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1 Marine cold-spells

2

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18 **Abstract**

19

20 Characterising ocean temperature variability and extremes is fundamental for understanding
21 the thermal bounds in which marine ecosystems have adapted. While there is growing
22 evidence of how marine heatwaves threaten marine ecosystems, prolonged periods of
23 extremely cold ocean temperatures, marine cold-spells, have received less global attention.
24 We synthesize the literature on cold ocean temperature extremes and their ecological impacts
25 and physical mechanisms. Ecological impacts of these events were observed across a range of
26 species and biophysical processes, including mass mortalities, range shifts, marine habitat
27 loss, and altered phenology. The development of marine cold-spells is often due to wind-
28 induced ocean processes, but a range of physical mechanisms are documented in the
29 literature. Given the need for consistent comparison of marine cold-spells, we develop a
30 definition for detecting these events from temperature time series and for classifying them
31 into four categories. This definition is used to consistently detect marine cold-spells globally
32 over the satellite record and to compare the characteristics of notable cold events. Globally,
33 marine cold-spells' occurrence, duration, and intensity are decreasing, with some areas, such
34 as the Southern Ocean, showing signs of increase over the past 15 years. All marine cold-
35 spell categories are affected by these decreases, with the exception of "IV Extreme" events,
36 which were so rare that there has been little decrease. While decreasing occurrences of
37 marine cold-spells could be viewed as providing a beneficial reduction in cold stress for
38 marine ecosystems, fewer cold spells will alter the temperature regime that marine
39 ecosystems experience and could have important consequences on ecological structure and
40 function.

41 1. Introduction

42

43 Extreme climatic events such as heat waves, droughts, cyclones or cold snaps are expected to
44 become more frequent with climate change (Drijthout et al., 2015; Collins et al. 2019).

45 Understanding why extreme events occur, how they are changing, their role in disrupting
46 ecosystems and impacting ecological function and services are important for assessing
47 ecosystem resilience and trends. Temperature extremes are of particular importance to
48 ecosystems as they may occur at the limits of species' thermal niches, posing a risk for their
49 survival. With global warming, there has been increasing attention on extremely warm ocean
50 temperature events, known as marine heatwaves (MHWs), which occupy the warm end of
51 this temperature range (Hobday et al., 2016; Frölicher et al., 2018; Oliver et al., 2018;
52 Holbrook et al., 2019; Smale et al., 2019). In contrast, extremely cold water events - marine
53 cold-spells (MCSs) - have received less comprehensive and global attention despite a rich
54 history of ecological and physically-based studies demonstrating acute and enduring impacts
55 on marine ecosystems (e.g. Crisp, 1964; Hurst, 2007). Yet extreme cold temperature events
56 are ecologically important phenomena which can shift the distribution of species, alter
57 composition of communities and even bring about evolutionary change (Parmesan, 2006;
58 Campbell-Staton et al., 2017). In some parts of the ocean, recent cold events have been found
59 to have comparable magnitude with major warm events (e.g. Southwest/Southeast Atlantic;
60 Lentini et al., 2001; Florenchie et al., 2004).

61

62 Extreme climatic events have been defined as “an episode or occurrence in which a
63 statistically rare or unusual climatic period alters ecosystem structure and/or function well
64 outside the bounds of what is considered typical or normal variability” (Smith, 2011a). Past
65 studies have used different definitions and terminology to identify cold marine extremes,
66 often with a regional or species-specific focus. For example, episodic mass mortality of
67 marine life associated with MCSs have been called “winterkills” and not limited to high-
68 latitudes (Hurst et al., 2007). “Degree cooling weeks” has been proposed as an accumulated
69 measure of cold temperature anomalies below a minimum monthly mean to assess cold-water
70 induced coral bleaching (González-Espinosa and Donner, 2020). In coral disease risk
71 modelling, “winter condition” and “cold snap” metrics have been defined as an integrated
72 measure of sea surface temperature (SST) anomalies over the winter season or cold
73 anomalies over the period when temperatures fall below one standard deviation lower than
74 the wintertime mean (Heron et al., 2010). In the eastern Pacific Ocean, reef fish-specific
75 metrics of critical thermal minima, an important metric for evaluating survival and tolerance
76 to cold ocean temperatures during La Niña events (Mora and Ospina, 2002), have been
77 applied to other fish kill events caused by extremely cold water (e.g. Hsieh et al., 2008).
78 Similarly, in Florida, cold temperature events are described based on ecological thresholds
79 for cold stress syndrome in manatees, with 20°C proposed as a risk metric for the syndrome's
80 occurrence (Bossart et al., 2003).

81

82 Other approaches to identify extremely cold water events use statistical methods with
83 remotely sensed SST data and, for example, long time series to construct climatological
84 measures of cold extremes based on local temperature variability, i.e. the 10th percentile
85 (Schlegel et al., 2017). Another common method is the analysis of SST anomalies over a
86 specific period or the application of principal component analysis or empirical orthogonal
87 functions (e.g. Walker, 1987; Miles et al., 2009; Kataoka et al., 2014). For climate mode

88 analyses, prolonged cold water events have been classified using indices based on SST
 89 anomalies and the exceedance from standard deviation over several months (e.g. Larkin and
 90 Harrison, 2001; Lutz et al., 2013; 2015; Pirhalla et al., 2015) or based on spatially averaged
 91 temperature anomalies below fixed thresholds (Lentini et al., 2001; Florenchie et al., 2004).
 92 In addition to remote sensing, field-based studies targeting ecological impacts use on-site
 93 observations, *in situ* data, and field survey results to characterise periods of extremely cold
 94 waters (Schwing and Pickett, 2004; Aretxabaleta et al., 2006; Lirman et al., 2011).

95
 96 In this study, we present the current state of knowledge on MCSs and then develop an
 97 approach for defining cold temperature extremes in a global context. First, we review the
 98 literature on cold ocean temperature extremes, noting both the occurrence and properties of
 99 past events as well as their physical and climatic drivers and impacts on ecosystems,
 100 fisheries, and their feedback on the climate system (Section 2). Then we propose a MCS
 101 definition that allows for the consistent comparison of MCS events on a global scale, with the
 102 intention of providing a methodology that can be adapted for a broad range of investigations
 103 of these extreme events (Section 3). With this methodology, we quantify the characteristics,
 104 occurrences, and trends of MCSs throughout the global ocean over the satellite record
 105 (Section 4). We discuss the results and conclude in Section 5.

106

107 2. Marine cold-spells in the literature

108

109 A robust body of literature exists on MCSs, although historically they have not been named
 110 as such, and studies have focussed on cold temperature extreme impacts on marine
 111 ecosystems, their underlying atmospheric and oceanographic processes, and, to a lesser
 112 extent, feedbacks on the physical climate system. The ecological impacts of these cold water
 113 events, especially those during winter, have been the subject of many studies over the past
 114 century (e.g. Storey, 1937; Horwood and Millner, 1998; Hoag, 2003; see references in Hurst,
 115 2007).

116

117 A full literature review of cold water events was conducted by searching in Google Scholar
 118 for the following terms in singular, plural, with and without hyphens: “cold snap”, “cold
 119 spell”, “winterkill”, “cold wave”, “cold event”, “cool(ing) event”, “cold water”, “cold
 120 extreme”, “cold shock”, “cold stress”, and “cold temperature”. We did not include specific
 121 climate modes of variability in our search terms, such as “La Niña”, because we did not want
 122 to be prescriptive about the drivers of the cold events. We restricted our examination to those
 123 events identifiable by a sea surface expression in ocean temperatures. The primary findings of
 124 this review have been tabulated (Table 1) and are discussed in more detail below. We begin
 125 with a review and synthesis of the wide ranging impacts of MCSs on marine ecosystems and
 126 services (Section 2.1). Then we describe the physical mechanisms associated with the
 127 occurrence of MCSs (Section 2.2).

128

129 **Table 1:** A selection of the most notable marine cold-spells (MCSs) from the literature, their
 130 time/region of occurrence, physical mechanisms, and impacts. Note that temperatures are
 131 reported in the same units as the original publication and a conversion to °C is provided
 132 where necessary.

Time	Region	Physical	Impacts	Duration	Minimum
------	--------	----------	---------	----------	---------

	(source)	mechanisms			SST/ temperatures
January 1940 (Winter)	Texas Coast (Gunter, 1941)	Rapid, wind- driven cooling of shallow waters	Extensive fish kills. Reduction of commercial catch	~10-11 days	~4°C
January/February 1951 (winter)	Texas Coast (Gunter, 1951)	Wind-driven cooling of shallow waters	Extensive fish kills. Reduction of commercial catch	~7 days	Approx. the same as the 1940 event
December 1958 (winter)	Pamlico Sound (North Carolina) (Wells et al., 1961)	Rapid, wind- driven (polar air) cooling of shallow waters	Extensive fish mortality	~ 4-5 days	41.4 °F (5 °C)
December 1962 / March 1963 (winter)	Britain & N.Europe (Crisp, 1964)	Severe winter air & ocean temperatures due to an arctic spell	Large numbers of fish, algae, molluscs, killings etc. Localized extinctions. 50% decrease in spawning-stock biomass.	~ 3 months	0.6 °C - 3.5 °C
January 1977 (winter)	Florida (Gilmore et al., 1978)	Arctic air invasion	Rapid chilling of shallow waters below lethal limits. Coral and fish mortality.	~26 days	~6-13 °C
May- July 1998 (spring/summer)	Gulf of Mexico (Muller- Karger, 2000)	Combination of wind-driven upwelling, northward migration of anti-cyclonic eddy and anomalously high river discharge and rainfall	Extensive fish kill, low-oxygen waters, increased chlorophyll concentrations	~ 2 months	~ SST < 18 °C
June- September 2003 (summer)	Southeast US coasts (Hyun & He 2010)	Wind-driven coastal upwelling	Increased chlorophyll & primary production. Fish mortality and appearance of non- native species. Disruptions to fisheries and recreational business.	~ 3 months	~23.8-26 °C
	Penghu	Anomalously	A mass fish kill,	~ 1 month	12.6 °C

January/February 2008 (winter)	Archipelago , southern Taiwan Strait (Chang et al., 2013)	strong and prolonged wind enhanced the southward cold China Coastal Current to intrude	including wild and caged species, occurred along with macroinvertebrates deaths and coral bleaching (Hsieh et al., 2008). Coastal fisheries declines resulted in economic losses (est. 10 million USD) .		
Mid-2009 / Mid-2010	N.Atlantic Subtropical Gyre	Reduced ocean heat transport (Josey et al., 2018)	-	~1 year	Peak cooling of ~0.8 °C
January 2010 (winter)	Florida (Colella et al., 2012)	Sustained movement of Arctic air mass caused the ocean temperature to rapidly decline in shallow regions.	A range of cold-sensitive wildlife species perished, including sea turtles (Avens et al. 2012), record-number deaths of American crocodile and Burmese pythons (Mazzotti et al. 2016); unprecedented number of manatee deaths (Barlas et al. 2011). Most severe coral bleaching on record (Colella et al., 2012; Lirman et al., 2011).	~ 12 days	8.7 °C
2013-2016	N.Atlantic Subpolar Gyre (Josey et al., 2018)	Combination of air-sea heat flux loss during 2014/15 & a re-emergence of a cold subsurface temperature anomaly developed in 2013/14.	-	~1-2 years	Annually-averaged anomalies of up to -1.4 °C
March 2017 (fall)	SE Australia (Wijffels et al., 2018)	Persistent, wind-driven, upwelling caused a rapid decrease in SST .	A mass die off of warm-water fishes occurred coinciding with high levels of algae.	Three weeks	SST decrease by 7°C; SST ~ 14°C

135

136 MCSs perturb biological systems, with responses ranging from little to no impacts to acute
137 ecological impacts on organisms, communities or ecosystems (e.g. see references in Table 1).
138 Ecological responses to extreme cold water events have been reported for a range of marine
139 environments, from the open ocean to coastal waters and to estuarine and intertidal systems
140 (Firth et al., 2015). These responses include severe disturbances, such as mass mortality (e.g.,
141 fish and invertebrate kills; Woodhead, 1964), population decrease, coral bleaching (Zapata et
142 al., 2011), changes in species distribution (e.g. range contraction; Firth et al., 2015) and
143 phenology (e.g. onset of the growing season; Jentsch et al., 2007). In the most extreme cases,
144 MCSs can trigger abrupt ecological responses, such as widespread mortalities that can be
145 difficult to recover (e.g., Matich et al., 2020) and may have evolutionary consequences for
146 species (e.g., Campbell-Staton et al., 2017; Grant et al., 2017). The severity of ecological
147 impacts depends on a combination of different factors, such as the MCS spatial extent,
148 duration, intensity, season of occurrence, as well as organisms' ability to adapt to MCSs and
149 their tolerance to climate extremes (Smith, 2011b; Grant et al., 2017).

150

151 **2.1.1. Marine ecological impacts**

152

153 In most cases, adverse consequences for marine life from MCSs were reported during winter
154 and documented during discrete cold events or over extended winter months, when
155 temperatures approach cold thermal minima. A combination of physiological and ecological
156 processes control species' cold limits (Stuart-Smith et al., 2017). When conditions exceed
157 these limits, mass mortality can occur. For example, large-scale fish mortality coincided with
158 or followed after a winter MCS in 1958/9 in Pamlico Sound (Wells et al., 1961) while severe
159 impacts on a variety of marine fish have occurred due to sudden and prolonged events in the
160 winters of 1940 (Miller, 1940), 1969/70 and 1977 (Gilmore et al., 1978) in southeast Florida.
161 As an indication of the potential scale of impact on population abundance, in Europe, a MCS
162 during the severe winter of 1962/3 may have been responsible for a 50% decrease in the
163 spawning-stock biomass of sole (*Solea solea*) in the North Sea (Millner and Whiting, 1996).
164 Off Texas, an estimated 90 millions pounds of fish were killed during two MCSs in 1940
165 (Gunter, 1941) and 1951 (Gunter, 1951) and around 2000-4000 individual fish were affected
166 during another MCS in 1982 (Holt and Holt, 1983). A similarly high rate of species mortality
167 was reported in the same region during other events in December 1983 (~14 million fish, ~1
168 million invertebrates), February 1989 (~11 million fish, ~13000 invertebrates), and December
169 1999 (~6 million fish) (McEachron et al., 1994). For 1940 and 1951 MCS events, the varying
170 magnitude of ecological response was attributed to a number of factors that have been
171 proposed in past events (Storey and Gudger, 1936), including rapid cooling, the cold limit,
172 and the timing, such as being the first event of the winter season versus a subsequent event
173 with potential for acclimatization (Gunter, 1951).

