These studies aim at
54 identifying the dominant mechanisms during MHWs among oceanic heat advection, air/sea heat flux, horizontal and vertical
55 mixing and entrainment at the mixed layer base depending on the methods used to calculate mixed layer heat budgets during
56 MHWs. The dominant mechanisms during the MHWs' onset and decay are region dependent (Elzahaby et al., 2022; Bian et
57 al., 2023) and also depend on the spatial resolution of the model, which controls its ability to resolve oceanic eddies (Bian et
58 al., 2024). This highlights the need for regional studies and observation-based studies to better understand MHWs (e.g.
59 Schlegel et al., 2021; Elzahaby et al., 2021; Dutheil et al., 2024; Lal et al., 2025).

60 In austral summer (from November to April), which is the time of the year where ENSO events generally reach their peak of
61 intensity, ENSO strongly modifies SST, ocean currents, precipitation, and wind over FP compared to climatology. Opposite
62 influences across different parts of the country are observed depending on the ENSO flavor, due to FP's geographical
63 position near the transition zone where ENSO SST anomalies change sign and ENSO non-linear effect on the South Pacific
64 Convergence Zone (SPCZ) position (Vincent et al., 2011; Pagli et al., 2025a). EN (LN) events typically warm (cool) the
65 northeastern half of FP while cooling (warming) the southwestern half, though the boundaries and intensity of these

66 anomalies vary by ENSO flavor. During extreme EP EN events, a strong northeastward migration of the SPCZ (Vincent et
67 al., 2011) induces enhanced precipitation and cloud cover in the northern half of FP, with intensified westerly wind
68 anomalies. This increases Ekman pumping which deepens the thermocline in the northeastern half of FP and results in a
69 weakening of the westward-flowing South Equatorial Current (SEC) and a strengthening of the South Equatorial
70 Countercurrent (SECC) (Martinez et al., 2009). In contrast, CP EN events cause a more moderate northeastward SPCZ shift
71 relative to its mean position and weaker surface winds over central FP. Moderate-to-strong LN events shift the SPCZ
72 southwest, reducing cloud cover and enhancing trade winds, strengthening the SEC and weakening the SECC. These
73 changes are amplified during very strong LN episodes (Pagli et al., 2025a). Overall, ENSO modulates surface ocean and
74 atmospheric conditions, altering the large-scale background state in which MHWs may develop.

75 The aim of this study is to analyze in detail past oceanic MHWs over FP in order to address the following questions: What
76 are the characteristics of past MHWs over FP and across the archipelagos? To what extent does ENSO drive, or modulate
77 these extreme events and their dynamics? What are the local mechanisms responsible for the onset/ decay of these events
78 across the area?

79 Section 2 describes the data and methods used to address these questions. Section 3 presents the characteristics of past
80 MHWs over FP, while section 4 explores their modulation by ENSO. Section 5 investigates the underlying mechanisms
81 driving these MHWs, and sections 6 and 7 provide the discussion and conclusions.

82

83 **2- Data and Methods**

84 **2.1-Data and reanalysis data**

85 Daily SST data were obtained from the Optimum Interpolation Sea Surface Temperature version 2 (OISSTv2) dataset, a
86 blend of in situ and satellite observations (Huang et al., 2021), covering the period from 1981 (01 Sept) to 2024 (31 Dec) on
87 a 0.25° grid. The mechanisms driving the MHWs detected over FP were investigated using the global eddy-resolving 1/12°
88 ocean reanalysis GLORYS12v1 (Lellouche et al., 2021), hereafter named GLORYS. In GLORYS the ocean and sea ice
89 general circulation model is NEMO (Madec et al., 2024). Daily oceanic variables—including potential temperature, mixed
90 layer depth, zonal and meridional currents—were analyzed. In addition, surface heat and momentum fluxes used to force the
91 oceanic model were analyzed. GLORYS reanalysis is forced by ERA-Interim until 2019 (Dee et al., 2011) and ERA5
92 afterwards (Hersbach et al., 2020). Due to the known large biases in radiative fluxes at the surface in ERA-Interim, large-
93 scale corrections were made using the NASA/GEWEX Surface Radiation Budget 3.0/3.1 product (Stackhouse et al., 2021)
94 for shortwave and longwave fluxes (Lellouche et al., 2021). Along track altimeter sea-level anomaly, satellite sea surface
95 temperature (AVHRR SST from NOAA) and sea-ice concentration (Ifremer/CERSAT) as well as in situ temperature and
96 salinity vertical profiles (CORA database from CMEMS) are assimilated in GLORYS. Tides are not represented explicitly in

97 GLORYS (Lellouche et al., 2018). Because of data assimilation, the heat and momentum budgets are not closed in GLORYS
98 but previous studies showed its realism for analyzing MHW heat budget in the South Pacific (Dutheil et al., 2024).
99 MHW detection was performed using both OISSTv2 (from 1981 to 2024) and GLORYS (from 1993 to 2024). However, the
100 mixed layer heat budget in GLORYS (see Methods) was limited to the period from 1993 to 2020 due to the forcing fields
101 (momentum and heat fluxes) data availability. For consistency with the OISST results, GLORYS fields were regridded onto
102 the spatial grid of the OISST dataset at 0.25° using a first order conservative remapping method.

103

104 **2.2-Methods**

105 **MHW detection**

106 MHWs were detected in the OISSTv2 dataset, and independently in the GLORYS reanalysis over the FP domain (165°W–
107 130°W, 30°S–0°S) for the period 1981–2024 (respectively 1993–2024), following the method described by Hobday et al.,
108 (2016). For each product, we used the 1993–2020 period as the climatological baseline. At each grid point, a MHW was
109 identified when daily SST exceeded the 90th seasonally varying percentile (SST^{90th}) (cf. Fig. S1 for austral summer and
110 winter average of the threshold over FP) for at least five consecutive days. SST^{90th} was computed with a moving 11-day
111 window to ensure enough daily SST samples for a robust 90th-percentile estimate. A 31-day moving window was then
112 applied to remove high-frequency noise. The same filter was used for the SST climatology. Events separated by less than
113 two days were considered as a single continuous event. Standard metrics were then calculated for each MHW, following the
114 methodology of Hobday et al. (2016). These included the maximum, mean, and cumulative intensity, duration, onset and
115 decline rates (defined as the mean SST rate of change from start to peak and from peak to end, respectively). The number of
116 events and the gaps between events were also computed. MHW intensity was expressed either in absolute terms (i.e., the
117 actual SST) or relative to the mean climatological baseline. MHWs were detected independently at each grid point; no
118 spatial connectivity was assumed between neighboring points. Then the daily analysis of MHW occurrence across the
119 domain was conducted to identify connected MHW areas (Lal et al., 2025). At each daily timestep, connected MHW pixels
120 were labeled, and the area of each labeled object was calculated. For each pointwise-detected MHW, the mean and
121 maximum spatial extent of the labeled object it belonged to were calculated over the event’s duration. Throughout the
122 manuscript, a distinction was made between MHWs occurring during the austral winter (referred to as “cold season”) and
123 those occurring during the austral summer (referred to as “warm season”), according to the date of their peak intensity.
124 The severity index (S) introduced by Sen Gupta et al., (2020) was also computed on a daily basis in OISSTv2:

$$Severity\ Index\ (S) = \frac{SST - SST_{clim}}{SST^{90th} - SST_{clim}} \quad (1)$$

125

126 where SST_{clim} is the SST climatology. $S > 1$ indicates that SST exceeds the 90th percentile (i.e., $SST > SST^{90th}$), while $0 < S$
127 < 1 reflects SST values warmer than the seasonal average but not exceeding the threshold. Conversely, $S < 0$ denotes SST

128 cooler than climatology. The severity of MHWs is generally described by values of S (Hobday et al., 2018). A MHW is
129 categorized as moderate ($1 < S \leq 2$), strong ($2 < S \leq 3$), severe ($3 < S \leq 4$) or extreme ($S \geq 4$).
130

131 In order to quantify the variability of the cumulative heat stress felt by the marine ecosystems, the daily Degree-Heating
132 Weeks (DHW), commonly employed in coral bleaching risk assessments, were computed for each austral summer from
133 1981 to 2024 following Skirving et al., (2020). First, daily temperature anomalies (HotSpot) were computed relative to the
134 local Maximum of Monthly Mean (MMM), defined as the climatological maximum of monthly mean temperatures
135 computed over the baseline period. DHW on each day were then estimated by summing the daily HotSpot anomalies
136 exceeding $1\text{ }^{\circ}\text{C}$ over the preceding 12 weeks (84 days). This accumulated value was divided by seven to express DHW in
137 $^{\circ}\text{C}$ -weeks.

138 Results were presented as averaged for the entire FP domain, and for each of the five main archipelagos: the Marquesas,
139 Tuamotu, Society, Gambier, and Austral Islands. The regions associated with each archipelago, over which MHW metrics
140 were aggregated, were defined using the official administrative geographic dataset for FP provided by the French
141 government (datagouv; see references).

142 Removing a long term temperature trend (shown in Fig. S2 for FP region) before applying the detection method is a
143 methodological choice as is the selection of a fixed versus a shifting baseline, both of which can influence the results and
144 their significance (Amaya et al., 2023; Sen Gupta, 2023; Capotondi et al., 2024; Smith et al., 2025). A central question
145 underlying these methodological choices is the definition of the “normal” state against which extreme ocean temperatures
146 are identified. This ambiguity complicates both the definition of MHWs and the communication of MHW-related risks to the
147 public. As a result, considerable discussion has emerged regarding MHW naming conventions and definition (Amaya et al.,
148 2023, Sen Gupta, 2023, Smith et al., 2025). While some disagreement persists in the community regarding the definition of a
149 MHW, it appears that both approaches are complementary, and the most appropriate depends on the specific research
150 question to address (Smith et al., 2025). Here, we followed the guidance of Smith et al. (2025) by explicitly distinguishing
151 MHW events identified using each approach and by clearly stating the motivation underlying the results presented. In the
152 context of a fixed-baseline framework, retaining the long-term trend is particularly appropriate when assessing the impacts
153 of MHWs on ecosystems or organisms with limited adaptive capacity. Conversely, when the focus is on interannual
154 variability, climate-mode relationships, or the physical mechanisms driving MHWs, removing the trend can be advantageous
155 for isolating these signals from the longer-term climate trends. For these reasons, the section that describes the MHWs
156 metrics over FP was made without removing the trend (section 3) and the sections analyzing the link with ENSO and the
157 mechanisms of MHW was made with detrended SST data (section 4-5). For section 3, complementary results based on
158 detrended SST data—where the MHW detection method and threshold computation were reapplied—are provided in the
159 Supplementary Information (SI). Briefly, detrending does not alter the main results — such as differences between
160 archipelagos, ENSO modulation, dominant mechanisms — but does slightly affect some quantitative MHW characteristics,
161 including their duration, intensity, and onset/decline rates.

162

163 **MHW/ENSO relationships**

164 The link between MHWs and ENSO was examined at two levels of complexity. First, MHW occurrence across FP in all
 165 seasons was analyzed separately for EN, LN, and Neutral (N) phases, based on the Oceanic Niño Index (ONI; NOAA), using
 166 the criterion that EN (respectively LN) conditions corresponded to ONI > 0.5 (resp. < -0.5) for at least five consecutive
 167 months (see Fig. S3 for the different periods considered as EN and LN). Second, ENSO diversity was considered using the
 168 FP-specific classification developed by Pagli et al. (2025a). This classification identified six ENSO clusters based on
 169 interannual relative SST anomalies, precipitation (PR), and 850 hPa zonal wind (U850) averaged over the austral summer:
 170 three EN types (Extreme EP, Strong Mixed, and CP), one group (EPLN+N) gathering Neutral (N) and weak EP LN group
 171 (EPLN+N), and two LN types (CP and Strong Mixed). The classified years are presented in Table S1 (including the 2023-
 172 2024 Strong Mixed EN event, cf. Pagli et al. 2025b). For this classification, the analysis of MHW-ENSO relationships was
 173 restricted to the austral summer. MHW characteristics were composited for each of the six ENSO groups. For each ENSO
 174 cluster, both the S index and percentage of days with $S \geq 1$ were computed over the FP domain. The maximum of DHW
 175 reached over the warm season was also computed each year and composited by ENSO clusters.