174

175 Although most reported impacts of MCSs are during the winter, there are scenarios where an
176 event which occurs during the summer could have ecological consequences. For example, a
177 summer MCS that coincides with a larval growth period could lead to lower larval survival
178 and reduced recruitment for the species the following year (e.g., Lotterhos and Markel, 2012;
179 Velázquez, 2003). A dramatic drop in summer temperature, which overcomes an organism's
180 ability to acclimate, could also impact performance, even if it does not cross lower thermal
181 limits for the species. Therefore, as species can have different thermal optima for

182 reproduction, growth, and survival, a summer MCS may impact these sensitive stages
183 (Bennett et al., 2019).

184

185 Cool range edges of distributions can be defined by cold thermal minima, or minimum
186 temperatures during particularly sensitive stages of a species life cycle (e.g., larval stage,
187 reproductive period). In general, the closer temperatures approach these species' thermal
188 limits the more sensitive an organism becomes to warm or cool temperature stress (Bennett et
189 al., 2019). As a result, shifts in the frequency and intensity of MCSs can alter physiological
190 performance and even eventually change a species' range (Pecl et al., 2017). At cool range
191 edges of species distributions, reduced MCSs may result in poleward range expansions or
192 movement of species to deeper depths where environmental conditions are becoming suitable
193 (Sorte et al., 2010; Cavanaugh et al., 2014).

194

195 Prolonged extreme cold events can have ecosystem-level effects on marine life, especially
196 when they impact foundational, habitat forming species. Corals are generally warm water
197 species that are sensitive to severely cooler conditions, with cold stress impacting the
198 symbiotic relationship with zooxanthellae or triggering direct mortality (e.g. Nielsen et al.,
199 2020). During 1977, a MCS off Florida caused hypothermal stress and mortality in many
200 local tropical and subtropical species, with as much as 90% mortality in shallow-water corals
201 (Roberts et al., 1982). In January 1981, cold air outbreaks in Florida caused shallow waters to
202 chill, with denser waters transported offshore inducing coral reef mortality (Walker et al.,
203 1982). The most severe MCS ever recorded in Florida occurred in January 2010, when polar
204 air masses plummeted water temperatures below the thermal limits of several coral species
205 and tropical reef organisms for ~12 days causing widespread and unprecedented mortalities
206 (Colella et al., 2012), strandings, metabolic stress, tissue damage, and hypothermic stunning
207 (Roberts et al., 2014) across large spatial and taxonomic scales (e.g. corals, manatee, fish,
208 turtles; Pirhalla et al., 2015). In the different species, mortality was highest in shallow and
209 nearshore environments compared to deeper habitats and was attributed to the higher number
210 of days that seawater temperatures were below 16°C (Schopmeyer et al., 2012). This 2010
211 MCS caused coral mortalities of 1-2 orders of magnitude higher than any mortalities
212 observed during previous summer MHWs and altered the composition and structure of many
213 reefs in the Florida Reef Tract, often favouring cold-resistant species and smaller colonies
214 (Lirman et al., 2011). However, there were some specific coral species for which no
215 mortalities were reported in benthic surveys during this event (Kemp et al., 2011). Similarly,
216 off Western Australia, some species of corals on subtropical reefs showed no response to
217 MCSs due to their stress tolerance and the broad thermal niche requirements of coral species
218 found in these high latitudes (Tuckett and Wernberg, 2018). Nevertheless, in high latitudes,
219 cold water stress can limit the development of subtropical reefs since reefs can be subject to
220 aperiodic winter cold-air outbreaks (Roberts et al., 1982).

221

222 Even if MCSs do not cause direct mortality, these events can often have sub-lethal impacts
223 such as suppressed growth, metabolic stress or reduced fitness (e.g., Burgess et al., 2009). For
224 example, manatees are at risk to cold stress syndrome during winter events (Barlas et al.,
225 2011) because they are unable to tolerate cold water temperature extremes below 20°C for
226 extended periods (Irvine, 1983; Bossart et al., 2003). MCSs can potentially affect the
227 foraging behaviour of seabirds by altering the distribution of their prey (Schumann et al.,
228 1988). Cold periods weaken immune functions of fish leading to loss of energy and nutrition

229 because of reduced feeding activities (Lee et al., 2014). This weakening can also cause
230 reductions in a prey species' ability to evade predation (Thomson and Lehner, 1976).
231 However, if the MCS develops slowly or if it is preceded by gradually decreasing
232 temperatures, it has been hypothesized that species may have a higher probability of survival
233 as they may acclimatise better than they would during a rapid temperature decrease (Gunter,
234 1951; Moore, 1976; McEachron et al., 1994).

235

236 Despite these numerous reported direct and indirect effects of MCSs, evidence suggests that
237 some marine organisms may be better able to acclimate or adapt to cold extremes compared
238 to warm extremes (Hicks and McMahan, 2002; Morgan et al., 2020; but see Jumbam et al.,
239 2008). This is because species often have hard upper limits for thermal tolerance, defined by
240 physiological thresholds that do not change under selection compared to lower thermal limits.
241 As a result, the short-term effects of MCSs may be less severe compared to the effects of
242 similar intensity MHWs (Morgan et al., 2020). However, at the poles, hard lower limits for
243 performance also exist as temperatures approach freezing, where molecular-level
244 perturbations occur (Pörtner et al. 2007).

245

246 Anomalously strong coastal upwelling (e.g. due to episodic wind bursts) can also result in
247 MCSs, leading to enhanced chlorophyll near the coast due to nutrient-rich upwelled waters
248 (e.g. Florida 2003; Yuan, 2006) or the development of planktonic blooms and mucilaginous
249 aggregates (e.g. Morrocoy National Park 1996, Laboy-Nieves et al., 2001). For some MCSs,
250 enhanced nutrient levels can increase primary productivity and chlorophyll levels
251 excessively, contributing to the development of hypoxic conditions (e.g. California Current
252 System 2002; Bograd and Lynn, 2003 ; Wheeler et al., 2003) and resulting in eutrophication
253 in some regions (Crawford et al., 2005). When unusually cold upwelled waters are adjacent
254 to a warm boundary current, conditions can be favourable for causing algal growth and fish
255 deaths (Wijffels et al., 2018).

256

257 In the Arctic, marine cold snaps can drive shifts in the formation of sea ice, which may have
258 ecological consequences for associated marine species (Massom and Stammerjohn, 2010;
259 Meredith et al., 2019). Sea ice fundamentally changes the marine environment, limiting light,
260 scouring the seafloor, limiting accessibility of surface air, and providing habitat for highly
261 adapted species, such as ice algae (Arrigo, 2014). The timing of sea ice formation and break
262 up is also a key driver of phytoplankton and zooplankton blooms (Stabeno et al., 2012),
263 which form the base of food webs in these regions and can have broader consequences for
264 marine species (Wassmann et al., 2011 ; Hunt et al., 2018). Major recent changes in
265 seasonality and extent of regional sea ice cover are having dramatic effects on the structure
266 and dynamics of polar marine ecosystems. Thus, changing patterns of MCSs in Arctic
267 regions will likely have consequences for coastal ecosystems in some regions, and may buffer
268 these effects by increasing or stabilizing sea ice.

269

270 MCSs are not always damaging for marine ecosystems and they may even benefit native taxa
271 by reducing the abundance of non-native species. Rapid cooling during MCSs can
272 incapacitate and kill non-endemic species rarely exposed to such low temperatures (e.g.
273 Storey, 1937; Wells et al., 1961). Based on the climate variability hypothesis, tropical species
274 have lower tolerance for winter minimums compared to temperate species, so MCSs could
275 have more severe impacts on these species, and halt or slow tropicalisation (Holt and Holt,

276 1983; Vergés et al., 2014). Off Florida, MCSs have caused more severe reductions to the
277 abundance of non-native fish than native and more resilient species (Rehage et al., 2016). Off
278 Japan, persistent and extremely cold temperatures in winter 2017/18 led to mortality of non-
279 native coral and tropical reef fish which had colonised Tosa Bay because of temperature
280 increases (Lerriorato and Nakamura, 2019). In the Gulf of Mexico, the winter 1970/71 MCS
281 caused greater mortalities in tropical fish species compared to endemic species (Thomson and
282 Lehner, 1976). The aftermath of a MCS has been proposed to provide a management
283 opportunity for targeted interventions to maintain (or exploit) the reduction in the abundance
284 of non-native species (Rehage et al., 2016). In addition to reducing abundance of non-native
285 species, MCSs that are related to upwelling may have beneficial impacts on productivity. For
286 example, enhanced populations of primary and secondary phytoplankton bloom species were
287 recorded during an anomalous upwelling event in East Australia towards the end of the
288 1997/98 El Niño, which increased nutrient levels to their 99th percentile value over the last
289 57 years (Lee et al., 2001). MCSs have also been associated with increased coastal primary
290 production around New Zealand (Chiswell and O'Callaghan, 2021).

291

292 Finally, MCS could temporarily favour species with low thermotolerance, which are expected
293 to decline in numbers as a result of global warming, e.g. Antarctic krill (Mintenbeck, 2017;
294 Veytia et al., 2020). Based on the climate variability hypothesis, tropical species have lower
295 tolerance for winter minimums compared to temperate species, so MCSs could have more
296 severe impacts on these species, and halt or slow tropicalisation (Vergés et al., 2014).
297 Upwelling-related MCSs have also been associated with increased coastal primary production
298 around New Zealand (Chiswell and O'Callaghan, 2021), similarly to enhanced populations of
299 primary and secondary phytoplankton bloom species seen during an anomalous upwelling
300 event in East Australia towards the end of the 1997/98 El Niño, which increased nutrient
301 levels to their 99th percentile value over the last 57 years (Lee et al., 2001)

302

303 **2.1.2. Marine ecosystem service impacts**

304

305 Marine ecosystems provide services that contribute to human well-being (TEEB, 2010),
306 including those that provide resources and food, biological control (e.g. of non-native
307 species), support marine habitats, and provide tourism and recreation (Smale et al., 2019).
308 Here, we find that MCSs can have a range of impacts on marine ecosystem services,
309 including fisheries and aquaculture (Santos et al., 2016).

310

311 MCSs have impacted economic activities of coastal communities and the related fisheries
312 industries. Reports on the Florida 2003 MCS showed disruption of tuna fishing and local
313 recreational businesses along the east US coast (Sun et al., 2004; Yuan, 2006). During the
314 1976-1977 El Niño, a cold SST anomaly caused the 1977 recruitment failure of the Brazilian
315 sardine (*Sardinella brasiliensis*) around the South Brazil Bight (Matsuura, 1996). Similarly,
316 along the south coast of Brazil, cold SST anomalies in 1977, 1987, and 1989 austral summer
317 spawning seasons (related to ENSO events) produced poor year classes (Lentini et al., 2001).
318 A substantial reduction of commercial catch was also reported the year following the Texas
319 MCS of 1951 (Gunter, 1951) similar to the 76% reduction in the catch for the three months
320 following the Texas MCS of 1940 (Gunter, 1941).

321

322 In general, the detection of local MCSs may help to inform managers and stakeholders of
 323 otherwise undocumented effects on target species, marine resources and services that
 324 contribute to the economies of coastal communities (e.g Barnes et al., 2011). With knowledge
 325 of these MCS induced mortalities, which can include spawners, fisheries managers can adopt
 326 measures (e.g. reduced bag and possession limits, increased size limits, gear restrictions etc.)
 327 that will aid the recovery of economically important fish populations (McEachron, 1994).
 328 However, cold water events can have a range of effects on fisheries. In the Taiwan Strait
 329 2008 MCS, while there was a mass die-off of cultured fish and a 50-80% decrease in catches
 330 of non-migratory species, there was a ~230% increase in the catches of migratory species that
 331 were attracted by the colder waters (Lee et al., 2014). In another case, after the Ningaloo
 332 Niño 2011 (MHW) event off Western Australia, a series of cooler than normal years and
 333 MCS events assisted the recovery of some economically important invertebrate fisheries due
 334 to an increase in primary production (Feng et al., 2020).

335

336 MCS can have long-term consequences for recreational fisheries, such as the January 2010
 337 MCS in South Florida (e.g. Boucek and Rehage, 2014; Santos et al., 2016), which was the
 338 most extreme cold event in 87 years (Rehage et al., 2016). This MCS resulted in a mass
 339 mortality of fish species, many of which were recreationally important in the Everglades
 340 (Santos et al., 2016). Other fish species were found to increase in abundance, which may be
 341 related to lower temperature tolerances or mass migration (Santos et al., 2016). This event
 342 highlights the long-recovery times from an extreme event, in which the catch structure had
 343 not recovered to its original state three years post-event (Santos et al., 2016).

344

345 2.2. Atmospheric and oceanic mechanisms

346

347 MCSs develop through a combination of physical mechanisms that control the ocean
 348 temperature by adding or removing heat within the ocean's surface mixed layer. The mixed
 349 layer temperature tendency varies owing to the following contributions (Moisan and Niiler
 350 1998; Oliver et al., 2021):

351

$$352 \quad \frac{\partial T_{mix}}{\partial t} = \frac{Q_{net} - Q_{sw(-h)}}{\rho c_p h} - \mathbf{u}_{mix} \bullet \nabla_h T_{mix} - \frac{T_{mix} - T_{(-h)}}{h} \left(\mathbf{w}_{(-h)} + \frac{\partial h}{\partial t} \right) + \text{Residual Eq.1}$$

353

354 where T_{mix} is the vertically-averaged mixed layer temperature, t is time, c_p the specific heat
 355 capacity of water, ρ is the seawater density, h the mixed layer depth, $\mathbf{u}_{mix} = (u, v)$ the two-
 356 dimensional mixed-layer horizontal velocity vector, and w the vertical velocity; the vertical

357 average is represented by $\bar{x}_{mix} = \frac{1}{h} \int_{-h}^0 x dz$. Q_{net} represents the sum of the air-sea heat fluxes

358 (shortwave, longwave, latent, sensible) with $Q_{sw(-h)}$ being the small fraction of shortwave
 359 radiation that escapes the base of the mixed layer. This equation relates the rate of mixed
 360 layer temperature change to the transfer of heat through air-sea heat flux, horizontal and
 361 vertical advection and the entrainment of deeper waters into the mixed-layer. The residual
 362 comprises additional mechanisms such as lateral induction and lateral and vertical diffusion,
 363 which usually have a much smaller contribution to heat changes than the terms explicitly
 364 described above.

365

366 In this section we will review the drivers of MCSs as drawn from past events in the literature,
367 focusing on cool temperature anomalies that have a surface expression. We start by
368 describing atmosphere driven MCS, followed by events driven primarily by anomalous ocean
369 processes, and finishing with the larger climate feedback processes that may be responsible
370 for/affected by MCSs.

371

372 **2.2.1. Ocean, atmosphere, and climate drivers of MCSs**

373

374 The development of past MCSs has been attributed to a variety of factors related to
375 atmospheric forcing through anomalous winds and air-sea heat fluxes (e.g. Economidis and
376 Vogiatzis, 1992; Gómez and Souissi, 2008; Pirhalla et al., 2015), as well as changes in ocean
377 currents and to anomalously strong upwelling (e.g. Yuan, 2006; Schlegel et al., 2017;
378 Wijffels et al., 2018).

379

380 Along continental shelves, air-sea heat fluxes that favour cooling tend to destabilise the
381 stratification and deepen the surface mixed layer, allowing for these surface cooled waters to
382 extend deeper. Shallow waters in particular (i.e. shallower than the local mixed-layer) may be
383 more susceptible to MCS as they respond quickly to air temperature drops and can reach
384 unprecedented low temperature levels when combined with heat losses (e.g. due to increased
385 winds; Pamlico Sound winter of 1958/59; Wells et al., 1961). During the winter of 1977 off
386 Florida, a MCS caused extensive cooling in nearby estuaries in a matter of days, due to wind-
387 driven mixing from a sudden and prolonged passage of an arctic cold front (Gilmore et al.,
388 1978). This MCS unfolded as three consecutive cold fronts, was accompanied by strong
389 northerly winds, and rapidly led to sensible and latent heat fluxes out of the shallow water
390 bodies (Roberts et al., 1982). Such cold air outbreaks can cause prolonged MCS duration
391 (e.g. seawater around Florida in January 1977 was below 16°C for 8 days, and in some
392 locations, reduced by 2-4°C from the seasonal average; Roberts et al., 1982) and can affect
393 large, shallow areas in high latitudes. A more extensive study on past (1981-2013) cold
394 events around the South Florida coast associated MCS occurrence with an enhanced north-
395 south atmospheric circulation that could favour cold air outbreaks or lead to low temperatures
396 due to the passage of cold fronts in combination with upwelling-related processes and
397 southward transport (Pirhalla et al., 2015).

398

399 An alternative mechanism for MCS development is horizontal flows of cool waters
400 associated with changes in the winds, along with vertical temperature advection related to
401 upwelling processes. The expansion and/or intensification of upwelling areas has emerged as
402 one of the most common drivers of MCS, e.g. in South Africa (Schumann et al., 1988;
403 Schlegel et al., 2017), in Venezuela's Morrocoy National Park in 1996 (Laboy-Nieves et al.,
404 2011), and in the Gulf of Mexico in 1998 (Muller-Karger, 2000), while La Niña has been
405 associated with extreme cold temperatures in the eastern Tropical Pacific (Mora and Ospina,
406 2002). In the southeast Atlantic, local air-sea heat fluxes were found to play a rather passive
407 role, acting as a buffer to regulate surface cold events (between 1982-1999), referred to as
408 Benguela Niñas, via latent heat flux anomalies. In the Benguela region, MCSs tended to
409 occur due to wind anomalies generated in the western and central equatorial Atlantic
410 (Florenchie et al., 2004) or a strengthening of equatorward winds (Walker, 1987), such as the
411 prolonged 1981-1983 MCS owing to an acceleration of upwelling-favourable winds (Walker,
412 1987). In the Southern tropical Indian Ocean intraseasonal cooling events have been

413 associated with reduced solar radiation, enhanced evaporation and strong entrainment during
414 the austral summer (Saji et al., 2006). Vertical processes at the base of the mixed layer were
415 found responsible for these cooling events mostly when the thermocline was shallow,
416 whereas atmosphere heat fluxes dominated the events when the thermocline was deep
417 (Vinayachandran and Saji, 2008). Similarly, cold blob events in the Northeast Pacific have
418 been attributed to vertical entrainment processes when their peak occurs during the summer,
419 where the mixed layer depth is shallower, whereas atmosphere heat fluxes and winds appear
420 to dominate cold events whose peak occurs during the winter (Tang et al., 2021).

421

422 MCSs have been reported to occur as a response to and during large-scale teleconnection
423 patterns, such as El Niño (February-March of 1985 along Peru; Friederich and Codispoti,
424 1987; Spinrad et al., 1989) La Niña (2008 MCS in the Taiwan Strait; Lee et al., 2014), or
425 Arctic Oscillation (MCS 2010 Florida; Kemp et al., 2011). In the southwestern Atlantic
426 Ocean, cold SST events have been linked to ENSO events based on the identification and
427 analysis of 13 cold SST anomalies ($< -1^{\circ}\text{C}$) that persisted for more than 60 days between
428 1982 and 1994 (Lentini et al., 2001). During the intense MCS in the Florida Keys in 2010
429 the southward movement of Arctic air masses induced severe cold seawater temperatures
430 below 12°C for approximately 2 weeks as the jet stream moved southwards, and northerly
431 winds developed (Kemp et al., 2011). Apart from an unusually extreme Arctic Oscillation
432 (AO) index, these conditions were also attributed to negative values of North Atlantic
433 Oscillation (NAO) (Colella et al., 2012; Kemp et al., 2011; Lirman et al., 2011). The results
434 of that study agree with Roberts et al. (2014) that indicated negative AO conditions and
435 movement of cold air masses from the north during two other MCSs in the region in 2001
436 and 2003 respectively. In contrast, positive NAO conditions coincided with several MCS
437 between 1998-2010 in Costa Rica, showing intensification of trade winds over Central
438 America that appeared to favour upwelling (Alfaro and Cortés, 2012). On interannual to
439 intraseasonal timescales, climate modes of variability such as La Niña and/or the Madden-
440 Julian Oscillation can precondition strong cooling events in the Indo-Pacific region (Lloyd
441 and Vecchi, 2010), while anomalous cooling events around Java have been related to remote
442 wind forcing and Kelvin wave activity (Delman et al., 2016). Around the Tasman Sea, MCSs
443 have been linked to the stalling of global wavenumber 4 atmospheric waves' eastward
444 propagation, which can drive northward advection of cooler surface waters and anomalously
445 strong south-westerly winds causing enhanced vertical mixing (Chiswell, 2021).

446

447 **2.2.2. Climate Feedbacks**

448

449 The feedbacks of MCSs on the climate system have been addressed by only a few studies.
450 Cool SST events in the southeast Atlantic and southwest Indian Ocean region have been
451 related to significant rainfall anomalies over large parts of southern Africa (Reason, 1998;
452 Lutz et al., 2015). For example, a possible decrease of precipitation along the south and west
453 African coasts has been suggested due to southeast Atlantic cold events, for the period 1951-
454 2010 (Florenchie et al., 2004; Lutz et al., 2015). This response has been attributed to changes
455 in atmospheric circulation (e.g. changes in moisture transport), although the signal was found
456 to be seasonally asymmetric in some regions.

457

458 In the North Atlantic, cold SST anomalies have been suggested as a common precursor to
459 most of the atmospheric heatwave events in Europe back to 1980 (Duchez et al., 2016b).

460 Although a causality has not been established, the 2015 cold anomaly in the North Atlantic
 461 has been hypothesized to cause a strong meridional SST gradient, which could have initiated
 462 a Rossby wave train leading to a Jet Stream position favourable to the development of a high
 463 pressure system, and a major summer atmospheric heatwave over central Europe ranked in
 464 the top ten over the past 65 years (Duchez et al., 2016b).

465

466 3. Defining marine cold-spells

467

468 To allow for the consistent comparison of marine cold-spells (MCSs) globally in this
 469 analysis, we propose a definition for MCS as a discrete, prolonged anomalously cold water
 470 event at a particular location, and as the inverse of the marine heatwave (MHW) definition in
 471 Hobday et al. (2016; 2018). The MHW definition was adapted from an established
 472 atmospheric heatwave definition that identifies a heatwave as a discrete event if temperatures
 473 exceeded above the 90th percentile threshold of the seasonally-varying climatology for at
 474 least three consecutive days (Perkins and Alexander, 2013). These definitions use a
 475 seasonally-varying climatology, rather than a static, time-invariant climatology, to determine
 476 if an atmospheric or oceanic temperature on a given day was anomalously high. Because
 477 seawater has a longer memory timescale than air, the MHW definition applied a period of
 478 five or more days above the 90th percentile threshold (rather than three days for the
 479 atmosphere), with no more than a two day dip below that threshold (Hobday et al., 2016). A
 480 “marine heat spike” occurs when the warm ocean temperature anomaly exceeds the threshold
 481 for less than five days and is not classified as a marine heatwave (Hobday et al., 2016).

482

483 For the MCS definition proposed here, “discrete” means that there is a definitive start and end
 484 date, “anomalous” means that the cold temperature anomaly exceeds below the 10th
 485 percentile of a seasonally-varying climatology, “prolonged” means that the cold anomaly
 486 persists for at least five days with no more than two days above the threshold. If a cold
 487 anomaly is below the 10th percentile for fewer than five days, the period is referred to as a
 488 “marine cold-snap”. A threshold based on the 10th percentile is proposed owing to the
 489 limitations in long-time series observations to quantify robustly and characterise ocean
 490 temperature extremes (Oliver et al., 2021). The World Meteorological Organization standard
 491 on the creation of climatologies is to use a period of 30 years (WMO, 2018). While fewer
 492 years can be used when necessary, caution is advised when using fewer than 20 years, and
 493 time series under ten years in length should not be used for the detection of ocean
 494 temperature extremes (Schlegel et al., 2019). By using the definition for MCSs proposed here
 495 we can identify a set of metrics (Table 2): count (n) or number of events during a time period,
 496 duration (D), mean intensity (i_{mean}), maximum intensity (i_{max}), and cumulative intensity (i_{cum}).
 497 Since the intensity metrics are based on temperature anomalies, their signs are negative by
 498 definition. A full list of the MHW metrics that could be applied to MCSs are presented in
 499 Table 2 of Hobday et al. (2016).

500

501 **Table 2:** The metrics proposed for marine cold-spells (MCSs) and used throughout the
 502 analyses. Note that any metrics in units of °C are effectively inverted from those given in
 503 Table 2 of Hobday et al. (2016), which provides the complete list of potential metrics.

504

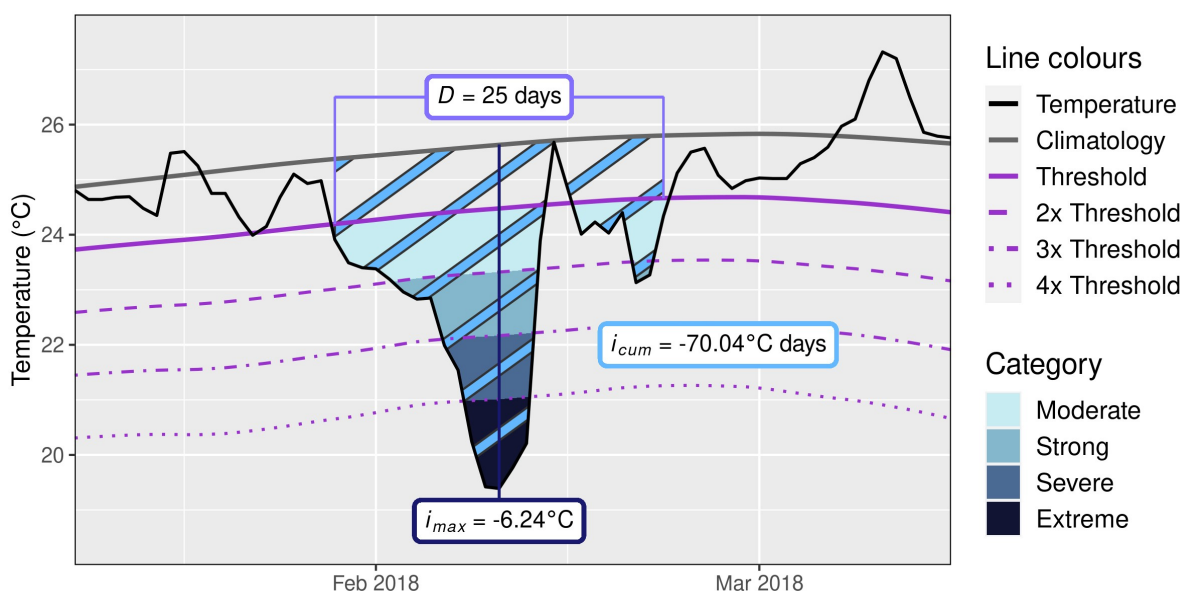
Metric (unit)	Definition
---------------	------------

Count (number of events)	n : number of MCSs in a period of time, usually one year
Duration (days)	D : count of days from start to end of MCSs
Mean intensity ($^{\circ}\text{C}$)	i_{mean} : mean temperature anomaly during the MCS
Maximum intensity ($^{\circ}\text{C}$)	i_{max} : lowest temperature anomaly during the MCS
Cumulative intensity ($^{\circ}\text{C days}$)	i_{cum} : sum of daily intensity anomalies over the duration of the event

505

506 The proposed MCS definition allows for consistent, quantitative comparison of MCS events
 507 historically and globally. While we propose that the definition use a 10th percentile,
 508 seasonally-varying threshold, we recognise that this threshold may not be considered extreme
 509 and not all events identified by this method will have damaging impacts on marine life or
 510 ecosystem services. To address this issue, we adopt the MHW category naming system,
 511 which has four categories of increasing severity (Hobday et al., 2018), and apply this system
 512 for MCSs (Figure 1). This system is reminiscent of naming conventions for other natural
 513 disasters such as hurricanes, tornadoes, or earthquakes (Hobday et al., 2018). The category
 514 system for MCSs is based on the difference between the seasonal climatology and the 10th
 515 percentile threshold. An event with a negative peak temperature anomaly that is not twice the
 516 difference between the seasonally varying climatology to the 10th percentile difference is
 517 classified as Category I “Moderate” (Figure 1). Similarly, if the peak anomaly is double the
 518 distance, but not triple, the event is Category II “Strong” and the same approach can be used
 519 to identify events that are Category III “Severe” and Category IV “Extreme”. Not all events
 520 identified within a given category will have the same damaging impacts on marine life or
 521 ecosystem services. The MCS definition used here does not depend on these criteria. Rather,
 522 the category system allows for a more quantitative understanding of the intensity of the
 523 events detected at a given location and how they may compare to other regions of the global
 524 ocean.