176

177 **Mixed layer heat budget and MHW category**

178 The mechanisms of MHWs were investigated through a mixed layer heat budget analysis performed in GLORYS based on
 179 the following equation (Moisan and Niiler, 1998; Oliver et al., 2021; Dutheil et al., 2024):

$$\underbrace{\frac{\partial \langle T \rangle'}{\partial t}}_{\text{tendency}} = \underbrace{-\langle \mathbf{U} \rangle \cdot \nabla \langle T \rangle'}_{\text{Horizontal advection HADV}} + \underbrace{\left(\frac{Q_{net}}{\rho c_p h} \right)'}_{\text{Air-sea heat flux } Q} + \underbrace{Residual'}_{RES} \quad (2)$$

180

181 with

$$\begin{aligned} Residual = & \underbrace{\langle \nabla \cdot (\kappa_h \nabla T) \rangle}_{\text{Horizontal mixing}} - \underbrace{\frac{1}{h} \kappa_z \frac{\partial T}{\partial z} \Big|_{-h}}_{\text{Vertical mixing}} - \underbrace{\left(\frac{\langle T \rangle - T_{-h}}{h} \right) \left(\frac{\partial h}{\partial t} + \mathbf{U}_{-h} \cdot \nabla h + w_{-h} \right)}_{\text{Entrainment}} \\ & + \underbrace{DA}_{\text{Data assimilation increments}} \end{aligned} \quad (3)$$

182

183 where $\rho = 1027 \text{ kg/m}^3$ is the mean density of sea water, $c_p = 4187 \text{ J} \cdot \text{K}^{-1} \cdot \text{kg}^{-1}$ is the specific heat capacity of seawater, κ_h
 184 and κ_z are the horizontal and vertical diffusivity coefficients in m^2/s , h is the mixed layer depth in m (defined as the depth
 185 where the density increase compared to density at 10 m depth corresponds to a temperature decrease of 0.2°C), T is the
 186 temperature in the mixed layer in K, \mathbf{U} is the horizontal current and w is the vertical velocity component both in m/s, Q_{net} is
 187 the net air-sea heat flux in W/m^2 . Brackets $\langle \cdot \rangle$ indicate the vertical averaging from the surface to the mixed layer depth.

188 The subscript h indicates the evaluation of the expression at the mixed layer depth. Each term of Eq (2-3) correspond to
 189 anomalies with respect to the daily climatology (as indicated by the prime) computed over 1993–2020.

190 The net surface air/sea flux Q_{net} (counted as positive when entering the ocean and expressed in $W \cdot m^{-2}$) can be decomposed
 191 as:

$$Q_{net} = SW + LHF + SHF + LW - SW(-h) \quad (4)$$

192

193 where SW is the net shortwave flux at the surface, $SW(-h)$ the shortwave flux leaving at the base of the mixed layer (light
 194 vertical penetrating function being parametrized following Paulson and Simpson, 1977 for type I water, Madec et al., 2024),
 195 LHF the net latent heat flux, SHF the net sensible heat flux, and LW the net longwave radiation flux. Concerning the
 196 residual, it encompasses several processes including: the effects of data assimilation, the entrainment at the base of the mixed
 197 layer (accounting for its space–time variability, vertical advection and lateral induction), and the horizontal/vertical turbulent
 198 mixing (see Eq. 3). However, at daily time scales this residual is generally dominated by vertical mixing (e.g. Dutheil et al.,
 199 2024). To quantify the contribution of each term during MHW events in terms of temperature evolution, the heat budget
 200 equation was integrated in time during the MHW from the event start (t_s):

201

$$\begin{aligned} & \langle T \rangle' (t) - \langle T \rangle' (t_s) \\ &= - \int_{t_s}^t \langle \mathbf{U}(\tilde{t}) \cdot \nabla \langle T(\tilde{t}) \rangle' \rangle d\tilde{t} + \int_{t_s}^t \frac{Q_{net}}{\rho c_p h}(\tilde{t})' d\tilde{t} + \int_{t_s}^t Residual(\tilde{t}) d\tilde{t} \end{aligned} \quad (5)$$

202 Following Elzahaby et al. (2022), at the peak time of each MHW, the contributions (integrated in time) of each term were
 203 assessed and compared to determine which term was dominant. Events were then categorized according to the dominant
 204 mechanism: **Q-MHW** when air-sea fluxes dominated, **HADV-MHW** when horizontal advection was dominant, **RES-**
 205 **MHW** when the residual term was dominant compared to Q and $HADV$ contribution separately as well as their sum, and
 206 **Mixed-MHW** when the relative difference between the Q and $HADV$ contributions was less than 10% of the total change of
 207 temperature from start to peak, and when their combined contribution was less than that of the residual term. For only a few
 208 events, none of the three terms on the right-hand side of Eq. (3) acted as positive drivers during MHW onset. These events
 209 were therefore excluded from the analysis.

210 To better understand the mechanisms controlling MHW onset and decay, the different terms of Eqs. (2) and (4), as
 211 well as wind (speed and direction), MLD, sea surface height (SSH) and surface oceanic currents anomalies were averaged
 212 over all MHWs occurring during the warm and cold seasons, separately. These averages were computed separately for each
 213 MHW type during the development phase, defined as the period from MHW onset to its peak intensity. During the decay
 214 phase, defined as the period from the peak to the end time, composites were constructed using all MHWs, including HADV,
 215 Q, and RES-MHWs. The full terms of Eq. (2) for these composites can be found in Appendix A (Fig. A1, A2).

216

217 3- MHW characteristics across the central South Pacific and FP archipelagos

218 Figure 1 presents the median characteristics of past MHWs—including their number, intensity, and duration—detected in the
219 central South Pacific from 1981 to 2024 in OISST, shown separately for austral summer and austral winter. For each
220 archipelago, Fig. 2a–d displays the distribution of these characteristics, along with absolute and cumulative intensity, to
221 assess the level of MHW exposure across FP.

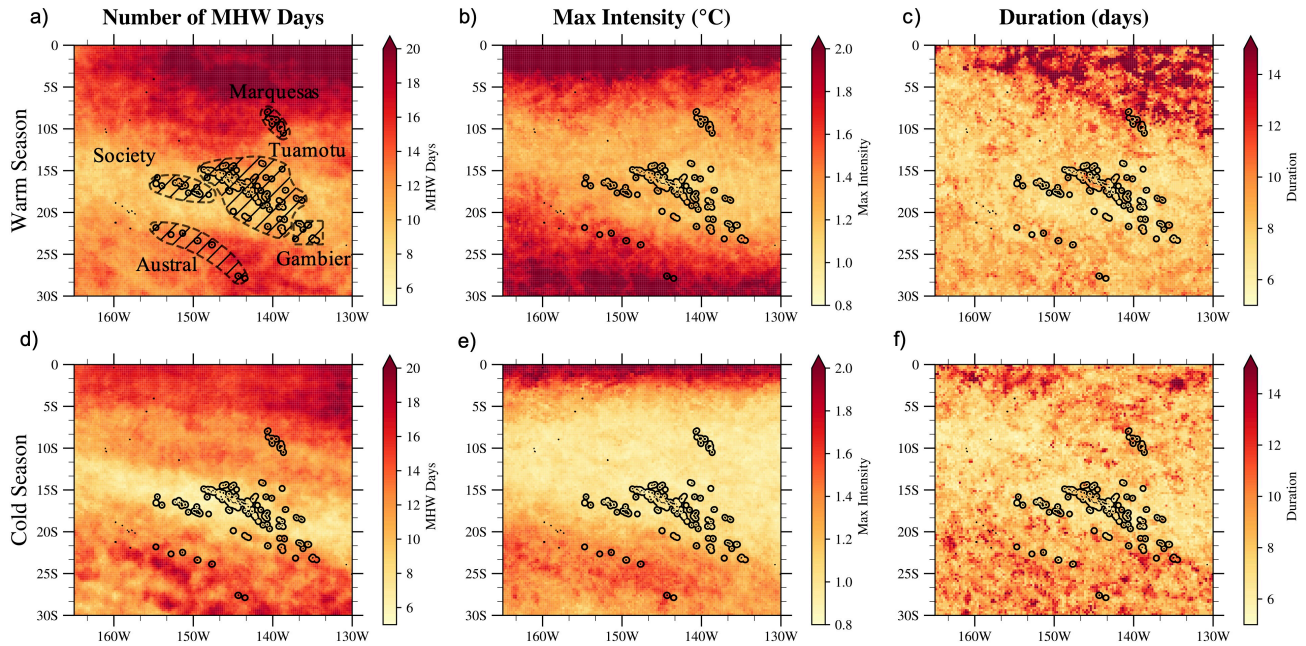
222 The total number of MHW days over the warm seasons of the period, expressed in mean number of MHW days per year is
223 heterogeneous across the region (Fig. 1a). It ranges from 7 to 13 days per year for central regions (Society-Tuamotu-
224 Gambier) and 13 to 18 days per year in the southwestern (Austral) and northeastern regions (near Marquesas) (Fig.1a).
225 During the cold season (Fig. 1d,e,f), most regions experience fewer MHW days compared to the warm season, with the
226 exception of the Austral and Gambier region, where the number of MHW days is comparable between the two seasons.

227 The most intense MHWs are observed north of 7°S and south of 25°S (Fig. 1b) leading to median maximum intensity values
228 of +1.7 °C and +1.5 °C in the Austral Islands during the warm and cold seasons, respectively (Fig. 2a). In the other
229 archipelagos, median intensity values range from +1.0 to +1.3 °C. Across all archipelagos, MHWs are more intense during
230 the warm season than during the cold season, both in terms of median and extreme values (Fig. 2a,b). Due to the large
231 meridional extent of FP, climatological temperatures vary significantly from south to north (see Fig. S1). Absolute
232 temperatures reached are therefore quite different between the Austral and Marquesas. In absolute terms, the most intense
233 heat exposure is found over the Society, Tuamotu, and Marquesas archipelagos, with median values ranging from 27.6 to
234 28.4 °C in the cold season and from 29.2 to 29.8 °C in the warm season (Fig. 2b). The most intense heat exposure exceeds
235 30 °C across most archipelagos during both seasons, except in the Gambier Islands (28.8 °C and 29.8 °C for the warm and
236 cold seasons, respectively) and in the Austral Islands during the cold season (28.8 °C) (Fig. 2b).

237 The median duration is around 7-10 days for both seasons, with longer duration for the Marquesas region over the warm
238 season (Fig. 1c). Most MHW events are short-lived events, across all five archipelagos (Fig. 2d). Longer events are
239 particularly frequent in the Marquesas during the austral summer, where 25% of MHWs last longer than 19–20 days, 5% last
240 more than 50 days, and the longest MHWs exceed 250 days in both seasons. In the Austral Islands, the upper tail of the
241 duration distribution is also shifted upward compared to other archipelagos, with 5% of MHWs lasting more than 45 days in
242 both seasons. For the others, 75% of the distribution lies between 10 and 17 days.

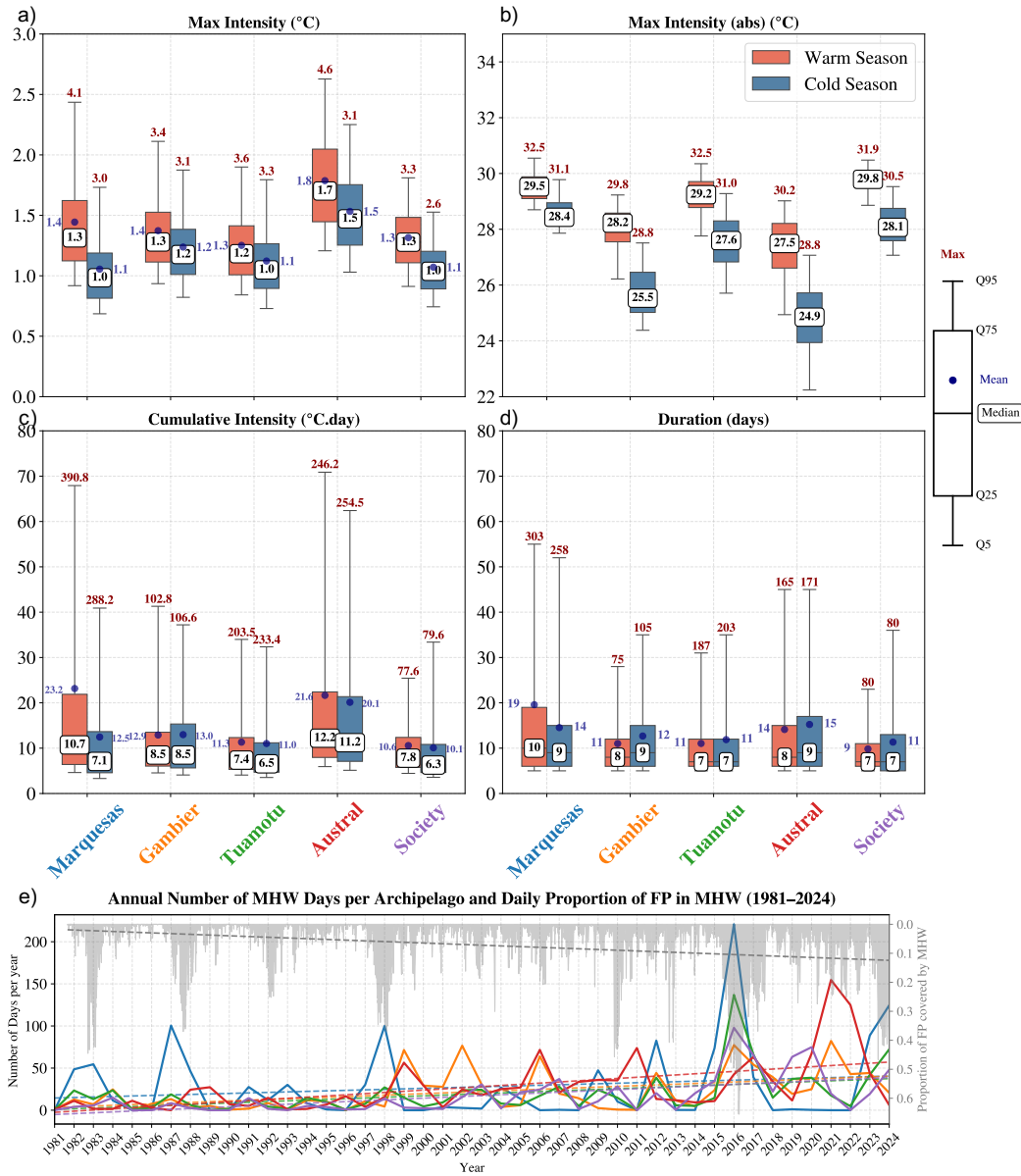
243 Cumulative intensity varies across FP in line with intensity and duration distributions (Fig. 2c). The Austral Islands (both
244 seasons) and the Marquesas (warm season) experience the highest cumulative intensities, with median values of 10 to
245 12 °C·days. In these regions, 25% of MHWs have cumulative intensities exceeding 20 °C·days, and 5% exceed 60 °C·days.
246 In the Society, Gambier, and Tuamotu Islands, median cumulative intensities are 7.8, 7.4, and 8.2 °C·days, respectively. In
247 these archipelagos, 25% of MHWs exceed 10 °C·days, and 5% exceed 30 °C·days—except in the Society Islands during the
248 warm season, where 5% of MHWs exceed 25 °C·days.

249 There is an overall positive trend of the number of MHW days over FP over the period for all archipelagos, as well
 250 as the area covered by MHWs over the FP region (Fig. 2e). Also, MHW occurrence varies greatly from year to year, and not
 251 similarly in each archipelago (Fig. 2e). In the Marquesas, several years may pass with few or no MHW events, followed by
 252 years with a very high number of MHW days.
 253 In the Austral Islands, MHWs are occurring more frequently each year, although substantial interannual variability remains,
 254 with some years—such as 2021 and 2022—characterized by a high number of MHW days.
 255 These differences led us to look at the link with ENSO (see Section 4).



256
 257 **Figure 1.** Median characteristics of MHWs detected over the FP region for the period 1981–2024 in the OISST dataset. The total number
 258 of days in MHW expressed in mean number of days per year, maximum intensity ($^{\circ}\text{C}$), and event duration (days) are displayed for the
 259 warm season (NDJFMA) in panels a, b, and c, respectively, and for the cold season (MJJASO) in panels d, e, and f, respectively. The
 260 names and locations of the archipelagos are shown in panel (a). The black dashed areas surrounding each archipelago in panel a represent
 261 the regions used to group MHW metrics by archipelago in Fig. 2.

Marine Heatwave Metrics by Archipelago and Season



262

263 **Figure 2.** Panels (a–d) show MHW metric distributions for each archipelago area (see the black dashed area in Fig. 1a) for warm
 264 (NDJFMA, in red) and cold seasons (MJJASO, in blue). The box plots were generated from all MHW events detected at each grid point
 265 within the delimited regions around each archipelago shown on the Fig. 1a. Panels a–d show, respectively, the maximum intensity reached
 266 in each event, its absolute value, the cumulative intensity, and the duration. The whisker plot limits are indicated on the right side using a
 267 labeled box plot example. In panel b, the mean value is not shown because it is very close to the median, and displaying both would reduce
 268 the readability of the plot. The difference between the mean and median maximum intensity can be assessed in panel a. Panel (e) displays
 269 the annual evolution of the number of MHW days (thick lines) over each archipelago along with their linear trends (dashed lines). Line
 270 colors match the archipelago colors used on the x-axes of panels c and d. The estimated trend slopes expressed in MHW days per decade
 271 are 6.1 days.decade⁻¹ for the Marquesas ($p = 0.26$), 8.6 days.decade⁻¹ for the Gambier ($p = 0.001$), 8.5 days.decade⁻¹ for the Tuamotu ($p =$
 272 0.002), 13.9 days.decade⁻¹ for the Austral Islands ($p \approx 10^{-6}$), and 10.2 days.decade⁻¹ for the Society Islands ($p \approx 10^{-5}$). The daily proportion

273 of FP covered by MHWs is shown in light gray, with its corresponding linear trend indicated by a gray dashed line. The slope of the gray
274 dashed line is $0.025 \text{ decade}^{-1}$ ($p < 10^{-7}$).

275

276 Additional metrics, such as onset and decline rate and maximum area, are provided in SI (Fig. S4). MHWs develop and
277 decay at a comparable pace across both seasons (MHWs develop slightly faster during the warm season than during the cold
278 season, not shown) and all archipelagos, with median growth rates ranging from 0.09 to 0.13 °C/day and decaying rates
279 ranging from 0.09 to 0.12 °C/day (Fig. S4a,b). MHWs occurring in the Marquesas tend to have larger spatial extents (median
280 of 1.7 million km² which is about 20% of the FP maritime Exclusive Economic Zone) compared to those in the Tuamotu,
281 Society, Austral, and Gambier Islands, where median values range from 400,000 to 600,000 km². Moreover, large MHWs
282 (more than 10⁶ km²) are more frequently detected over the Tuamotu and Society Islands than in the Austral and Gambier
283 Islands.

284 Equivalent analyses to those of Fig. 1 and 2 using the detrended MHW dataset are also available in Fig. S5, S6. In brief,
285 detrending the data does not alter the differences observed between archipelagos but slightly reduces MHW intensities across
286 all regions, except in the Marquesas where the SST trend is weak and negative (Fig. S2). Detrending also reduces MHW
287 duration across all archipelagos. Consequently, cumulative intensity is slightly reduced everywhere except in the Marquesas,
288 where it is a bit increased. Additionally, detrending leads to a slight increase in the onset rate of MHWs.

289 The same analysis for MHWs detected in GLORYS over 1993-2024 is shown in SI (Fig. S7). For the FP region, median
290 values and inter-archipelagos differences are consistent between OISST and GLORYS. However some differences can be
291 seen, detected MHWs are generally longer and weaker in GLORYS than in OISST in agreement with Pilo et al., (2019) and
292 Chevillard et al., (2025). Despite these differences, the coherence between the products gives us confidence in the ability of
293 GLORYS to simulate the past MHWs realistically and thus to analyze processes underlying MHWs in GLORYS (cf section
294 5).

295

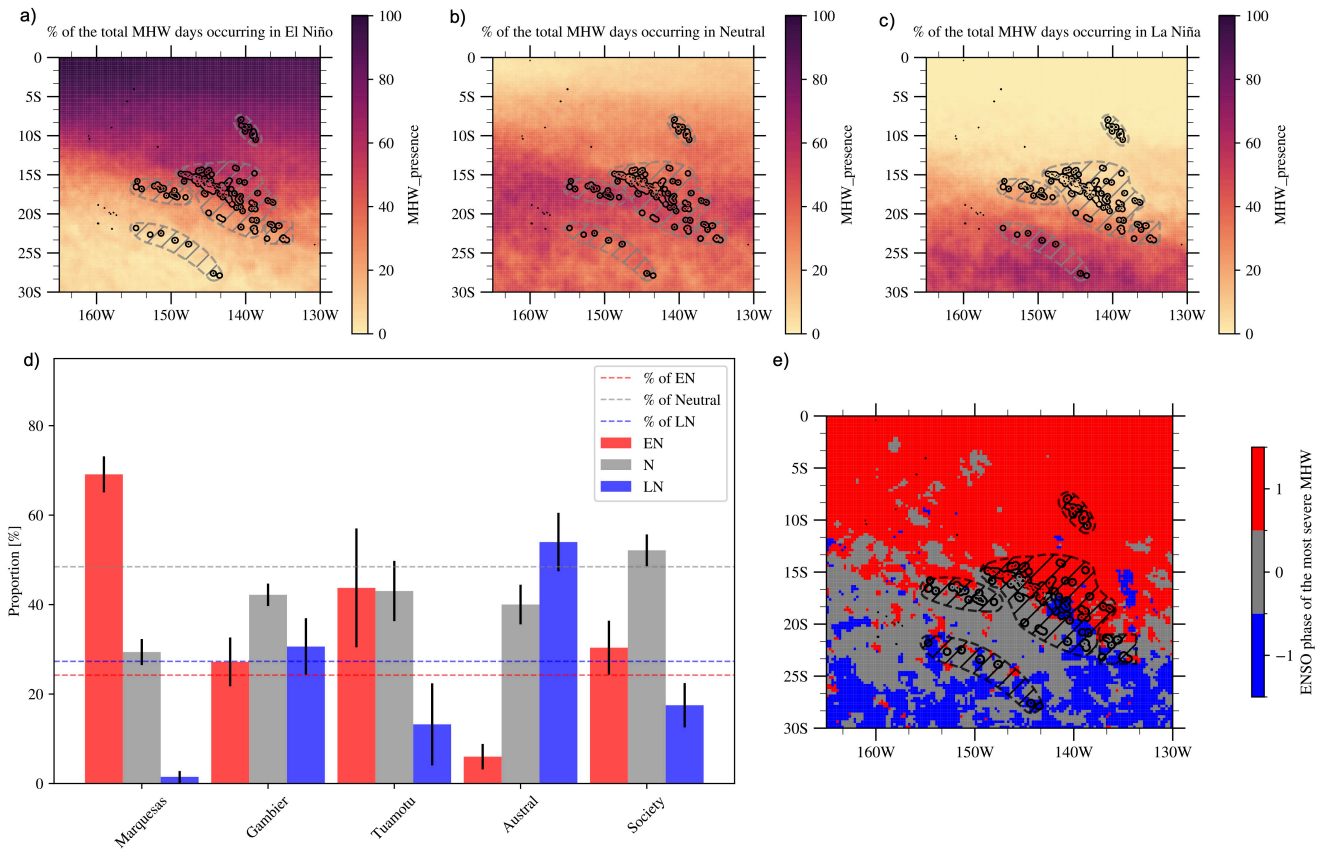
296 **4- ENSO as a driver of MHWs**

297 We now analyse the link between ENSO and MHWs properties, and examine the modulation of MHWs by ENSO. In section
298 4.1, we first simply separated days into El Niño (EN), La Niña (LN) or Neutral (N) conditions (without differentiating
299 seasons, cf. Methods for identification of EN and LN periods). Section 4.2 discusses ENSO spatial diversity/flavors using
300 the Pagli et al. (2025a,b)'s classification. MHWs analyzed here are those detected in the detrended SST of OISST (cf.
301 section 2.2).

302 **4.1- Modulation of MHW occurrence and intensity**

303 Figure 3a–c shows the proportion of MHW days occurring during EN, N, and LN conditions at each grid point. Using the
304 proportion of MHW events starting in EN/LN/N instead of days does not change the conclusions (not shown). A clear spatial
305 modulation of MHWs by ENSO emerges. During EN, MHWs are more frequent in the northeast region—from the Society
306 and northern Tuamotu to the Marquesas—where up to 70% of MHW days occur during EN (Fig. 3d). In contrast, MHWs are
307 less common in the Austral islands during EN, accounting for only 5% of MHW days (Fig. 3d). During LN, the spatial
308 distribution of MHW shifts southwestward, with ~60% of MHW days in the Austral islands occurring during this phase (Fig.
309 3d). In the central region, where MHWs mostly occur during N periods (Fig. 3b), EN still enhances MHW occurrence over
310 the Society and Tuamotu archipelagos (Fig. 3d). For the Gambier Islands, EN and LN show no significant effects (Fig. 3d).
311 Figure 3e shows the ENSO phase associated with the start time of the most severe MHW (in terms of S, cf. section 2.2) at
312 each grid point, which closely aligns with the spatial modulation patterns described above. The most intense MHWs in the
313 northeastern region (north and east Tuamotu and Marquesas) tend to occur during EN, while those in the southwestern
314 region (Austral and south Tuamotu) are mostly associated with LN. In the central region (Society, west Tuamotu, Gambier),
315 the signal is more variable, but the most severe events are triggered during neutral phases.