525



526

527 **Figure 1:** An example of a marine cold-spell (MCS). The portion of the time series
 528 experiencing one of the four possible categories are filled accordingly. The metrics shown are

529 duration (D ; days), maximum intensity (i_{max} ; °C), and cumulative intensity (i_{cum} ; °C days).
530 The cumulative intensity of the event is the area covered by hatching.

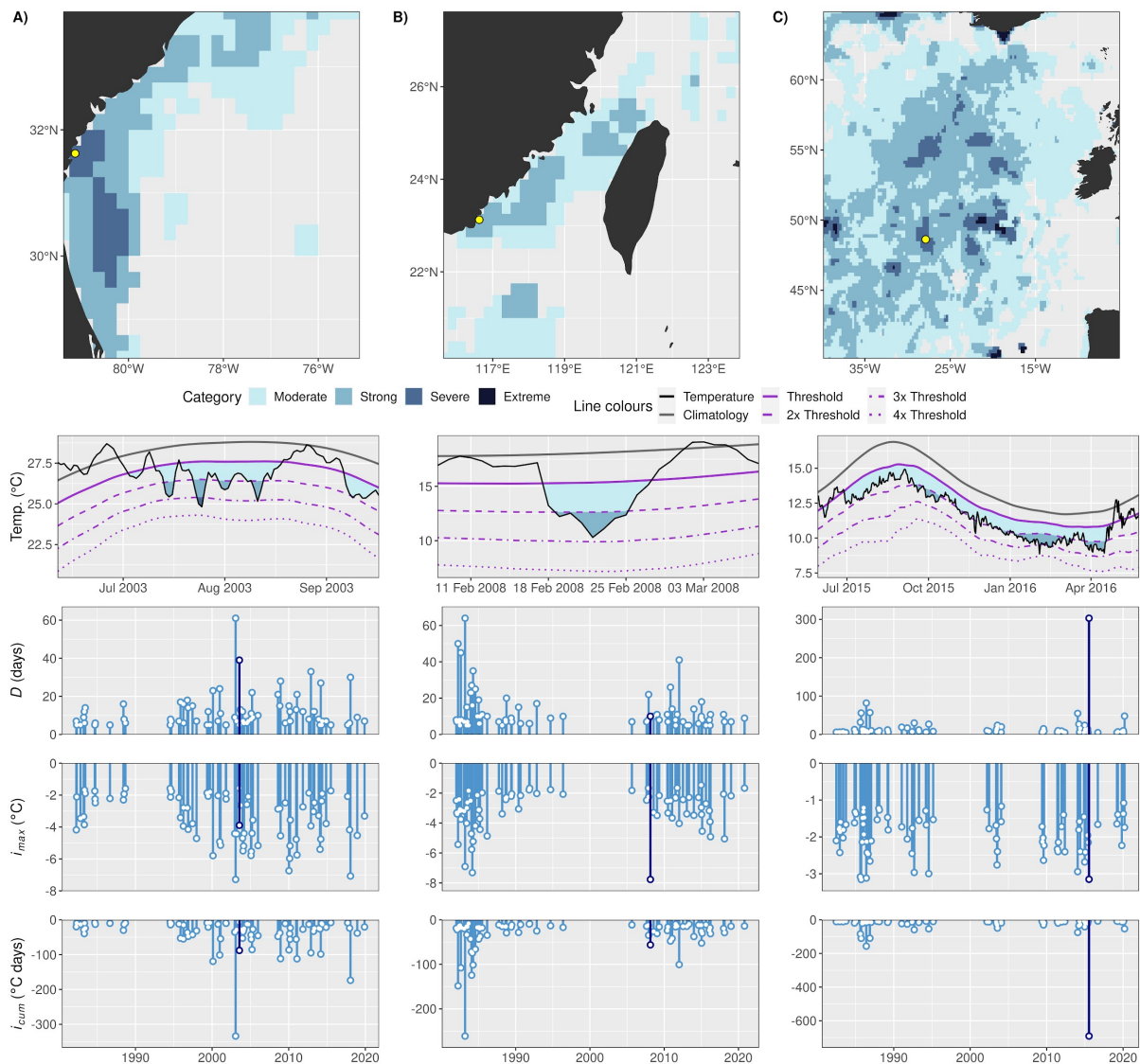
531

532 While performing the global analysis of MCSs using the definition proposed here, it became
533 clear that near-ice regions of the ocean (i.e. polar and subpolar seas) were problematic for the
534 accurate detection of events and the modelling of global trends (see section 4.2). At issue
535 were category thresholds with temperature values below the freezing point of seawater. To
536 address this we introduce an additional flag to the MCS categories: whenever a MCS was
537 detected and the 10th percentile threshold was below -1.7°C it was flagged as an “Ice” event.
538 In addition to this, “near-ice regions” were defined to be the collection of points in the ocean
539 where at least one “Ice” MCS was experienced within a given SST time series (Figure S1).
540 This does not affect the calculation of the 10th percentile threshold and, therefore, has no
541 impact on the metrics or trends calculated for MCSs. In this way the basic MCS metrics
542 (Table 1) are still globally comparable, and because the ice flag is optional, a researcher may
543 choose to use it or not depending on the research question at hand.

544

545 The MCS definition proposed here was applied to three well known MCS events, which we
546 considered in more detail as case studies. The 2003 Florida MCS (Figure 2A) occurred at the
547 peak of summer and was due to seasonally anomalous upwelling (Hyun and He, 2010). The
548 2008 MCS of the Taiwan Strait (Figure 2B) led to the die offs of both wild reef fish (Hsieh et
549 al. 2008) and cage farmed fish (Lee et al. 2014). The 2013-2016 North Atlantic “cold blob”
550 (Figure 2C) was one of the largest MCSs in the satellite record. While this event persisted to
551 the south of Greenland for years (Duchez et al., 2016b; Josey et al., 2018), its ecological
552 consequences are unclear due to limited ecological observations.

553



554
 555 **Figure 2:** Three notable marine cold-spells (MCS) from the literature. Column A) shows the
 556 2003 Summer Florida MCS; B) the 2008 Taiwan Strait MCS; and C) the North Atlantic
 557 Ocean cold blob of roughly 2013-2016. The top row of panels show the highest MCS
 558 category that occurred in each pixel during the duration of the MCS at the focal pixel (i.e. the
 559 pixel with the most intense temperature anomaly; yellow point). The second row of panels
 560 show the time series of the MCS from the focal pixel. The last three rows of panels are
 561 lollipop plots that show a key MCS metric for the events at the focal pixel for the full 39 year
 562 time series. These metrics are duration (D ; days), maximum intensity (i_{max} ; °C), and
 563 cumulative intensity (i_{cum} ; °C days). The MCS from the focal pixel is highlighted in dark blue
 564 in the bottom three panels. Note that the greatest impacts of the Taiwan MCS (B) in the
 565 literature were recorded to the southwest of the island, but no MCSs were detected there with
 566 the OISST product.
 567

Case study: The Florida 2003 marine cold-spell

During summer 2003, a well-documented, intense, cold water event was observed in the southeast coast of the United States with ocean temperature anomalies 4°C – 8°C below normal (Fig. 2A; Sun et al., 2004). This MCS evolved as six distinctive cold wakes in some regions over three months (June-September) and was caused by anomalous coastal upwelling. The anomalous upwelling was forced primarily by the strongest and most

persistent southerly winds over the last seven years, elevating the thermocline in combination with southward-propagating coastally trapped waves, which enhanced the ocean response (Yuan 2006; Aretxabaleta et al., 2006; 2007; Miles et al., 2009; Hyun & He, 2010). An anomalous atmospheric teleconnection pattern (unusually strong and westward-displaced Azores High) was responsible for the anomalous wind patterns off the US east coast, affecting also European summer heatwaves (Schwing and Pickett, 2004). Although this large-scale atmospheric pattern was a principal driving mechanism, local oceanographic processes led to spatial differences in the observed cold water masses. In particular, off the Mid-Atlantic coast, the main contribution to the MCS came from southward advection of cold water from the North Atlantic (Sun et al., 2004). In the South Atlantic Bight, the anomalously cold water likely originated from deep parts of the Gulf Stream, owing to the passage of cyclonic frontal eddies (Aretxabaleta et al., 2006). Furthermore, high precipitation and river discharge during spring 2003, increased salinity stratification through elevated freshwater input, causing a positive feedback, whereby Ekman velocity in the upper ocean layer was enhanced, and upwelling therefore strengthened (Aretxabaleta et al., 2006). Strong thermal stratification during the summer was considered an additional preconditioning mechanism, which in combination with the persistent upwelling-favourable winds strengthened the upwelling and allowed the cold bottom water to intrude further onshore and northward (Aretxabaleta et al., 2006). This unusual upwelling and intrusion was potentially facilitated by the intensity and shoreward proximity of the Gulf Stream core (Hyun and He, 2010). Upwelling in the mid-Atlantic is not normally a summer phenomenon and is sometimes absent from the seasonal means of some years (Schwing and Pickett, 2004).

This MCS was accompanied by enhanced chlorophyll concentration along the east coast of the United States in July 2003, most likely owing to the nutrient-rich bottom water that was upwelled (Yuan, 2006). Other observations showed well-developed subsurface phytoplankton blooms, increased primary production, mortality of reef fish, cold shock of turtle hatchlings (Aretxabaleta et al., 2006; 2007), and the presence of rockfish that otherwise appear during the fall (Sun et al., 2004). The event interfered with tuna fishing and other fisheries of the region (no specific interference is given), aggravating existing difficulties for recreational businesses as well, due to the weak economy and rainy summer season of that year (Sun et al., 2004; Yuan., 2006).

568

Case Study: Taiwan Strait 2008 marine cold-spell

In late January/early February 2008, a rapid decrease in winter ocean temperatures ($\sim 11^{\circ}\text{C}$ over one month), accompanied by persistently low temperatures, led to a mass kill of coral reef fishes and macroinvertebrates in the Penghu Archipelago, near Taiwan Island (Fig. 2B; Hsieh et al., 2008). The cold ocean temperatures were below the critical minimum for some reef fishes (Hsieh et al., 2008), with a minimum anomaly 7°C cooler than average (Chang et al., 2009). Mass kills were also reported for caged-fish aquaculture (~ 500 tons; Lee et al., 2014), resulting in economic losses with declines in coastal fisheries (Chang et al., 2013).

The marine cold spell developed from atypical atmospheric influences on the ocean currents. In the Taiwan Strait, unusually strong and prolonged cold northeasterly winds caused the

cold China Coastal Current to shift southward (Chang et al., 2009; Chang et al., 2013). A branch of the cold current extended southeast to the Penghu Archipelago, whereas typically warmer Kuroshio water and South China Sea water extended northward into the eastern Taiwan Strait (Chang et al., 2009). Thus, an unusual cross-strait transport of cold waters contributed to the MCS and the ecological impacts reported in the Penghu Archipelago (Shen et al., 2020). Regional relationships between the strengthened winter monsoon and a La Niña phase may offer pathways toward predictability of MCS in the Taiwan Strait and the development of early warning systems at sub-seasonal to seasonal time scales (Cheng and Chang, 2018).