316



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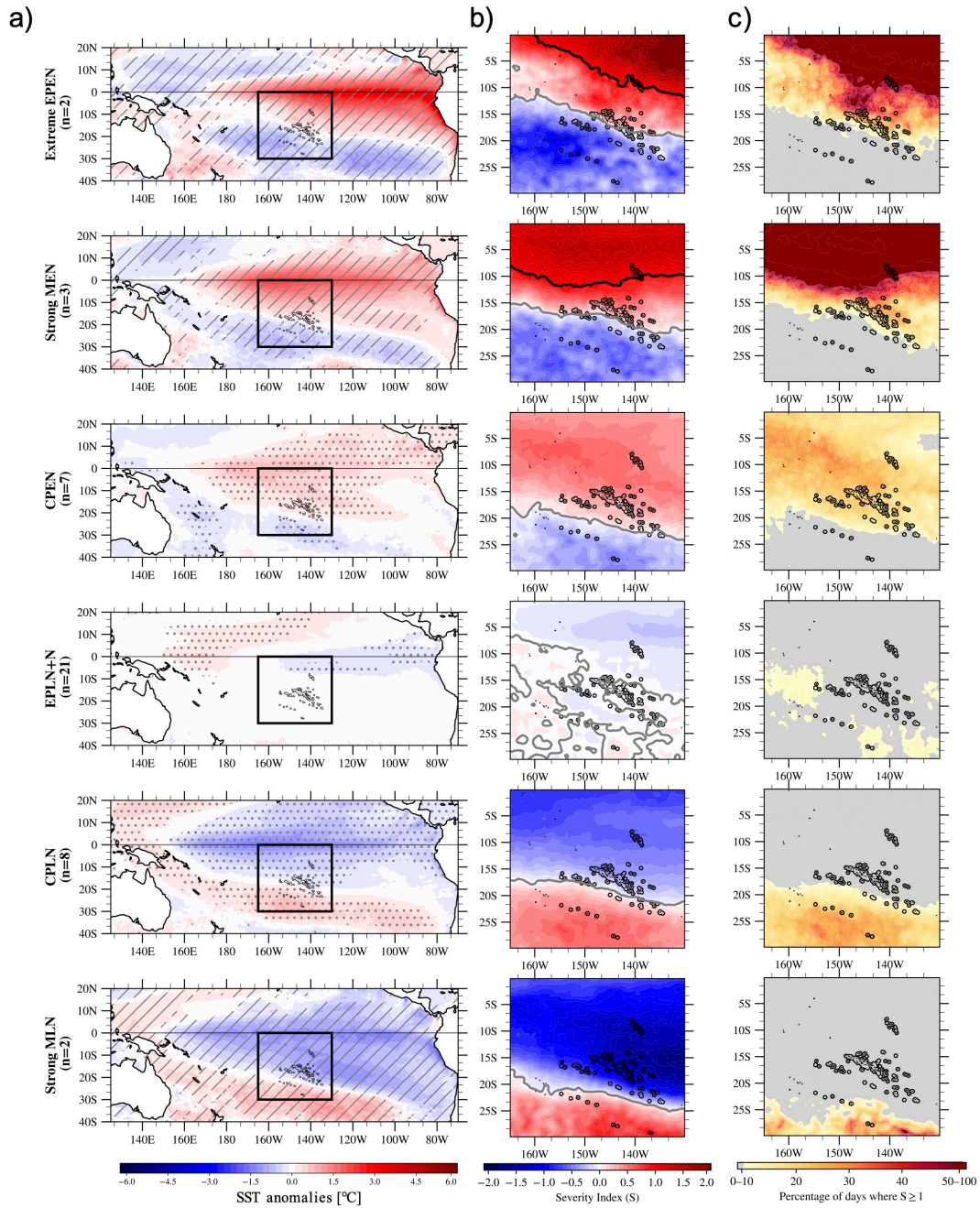
318 **Figure 3.** Proportion of MHWs occurring during different ENSO phases: El Niño (panel a), Neutral (panel b), and La Niña (panel c).
 319 Panel d shows the average percentage of MHWs associated with each ENSO phase for the five archipelagos of FP. The horizontal dashed
 320 lines indicate the proportion of El Niño (red), La Niña (blue), and Neutral (gray) days over the study period (1981–2024). Comparing the
 321 bars with the same-colored dashed lines—showing the fraction of El Niño/La Niña/Neutral days in that period—reveals how strongly
 322 ENSO modulates MHW occurrence. Black error bars indicate the spatial standard deviation of the statistics calculated across grid points
 323 associated with each archipelago area (black dashed outlines in panel e). Panel e shows the ENSO phase associated to the start time of the
 324 most severe MHW at each grid point (defined following the categories of Hobday et al., 2018, cf. Methods). SST was detrended prior to
 325 MHW detection for this analysis (similar results were obtained without removing the trend, not shown). The same figure for austral and
 326 boreal summer MHWs separately is shown in SI, Fig. S8-S9. Also, similar modulation is obtained in GLORYS over the same period (not
 327 shown).

328

329 Similar conclusions were obtained with MHWs detected without having removed the trend in OISST as well as with MHWs
 330 detected in GLORYS over the same period (not shown). As shown in SI (Fig. S8 and S9), the MHW spatial patterns
 331 modulated by ENSO revealed in Fig. 3 are exacerbated during austral summer (NDJFMA) during the peak of ENSO events
 332 but weakened during austral winter (MJJASO). We therefore focus on the austral summer season for a more in-depth
 333 analysis that includes ENSO diversity.

334 **4.2- Modulation of MHWs by the diverse flavors of ENSO**

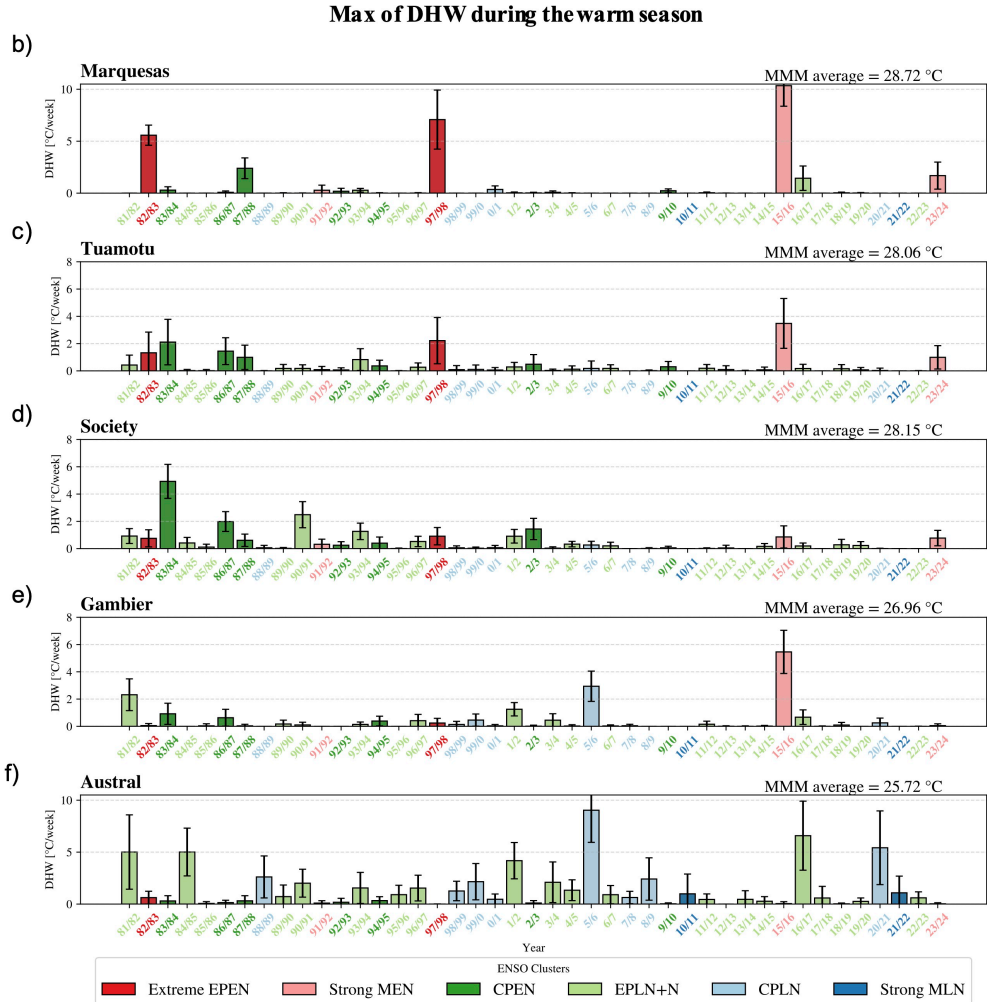
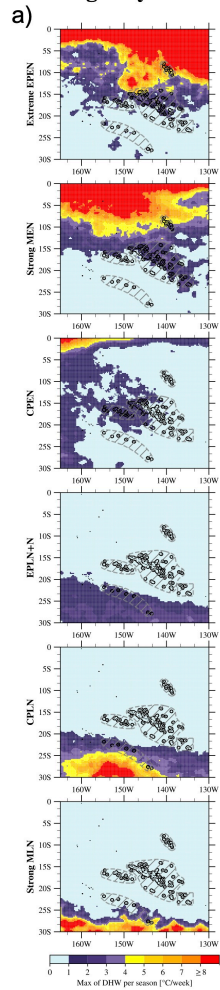
335 There is an important diversity of ENSO impacts during austral summer over FP especially in terms of SST intensities and
336 spatial patterns (Pagli et al., 2025a and Fig. 4a). Figure 4 recalls the six ENSO clusters defined by Pagli et al. (2025a,b) at
337 the FP scale (cf. section 2.2 and Table S1). NDJFMA composites (average across years of each cluster) of SST anomalies at
338 the Pacific scale (in °C) and local scale (expressed in terms of S index) are shown in panels a and b, respectively. The
339 composite of the percentage of days where $S \geq 1$ is shown in panel c. Figure 5 highlights how the different ENSO flavors
340 impact cumulative heat stress over the warm season at the FP scale, as depicted by DHW that takes into account the time
341 integration of the heat stress and is recognized as an indicator of coral bleaching. The maximum of DHW reached for each
342 austral summer averaged over years from each ENSO clusters is displayed in Fig. 5a and the same quantity averaged over
343 each archipelago and for each year of the period is displayed in Fig. 5b-f. In SI (Fig. S10), MHW intensity, duration, and the
344 number of MHW days composited for each ENSO cluster are displayed.



345

346 **Figure 4.** Composites of SST anomalies (linearly detrended) averaged over NDJFMA for the ENSO classification of Pagli et al., (2025a,b)
 347 at the Pacific scale (a). Cluster composites of S for NDJFMA are shown in the panel b, with isolines corresponding to $S = 0$ and $S = 1$
 348 displayed in gray and black, respectively. The cluster composites of the percentage of days where $S \geq 1$ over NDJFMA is shown on panel
 349 c. Gray (dark red) area corresponds to regions where 0 to 10% (50-100%) of the NDJFMA days satisfy this criteria. In panel a, dots
 350 indicate anomalies significant at the 90% confidence level based on a two-tailed Student t-test. The number of years (n) in each ENSO
 351 cluster is indicated on the y-axis of panel a. For clusters spanning two or three years, gray hatching marks regions where anomalies share
 352 the same sign across all years in the cluster.

**Max of DHW during
the warm season
averaged by cluster**



354

355 **Figure 5.** ENSO cluster composites of the maximum of DHW over the warm season (a) and yearly maximum of DHW averaged over each
 356 archipelago region (b-f). For each archipelago, the spatial average of the Maximum Monthly Mean (MMM) used to compute the DHW is
 357 indicated on the top right of panels b-f. Year labels on x-axis and bars are colored by ENSO cluster. The black error bars show ± 1 standard
 358 deviation across all pixels within each archipelago area. These results were computed using detrended SST data; for DHW values based on
 359 non-detrended SST data, see Fig. S11.

360

361 Figure 4 refines the ENSO modulation of MHWs during the warm season, as introduced in section 4.1 (Fig. 3). On average
 362 over the austral summer, during strong EN events, classified in strong Mixed EN (MEN) and extreme Eastern Pacific EN
 363 (EPEN) clusters, the Marquesas region and equatorward areas remain in a MHW state throughout the entire summer (90–
 364 100% of MHW days, and $S \geq 1$ on average over the 6 months; see Fig. 4b,c). These MHWs are very long and intense (Fig.

365 S10b,c), resulting in exceptionally strong cumulative heat stress over this region (Fig. 5a). Further south, MHWs are favored
366 ($0 < S < 1$) in a band extending from the Marquesas to northern Tuamotu and Society Islands only (Fig. 4b,c). Over this
367 MHW-favored area, the proportion of days with $S \geq 1$ during the warm season increases gradually from south (10%) to north
368 (50%). In contrast no MHWs are detected in the far southern regions during strong MEN and extreme EPEN events. During
369 Central Pacific EN (CPEN), all archipelagos—except the Austral Islands—experience SSTs warmer than usual (Fig. 4a),
370 though still below the MHW threshold on average over the austral summer (Fig. 4b). These warmer SST favor MHW
371 development and result in an average of ~30% MHW days during the warm season (Fig. 4c), with a slight increase of
372 cumulative heat stress on average for central regions (Fig. 5a). Conversely, in the southwest, S values are on average
373 negative (Fig. 4), indicating unfavorable conditions for MHWs. During neutral years to weak LN (EPLN+N), S anomalies
374 across FP are weak and close to zero, only a few MHWs occur during some of these years over this region. During Central
375 Pacific LN (CPLN-englobing most of the LN events), MHWs are favored in the southern Society Islands, extreme south
376 Tuamotu, and the Gambier Islands, with around 20–30% of MHW days over the warm season. MHWs are generally
377 unfavored elsewhere. This leads to an increase of cumulative heat stress in the Austral Islands (Fig. 5a). Finally, during
378 strong Mixed LN (MLN) events, MHWs are favored exclusively in the extreme south of the Austral Islands (i.e., Rapa Iti),
379 where they are associated with strong cumulative heat stress, while unfavorable conditions prevail across the rest of FP (Fig.
380 5a).

381 Periods of increased cumulative heat stress coincide spatially with positive SST anomalies associated with the ENSO
382 clusters. However, the magnitude of DHW can vary from year to year even for similar mean SST anomalies over the season
383 and across archipelagos. This is because it reflects the time-integrated effect of SST anomalies and therefore the risk for
384 coral bleaching is not systematically reached where ENSO-related SST anomalies are positive (Fig. 5b-f). In the Marquesas,
385 very strong cumulative heat stress occurred during the 1982/83, 1997/98, 2015/16, and 2023/24 El Niños (extreme EPEN and
386 strong MEN) while 1991/92 (a strong MEN) was comparatively associated with weaker cumulative intensity (Fig. 5b). We
387 can note also that 1987/88 (CPEN) produced a strong heat stress over the Marquesas. In the Tuamotu, the same years in
388 addition to 1983/84, 1986/87 (CPEN) are linked to the highest cumulative heat stress (Fig. 5c), but with lower cumulative
389 heat stress than in the Marquesas. Interestingly, the 1991/92 strong MEN event, despite being extreme for FP in terms of
390 SPCZ displacement and tropical cyclone activity (Vincent et al., 2011; Pagli et al., 2025a,b), was not as intense in terms of
391 MHWs over the Marquesas and Tuamotu. In the Society archipelago, 1983/84, 2009/10, 2002/03 (CPEN) and neutral years
392 1990/91, 2016/17 (EPLN+N) correspond to the strongest DHW values (Fig. 5d). While strong MEN and extreme EPEN
393 years also produce considerable cumulative intensities in this region, they are not the highest, highlighting that the strongest
394 EN events (as defined on a global scale) do not always correspond to the most severe impacts over FP. In the Gambier
395 Islands, both EN and LN events can produce significant cumulative heat stress (2005/06 CPLN and 2015/16 strong MEN)
396 during the warm season (Fig. 5e), with no consistent influence of specific ENSO clusters on the cumulative heat stress. This
397 aligns with the unclear ENSO modulation highlighted for the Gambier Islands in Fig. 3. In the Austral Islands, the strongest
398 cumulative heat stress are observed in 1988/89, 2005/06 and 2020/21 LN years, particularly CPLN events.

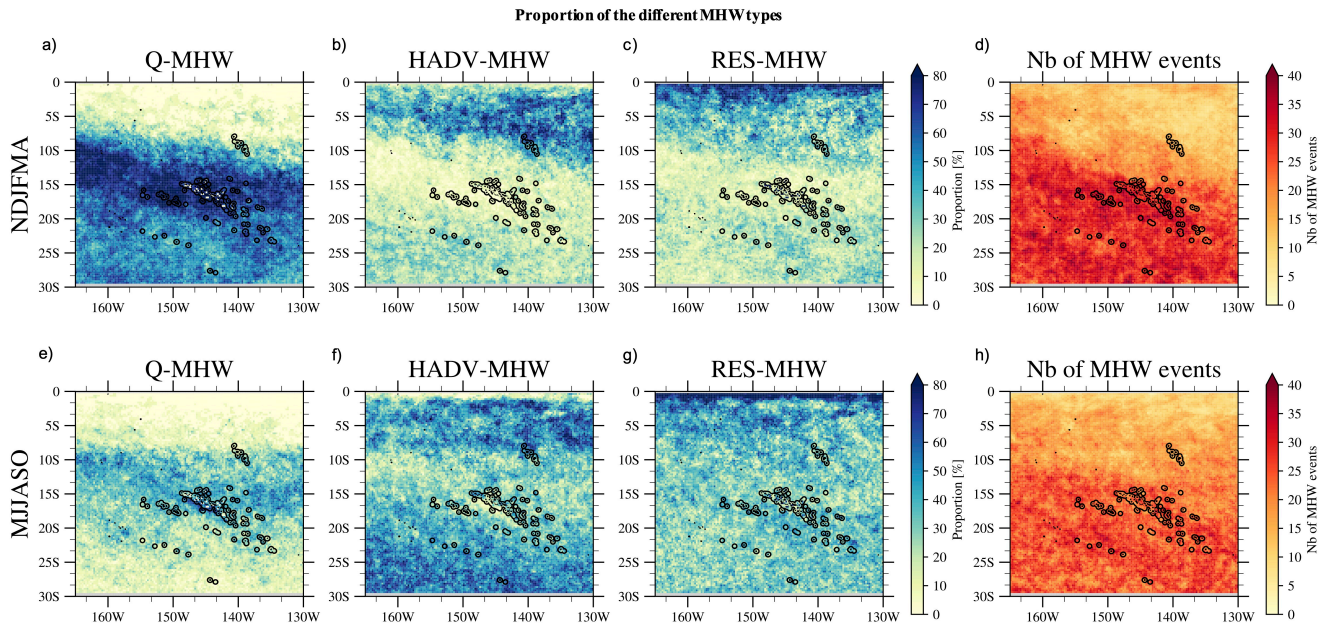
399 These conclusions were drawn from analyses based on detrended SST data, aiming to isolate the ENSO imprint on
 400 cumulative heat stress over FP. However, when using the non-detrended SST data—which reflects the total heat stress
 401 exposure experienced at the surface—the maximum DHW values over the warm season for years occurring after 2000 are
 402 amplified over the Tuamotu, Society, and Gambier archipelagos (Fig. S11) especially in 2015/16 (strong MEN) that has been
 403 associated with massive wide coral bleaching over FP (Hédouin et al., 2020) and more recently in 2023/24 (strong MEN).

404 5- Physical mechanisms generating and dissipating MHWs over 1993-2020

405 5.1- MHW development

406 In this section we investigate the physical mechanisms of the MHWs in the GLORYS oceanic reanalysis (over the 1993-
 407 2020 period, see Methods in section 2.2). We examined the dominant local mechanisms of MHWs development across the
 408 territory for austral summer and winter separately (Fig. 6)—focusing on air-sea surface heat fluxes, horizontal advection,
 409 and residual terms (see Eq. 2). The residual term consisted mainly of the vertical/horizontal mixing and entrainment at the
 410 bottom of the mixed layer plus implicit heat sources/losses due to the assimilation in GLORYS (see Eq. 3). Also, because the
 411 vertical mixing may be poorly represented in GLORYS (due to the lack of explicit tidal forcing) and because the magnitude
 412 of the data-assimilation increments is unknown here, interpreting in detail this residual is beyond the scope of this study.

413



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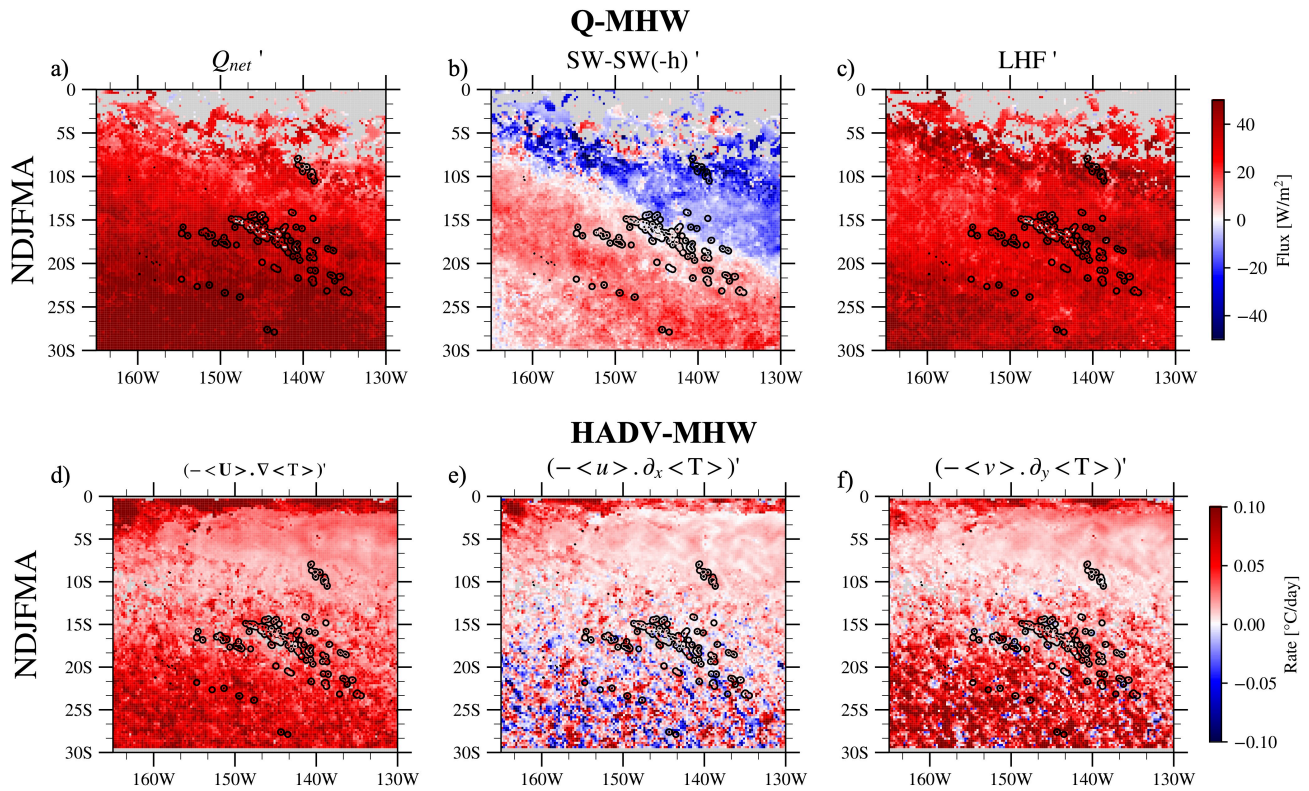
415 **Figure 6.** Proportion of the different MHW types for all events detected in austral summer and austral winter separately (d,h) in GLORYS,
 416 during the 1993-2020 period. Panels a and e show the proportion of Q-MHWs in austral summer and winter, respectively; panels b and f
 417 show HADV-MHWs; panels c and g show RES-MHWs. Mixed events are not shown, as they represent only a small number of cases.

418 MHWs are driven by different mechanisms depending on the region and the season (Fig. 6), and a strong differentiation
419 appears at about 10°S. During austral summer, MHWs are primarily driven by air/sea fluxes in most archipelagos south of
420 10°S, especially in the central regions (Society and central Tuamotu), accounting for 70–80% of total events (Fig. 6a).
421 HADV-MHWs and RES-MHWs represent 0 to 30% of the total events except for MHWs occurring in the equatorward
422 region, north of 5°S/10°S (Fig. 6b,c). Here, HADV-MHWs dominate and account for 60-70% of the events south of 2°S.
423 The residual becomes dominant in a thin equatorial band due to the particular dynamics of the region with notably the
424 equatorial upwelling (e.g. Deppenmeier et al., 2021). During austral winter, the proportion between MHWs types is more
425 balanced in central regions with a slight dominance of Q-MHWs compared to HADV-MHWs and RES-MHWs (Fig. 6e,f,g).
426 HADV-MHWs proportion increases across the southern subtropical region (south of 20°S) compared to summer accounting
427 for more than 60% of total events. RES-MHWs proportion slightly increases across FP in winter compared to summer too.
428 Following our classification criteria (cf. section 2.2), mixed-MHW were almost never defined over both seasons (not
429 shown).