569

Case study: The 2013-2016 Atlantic cold Blob

From 2013 to 2016, exceptionally cold surface temperatures developed in the eastern North Atlantic subpolar Gyre that extended up to 700 m deep (Fig. 2C; Josey et al., 2018). This event received considerable attention as a sudden and intense cold feature that occurred near the long-term cooling area of the subpolar Atlantic, amidst a generally warming trend of the planet due to anthropogenic climate change. During its peak in the summer of 2015, referred to as the “Big Blue Blob”, temperature anomalies were at least 2°C lower than the climatology of 1948-2015 (Duchez et al., 2016b). This MCS occurred in a highly variable region, influenced by multiple drivers on a wide range of timescales (Yeager et al., 2016). Therefore, many possible contributors have been proposed, such as the combination of severe atmosphere-driven air-sea heat losses during the winter of 2014/2015 with the re-emergence of cold subsurface water masses originating in the winter of 2013/14 (Duchez et al., 2016a). The latter study argued that the development of this MCS was due to processes that acted on sub-annual timescales and should not be confused with the long-term cooling trend of the adjacent region described by Drijfhout et al., (2012) and Rahmstorf et al., (2015). The 2014/15 heat loss was associated with a positive state of the NAO (and of the East Atlantic Pattern; Josey et al., 2018) and characterized by strong westerly winds, as a result of an intensification of the meridional surface pressure gradient. A potential reduction in the Atlantic Meridional Overturning Circulation (AMOC) in the post-1995 decades, might also have had a role to play in preconditioning the subpolar North Atlantic for this anomalously cold temperatures, through intrinsic climate processes (Yeager et al., 2016). Bhatrasataponkul, (2018) however, indicated that surface forcing alone was insufficient to explain this cold event, suggesting that freshening and upper ocean cooling would increase stratification and therefore enhance the persistence of the cold blob.

As of the writing of this paper no literature was found on the potential ecological/fisheries impacts of this event. This is likely due to the location of this event in the open ocean where less research of this type is conducted.

570

4. Global patterns in marine cold-spells

571

572

573 MCSs and their characteristics and categories were calculated globally from 1982 - 2020 at a
 574 ¼ degree resolution using the National Oceanic and Atmospheric Administration (NOAA)
 575 daily OISST v2.1 product (Reynolds et al., 2007; Banzon et al., 2016; Banzon et al., 2020;

576 Huang et al., 2021) with a climatological baseline period of 1982 - 2011. This period was
577 chosen as it was the closest match to the period suggested by the World Meteorological
578 Organization (WMO, 2018) given that the first full year of OISST data was 1982. We
579 examined the mean annual state and annual trends of MCSs and compared their spatial
580 patterns with those of MHWs and the underlying sea surface temperature anomaly (SSTa)
581 distribution. This section concludes with a summary of the annual statistics and trends for
582 MCS categories.

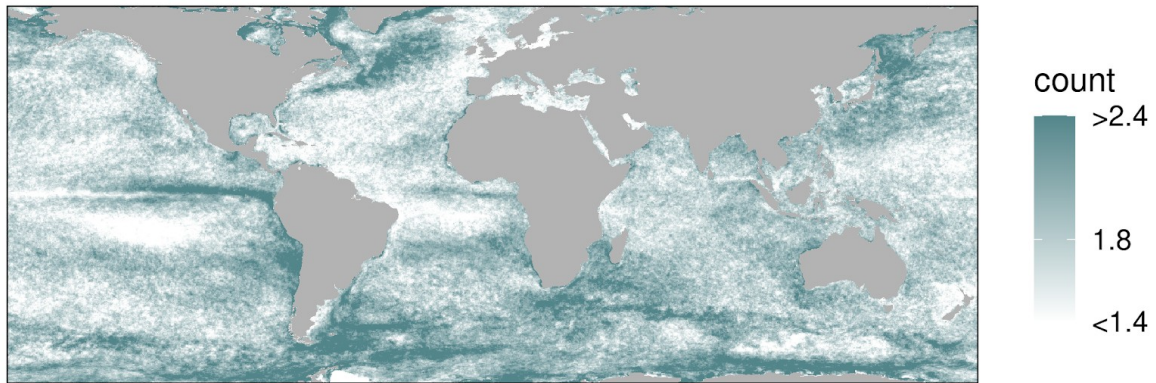
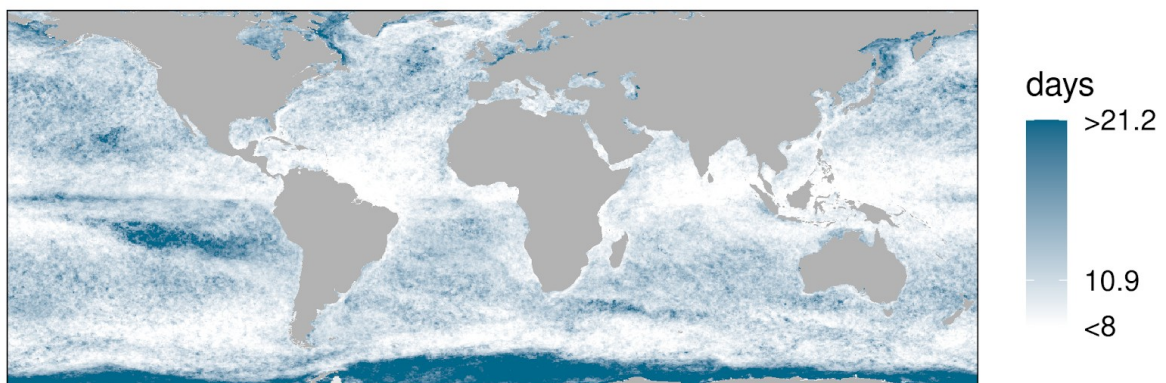
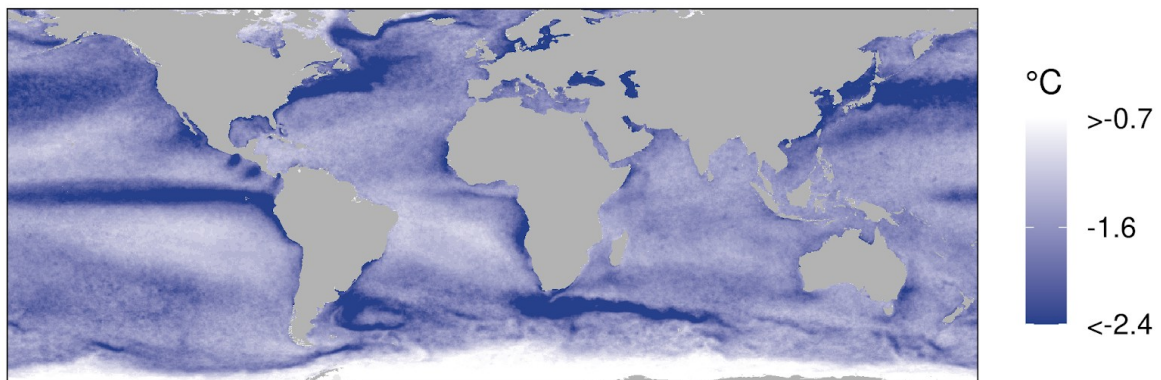
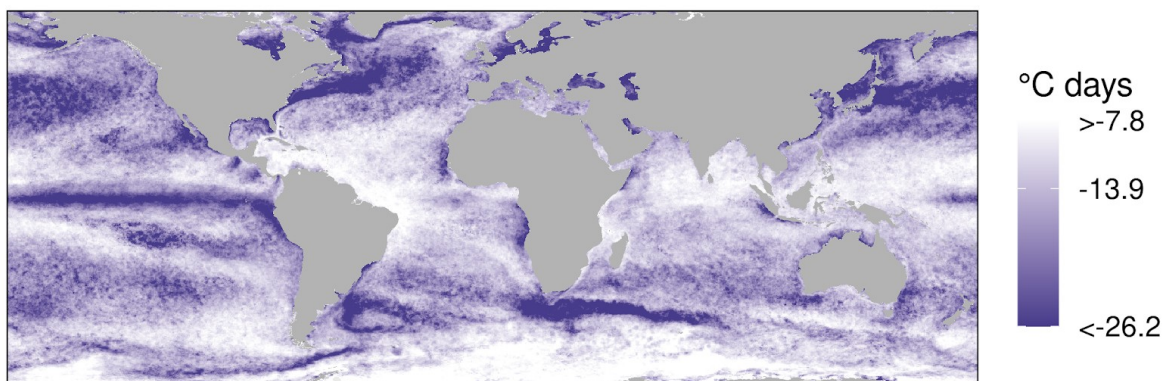
583

584 **4.1. Mean state**

585

586 Throughout the global ocean, the mean annual count of MCSs was not spatially uniform.
587 Higher annual counts of MCSs were observed in the western boundary currents and eastern
588 equatorial Pacific (Figure 3A). The areas in which the annual count of MCSs were highest
589 tended not to coincide with the regions with greatest event duration (Pearson correlation
590 coefficient; $r = 0.10$; Figure 3B). For example, many areas of open ocean that experienced
591 relatively low annual counts of events displayed high annual durations. The maximum
592 intensity of MCSs was greatest in the equatorial Pacific and the western boundary currents
593 (Figure 3C). This pattern corresponds to areas of high SST variance, and the spatial maps of
594 maximum MCS intensity and SST variance are strongly correlated ($r = -0.90$; i.e. anomalies
595 are more negative with increased variance). The global patterns in the cumulative intensity of
596 MCSs match closely with maximum intensity ($r = 0.78$; Figure 3D).

597

A) Mean MCS annual count (n)**B) Mean MCS duration (D)****C) Mean MCS maximum intensity (i_{max})****D) Mean MCS cumulative intensity (i_{cum})**

598

599

600

Figure 3: Global patterns of mean annual marine cold-spell (MCS) metrics calculated from 1982-2020. Maps shown for annual mean A) count (n); B) duration (D ; days); C) maximum

601 intensity (i_{max} ; °C); D) cumulative intensity (i_{cum} ; °C days). For each panel's colourbar labels
602 the three values shown are the 5th, 50th, and 95th percentile of the global values. For clearer
603 visualisation, any values above or below the 5th or 95th percentile are shown as those
604 percentiles. Note that more intense MCSs (C, D) have more negative values, while increased
605 counts (A) and durations (B) of MCSs have positive values. These same plots with median
606 annual values may be seen in Supplementary Figure S2.

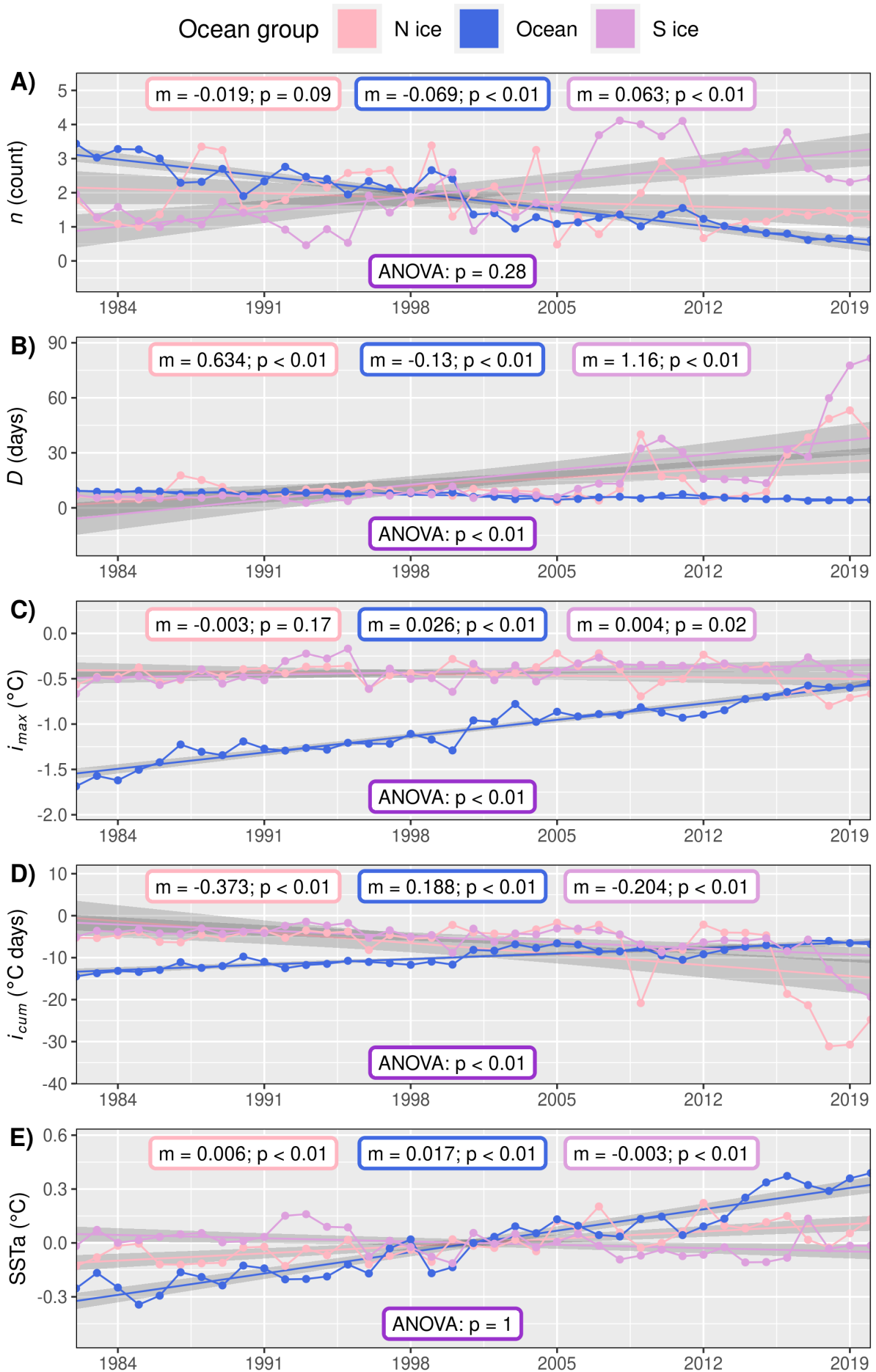
607

608 **4.2. Trends**

609

610 The trends of annual changes in MCS metrics varied substantially between near-ice and ice-
611 free areas of the ocean. Separate analyses were performed for each region. The near-ice
612 regions generally corresponded to the Arctic Ocean, Southern Ocean, and portions of the
613 subpolar seas. The annual values for the MCS metrics used in the following analyses were
614 created by spatially averaging the MCS metrics per pixel per year. Annual trends were
615 calculated with linear models, and the difference between the annual values were determined
616 with a one-way analysis of variance (ANOVA). For the open ocean and southern near-ice
617 region, the trends in the annual count were significant ($p < 0.01$; Figure 4A). These trends
618 were negative (i.e. fewer events per year) in the open ocean (-0.069 events/year) and northern
619 near-ice region (-0.019 events/year) but positive in the southern near-ice region (0.063
620 events/year). The differences in the annual count of MCSs between the regions were not-
621 significant ($p = 0.28$).

622



623
624
625

Figure 4: Trends in the marine cold-spell (MCS) metrics for the open ocean (blue) and northern (pink) and southern near-ice regions (purple). The near-ice regions are defined as

626 having had at least one “Ice” flagged MCS. The annual values are the spatially averaged
627 results of the MCS metrics per pixel in the given region for the given year. The slope (m ;
628 units/year) and significance (p -value) of fitted linear models are shown in colour
629 corresponding labels at the top of each panel, with the bottom label in each panel showing the
630 significance of a one-way ANOVA for the given metric. The definition of the metrics (A-D)
631 is given in Table 2. The sea surface temperature anomaly (SSTa) values in panel E are the
632 spatial average of the annual SSTa values per pixel per group; they are not from the
633 seasonally varying climatologies created via the MCS algorithm.

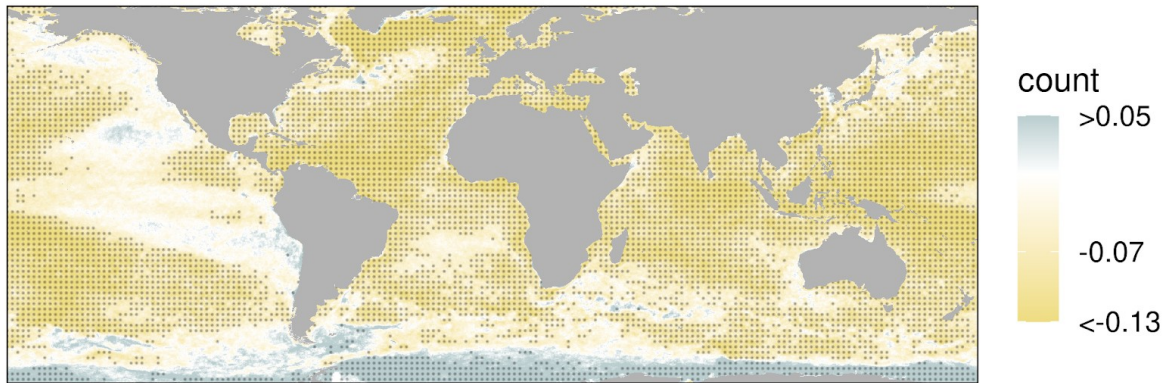
634

635 The most rapid decreases in MCS count were in the high-latitude and tropical North Atlantic,
636 the tropical Indo-Pacific, and the mid-latitude regions of the North Pacific and South Pacific,
637 where the significant declines exceed one fewer event per decade ($p < 0.05$; Figure 5A).

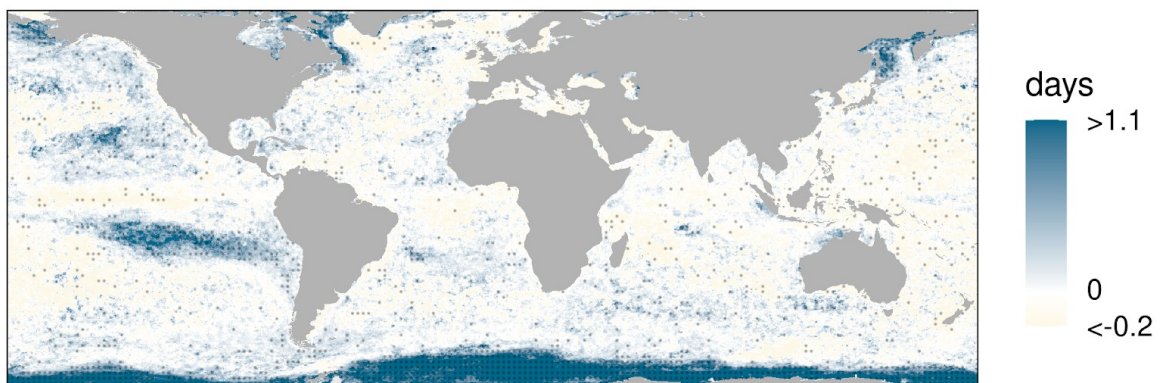
638 Much of the eastern Pacific has had no noticeable change in MCS count, with most of the
639 Southern Ocean experiencing significantly increased counts ($p < 0.05$). Given the record
640 length (39 years), this spatial pattern confounds the influence of long-term climate change
641 with multi-decadal variability, which is most notably due to the Atlantic Multidecadal
642 Oscillation and the Interdecadal Pacific Oscillation (e.g. as for MHWs in Oliver et al., 2018).

643

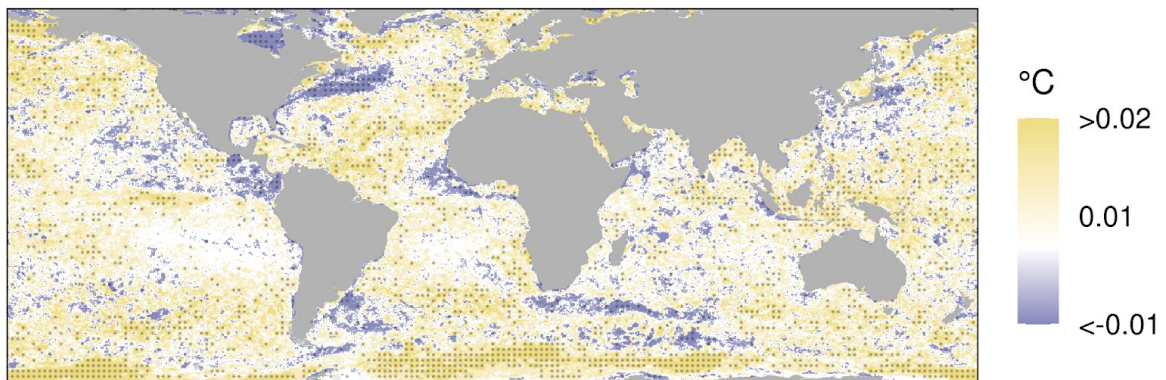
A) Trends for MCS annual count (n)



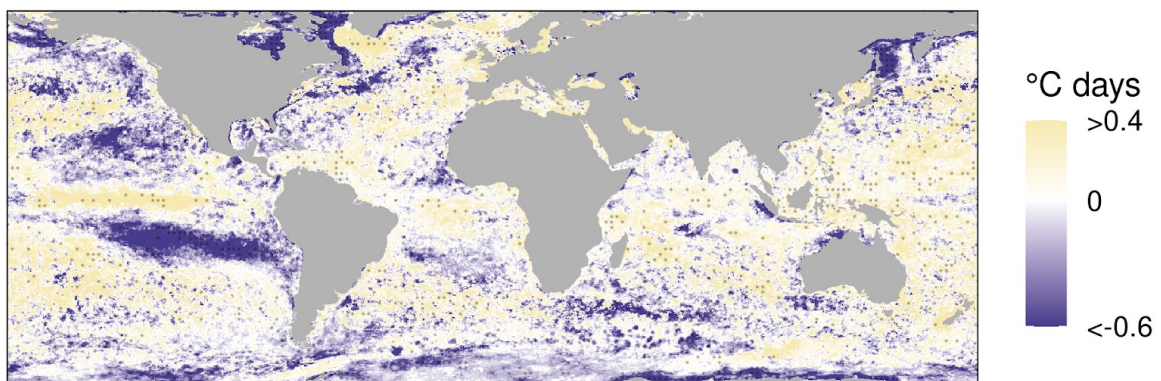
B) Trends for MCS duration (D)



C) Trends for MCS maximum intensity (i_{max})



D) Trends for MCS cumulative intensity (i_{cum})



644

645 **Figure 5:** Global patterns of annual trends in marine cold-spell (MCS) metrics calculated

646 from 1982-2020. The values in the colourbar labels for each panel are unit/year: A) count

647 (n); B) duration (D ; days); C) maximum intensity (i_{max} ; °C); D) cumulative intensity (i_{cum} ; °C
648 days). The legend of each panel shows the global 5th, 50th, and 95th percentiles of the trends
649 per pixel. The values above/below the 5th/95th percentiles were rounded to the nearest
650 respective percentile for improved data visualisation. Note that MCS maximum intensity (C)
651 and MCS cumulative intensity (D) are in negative units, so trends that show increasing
652 intensity (negative) of these metrics are blue, while a lessening intensity (positive) is yellow.
653 For example, most of the ocean is experiencing decreases in the maximum intensity of MCSs
654 (C) (i.e. the maximum negative temperature anomalies are lessening, thereby reducing in
655 magnitude), but the cumulative intensity of MCSs (D) over much of the ocean is increasing
656 (i.e. the sum of the temperature anomalies during an event may be becoming more negative).
657 The global trends in change to both maximum and cumulative intensity are however weak.
658 Statistically significant ($p \leq 0.05$) trends are shown with stippling.
659

660 For all three ocean regions, the change in the duration of MCSs was significant ($p < 0.01$;
661 Figure 4B). This change was negative (i.e. shorter events per year) in the open ocean (-0.13
662 days/year) but positive in the northern near-ice region (0.634 days/year) and southern near-
663 ice region (1.16 days/year). For the near-ice regions, these increases in duration are relatively
664 extreme and due largely to the rapid increases in durations since 2015. Between the three
665 regions, the annual durations are significantly different ($p < 0.01$). Spatially, most of the mid-
666 latitudes show a slight non-significant decrease in MCS duration, whereas significant ($p <$
667 0.05) increases in MCS duration were found throughout most of the Southern Ocean, the
668 eastern equatorial Pacific, and some of the subpolar seas (Figure 5B). Generally, the areas
669 where MCS are increasing in count, such as the Southern Ocean and eastern Pacific, are also
670 the areas in which durations are increasing ($r = 0.48$).

671
672 None of the three ocean regions showed significant decreases (strengthening) in MCS
673 maximum intensity. In the open ocean, the maximum intensity of MCSs has reduced
674 significantly (become warmer) over the satellite era from a mean of -1.68°C in 1982 to -
675 0.54°C in 2020 (+0.026°C/year; $p < 0.01$; Figure 4C). The northern near-ice region (Figure
676 S1) has shown a very slight non-significant strengthening of intensity (-0.003°C/year, $p =$
677 0.17), while the southern near-ice region has seen a very slight but significant weakening
678 (+0.004°C/year; $p = 0.02$). The annual maximum intensity of MCS is significantly different
679 between the regions ($p < 0.01$). Because MCS intensities are negative values, positive
680 (negative) trends (i.e. areas of yellow (blue) in Figure 5C) indicate a lessening
681 (strengthening) of MCS intensity. While most of the Southern Ocean shows significant
682 decreases in MCS intensity of +0.015°C/year ($p < 0.05$), the poleward extensions of the
683 western boundary currents, the Hudson Bay, and the Arctic Archipelago are becoming
684 significantly more intense with a trend of -0.005°C/year or greater ($p < 0.05$).

685
686 The cumulative intensity of MCSs changed significantly in all three regions ($p < 0.01$; Figure
687 4D). The open ocean showed a weakening (+0.188°C days/year; $p < 0.01$), while the northern
688 near-ice region (-0.373°C days/year) and southern near-ice region (-0.204°C days/year)
689 showed strengthening. The trends in cumulative intensity use the same sign convention as for
690 maximum intensity, which means that negative values indicate a strengthening trend. The
691 changes in the cumulative intensity of MCSs most closely matches the changes to the
692 duration of these events, with increasing event duration strengthening the corresponding
693 cumulative intensities (Figure 5D; $r = -0.67$). Changes in cumulative intensity will be

694 reflected in changes to both intensity and duration. Since the changes to MCS intensity are
695 either negligible or slightly weakening, the changes in MCS duration are controlling the
696 reported changes in cumulative intensity. Note however that this pattern does not hold in the
697 Southern Ocean, which is seeing the most dramatic increases to MCS duration accompanied
698 by decreases to maximum intensity.

699

700 To provide context for the global trends in MCS metrics, the annual SST anomalies for the
701 three regions were analysed with the same linear model and ANOVA tests (Figure 4E). The
702 open ocean shows a significant warming trend of $0.017^{\circ}\text{C}/\text{year}$ ($p < 0.01$), exceeding the
703 expected rate from the Intergovernmental Panel on Climate Change (IPCC, 2013; 0.11
704 $^{\circ}\text{C}/\text{dec}$) and is a straightforward explanation for the weakening found in MCS metrics (with
705 the exception of the eastern equatorial Pacific). The northern near-ice region is also warming
706 significantly ($0.006^{\circ}\text{C}/\text{year}$; $p < 0.01$), but at a much slower rate than is projected by the
707 IPCC (Collins et al., 2019). One explanation is that no ocean pixels further than 70° from the
708 equator were used here, meaning that many of the fastest warming regions of the Arctic were
709 not included in the northern near-ice region. We may also see that there are both strong
710 positive and negative trends in MCS intensity in the higher latitudes (Figure 5C; D). In the
711 southern near-ice region, the annual rate of change in SST anomalies has been significantly
712 negative ($-0.003^{\circ}\text{C}/\text{year}$; $p < 0.01$), indicating a shift in the temperature regime in the
713 Southern Ocean. A closer analysis of pixels in this region revealed that while the positive
714 SST anomalies during open water periods may be increasing (a warming trend), the duration
715 of the ice cover periods (i.e. days with temperatures below -1.7°C) are generally lengthening.
716 This feature is why the duration, and thereby cumulative intensity, of MCSs in the southern
717 near-ice region are increasing while the maximum intensities are weakening. This area is
718 generally close to freezing, and indeed the MCS threshold in winter is $\sim -1.7^{\circ}\text{C}$, so intensities
719 cannot strengthen there. Instead, earlier onset of freezing and later break-up of ice in the
720 season could extend the duration of identified MCS events. Further investigation into how
721 this result compares with different satellite products was beyond the scope of this study. We
722 further discuss whether or not these near-ice events should be considered as MCSs in Section
723 4.4.