430

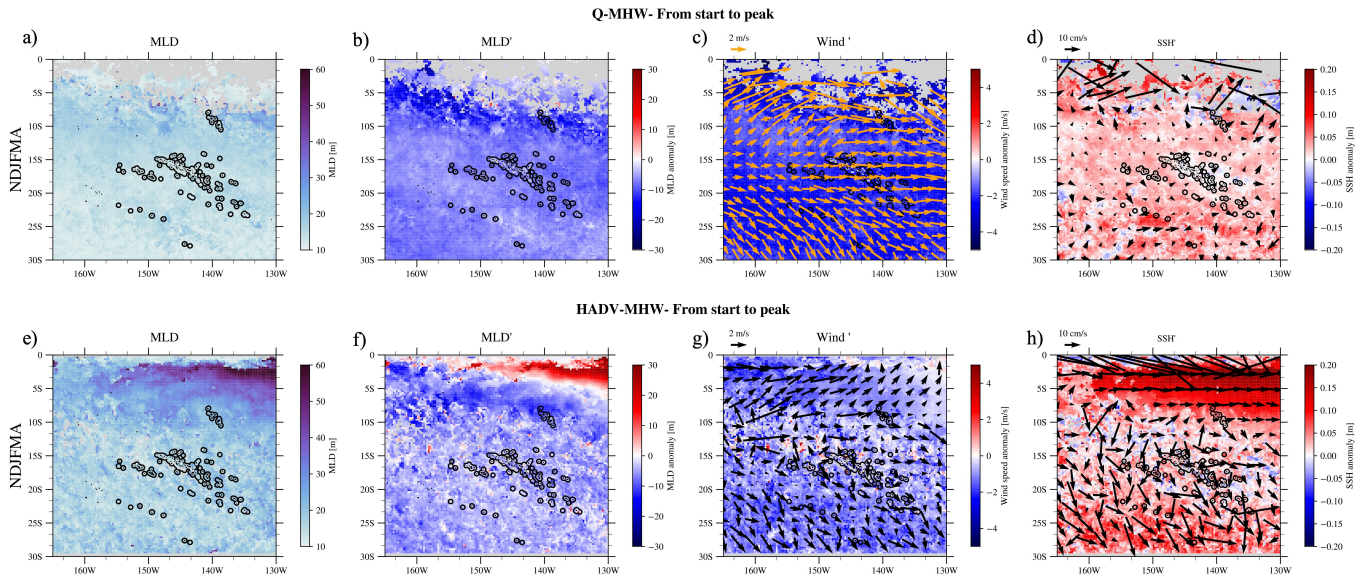
431 We now look at the mechanisms of MHW development for Q-MHWs and HADV-MHWs separately. For each MHW type,
432 the terms in Eq. (2) were averaged from start to peak at each grid point and then composited over all events for austral
433 summer and winter separately (Fig. A1). Only the results for the austral summer MHWs are presented in this section and
434 those for austral winter MHWs are available in Appendix A. The standard deviation associated to the mean composites
435 presented in Fig. A1 and A2 are presented respectively in Fig. S12 and S18. Because Q-MHWs are, by construction,
436 dominated by the air–sea heat budget term contribution, we focus on Q_{net} and its leading components, shown in Fig. 7a–c.
437 Conversely, since HADV-MHWs are driven by horizontal advection contribution, we focus in Fig. 7d–f on the horizontal
438 heat advection term and its zonal and meridional components. MLD (full field and anomalies), wind, SSH, and surface-
439 current anomalies are shown in Fig. 8. These results for austral winter are available in SI.

From start to peak



440

441 **Figure 7.** Composites of the net air-sea heat flux (and its dominant components : SW-SW(-h) and LHF) for Q-MHWs and of the
 442 horizontal-advection term (and its decomposition into zonal and meridional components) for HADV-MHWs, for events peaking in the
 443 warm season (NDJFMA), averaged over the onset-to-peak period (cf. section 2.2). Panels a-c show Q-MHW composites of (a) net air-sea
 444 heat flux Q_{net} (b) the net shortwave flux stored in the mixed-layer (SW - SW(-h)), and (c) LHF anomalies. Panels d-f show HADV-
 445 MHW composites of (d) horizontal advection and its (e) zonal and (f) meridional components. In each panel, the composite corresponds to
 446 the averaged across all MHWs of the corresponding type (Q-MHW or HADV-MHW) detected at each grid point.



447

448 **Figure 8.** conditions from start to peak of Q-MHWs (upper panels (a–d)) and of HADV-MHWs (lower panels (e–h)). MLD (a, e), MLD
 449 anomalies (b, f), 10m-wind (speed and direction) anomalies (c, g), and SSH with oceanic currents averaged over the upper 0–30 m (d, h)
 450 for MHWs in NDJFMA. Anomalies are relative to the mean seasonal cycle computed over the whole period (1993–2020).

451

452 Q-MHWs

453 The Q_{net} anomalies driving Q-MHWs development are dominated by LHF anomalies (Fig. 7a–c). Anomalously weak surface
 454 winds (Fig. 8c) reduce evaporation, thereby warming the mixed layer. The net SW anomalies in the mixed-layer play a
 455 secondary role but still modulate Q_{net} during Q-MHWs onset in summer, with a spatially complex pattern (Fig. 7b). In the
 456 northeast, where most events occur under EN, negative net SW anomalies in the mixed layer tend to damp Q-MHWs
 457 development. They are negative because incoming SW anomalies are weakly positive or negative (Fig. S13b) due to
 458 enhanced convection during EN (Pagli et al., 2025a) and thus do not offset the increased SW loss through the mixed-layer
 459 base (Fig. S13c) caused by a shoaled mixed layer under anomalously weak winds (Fig. 8b,c). In the southwest by contrast,
 460 where MHWs are favored during LN, net SW anomalies generally reinforce the warming during the onset of the event,
 461 consistent with clearer skies and enhanced incoming SW (Fig. S13a,b,c) typically seen during LN due to anomalously dry
 462 conditions over austral summer (Pagli et al., 2025a).

463 Although air–sea flux anomalies account for most of the variability in the $Q_{net}/(\rho C_p h)$ term of Eq. (2), mixed-layer shoaling
 464 during onset (Fig. S15e) slightly increases the air/sea flux-term warming. In other words, a shallower mixed layer heightens
 465 its sensitivity to flux changes. Still, this effect is minor compared with the flux anomalies themselves (Fig. S15c). Horizontal
 466 advection does not exhibit a strong and systematic contribution for Q-MHWs during onset, as indicated by the noise present
 467 in HADV-MHWs composite during MHW development (Fig. A1c).

468 Results are broadly similar across seasons (Fig. A1e-h Fig. S14a-c, and Fig. S13d-f). During austral winter—when the
469 seasonal mixed layer is thicker—the required LHF anomalies, and thus the wind-speed anomalies needed for Q-MHWs to
470 develop, are larger than in austral summer (Fig. S17a,b,c). This also explains why Q-MHWs are more frequent in austral
471 summer than in austral winter (Fig. 6a,b). Also, in winter, SW variations during MHW development are highly event-
472 dependent with no clear pattern on the composite shown in Fig. S14b. They can either reinforce or damp the warming
473 associated to reduced evaporation (Fig. S14a,b,c).

474

475 **HADV-MHWs**

476 North of 10° S (but south of 3°S, out of the equatorial wave guide)—where most HADV-MHWs occur during EN (cf. Fig. 3
477 and 4)—both zonal and meridional heat advection contribute (Fig. 7d,e,f). The warming during the onset is associated to
478 eastward current anomalies that transport the climatologically warmer waters from the west (Fig. 8h, $u' \cdot \partial_x \bar{T}$ in the $\mathbf{U}' \cdot \nabla \bar{T}$
479 term, Fig. S16g, h). In addition, the EN-enhanced SST gradient is advected by the mean circulation to higher latitudes,
480 fueling HADV-MHWs' onset south of 10° S and up to 20°S ($\bar{\mathbf{U}} \cdot \nabla T'$ term, Fig. S16d,e,f).

481 Moving southward, the signal becomes noisier, but meridional advection shows the most systematic warming during the
482 development stage (Fig. 7f). This arises from persistent southeastward anomalous currents that can be forced directly by
483 wind anomalies (Fig. 8g, h) and/or from geostrophic adjustment and/or from anomalous circulation linked to westward-
484 propagating anticyclonic eddies (positive SSH, Fig. 8h; the composite method, done for MHWs at each grid point separately,
485 smooths out eddy patterns, with only their SSH contribution during the MHW's onset at the grid point being visible), which
486 likely also contribute to the noise seen in Fig. 8h.

487 Air-sea flux contributions during HADV-MHWs are less systematic as shown by the noise present in the composite in Fig.
488 A1j, sometimes reinforcing the advective warming and sometimes damping it from one event to another. Nevertheless, in the
489 Marquesas—where most events occur under EN—the net air/sea heat flux term tends, on average, to damp the MHW
490 development (Fig. A1j). Southwest of the Marquesas, over other archipelagos, the air/sea flux term generally provides a
491 slight warming, though with strong event-to-event variability (Fig. A1j). Conclusions about the onset mechanisms of
492 HADV-MHWs are very similar in austral winter (Fig. A1m-p).

493 The residual term contribution to MHW onset composited for Q-MHWs and HADV-MHWs presents a strong inter-event
494 variability and is hard to interpret here (Fig. A1d, h, l, p). On average, for MHWs occurring north of 10°S, the residual
495 term contributes to the warming of the mixed layer during the MHW onset for both Q- and HADV-MHWs and over both
496 seasons. This may be linked to reduced vertical mixing caused by the weaker winds and shallower MLD observed during the
497 MHW development (Fig. 8b, c, f, g and Fig. S17b, c, f, g).

498 RES-MHWs constitute a substantial fraction of events over FP (Fig. 6c,g). Fig. A1q-x shows the composites of the different
499 terms of Eq. (2) during their onset. By construction, their development is driven by the residual term which may be
500 dominated by vertical processes (mixing and entrainment), while contributions from air-sea fluxes and horizontal heat
501 advection are highly variable from event to event and show no systematic pattern.

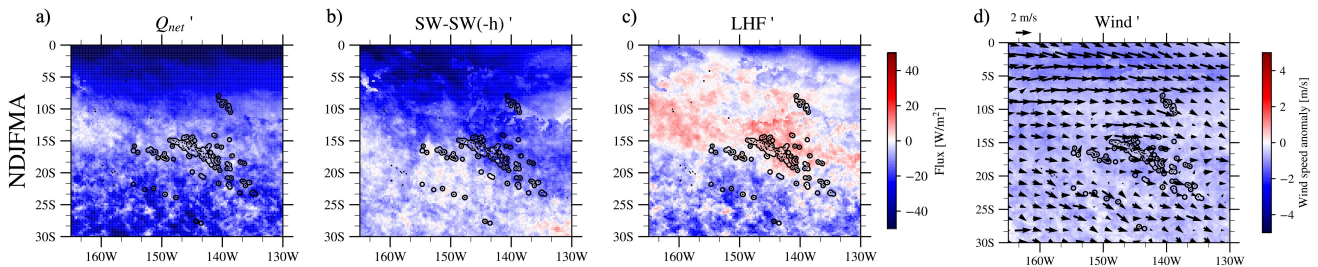
503 **5.2- MHW decay**

504 We now investigate the decay stage (peak to end) of MHWs over FP. As the classification into different MHWs types has
 505 been solely designed for the developing phase (classification criteria applied regarding the terms contribution integrated
 506 from onset to peak time, cf. section 2.2), we used all MHWs together to study the decaying stage of MHWs (after verifying
 507 that decaying mechanisms do not significantly differ between MHWs types).

508 In austral summer, the transition from onset to decay (Fig. 9a,d) is dominated by cooling from the air–sea heat-flux budget
 509 term of Eq. (2) (Fig. A2). It is mainly due to negative Q_{net} anomalies that are mainly explained by the anomalies of the net
 510 SW in the mixed-layer in the north and of surface LHF in the south (Fig. 9a, b, c). Over the northeastern half of FP, it is the
 511 negative incoming SW anomalies that explain the most the cooling of mixed-layer temperature while LHF' continues on
 512 average to warm but with a strong inter-events variability. In the southwestern half, it is more systematically the cooling due
 513 to negative LHF anomalies i.e. increased evaporation that causes the decaying of MHWs. This can be due to increases in
 514 wind speed and/or SST or to a decrease in air moisture above the ocean surface (a drier air mass increasing evaporation).
 515 When looking at the composite of the wind speed anomalies for the MHW decay (Fig. 9d), these are still negative, but less
 516 than during onset, meaning that MHW warm SST and/or decrease in the surface atmosphere moisture may play a role.

517 In austral winter, the role of SW anomalies weakens and on average MHW decay is caused mainly by negative LHF
 518 anomalies that are more systematically associated to positive or neutral wind speed anomalies (Fig. S19), with possibly also
 519 a role of warm SST.

All MHWs - From peak to end



520

521 **Figure 9.** Composites of the net air–sea heat flux (and its dominant components) as well as surface wind anomalies averaged over the
 522 decay period i.e. from peak to end (cf. Methods) for all MHWs peaking in austral summer. Panels a–c show MHW composites of (a) net
 523 air–sea heat flux Q_{net} (b) the net shortwave flux in the mixed-layer ($SW - SW(-h)$), and (c) LHF anomalies. In each panel, the composite
 524 is averaged across all MHWs (without distinguishing by type as done during the onset period) detected at each grid point.

525

526 During MHW decay, the residual term is more spatially coherent and exhibits less noise (Fig. A2d,h) than during the onset
 527 for Q- and HADV-MHW types (right column of Fig. A1). In austral summer, it produces anomalous warming of the mixed

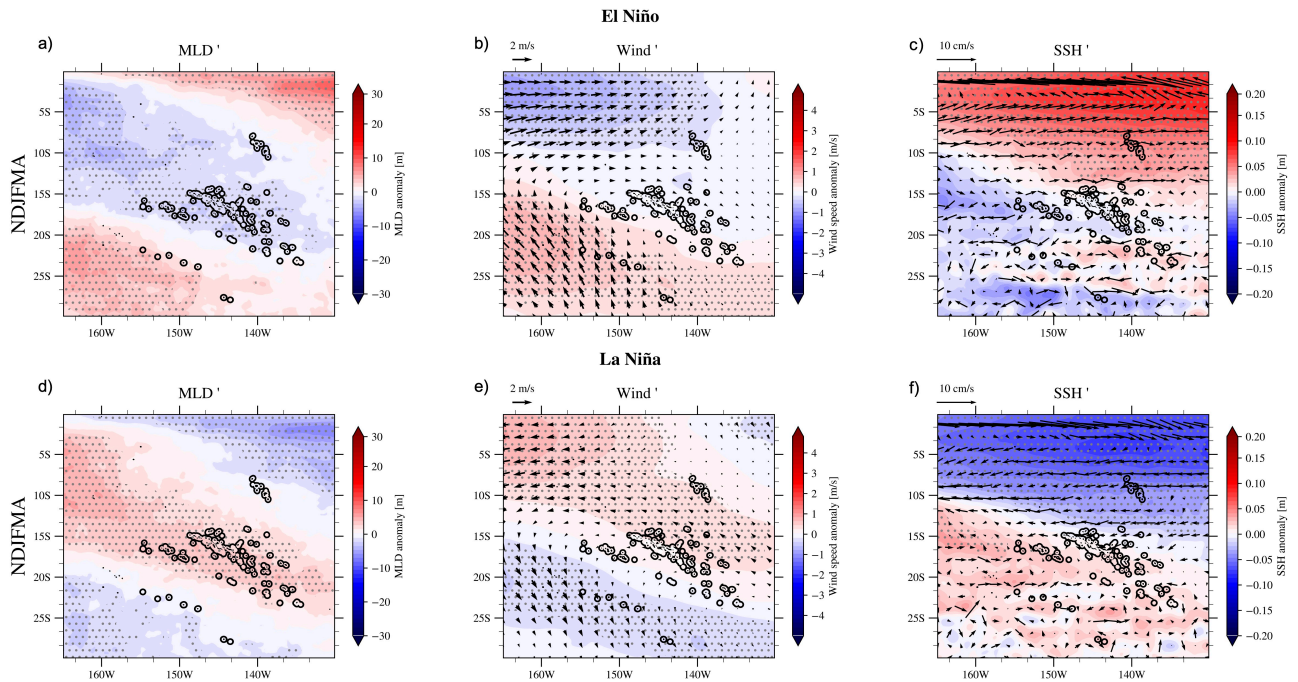
528 layer; in austral winter, it warms north of $\sim 10^{\circ}\text{S}$ and cools south of $\sim 15^{\circ}\text{S}$. The nature of the residual is complex and can
529 result from different processes. The ability of their parametrization in GLORYS and the increments of data assimilation vary
530 in space and time. Our approach (heat budget not completely closed in a reanalysis) does not allow us to interpret more in
531 depth this residual term. Modeling approaches capable of accurately resolving this term could enhance our understanding of
532 the underlying processes.

533

534 **5.3- The role of ENSO**

535 The role of ENSO and its diversity in modulating the spatial distribution of MHWs has been highlighted in section
536 3.2 (Fig. 3, 4, 5). The preceding details on the mechanisms involved during the onset and decay phases of MHWs across FP
537 further help to understand ENSO's influence. EN generates positive SST anomalies over the northeastern half of FP and
538 negative anomalies over the southwestern half, with the opposite pattern observed during LN (Fig. 4). These SST anomalies,
539 depending on their signs, reduce or increase the gap to the MHW threshold depending on the region, thereby creating a
540 favorable or unfavorable background state for MHW development. Figure 10 displays surface wind, mixed layer, SSH and
541 surface currents averaged for EN and LN separately. EN periods are characterized by a significant shoaling of the mixed
542 layer, and reduced wind speeds across most archipelagos, therefore creating a favorable environment for MHWs
543 development (by reducing evaporation, rendering the mixed-layer more sensitive to warming from air/sea fluxes and
544 potentially also reducing the efficiency of vertical processes – upwelling, mixing, entrainment - in cooling the mixed layer)
545 over most regions except around Austral Islands (Fig. 10a,b). In addition to that, eastward current anomalies to the north
546 bring warmer waters from the west and induce deeper thermocline over the northeastern part. Conversely, LN periods are
547 associated with a deeper mixed layer over most regions, limiting the MHWs' development. Furthermore, LN events are
548 associated with a deeper (shallower) thermocline to the southwest (northeast) and a shallower mixed layer and weaker winds
549 over the Austral Islands and their southwestern margins due to the anomalous northwesterly winds (Fig. 10e). This clearly
550 aligns with the spatial modulation of MHWs by ENSO revealed in Fig. 3. ENSO thus acts as a large-scale forcing over FP,
551 promoting the development of MHWs in some regions while inhibiting them in others. Although a full characterization of
552 how different ENSO flavors modulate MHW mechanisms is beyond the scope of this study, Fig. 4–5 suggest that both the
553 spatial pattern and the amplitude of wind, mixed-layer and currents interannual anomalies likely depend on the ENSO flavor,
554 consistent with flavor-dependent wind and precipitation anomalies (Pagli et al., 2025a). This can explain the differences
555 observed in MHW properties and occurrences during the different EN and LN flavors (Fig. 4,5, S10).

556



557

558 **Figure 10.** Austral summer El Niño and La Niña composites of the MLD (a,d), 10m-wind speed and direction (b,e), SSH and oceanic
559 horizontal currents averaged from the surface to 30m (c,f) anomalies. Gray dots mark anomalies significant at the 95% confidence level
560 (two-tailed Student t-test). The effective number of degrees of freedom have been computed as $n \frac{(1-\rho_1)}{(1+\rho_1)} - 1$ following Bretherton et al.,
561 (1999) where ρ_1 is the lag-1 autocorrelation of the each field and n is the total number of timestep (number of days here).

562 6- Discussion

563 Our results regarding the classification of MHWs into different types (Q, HADV, RES) over the South Central Pacific (Fig.
564 6) align with previous global modeling studies investigating dominant MHW mechanisms with mesoscale-resolving models
565 (Marin et al., 2022, Bian et al., 2023,2024) when looking at the spatial repartition of Q-MHWs and HADV-MHWs
566 dominated-regions. It is interesting to note that the conclusions obtained here about the mechanisms of all MHWs in FP
567 correspond to that obtained by looking at the most extreme events over the region in the global-scale study of Marin et al.,
568 (2022) (their Fig. 3 and 4). RES-MHWs, which are predominant in the equatorial region north of 2°S, have been mainly
569 attributed to anomalous vertical mixing processes that warm the mixed layer during the onset and decay phases (Bian et al.,
570 2023). Further south, over FP, the residual contributions observed during onset and decay in our analysis (Fig. A1, A2) have
571 not been explored in detail in this study because the amplitude of the data assimilation increments is unknown. Nevertheless,
572 as stated in our study this residual may partly reflect the effect of weakened winds during MHW onset and decay (Fig. 9)
573 that are favored by EN (in the northeast) and LN (in the southwest), which can reduce vertical heat transfer through diffusion
574 and local mixing (Vogt et al., 2022). It has also been shown that mesoscale eddies can inhibit the vertical mixing driven by
575 internal waves over the region, limiting subsurface cooling and thereby promoting the development of extreme subsurface

576 temperatures (Wyatt et al., 2023). Tides—and therefore internal tides—are not explicitly represented in GLORYS, and FP is
577 a major internal-tide generation region (Zaron, 2019). The substantial number of RES-MHWs detected over FP (Fig. 6c,g)
578 therefore highlights the need for regional modeling that resolves tidal processes.

579 One limitation of our study is its focus on surface temperatures, whereas extreme temperatures can also occur throughout the
580 water column with severe impacts on ecosystems (Wyatt et al., 2023) — either synchronously with the surface, more intense,
581 less intense, or even entirely decoupled from surface extremes (Zhang et al., 2023). The mechanisms driving these
582 subsurface extremes may differ from those at the surface revealed in this work, due to the vertical structure of ocean currents
583 in the region and the progressive attenuation of air–sea flux influences with depth. Our analysis gives confidence in
584 GLORYS, to study vertical extent of MHW. Lal et al. (2025) showed that surface MHWs in the extreme western part of FP
585 are generally confined to the seasonal mixed layer north of 20°S, but extend deeper south of this latitude, providing an
586 indication of what might be expected for the vertical extent of MHWs detected over FP in this study.

587 We showed that ENSO provided favorable or unfavorable background conditions for MHW development during the warm
588 season and to a lesser extent over the austral winter, depending on the region within FP and the ENSO phase. However,
589 except in the extreme northern regions, including the Marquesas during extreme EPEN and strong MEN events—where the
590 surface ocean remains in a persistent MHW state throughout the whole warm season—the actual triggers of the mechanisms
591 creating MHW onset (extreme LHF and SW anomalies) remain to be fully understood. Intra-seasonal processes such as the
592 Madden–Julian Oscillation (MJO), equatorial wave activity, and/or stochastic weather/oceanic events (Tropical Cyclones,
593 prolonged periods of high/ weak surface winds, prolonged precipitation/clear sky periods, SPCZ intra-seasonal variability,
594 oceanic eddies) may initiate or terminate MHWs. In this context, ENSO primarily modulated the background state,
595 influencing how these intra-seasonal triggers affect MHW development and persistence (MJO-ENSO compound events as an
596 example, Dutheil et al., 2024). Further work is needed to understand how ENSO and these higher frequency variations
597 interact together.

598 Our work builds on ongoing efforts to understand the characteristics and mechanisms of MHWs across South Pacific
599 countries (Holbrook et al., 2022, Dutheil et al., 2024; Lal et al., 2025). MHWs display distinct features between the western
600 and central South Pacific, underscoring the need for such regional analyses. Even within the FP region, while we present
601 results at the archipelago scale, notable variability was found within the Tuamotu archipelago itself, which spans from about
602 10°N to 23°S (Fig. 3e).

603 Many of the FP islands (except in the Marquesas) are fringed by reefs that enclose lagoons, which most of the time represent
604 a key economic resource for local communities. MHWs can have devastating impacts on such ecosystems (Glynn, 1984;
605 Mumby et al., 2001b; Andréfouët et al., 2015; Andréfouët and Adjeroud, 2019; Hédouin et al., 2020). These lagoons exhibit
606 diverse geomorphological characteristics, such as differences in size and degree of openness to the open ocean, making it
607 challenging to assess how large-scale oceanic MHWs propagate into these more sheltered environments. To achieve this at
608 the atoll and lagoon scale, this requires validating high-resolution satellite SST products against in-situ observations (e.g.,
609 ReefTemp; Van Wynsberge et al., 2017; Le Gendre et al., 2024), alongside a detailed understanding of lagoon

610 hydrodynamics (Bruyère et al., 2023). Additionally, the development of hydrodynamical or statistical models that relate
611 lagoon interior surface temperatures to oceanic temperatures and ocean–meteorological conditions could help compensate
612 for the current lack of high-resolution SST data (Van Wynsberge et al., 2017, 2024).

613 In Fig. 5 we related ENSO flavors to DHW, the NOAA metric used to monitor coral bleaching globally. NOAA’s historical
614 alert levels are: 0–4 (possible bleaching), 4–8 (reef-wide bleaching risk), and >8 (reef-wide bleaching with potential
615 mortality). In our record, the 8 threshold is rarely reached in the Society and Tuamotu—even in 2015/16 (Fig. 5; Fig. S11),
616 when widespread bleaching was documented (Hédouin et al., 2020). This underscores known limitations of the standard
617 DHW formulation, which can underpredict bleaching and overlooks regional sensitivities. It has been shown that tuning the
618 hotspot definition, accumulation window, and/or bleaching threshold improves coral bleaching forecast skill (e.g. Lachs et
619 al., 2021; Whitaker and DeCarlo, 2024) but that these adjustments often become region- or location-specific, rendering
620 generalization difficult. Accordingly, Fig. 5 quantitative results should not be read as direct indicator of coral bleaching;
621 rather, it shows how ENSO modulates cumulative heat stress across FP’s archipelagos. Bleaching occurrence is also
622 modulated by other environmental factors than heat stress—e.g., UV-exposition, the shortwave radiation reaching colonies at
623 depth, salinity, water depth, nutrient supply, and local hydrodynamics (DeCarlo et al., 2020; Gonzalez-Espinoza and Donner,
624 2021). As an example, over FP increased cloud cover has been suspected to spare Society Islands from massive coral
625 bleaching in the extreme EPEN 1997/98 event (Mumby et al., 2001).