724

725 **4.3. Asymmetry between MHWs and MCSs**

726

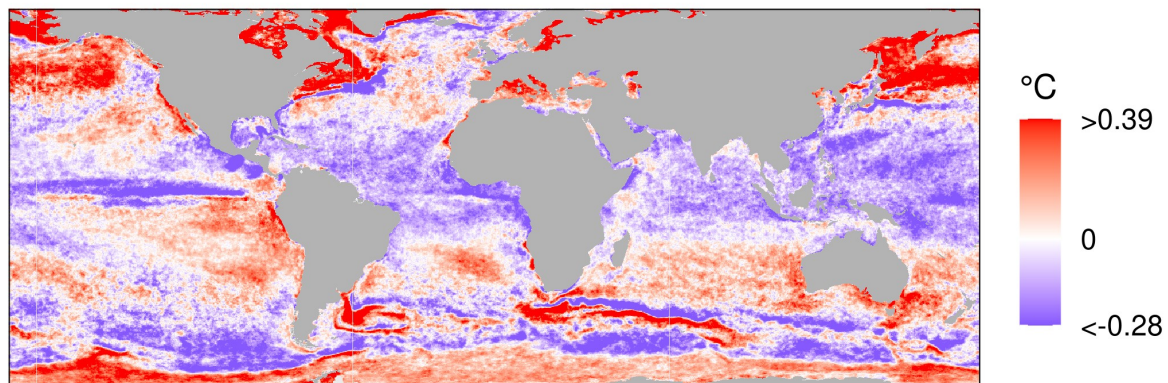
727 We measured the asymmetry between MHWs and MCSs by comparing their intensity values
728 spatially. We calculated the asymmetry between MHW maximum intensity and MCS
729 maximum intensity as $i_{max,MHW} + i_{max,MCS}$, being the sum of the two metrics given the defined
730 sign conventions (e.g. $i_{max,MHW} > 0$, $i_{max,MCS} < 0$). In this sum, negative values indicated MCS
731 maximum intensities were more intense than those from MHWs, while positive values
732 indicated the reverse. Notably, MCSs were more intense than MHWs in some parts of the
733 ocean (Figure 6A, blue areas). For example, much of the Tropics and the equatorward side of
734 western boundary current extensions exhibited this feature. On the other hand, MHWs were
735 more intense than MCSs at high-latitudes and on the poleward side of western boundary
736 current extensions (Figure 6A, red areas).

737

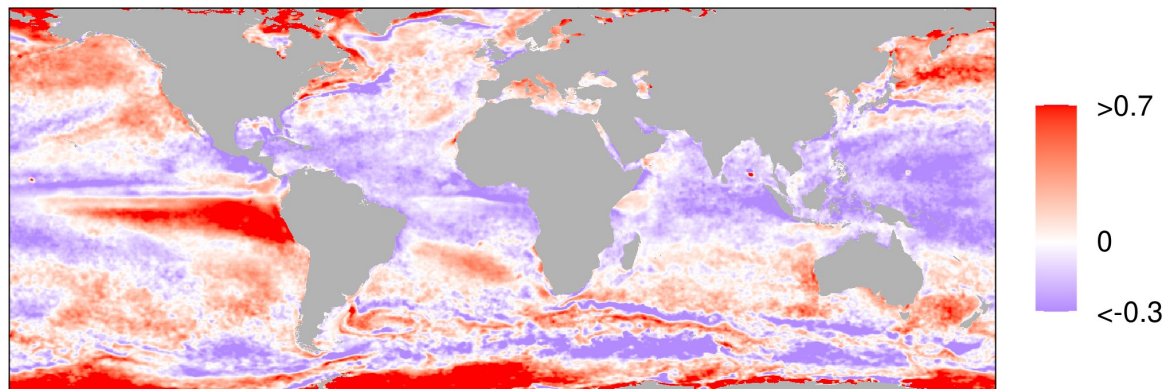
738 This asymmetry can be explained by the underlying temperature distribution. If the SSTa
739 distribution was normally distributed, the warm and cold tails would be symmetric with
740 warm and cold extremes to be of equivalent intensities and opposite in sign. However, if the

741 temperature distribution is skewed, then the intensity of extremes on the skewed side of the
 742 distribution can be expected to be more intense than on the non-skewed side. For example,
 743 the portions of western boundary current extensions dominated by cold-core eddies (the
 744 equatorward side) will have a negative SST skewness, while areas dominated by warm-core
 745 eddies (the poleward side) will have a positive SST skewness (see Thompson and Demirov
 746 (2006) for an analogous signal in sea surface heights). A comparison of the SSTa skewness
 747 (Figure 6B) with the asymmetry between MHW and MCS intensity (Figure 6A) shows that
 748 areas of positive SST skewness correspond to areas of greater MHW intensity while areas of
 749 negative SST skewness correspond to areas of greater magnitude MCS intensity ($r = 0.48$).
 750

A) Sum of maximum intensities ($i_{max,MHW} + i_{max,MCS}$)



B) SSTa skewness



751
 752 **Figure 6:** The global relationship of the sum of marine heatwave (MHW) and marine cold-
 753 spell (MCS) intensities with SST anomaly (SSTa) skewness calculated from 1982-2020. A)
 754 The sum of the maximum intensities of MHWs and MCSs as determined by adding the
 755 average maximum intensity of the events at each pixel. Blue areas show greater MCS
 756 intensities. B) The standardised skewness of SSTa. The values shown in each colourbar label
 757 are the 5th, 50th and 95th percentiles of the values in each panel. Any values above or below
 758 those percentiles are rounded to their nearest percentile for better plotting. Median values for
 759 panel A may be seen in Supplementary Figure S3.
 760

760

761 4.4. Categories

762

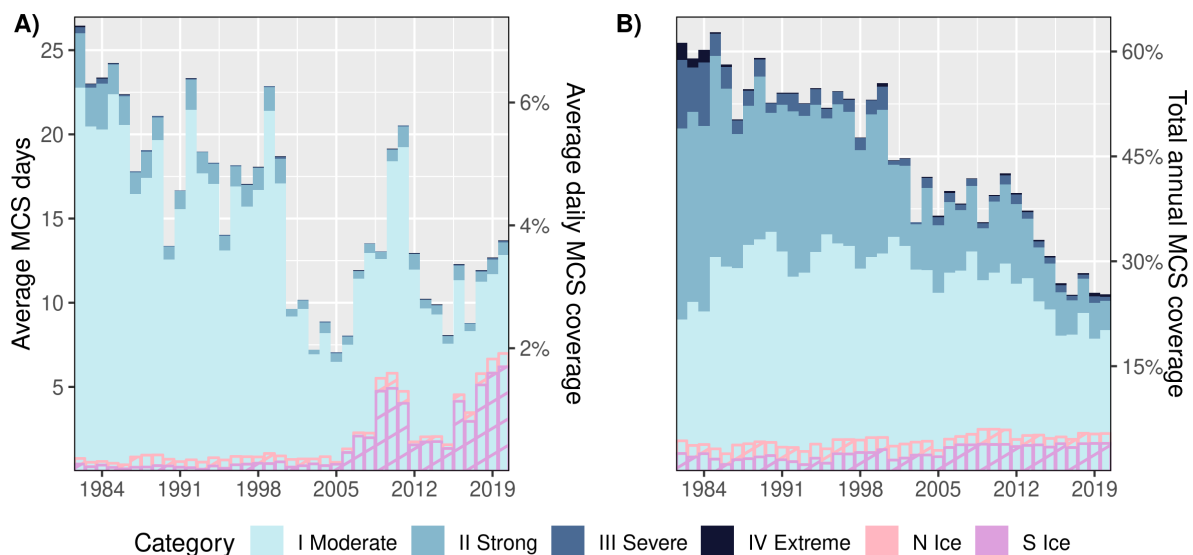
763 At a global scale, the category ranks of MCSs are decreasing (Figure 7). The average MCS
 764 days per year was highest in 1982 at 26 days and lowest in 2005 at 7 days (Figure 7A; left y-
 765 axis). There was a temporary increase in the average MCS days per year from 2007, peaking
 766 in 2011, before decreasing again to around 12 days/year. Almost all MCS days in any given

767 year have been “I Moderate”, but the proportion of “II Strong” days has remained steady
 768 since 2005. Based on the contribution of MCS days from the southern near-ice area (Figure
 769 7A; purple shading), the increase in MCS days has been largely due to the increasing duration
 770 of MCSs in the Southern Ocean (Figure 5B). The average number of MCS days per year in
 771 the open ocean (non-shaded region) has decreased significantly from 26 days in 1982 to 7
 772 days in 2020 (linear trend of -0.5 days/year; $R^2 = 0.71$; $p < 0.01$; Figure 7A). At the start of
 773 the satellite period, roughly 6 - 7% of the surface of the ocean was experiencing a MCS of
 774 any given category on any day of the year (Figure 7A; right y-axis). This coverage has
 775 reduced roughly in half since 2012 with now only 2 - 4% of the ocean experiencing MCSs on
 776 any day. The proportion of the daily coverage of MCSs of any category other than “I
 777 Moderate” has almost disappeared.

778

779 The overall amount of the surface of the ocean that experienced a MCS each year has also
 780 reduced significantly from 61% in 1982 to 25% in 2020 ($m = -0.9\%/year$; $R^2 = 0.91$; $p <$
 781 0.01 ; Figure 7B). Category “IV Extreme” MCSs have been very rare throughout the satellite
 782 record, but from 1982 - 1984 the occurrence of “III Severe” events was not uncommon. In
 783 recent years, however, almost all MCS coverage of the surface of the ocean over a given year
 784 has been only “I Moderate”. The annual number of MCS days for the near-ice regions, which
 785 are “I Moderate” category events, has increased significantly at 0.13 days/year ($p < 0.01$; R^2
 786 $= 0.54$), largely owing to the sudden and rapid increases in 2007 and 2016. Even though the
 787 southern near-ice region now contributes half of the annual count of MCS days, there has
 788 been no increase in the surface area of the ocean affected by this region (Figure 7B) as it
 789 cannot expand any larger than its predefined boundary (Figure S1).

790



791

792 **Figure 7:** Global annual summary of marine cold-spell (MCS) categories. A) Average annual
 793 MCS days for the ocean (left y-axis), which may be divided by 365 to determine the average
 794 daily coverage (% area) of the ocean for a given year (right y-axis); B) The total area (%
 795 of the ocean that experienced one or more MCSs over the given year, and what the highest
 796 category experienced was. The colour of the bars show the contribution from the
 797 corresponding categories. The contributions from the northern near-ice region (N Ice; pink)
 798 and southern near-ice region (S Ice; purple) are shown as overlays. Note that in all panels
 799 there is a general decreasing trend, with the exception of an increase in “I Moderate” category
 800 events starting in ~2007 due to increases in the duration and spatial extent of events primarily
 801 in the Southern Ocean.

802

803 **5. Discussion and conclusions**

804

805 Marine cold-spells are ocean temperature extreme events with ecological and societal impacts
806 and have been the focus of regional and species-specific studies. However, the field has
807 lacked a standard use of terminology and framework for defining MCSs to facilitate global
808 applications and comparisons across studies. We have synthesized an extensive body of
809 knowledge within a MCS framework based on their global occurrences, physical
810 mechanisms, and ecological impacts. MCSs have caused ecosystem disturbances including
811 mass fish and invertebrate kills (e.g. Woodhead, 1964), population decreases, coral bleaching
812 (Zapata et al., 2011), changes in species distribution (e.g. range shifts) and phenology (e.g.
813 onset of the growing season; Jentsch et al., 2007), with most severe impacts usually occurring
814 during winter months. As illustrated by selected case studies, changes in air-sea heat fluxes
815 and both horizontal and vertical ocean currents can contribute to MCSs. In coastal regions,
816 cold air outbreaks over shallow waters can cause rapid chilling of waters, while extremely
817 strong winds can induce unusual upwelling and changes in coastal currents resulting in
818 MCSs.

819

820 While past studies have used a range of identification conventions for MCS-related events,
821 these conventions have not been widely or consistently used by the marine science
822 community. Based on uptake of the recently developed MHW definition (Hobday et al.,
823 2016; 2018), we have chosen to adapt this methodology as a potential tool for investigating
824 cold ocean temperature extremes. By applying this definition to identify cold extremes, the
825 method can be applied to SST time series for the detection of MCSs. However, ocean
826 temperatures have a lower limit set by the freezing point of seawater and near-ice regions of
827 the ocean often are close to this temperature, confounding the use of percentiles for the
828 detection events. To accommodate this issue, we have introduced an “Ice” flag into the MCSs
829 definition, which is activated when the 10th percentile threshold on any day during a MCS is
830 below -1.7°C . By adapting the widely used Hobday et al. (2016; 2018) MHW definition, we
831 anticipate that the MCS definition proposed here will have the potential to be widely
832 applicable in the marine sciences, with implementations in marine heatwave/cold-spell
833 studies (e.g. Schlegel and Smit, 2018) and SST data visualisation products, such as the
834 Marine Heatwave Tracker (<http://www.marineheatwaves.org/tracker.html>; Schlegel, 2020).
835 We contend that there is no single correct way to select a methodology for the detection of
836 MCSs, rather the choice must be defined by the research objectives or stakeholder needs. The
837 definition proposed here aims to provide a useful framework for comparing MCS events
838 across different regions and time periods. Through analysis of global gridded time series of
839 SST, we found that MCSs have been prevalent throughout the global ocean over the satellite
840 period but that their frequency and intensity are in decline globally, with the exception of the
841 Southern Ocean and eastern equatorial Pacific. The MCS trends are in direct contrast with
842 MHW trends, which are increasing in both duration and intensity over almost all of the global
843 ocean (Oliver et al., 2018). Indeed, regions of the ocean where MCSs are not diminishing
844 tend also to be regions where MHWs are not increasing.