626 While the OISST dataset has been shown to be well-suited for the analysis carried out in this study (Gupta and Sil 2024),
627 differences between SST products can be significant for some commonly used MHW metrics (Chevillard et al., 2025) and
628 this should be kept in mind. For analyzing ENSO modulation, products generally yield consistent patterns (here OISST and
629 GLORYS are coherent). However, at the archipelago scale, quantitative metrics can differ between products (Fig. S7).

630 Our results provide crucial insights into the mechanisms driving MHWs over FP and their link with ENSO, which are
631 essential for improving seasonal-to-interannual forecasts of these extreme events. The forecasting skill of MHWs varies
632 significantly depending on season, region, and lead time (de Boissésion and Balmaseda, 2024; Cohen et al., 2025; Jacox et
633 al., 2022). In particular, there is a strong ENSO imprint on the predictability of these events. Over the northeastern region of
634 FP, MHWs appear much more predictable than in southern regions, with minimal forecast skill in the central areas where
635 MHWs are primarily controlled by air–sea fluxes (Fig. 6). In the southwestern part of FP, MHW forecast skill is also weak,
636 likely due to the dominant influence of horizontal advection (HADV) and mesoscale circulation features during the MHW
637 onset and decay. These findings point to the need for higher-resolution models, along with an expanded network of ocean
638 observations, to improve verification of the models and forecasting capabilities in this region.

639 Across the entire FP region, both the number of MHW days and event durations have increased over time (Fig. S20).
640 However, maximum intensity has increased only in the southwestern half of the country—including the Society
641 Archipelago, southern Tuamotu, Gambier, and Austral Islands—while the northern Tuamotu and Marquesas have
642 experienced a decrease in maximum MHW intensity over time (Fig. S20b). The spatial pattern of this trend closely mirrors
643 that of the long-term SST trend across the region (see Fig. S1). The underlying cause of this cooling trend in the northeast

644 which extends more broadly in the eastern tropical Pacific remains to be clarified—whether it reflects the influence of global
645 warming, natural tropical Pacific decadal variability, or more likely a combination of both (Watanabe et al., 2024).
646 Therefore, the observed cooling trend in MHWs intensity over the northeastern region needs to be interpreted carefully.
647

648 **7- Conclusion**

649 The present study provides a comprehensive assessment of MHWs in the south central Pacific across FP, characterizing their
650 spatial and seasonal variability, mechanisms, and modulation by ENSO and its various flavors. MHWs were analyzed using
651 OISST data for the 1981–2024 period, as well as with the GLORYS reanalysis for 1993–2024. GLORYS agreement with
652 OISST gave us confidence in the ability of the reanalysis to study MHW mechanisms over 1993–2020. Hence, by examining
653 the mixed layer heat budget during MHWs in GLORYS, we were able to determine the main mechanisms at work during
654 MHW intensification and decay phases.

655 We showed that MHW occurrence, intensity, and duration vary significantly between archipelagos and seasons. The
656 Marquesas and Austral Islands experienced the highest number of MHW days during the warm season, as well as the most
657 intense and long-lasting events. In contrast, the Society, Tuamotu, and Gambier Islands tend to experience MHWs of lower
658 intensity and duration, particularly during the cold season. Cumulative intensity and duration extremes also varied spatially,
659 reflecting region-specific mechanisms.

660 Our results highlight the dominant role of air–sea fluxes in driving MHWs in the central regions (Society–Tuamotu–
661 Gambier), while oceanic advection is the key mechanism generating MHWs in the Marquesas and equatorward zones up to
662 2°S where vertical processes dominate. In the Austral Islands and poleward zones, both air-sea fluxes and horizontal
663 advection contribute comparably. During the cold season, the role of horizontal advection becomes more prominent across
664 FP, while the impact of surface fluxes is dampened by a deeper seasonal mixed layer. Generally, most of MHWs decay is
665 driven by air-sea fluxes.

666 We also demonstrated that ENSO exerts a strong and spatially structured modulation on MHWs in FP. EN favors MHW
667 development in the northeastern region (Marquesas–northern Tuamotu), while LN promotes MHWs in the southwest
668 (Austral Islands). These effects are linked to seasonally persistent changes in SST, surface wind speed, MLD, and oceanic
669 horizontal advection patterns.

670 This work provides new insights into the processes controlling MHWs across FP and their connection to large-scale climate
671 variability. It also offers a framework for understanding how future changes in ENSO behavior and ocean–atmosphere
672 coupling might influence the frequency and severity of MHWs over the region.

673

674

675 *Authors contribution*

676 BP, TI and SC designed the study and wrote the initial manuscript draft. BP performed the analysis presented in this
677 manuscript. Discussions and iterative feedback from all co-authors significantly contributed to the revision of the
678 manuscript.

679

680 *Competing interests*

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

682

683 *Acknowledgments*

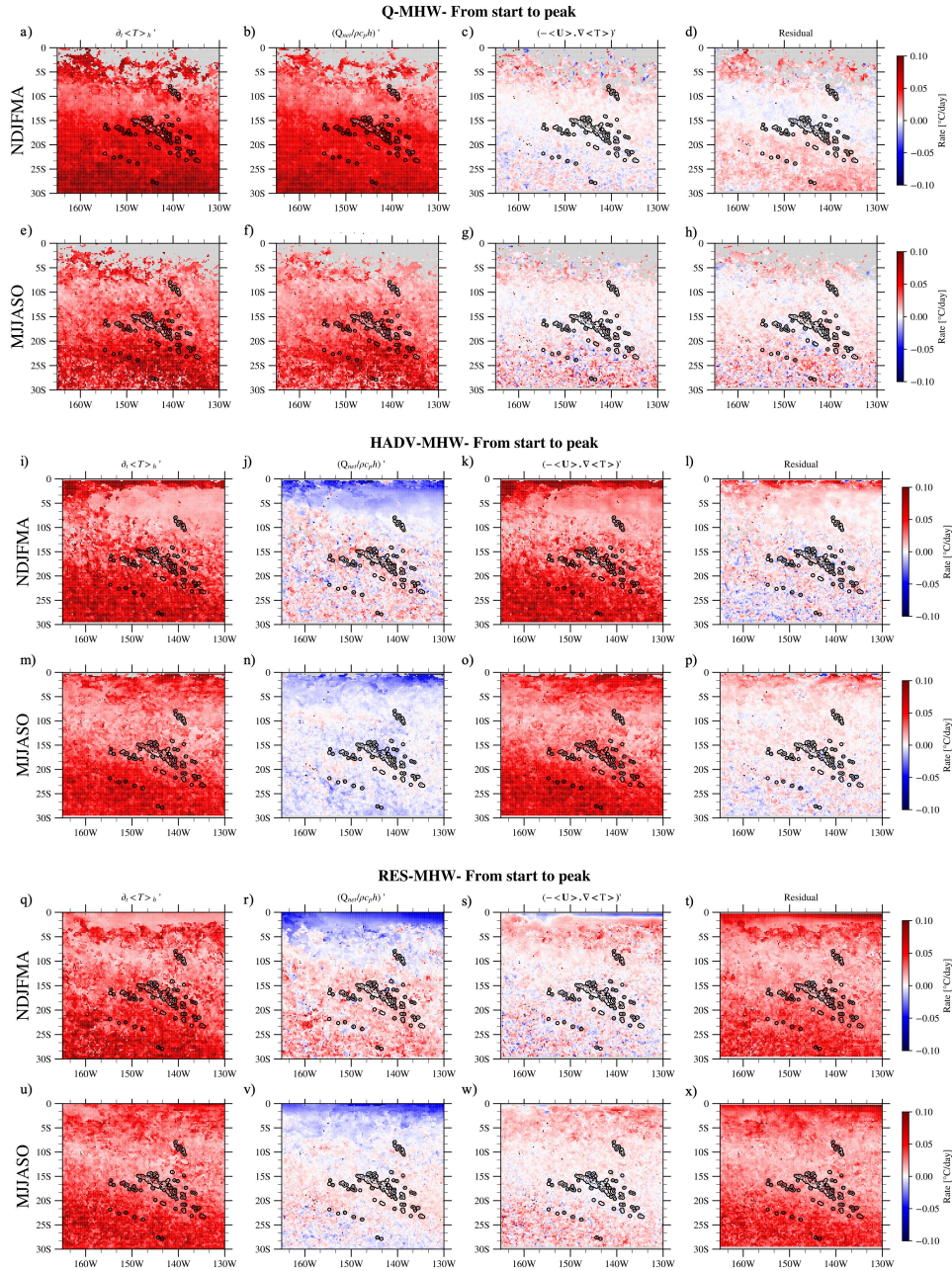
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688 HEAT). We acknowledge the use of Python and NOAA Pyfer- ret languages and of the several data servers listed below.

689

690 *Data Availability Statement*

691 All datasets used in this study are open source and available online. The OISSTv2 data were downloaded from
692 <https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html>. The GLORYS reanalysis is available on Copernicus
693 https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/description. The official administrative
694 geographic dataset used for delimitating the archipelagos of French Polynesia are available
695 at <https://www.data.gouv.fr/fr/datasets/geographie-administrative-de-la-polynesie-francaise/>. All scripts used to obtain the
696 results presented in this study were written in Python and Pyferret and can be shared upon request.

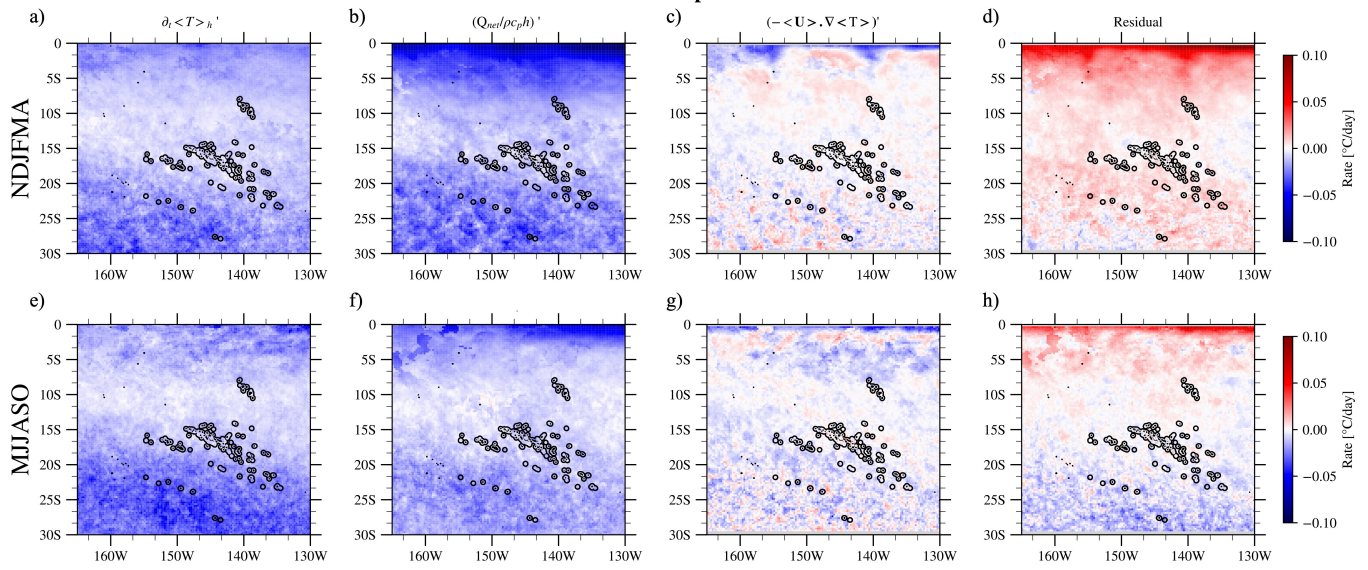
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699

700 **Figure A1.** Composites across all events at each grid point of the different term of the heat budget analysis Eq. (2) averaged from start to
 701 peak for each MHW type and for each season separately. The first column corresponds to the mixed-layer temperature tendency term, the
 702 second one corresponds to air/sea flux heat budget term, the third one corresponds to the horizontal heat advection term and the fourth one
 703 corresponds to the residual term. They are all expressed in °C/day. Panels a–d and e–h show composites of Q-MHWs during austral
 704 summer and winter, respectively. Panels i–l and m–p show composites of HADV-MHWs for summer and winter, respectively. Panels q–t
 705 and u–x present composites of RES-MHWs in austral summer and winter, respectively.

All MHWs - From peak to end



706

707 **Figure A2.** Composites across all events at each grid point of the different term of the heat budget analysis Eq. (2) averaged from peak to
 708 end for all MHWs and for each season separately. The first column corresponds to the mixed-layer temperature tendency term, the second
 709 one corresponds to air/sea flux heat budget term, the third one corresponds to the horizontal heat advection term and the fourth one
 710 corresponds to the residual term. They are all expressed in °C/day. Panels a-d and e-h show the composite over MHWs in austral summer
 711 and winter respectively.

712

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