845

846 This work is an important synthesis and extension of the diverse body of existing knowledge
847 on MCSs. This study is the first investigation to quantify and report on MCS occurrence and
848 trends in a global context. These results can be used as a road map for policy makers and

849 managers to know where, and to what degree, certain parts of the ocean are exposed to
850 MCSs, and the degree to which this exposure may be changing with time. Importantly, we
851 show that MCSs lead to significant impacts on marine ecosystems, with the potential to
852 disrupt fisheries and aquaculture operations.

853

854 Importantly, MCSs are declining globally, which will contribute to changing the temperature
855 regime experienced by many marine ecosystems. This could alter the structure and function
856 of these ecosystems. For example, less extreme cold events could shift selection pressure
857 away from cold hardy species and change local patterns of adaptation (e.g., Campbell-Staton
858 et al., 2017). In a warming ocean, MCSs could play a role in slowing the spread of non-
859 native or invasive species (Rehage et al., 2016) or warm-adapted species, such as those that
860 shift poleward (Pecl et al., 2017), offering refuge for cold-adapted local taxa (Feng et al.,
861 2020). The occurrence of these events should be considered in restoration efforts involving
862 translocation of warm-adapted species to cooler regions, given species' potential exposure to
863 cold stress which could affect how they establish (e.g. Nielsen et al., 2020). It is unclear how
864 the underlying atmospheric and oceanographic mechanisms that drive the formation of MCSs
865 will change in the future, and therefore challenging to predict regional shifts in cold ocean
866 extremes. Yet, with increasing concern regarding global ocean warming and intensifying
867 research efforts on the increasing impacts of MHWs, there is a need for understanding how
868 fewer, shorter, less intense MCSs could affect marine ecosystems. Given their dual roles in
869 shaping marine ecosystems with implications for societal needs, identifying when and where
870 prolonged periods of cold water occur, and how they will change, are important steps for
871 managing and protecting our marine estate.

872

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874

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876 may be downloaded from: [https://www.ncei.noaa.gov/data/sea-surface-temperature-
877 optimum-interpolation/v2.1/access/avhrr/](https://www.ncei.noaa.gov/data/sea-surface-temperature-optimum-interpolation/v2.1/access/avhrr/). The code used for these analyses may be found at
878 this GitHub repository: <https://github.com/robwschlegel/MCSglobal>. The additions to the
879 methodology for detecting and quantifying MCSs proposed in this study are available via the
880 R package heatwaveR: <https://robwschlegel.github.io/heatwaveR/>. Lastly, we would like to
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882 Their keen insight and gracious criticisms were instrumental in polishing the text.

883

884 **Author contributions**

885

886 **RWS:** Methodology, Software, Validation, Formal analysis, Data Curation, Writing -
887 Original Draft, Visualization, Project administration. **SD:** Literature Review, Writing -
888 Original Draft. **JAB:** Literature Review, Writing - Original Draft, Supervision. **KFD:**
889 Literature Review, Writing - Review & Editing. **ECJO:** Conceptualization, Methodology,
890 Writing - Original Draft, Supervision.

891


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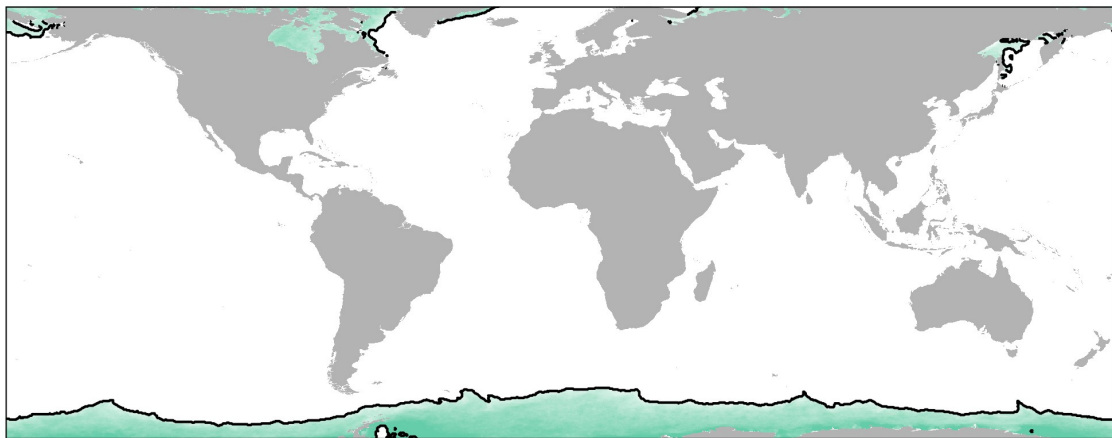
893

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900

901 **Supplementary figures**

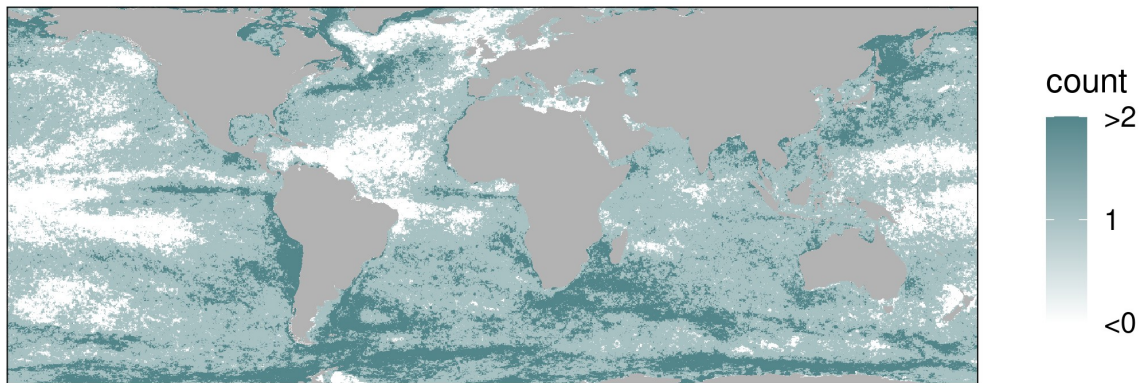
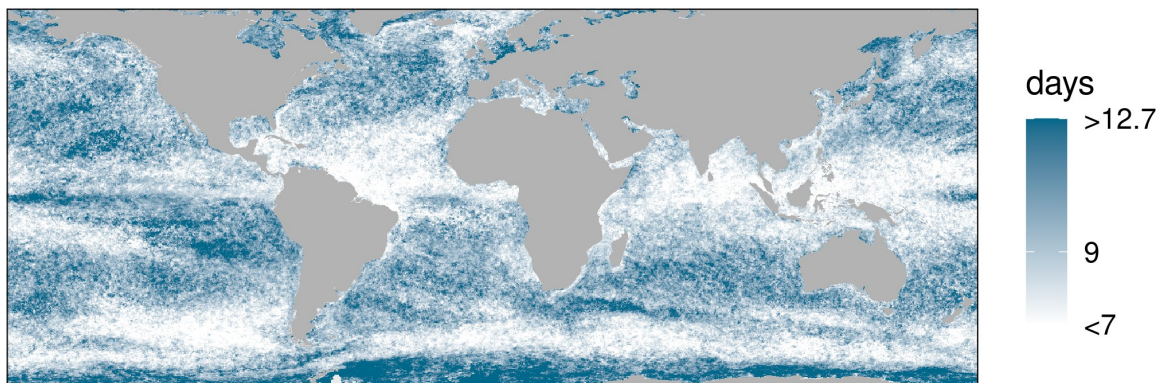
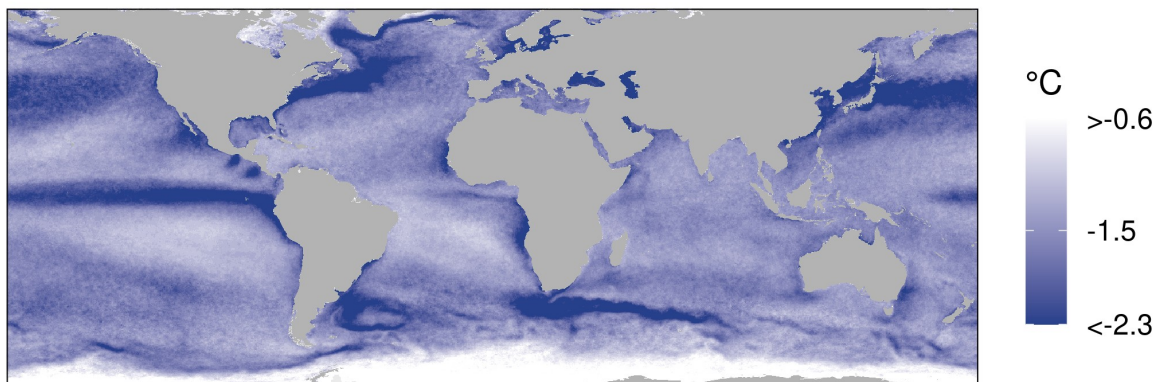
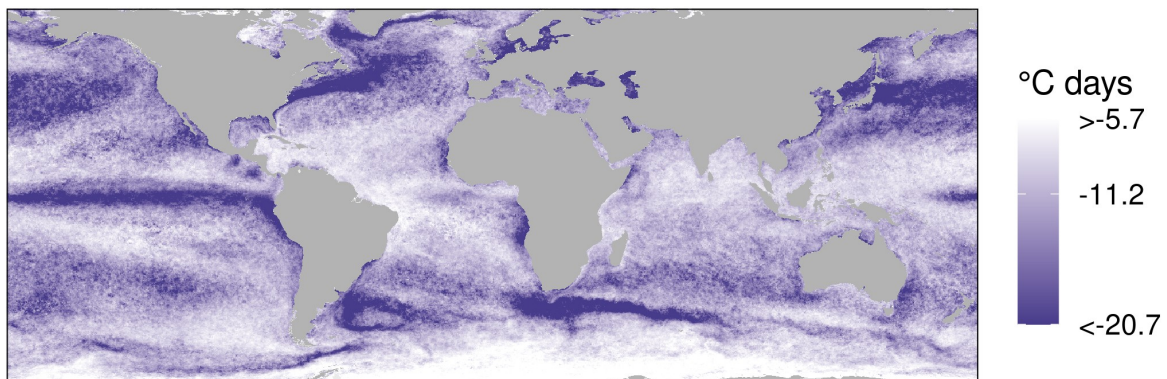
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Ice MCS proportion 
0.00 0.25 0.50 0.75 1.00



903

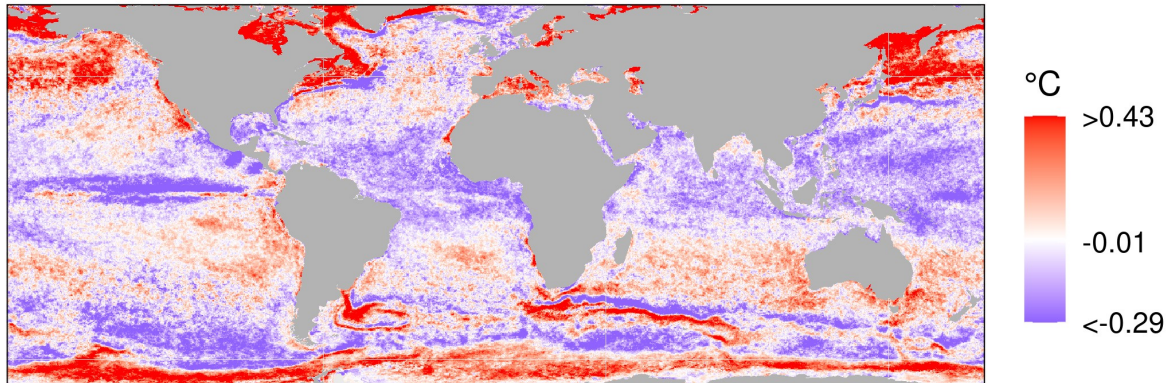
904 **Figure S1:** The areas of the ocean that have been denoted as “near-ice” are denoted by black
905 contours and are determined when at least one marine cold-spells (MCSs) has been flagged
906 as an “Ice” event at any point over the 39-year time series. Within these near-ice regions,
907 values (green shading) show the proportion of MCSs that can be classified as “Ice” events.
908 This “Ice” classification is determined whenever the 10th percentile threshold during a MCS
909 is below -1.7°C at any point during the event. A proportion of 1.0 means that every MCS at
910 the given pixel is classified as an “Ice” event. A proportion of 0.0 means none of the MCSs
911 are “Ice” events. There are some areas within the near-ice regions that show values of zero,
912 because, in the satellite record, these areas are always frozen (-1.8°C) so it is not possible to
913 detect MCSs there.

A) Median MCS annual count (n)**B) Median MCS duration (D)****C) Median MCS maximum intensity (i_{max})****D) Median MCS cumulative intensity (i_{cum})**

914 **Figure S2:** As in Figure 3, except with the median values per pixel, rather than the means.
 915 Note that the same broad patterns are seen in both, with only minor changes to the 5th, 50th,

916 and 95th percentile values shown in the legends of each panel. The difference between the
917 mean (Figure 3) and median (Figure S2) values is most pronounced in the count of events
918 (panel A).
919

Sum of median maximum intensities ($i_{max,MHW} + i_{max,MCS}$)



920 **Figure S3:** As in in Figure 6A, but with median values rather than means. Note that the same
921 patterns are clearly visible with only minor changes to the 5th, 50th, and 95th percentile values
922 in the legend.

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